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

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9 Author Note

¹³   Abstract

¹⁴   As they develop into mature speakers of their native language, infants must not only learn

¹⁵ words but also the sounds that make up those words. To do so, they must strike a balance

¹⁶ between accepting speaker dependent variation (e.g. mood, voice, accent), but

¹⁷ appropriately rejecting variation when it (potentially) changes a word's meaning (e.g. cat

¹⁸ vs. hat). This meta-analysis focuses on studies investigating infants' ability to detect

¹⁹ mispronunciations in familiar words, or mispronunciation sensitivity. Our goal was to

²⁰ evaluate the development of infants' phonological representations for familiar words as well

²¹ as explore the role of experimental manipulations related to theoretical questions and of

²² analysis choices. The results show that although infants are sensitive to mispronunciations,

²³ they still accept these altered forms as labels for target objects. Interestingly, this ability is

²⁴ not modulated by age or vocabulary size, suggesting that a mature understanding of native

²⁵ language phonology may be present in infants from an early age, possibly before the

²⁶ vocabulary explosion. These results support several theoretical assumptions made in the

²⁷ literature, such as sensitivity to mispronunciation size and position of the

²⁸ mispronunciation. We also shed light on the impact of data analysis choices that may lead

²⁹ to different conclusions regarding the development of infants' mispronunciation sensitivity.

³⁰ Our paper concludes with recommendations for improved practice in testing infants' word

³¹ and sentence processing on-line.

³²   *Keywords:* language acquisition; mispronunciation sensitivity; word recognition;

³³ meta-analysis; lexicon; infancy

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

35   In a mature phono-lexical system, word recognition must balance flexibility to slight

36 variation (e.g., speaker identity, accented speech) while distinguishing between phonological

37 contrasts that differentiate words in a given language (e.g. cat-hat). This meta-analysis

38 examines the latter, focusing how infants apply the relevant phonological categories of their

39 native language, aggregating twenty years' worth of studies using the mispronunciation

40 sensitivity paradigm. The original study of Swingley & Aslin (2000) presented

41 American-English learning 18- to 23-month-olds with pairs of images of words they were

42 very likely to know (e.g. a baby and a dog) and their eye movements to each image were

43 recorded. Infants either heard the correct label (e.g. "baby") or a mispronounced label

44 (e.g. "vaby") for one of the images. Although infants looked at the correct target image in

45 response to both types of labels, correct labels elicited more looking to the target image

46 than mispronounced labels. Swingley & Aslin (2000) concluded that already before the

47 second birthday, children's representations for familiar words are phonologically well

48 specified. As we will review below, there are opposing theories and resulting predictions,

49 supported by empirical data, as to how this knowledge is acquired and applied to lexical

50 representations. The time is thus ripe to aggregate all publicly available evidence using a

51 meta-analysis. In doing so, we can examine developmental trends making use of data from

52 a much larger and diverse sample of infants than is possible in most single studies.

53   An *increase* in mispronunciation sensitivity with age is predicted by a maturation

54 from holistic to more detailed phono-lexical representations and has been supported by

55 several studies (Altvater-Mackensen, 2010; Altvater-Mackensen, Feest, & Fikkert, 2014;

56 Feest & Fikkert, 2015; Mani & Plunkett, 2007). The first words that infants learn are often

57 not similar sounding (e.g. mama, ball, kitty; Charles-Luce & Luce, 1995) and encoding

58 representations for these words using fine phonological detail may not be necessary.

59 According to PRIMIR (Curtin & Werker, 2007; Werker & Curtin, 2005) infants' initially

60 episodic representations give way to more abstract phonological word forms, as the infant

61 learns more words, the detail of which can be accessed more or less easily depending on

62 factors such as the infant's age or the demands of the task. This argument is supported by

63 the results of Mani & Plunkett (2010), who found that 12-month-old infants with a larger

64 vocabulary showed a greater sensitivity to vowel mispronunciations than infants with a

65 smaller vocabulary.

66   Yet, the majority of studies examining a potential association between

67 mispronunciation sensitivity and vocabulary size have concluded that there is no

68 relationship (Bailey & Plunkett, 2002; Ballem & Plunkett, 2005; Mani, Coleman, &

69 Plunkett, 2008; Mani & Plunkett, 2007; Swingley, 2009; Swingley & Aslin, 2000, 2002;

70 Zesiger, Lozeron, Levy, & Frauenfelder, 2012). Furthermore, other studies testing more

71 than one age have found *no difference* in mispronunciation sensitivity (Bailey & Plunkett,

72 2002; Swingley & Aslin, 2000; Zesiger et al., 2012). Such evidence supports an early

73 specificity hypothesis, which suggests continuity in how infants represent familiar words.

74 According to this account, infants represent words with phonological detail already at the

75 onset of lexical acquisition and that this persists throughout development.

76   There are no theoretical accounts that would predict *decreased* mispronunciation

77 sensitivity, but at least one study has found a decrease in sensitivity to small

78 mispronunciations. Here, 18- but not 24-month-old infants showed sensitivity to more

79 subtle mispronunciations that differed from the correct pronunciation by 1 phonological

80 feature (Mani & Plunkett, 2011). Mani & Plunkett (2011) argue that when faced with

81 large and salient mispronunciations, infants' sensitivity to small 1-feature

82 mispronunciations may be obscured. This would especially be the case if infants show

83 graded sensitivity to different degrees of mispronunciations (see below), as Mani &

84 Plunkett (2011) found with 24- but not 18-month-olds in their study.

85   To disentangle the predictions that phono-lexical representations are progressively

86 becoming more specified or are specified early, we investigate the relationship between

mispronunciation sensitivity and age as well as vocabulary size by aggregating 20 years of mispronunciation sensitivity studies. But, this may not account for all variability found in the literature. Indeed, different laboratories may vary in their approach to creating a mispronunciation sensitivity experiment, using different types of stimuli and methodologies. Many studies pose more nuanced questions, such as examining the impact of number of phonological features changed (mispronunciation size) or the location of the mispronunciation. Some studies may differ in their experimental design, presenting a distractor image that is either familiar or completely novel. In our meta-analysis we code for features of the experiment that are often reported but vary across studies and include an analysis of these features to shed further light on early phono-lexical representations and their maturation.

These research questions and experimental manipulations have the potential to create experimental tasks that are more or less difficult for the infant to successfully complete. The PRIMIR Framework (Processing Rich Information from Multidimensional Interactive Representations; Curtin & Werker, 2007; Werker & Curtin, 2005) describes how infants learn to organize the incoming speech signal into phonetic and indexical detail. The ability to access and use this detail, however, is governed by the task or developmental demands probed in a particular experiment. For example, if infants are tested on a more subtle mispronunciation that changes only one phonological feature, they may be less likely to identify the change in comparison to a mispronunciation that changes two or three phonological features (White & Morgan, 2008). If older infants are more likely to be tested using a more demanding mispronunciation sensitivity task, this may attenuate developmental effects across studies. Note, however, that those studies we reviewed above reporting change (Altvater-Mackensen, 2010; Altvater-Mackensen et al., 2014; Feest & Fikkert, 2015; Mani & Plunkett, 2007) or no change (Bailey & Plunkett, 2002; Swingley & Aslin, 2000; Zesiger et al., 2012) all presented the same task across ages.

The first set of questions concerns how infants' sensitivity is modulated by different

kinds of mispronunciations. Following on the above example, some experiments examine infants' sensitivity to factors that change the identity of a word on a measurable level, or *mispronunciation size* (i.e. 1-feature, 2-features, 3-features), finding that infants are more sensitive to larger mispronunciations (3-feature-changes) than smaller mispronunciations (1-feature changes) for both consonant (Bernier & White, 2017; Tamasi, 2016; White & Morgan, 2008) and vowel (Mani & Plunkett, 2011) mispronunciations, known as graded sensitivity. This also has consequences for understanding the developmental trajectory of mispronunciation sensitivity, as adults show similar graded sensitivity (Bailey & Hahn, 2005).

The position of mispronunciation in the word may differentially interrupt the infant's word recognition process, but the degree to which position impacts word recognition is a matter of debate. The COHORT model (Marslen-Wilson & Zwitserlood, 1989) describes lexical access in a linear direction, with the importance of each phoneme decreasing as its position comes later in the word. In contrast, the TRACE model (McClelland & Elman, 1986) describes lexical access as constantly updating and reevaluating the incoming speech input in the search for the correct lexical entry, and therefore can recover from word onset and to a lesser extent medial mispronunciations. To evaluate these competing theories, studies often manipulate the *mispronunciation position*, whether onset, medial, or coda, in the word.

Consonantal changes may be more disruptive to lexical processing than vowel changes, known as the consonant bias, and a learned account predicts that this bias emerges over development and is impacted by the language family of the infants' native language (for a review see Nazzi, Poltrock, & Von Holzen, 2016). Yet, the handful of studies directly comparing sensitivity to consonant and vowel mispronunciations mostly find symmetry as opposed to an asymmetry between consonants and vowels for English- (Mani & Plunkett, 2007, 2010; but see Swingley, 2016) and Danish-learning infants (Højen et al., n.d.) and do not compare infants learning different native languages (for

141 cross-linguistic evidence from word-learning see Nazzi, Floccia, Moquet, & Butler, 2009).

142 In the current meta-analysis, we examine infants' sensitivity to the *type of*

143 *mispronunciation*, whether consonant or vowel, across different ages and native language

144 families to assess the predictions of the learned account of the consonant bias.

145   A second set of questions is whether the experimental context modulates infants'

146 responses to mispronunciations. In order to study the influence of mispronunciation

147 position, many studies control the *phonological overlap between target and distractor labels.*

148 For example, when examining sensitivity to a vowel mispronunciation of the target word

149 "ball", the image of a ball would be paired with a distractor image that shares onset

150 overlap, such as "bed", as opposed to a distractor image that does not share onset overlap,

151 such as "truck". This ensures that infants cannot use the onset of the word to differentiate

152 between the target and distractor images (Mani & Plunkett, 2007). Instead, infants must

153 pay attention to the mispronounced phoneme in order to successfully detect the change.

154   Mispronunciation sensitivity may also be modulated by *distractor familiarity*:

155 whether the distractor used is familiar or unfamiliar. This is a particularly fruitful question

156 to investigate within the context of a meta-analysis, as mispronunciation sensitivity in the

157 presence of a familiar compared to unfamiliar distractor has not been directly compared.

158 Most studies present infants with pictures of two known objects, thereby ruling out the

159 unlabeled competitor, or distractor, as possible target. It is thus not surprising that infants

160 tend to look towards the target more, even when its label is mispronounced. In contrast,

161 other studies present infants with pairs of familiar (labeled target) and unfamiliar

162 (unlabeled distractor) objects (Mani & Plunkett, 2011; Skoruppa, Mani, Plunkett, Cabrol,

163 & Peperkamp, 2013; Swingley, 2016; White & Morgan, 2008). By using an unfamiliar

164 object as a distractor, the infant is presented with a viable option onto which the

165 mispronounced label can be applied (Halberda, 2003; Markman, Wasow, & Hansen, 2003).

166   In sum, the studies we have reviewed begin to paint a picture of the development of

167 infants' use of phonological detail in familiar word recognition. Each study contributes one

168 separate brushstroke and it is only by examining all of them together that we can achieve a

169 better understanding of the big picture of early phono-lexical development. Meta-analyses

170 can provide unique insights by estimating the population effect, both of infants' responses

171 to correct and mispronounced labels, and of their mispronunciation sensitivity. Because we

172 aggregate data over age groups, this meta-analysis can investigate the role of maturation

173 by assessing the impact of age, and when possible vocabulary size. We also test the

174 influence of different linguistic (mispronunciation size, position, and type) and contextual

175 (overlap between target and distractor labels; distractor familiarity) factors on the study of

176 mispronunciation sensitivity. Finally, we explore potential data analysis choices that may

177 influence different conclusions about mispronunciation sensitivity development as well as

178 offer recommendations for experiment planning, for example by providing an effect size

179 estimate for a priori power analyses (Bergmann et al., 2018).

Methods

181   The present meta-analysis was conducted with maximal transparency and

182 reproducibility in mind. To this end, we provide all data and analysis scripts on the

183 supplementary website (https://osf.io/rvbjs/) and open our meta-analysis up for updates

184 (Tsuji, Bergmann, & Cristia, 2014). The most recent version is available via the website

185 and the interactive platform MetaLab (https://metalab.stanford.edu; Bergmann et al.,

186 2018). Since the present paper was written with embedded analysis scripts in R (R Core

187 Team, 2018) using the papaja package (Aust & Barth, 2018) in R Markdown (Allaire et

188 al., 2018), it is always possible to re-analyze an updated dataset. In addition, we followed

189 the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)

190 guidelines and make the corresponding information available as supplementary materials

191 (Moher, Liberati, Tetzlaff, Altman, & PRISMA Group", 2009). Figure 1 plots our

192 PRISMA flowchart illustrating the paper selection procedure.

193   (Insert Figure 1 about here)

Study Selection

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

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

197 Google Scholar search engine to search for papers citing the original Swingley & Aslin

198 (2000) publication. This search was conducted on 22 September, 2017 and yielded 288

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

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

201 data was reported; (2) the experiment examined familiar word recognition and

202 mispronunciations; (3) infants studied were under 31-months-of-age and typically

203 developing; (4) the dependent variable was derived from proportion of looks to a target

204 image versus a distractor in a eye movement experiment; (5) the stimuli were auditory

205 speech. The final sample ($n = 32$) consisted of 27 journal articles, 1 proceedings paper, 2

206 theses, and 2 unpublished reports. We will refer to these items collectively as papers. Table

207 1 provides an overview of all papers included in the present meta-analysis.

208   (Insert Table 1 about here)

Data Entry

210   The 32 papers we identified as relevant were then coded with as much consistently

211 reported detail as possible (Bergmann et al., 2018; Tsuji et al., 2014). For each experiment

212 (note that a paper typically has multiple experiments), we entered variables describing the

213 publication, population, experiment design and stimuli, and results. For the planned

214 analyses to evaluate the development of mispronunciation sensitivity and modulating

215 factors, we focus on the following characteristics: 1) Condition: Were words mispronounced

216 or not; 2) Mean age reported per group of infants, in days; 3) Vocabulary size, measured by

217 a standardized questionnaire or list; 4) Size of mispronunciation, measured in features

218 changed; 5) Position of mispronunciation: onset, medial, coda; 6) Type of

219 mispronunciation: consonant, vowel, or both; 7) Phonological overlap between target and

220 distractor: onset, medial, coda, none; 8) Distractor familiarity: familiar or unfamiliar. A

221 detailed explanation for moderating factors 3-8 can be found in their respective sections in

222 the Results.[1] We separated conditions according to whether or not the target word was

223 mispronounced to be able to investigate infants' looking to the target picture as well as

224 their mispronunciation sensitivity, which is the difference between looks to the target in

225 correct and mispronounced trials. When the same infants were further exposed to multiple

226 mispronunciation conditions and the results were reported separately in the paper, we also

227 entered each condition as a separate row (e.g., consonant versus vowel mispronunciations;

228 Mani & Plunkett, 2007). The fact that the same infants contributed data to multiple rows

229 (minimally those containing information on correct and mispronounced trials) leads to

230 shared variance across effect sizes, which we account for in our analyses (see next section).

231 We will call each row a record; in total there were 251 records in our data.

232 **Data analysis**

233   Effect sizes are reported for infants' looks to target pictures after hearing a correctly

234 pronounced or a mispronounced label (object identification) as well as the difference

235 between effect sizes for correct and mispronounced trials (i.e. mispronunciation sensitivity).

236 The effect size reported in the present paper is based on comparison of means,

237 standardized by their variance. The most well-known effect size from this group is Cohen's

238 d (Cohen, 1988). To correct for the small sample sizes common in infant research, however,

239 we used Hedges' g instead of Cohen's d (Hedges, 1981; Morris & DeShon, 2002).

240   We calculated Hedges' g using the raw means and standard deviations reported in the

241 paper ($n = 177$ records from 25 papers) or reported t-values ($n = 74$ records from 9

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[1] Two papers tested bilingual infants (Ramon-Casas & Bosch, 2010; Ramon-Casas, Swingley, Sebastián-Gallés, & Bosch, 2009), yielding 2 and 4 records, respectively. Due to this small number, we do not investigate the role of multilingualism, but do note that removing these papers from the meta-analysis did not alter the pattern of results.

242 papers). Two papers reported raw means and standard deviations for some records and

243 just t-values for the remaining records (Altvater-Mackensen et al., 2014; Swingley, 2016).

244 Raw means and standard deviations were extracted from figures for 3 papers. In a

245 within-participant design, when two means are compared (i.e. looking during pre- and

246 post-naming) it is necessary to obtain correlations between the two measurements at the

247 participant level to calculate effect sizes and effect size variance. Upon request we were

248 provided with correlation values for one paper (Altvater-Mackensen, 2010); we were able to

249 compute correlations using means, standard deviations, and t-values for 5 papers (following

250 Csibra, Hernik, Mascaro, Tatone, & Lengyel, 2016; see also Rabagliati, Ferguson, &

251 Lew-Williams, 2018). Correlations were imputed for the remaining papers (Bergmann &

252 Cristia, 2016). For two papers, we could not derive any effect size (Ballem & Plunkett,

253 2005; Renner, 2017), and for a third paper, we do not have sufficient information in one

254 record to compute effect sizes (Skoruppa et al., 2013). We compute a total of 106 effect

255 sizes for correct pronunciations and 150 for mispronunciations. Following standard

256 meta-analytic practice, we remove outliers, i.e. effect sizes more than 3 standard deviations

257 from the respective mean effect size. This leads to the exclusion of 2 records for correct

258 pronunciations and 3 records for mispronunciations.

259   To consider the fact that the same infants contributed to multiple datapoints, we

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

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

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

263 In the random effect structure we take into account the shared variance of effect sizes

264 drawn from the same paper, and nested therein that the same infants might contribute to

265 multiple effect sizes.

266   Mispronunciation sensitivity studies are typically examine infants' proportion of

267 target looks (PTL) in comparison to some baseline measurement. PTL is calculated by

268 dividing the percentage of looks to the target by the total percentage of looks to both the

²⁶⁹ target and distractor images. Across papers the baseline comparison varied; since other

²⁷⁰ options were not available to us, we used the baseline reported by the authors of each

²⁷¹ paper. Over half of the records ($n = 129$) subtracted the PTL score for a pre-naming phase

²⁷² from the PTL score for a post-naming phase, resulting in a Difference Score. The

²⁷³ Difference Score is one value, which is then compared with a chance value of 0. Pre

²⁷⁴ vs. Post ($n = 69$ records) accomplishes the same analysis, directly compare the post- and

²⁷⁵ pre-naming PTL scores with one another using a statistical test (e.g. t-test, ANOVA). This

²⁷⁶ requires two values, one for the pre-naming phase and one for the post-naming phase. The

²⁷⁷ remaining records used a Post dependent variable ($n = 53$ records), which compares the

²⁷⁸ post-naming PTL score with a chance value of 50%. Here, the infants' pre-naming phase

²⁷⁹ baseline preferences are not considered and instead target fixations are evaluated based on

²⁸⁰ the likelihood to fixate one of two pictures (50%). Standardized effect sizes based on mean

²⁸¹ differences, as calculated here, preserve the sign. Consequently, positive effect sizes reflect

²⁸² more looks to the target picture after naming, and larger positive effect sizes indicate

²⁸³ comparatively more looks to the target.

²⁸⁴   Finally, we assess the statistical power of studies included in our meta-analysis, as

²⁸⁵ well as calculate the sample size required to achieve a 80% power considering our estimate

²⁸⁶ of the population effect and its variance. Failing to take effect sizes into account can lead

²⁸⁷ to either underpowered research or testing too many participants. Underpowered studies

²⁸⁸ will lead to false negatives more frequently than expected, which in turn results in an

²⁸⁹ unpublished body of literature (Bergmann et al., 2018). At the same time, underpowered

²⁹⁰ studies with significant outcomes are likely to overestimate the effect, leading to wrong

²⁹¹ estimations of the population effect when paired with publication bias (Jennions, Mù,

²⁹² Pierre, Curie, & Cedex, 2002). Overpowered studies mean that participants were tested

²⁹³ unnecessarily, which has ethical implications particularly when working with infants and

²⁹⁴ other difficult to recruit and test populations.

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 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

321 (Viechtbauer, 2010). To investigate how development impacts mispronunciation sensitivity,

322 our core theoretical question, we first introduced age (centered; continuous and measured

323 in days but transformed into months for ease of interpreting estimates by dividing by

324 30.44) as a moderator to our main model. Second, we analyzed the correlation between

325 reported vocabulary size and mispronunciation sensitivity using the package meta

326 (Schwarzer, 2007). For a subsequent investigation of experimental characteristics, we

327 introduced each separately as a moderator: size of mispronunciation, position of

328 mispronunciation, type of mispronunciation, phonological overlap between target and

329 distractor labels, and distractor familiarity (more detail below).

Results

Publication Bias

332   Figure 2 shows the funnel plots for both correct pronunciations and mispronunciations

333 (code adapted from Sakaluk, 2016). Funnel plot asymmetry was significant for both correct

334 pronunciations (Kendall's $\tau = 0.52$, $p < .001$) and mispronunciations (Kendall's $\tau = 0.16$,

335 $p = 0.005$). These results, quantifying the asymmetry in the funnel plots (Figure 2),

336 indicate bias in the literature. This is particularly evident for correct pronunciations, where

337 larger effect sizes have greater variance (bottom right corner) and the more precise effect

338 sizes (i.e. smaller variance) tend to be smaller than expected (top left, outside the triangle).

339   The stronger publication bias for correct pronunciation might reflect the status of

340 this condition as a control. If infants were not looking to the target picture after hearing

341 the correct label, the overall experiment design is called into question. However, even in a

342 well-powered study one would expect the regular occurrence of null results even though as

343 a population, infants would reliably show the expected object identification effect.

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

345 factors besides publication bias, such as heterogeneity in the data. There are various

346 possible sources of heterogeneity, which our subsequent moderator analyses will begin to

347 address. Nonetheless, we will remain cautious in our interpretation of our findings and

348 hope that an open dataset which can be expanded by the community will attract

349 previously unpublished null results so we can better understand infants' developing

350 mispronunciation sensitivity.

351   (Insert Figure 2 about here)

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

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

354 correct pronunciations indicates that the data contain evidential value (Z = -17.93, $p <$

355 .001) and we find no evidence of a large proportion of p-values just below the typical alpha

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

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

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

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

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

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

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

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

364 meta-analysis.

365 **Meta-analysis**

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

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

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

369 0.919 (SE = 0.122), a large effect, which was significantly different from zero (CI [0.679,

370 1.158], $p <$ .001) with a CI lower bound of 0.68. We then calculated the meta-analytic

371 effect for object identification in response to mispronounced words. In this case, the

372 variance-weighted meta-analytic effect size was 0.251 (SE = 0.06), a small effect, which was

373 also significantly different from zero (CI [0.134, 0.368], $p < .001$). When presented with a

374 correct or mispronounced label, infants fixated the correct object.

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

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

377 evaluate mispronunciation sensitivity, we compared the effect size Hedges' g for correct

378 pronunciations with mispronunciations directly. To this end, we combined the two

379 datasets. When condition was included (correct, mispronounced), the moderator test was

380 significant (QM(1) = 102.114, $p < .001$). The estimate for mispronunciation sensitivity was

381 0.606 (SE = 0.06), and infants' looking behavior across conditions was significantly

382 different (CI [0.489, 0.724], $p < .001$). This confirms that although infants fixate the

383 correct object for both correct pronunciations and mispronunciations, the observed

384 fixations to target (as measured by the effect sizes) were significantly greater for correct

385 pronunciations, suggesting sensitivity to mispronunciations.

386 The estimated effect for mispronunciation sensitivity in this meta-analysis is 0.61,

387 and the median sample size is 24 participants. If we were to assume that researchers assess

388 mispronunciation sensitivity in a simple paired t-test, the resulting power is 54%. In other

389 words, only about half the studies should report a significant result even with a true

390 population effect. Reversely, to achieve 80% power, one would need to test 44 participants.

391 Heterogeneity was significant for both correctly pronounced (Q(103) = 626.38, $p <$

392 .001) and mispronounced words, (Q(146) = 466.45, $p < .001$), as well as mispronunciation

393 sensitivity, which included the moderator condition (QE(249) = 1,092.83, $p < .001$). This

394 indicated that the sample contains unexplained variance leading to significant difference

395 between studies beyond what is to be expected based on random sampling error. In our

396 moderator analysis we investigate possible sources of this variance.

397 **Object Recognition and Mispronunciation Sensitivity Modulated by Age.**

398 To evaluate the different predictions we laid out in the introduction for how

399 mispronunciation sensitivity will change as infants develop, we next added the moderator

400 age (centered; continuous and measured in days but transformed into months for ease of

401 interpreting estimates by dividing by 30.44 for Figure 3).

402   In the first analyses, we investigate the impact of age separately on conditions where

403 words were either pronounced correctly or not. Age did not significantly modulate object

404 identification in response to correctly pronounced (QM(1) = 0.537, p = 0.464) or

405 mispronounced words (QM(1) = 1.663, p = 0.197). The lack of a significant modulation

406 together with the small estimates for age (correct: β = 0.014, SE = 0.019, 95% CI[-0.023,

407 0.05], p = 0.464; mispronunciation: β = 0.015, SE = 0.011, 95% CI[-0.008, 0.037], p =

408 0.197) indicates that there was no relationship between age and target looks in response to

409 a correctly pronounced or mispronounced label. However, previous experimental studies

410 (e.g. Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998) and a recent meta-analysis

411 (Frank, Lewis, & Macdonald, 2016) have found that children's speed and accuracy in

412 recognition of correctly pronounced words increases with age. Perhaps older children are

413 more likely to be tested on less-frequent, later learned words than younger children, which

414 could lead to a lack of a relationship between age and target looks in response to correct

415 pronunciations in the current meta-analysis.

416   We then examined the interaction between age and mispronunciation sensitivity

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

418 (QM(3) = 104.837, p < .001). The interaction between age and mispronunciation

419 sensitivity, however, was not significant (β = 0.012, SE = 0.013, 95% CI[-0.014, 0.038], p =

420 0.361). The small estimate, as well as inspection of Figure 3, suggests that as infants age,

421 their mispronunciation sensitivity neither increases or decreases.

422   (Insert Figure 3 about here)

423   **Vocabulary Correlations.**   Children comprehend more words than they can

424 produce, leading to different estimates for comprehension and production and we planned

425 to analyze these correlations separately. Of the 32 papers included in the meta-analysis, 13

426 analyzed the relationship between vocabulary scores and object recognition for correct

427 pronunciations and mispronunciations (comprehension = 11 papers and 39 records;

428 production = 3 papers and 20 records). Although production data may be easier to

429 estimate for parents in the typical questionnaire-based assessment, we deemed 3 papers for

430 production correlations too few to analyze. We also note that individual effect sizes in our

431 analysis were related to object recognition and not mispronunciation sensitivity, and we

432 therefore focus exclusively on the relationship between comprehension and object

433 recognition for correct pronunciations and mispronunciations.

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

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

436 recognition in response to correct pronunciations for 9 of 10 records, with correlation values

437 ranging from -0.16 to 0.48. The weighted mean effect size Pearson's r of 0.14 was small but

438 did differ significantly from zero (CI [0.03; 0.25] $p = 0.012$). As a result, we can draw a

439 tentative conclusion that there is a positive relationship between comprehension scores and

440 object recognition in response to correct pronunciations.

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

442 mispronunciations. Higher comprehension scores were associated with greater object

443 recognition in response to mispronunciations for 17 of 29 records, with correlation values

444 ranging from -0.35 to 0.57. The weighted mean effect size Pearson's r of 0.05 was small and

445 did not differ significantly from zero (CI [-0.01; 0.12] $p = 0.119$). The small correlation

446 suggests either a very small positive or no relationship between vocabulary and object

447 recognition for mispronunciations.

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

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

450 mispronunciation sensitivity studies in general and the decreasing number of

mispronunciation studies measuring vocabulary. This decrease in mispronunciation

sensitivity studies measuring and reporting vocabulary size correlations is surprising,

considering its theoretical interest.

(Insert Figure 4 about here)

Interim discussion: Development of infants' mispronunciation sensitivity.
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 across all ages. Furthermore, although we found a relationship between
vocabulary size (comprehension) and target looking for correct pronunciations, we found
no relationship between vocabulary and target looking for mispronunciations. This may be
due to too few studies including reports of vocabulary size and more investigation is needed
to draw a firm conclusion. These findings support the arguments set by the early
specification hypothesis that infants represent words with phonological detail already at
the beginning of the second year of life.

Our power analysis revealed that mispronunciation sensitivity studies typically
underpowered, with 54% power and would need to increase their sample from an average of
24 to 44 infants to achieve 80% power. While this number does not seem to differ
dramatically from the observed sample sizes, the impact of the smaller sample sizes on
power is thus substantial and should be kept in mind when planning future studies.
Furthermore, 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 and factors influencing this ability.

The studies examined in this meta-analysis examined mispronunciation sensitivity, but many also included more specific questions aimed at uncovering more detailed phonological processes at play during word recognition. Not only are these questions theoretically interesting, they also have the potential to change the difficulty of a mispronunciation sensitivity experiment. It is possible that the lack of developmental change in mispronunciation sensitivity found by our meta-analysis does not capture a true lack of change, but is instead influenced by differences in the types of tasks given to infants of different ages. We examine this possibility in a set of moderator analyses

Moderator Analyses

If infants' word recognition skills are generally thought to improve with age and vocabulary size, research questions that tap more complex processes may be more likely to be investigated in older infants. In this section, we consider each moderator individually and investigate its influence on mispronunciation sensitivity. For most moderators (except mispronunciation size), we combine the correct and mispronounced datasets and include the moderator of condition, to study mispronunciation sensitivity as opposed to object recognition. To better understand the impact of these moderators on developmental change, we include age as subsequent moderator. Results of the 5 main moderator tests (mispronunciation size, mispronunciation position, mispronunciation type, distractor overlap, distractor familiarity) as well as the individual effects for each moderator interaction are reported in Table 2. The statistic that tests whether a specific moderator explains a significant proportion of variance in the data, QM, was significant for all moderators and subsequent significant interactions of critical terms are interpreted. Finally, we analyze the relationship between infant age and the moderator condition they were tested in using Fisher's exact test, which is more appropriate for small sample sizes (Fisher, 1922). This evaluates the independence of infants' age group (divided into quartiles unless otherwise specified) and assignment to each type of condition in a particular moderator.

503   (Insert Table 2 about here)

504   **Size of mispronunciation.**   To assess whether the size of the mispronunciation

505 tested, as measured by the number of features changed, modulates mispronunciation

506 sensitivity, we calculated the meta-analytic effect for object identification on a subset of the

507 overall dataset, with 90 records for correct pronunciations, 99 for 1-feature

508 mispronunciations, 16 for 2-feature mispronunciations, and 6 for 3-feature

509 mispronunciations. Each feature change (from 0 to 3; 0 representing correct

510 pronunciations) was considered to have an graded impact on mispronunciation sensitivity

511 (Mani & Plunkett, 2011; White & Morgan, 2008) and this moderator was coded as a

512 continuous variable. We did not include records for which the number of features changed

513 was not specified or consistent within a record (e.g., both 1- and 2-feature changes within

514 one mispronunciation record).

515   The model results revealed that as the number of features changed increased, the

516 effect size Hedges' g significantly decreased (Table 2). We plot this relationship in Figure 5.

517 Age did not modulate this effect. Finally, results of Fisher's exact test were not significant,

518 $p = 0.703$.

519   (Insert Figure 5 about here)

520   **Position of mispronunciation.**   We next calculated the meta-analytic effect of

521 mispronunciation sensitivity (moderator: condition) in response to mispronunciations on

522 the onset ($n = 143$ records), medial ($n = 48$), and coda phonemes ($n = 10$). We coded the

523 onset, medial, and coda positions as continuous variables, to evaluate the importance of

524 each subsequent position (Marslen-Wilson & Zwitserlood, 1989). We did not include data

525 for which the mispronunciation varied within record in regard to position ($n = 40$) or was

526 not reported ($n = 10$).

527   The model results revealed that mispronunciation sensitivity decreased linearly as the

528 position of the mispronunciation moved later in the word, with sensitivity greatest for

onset mispronunciations and smallest for coda mispronunciations (Table 2). We plot this relationship in Figure 6. When age was added as a moderator, however, the interaction between age, condition, and mispronunciation position was small and not significant. Due to the small sample size of coda mispronunciations, we only included 3 age groups in Fisher's exact test. The results were significant, $p = 0.02$. Older infants were more likely to be tested on onset mispronunciations, while younger infants were more likely to be tested on medial mispronunciations.

(Insert Figure 6 about here)

Type of mispronunciation (consonant or vowel).   We next calculated the meta-analytic effect of mispronunciation sensitivity (moderator: condition) in response to the type of mispronunciation, consonant ($n = 145$) or vowel ($n = 71$). Furthermore, sensitivity to consonant and vowel mispronunciations is hypothesized to differ depending on the language family of the infant's native language. Infants learning American English ($n = 56$), British English ($n = 66$), Danish ($n = 6$), Dutch ($n = 58$), and German ($n = 21$) were classified into the Germanic language family ($n = 207$). Infants learning Catalan ($n = 4$), Spanish ($n = 4$), French ($n = 8$), Catalan and Spanish simultaneously (i.e. bilinguals; $n = 6$), and Swiss French ($n = 6$) were classified into the Romance language family ($n = 28$). We therefore conducted two sets of analyses, one analyzing consonants and vowels alone and a second including langauge family (Germanic vs. Romance) as a moderator. We did not include data for which mispronunciation type varied within experiment and was not reported separately ($n = 23$).

The model results revealed that mispronunciation sensitivity did not differ between consonant and vowel mispronunciations (Table 2). We plot this relationship in Figure 7a. When age was added as a moderator, however, the model revealed that as infants age, mispronunciation sensitivity grows larger for vowel mispronunciations but stays steady for consonant mispronunciations (Figure 7b). The results of Fisher's exact test were significant, $p < .001$. Older infants were more likely to be tested on consonant

556 mispronunciations, while younger infants were more likely to be tested on vowel

557 mispronunciations. Whether consonant or vowel mispronunciations are more "difficult" is a

558 matter of theoretical debate, but some evidence suggest that it may be influenced by

559 infants' native language (Nazzi et al., 2016). We next examined whether this was the case.

560   (Insert Figure 7 about here)

561   The model results revealed that mispronunciation sensitivity for consonants was

562 similar for Germanic and Romance languages. Mispronunciation sensitivity for vowels,

563 however, was greater for Germanic compared to Romance languages (Table 2). We plot

564 this relationship in Figure 8a. Adding age as a moderator revealed a small but significant

565 estimate for the four-way interaction between mispronunciation type, condition, language

566 family, and age. As can also be seen in Figure 8b, for infants learning Germanic languages,

567 sensitivity to consonant and vowel mispronunciations did not change with age. In contrast,

568 infants learning Romance languages show a decrease in sensitivity to consonant

569 mispronunciations, but an increase in sensitivity to vowel mispronunciations with age. Due

570 to the small sample size of infants learning Romance languages, we were unable to use

571 Fisher's exact test.

572   (Insert Figure 8 about here)

573 **Phonological overlap between target and distractor.**   We next examined the

574 meta-analytic effect of mispronunciation sensitivity (moderator: condition) in response to

575 mispronunciations when the target-distractor pairs either had no overlap ($n = 80$) or shared

576 the same onset phoneme ($n = 104$). We did not include data for which the overlap included

577 other phonemes (i.e. onset and medial, coda) or the distractor was an unfamiliar object.

578   The model results revealed that mispronunciation sensitivity was greater when

579 target-distractor pairs shared the same onset phoneme compared to when they shared no

580 phonological overlap (Table 2). We plot this relationship in Figure 9a. Adding age as a

581 moderator revealed a small but significant estimate for the three-way interaction between

age, condition, and distractor overlap (Figure 8b). Mispronunciation sensitivity increased with age for target-distractor pairs containing onset overlap, but decreased with age for target-distractor pairs containing no overlap. The results of Fisher's exact test were significant, $p < .001$. Older infants were more likely to be tested in experimental conditions where target and distractor images overlapped on their onset phoneme, while younger infants were more likely to be tested in experimental conditions that did not control for overlap.

(Insert Figure 9 about here)

Distractor familiarity. We next calculated the meta-analytic effect of mispronunciation sensitivity (moderator: condition) in experiments were the target image was paired with a familiar ($n = 179$) or unfamiliar ($n = 72$) distractor image.

The model results revealed that infants' familiarity with the distractor object (familiar or unfamiliar) did not impact their mispronunciation sensitivity, nor was this relationship influenced by the age of the infant. The results of Fisher's exact test were not significant, $p = 0.072$.

Interim discussion: Moderator analyses. Mispronunciation sensitivity was modulated overall by the size of the mispronunciation tested, whether target-distractor pairs shared phonological overlap, and the position of the mispronunciation. Neither distractor familiarity (familiar, unfamiliar) or type of mispronunciation (consonant, vowel) were found to impact mispronunciation sensitivity.

The developmental trajectory of mispronunciation sensitivity was influenced by type of mispronunciation and overlap between the target and distractor labels, but mispronunciation size, mispronunciation position, and distractor familiarity were found to have no influence. Finally, in some cases there was evidence that older and younger infants were given experimental manipulations that may have rendered the experimental task more or less difficult. In one instance, younger infants were given a more difficult task,

608 mispronunciations on the medial position, which is unlikely to contribute to the lack of

609 developmental effects in our main analysis. Yet, this was not always the case; in a different

610 instance, older children were more likely to be given target-distractor pairs that overlapped

611 on their onset phoneme, a situation in which it is more difficult to detect a

612 mispronunciation and may have bearing on our main developmental results. We return to

613 these findings in the General Discussion.

614 Exploratory Analyses

615   We next considered whether an effect of maturation might have been masked by

616 other factors we have not yet captured in our analyses. A strong candidate that emerged

617 during the construction of the present dataset and careful reading of the original papers

618 was the analysis approach. We observed, as mentioned in the Methods section, variation in

619 the dependent variable reported, and additionally noted that the size of the chosen

620 post-naming analysis window varied substantially across papers. Researchers' analysis

621 strategy may be adapted to infants' age or influenced by having observed the data. For

622 example, consider the possibility that a particular study does not find that infants looked

623 to the target object upon hearing a correct pronunciation. With this pattern of behavior,

624 interpreting an effect of mispronunciation sensitivity becomes difficult; how can infants

625 notice a phoneme change when they do not even show recognition of the correct

626 pronunciation? A lack of recognition or a small effect for correct pronunciations would be

627 more difficult to publish (Ferguson & Heene, 2012). In order to have publishable results,

628 adjustments to the analysis approach could be made until a significant effect of recognition

629 for correct pronunciations is found. But, these adjustments would also need to be made for

630 the analysis of mispronunciations, which may impact the size of the mispronunciation

631 sensitivity effect. Such a scenario could explain the publication bias suggested by the

632 asymmetry for correct pronunciations in the funnel plot shown in Figure 2 (Simmons,

633 Nelson, & Simonsohn, 2011). This could lead to an increase in significant results and even

634 alter the developmental trajectory of mispronunciation sensitivity.

635   We examine whether variation in the approach to data analysis may be have an

636 influence on our conclusions regarding infants' developing mispronunciation sensitivity. To

637 do so, we analyzed analysis choices related to timing, specifically the post-naming analysis

638 window, as well as type of dependent variable in our coding of the dataset because they are

639 consistently reported. Further, since we observe variation in both aspects of data analysis,

640 summarizing typical choices and their impact might be useful for experiment design in the

641 future and might help establish field standards. In the following, we discuss the possible

642 theoretical motivation for these data analysis choices, the variation present in the current

643 meta-analysis dataset, and the influence these analysis choices may have on reported

644 mispronunciation sensitivity and its development. We focus specifically on the size of the

645 mispronunciation sensitivity effect, considering the whole dataset and including condition

646 (correct pronunciation, mispronunciation) as a moderator.

647   **Timing.**   When designing mispronunciation sensitivity studies, experimenters can

648 choose the length of time each trial is presented. This includes both the length of time

649 before the target object is named (pre-naming phase) as well as after (post-naming phase)

650 and is determined prior to data collection. Evidence suggests that the speed of word

651 recognition is slower in young infants (Fernald et al., 1998), which may lead researchers to

652 include longer post-naming phases in their experiments with younger infants. The

653 post-naming analysis window, in contrast, represents how much of this phase was included

654 in the statistical analysis and can be chosen after the experimental data is collected and

655 perhaps observed. If infant age is influencing the length of these windows, we should

656 expect a negative correlation.

657   Across papers, there was wide variation in the length of the post-naming phase

658 ($Median$ = 3500 ms, range = 2000 - 9000) and the post-naming analysis window ($Median$ =

659 2500 ms, range = 1510 - 4000). The most popular post-naming phase length was 4000 ms

660 (n = 74 records) and 2000 ms (n = 97 records) was the most popular for the post-naming

661 analysis window. About half of the records were analyzed using the whole post-naming

662 phase presented to the infant ($n = 124$), while the other half were analyzed using a shorter

663 portion of the post-naming time window, usually excluding later portions ($n = 127$).

664   There was no apparent relation between infant age and post-naming phase length (r

665 $= 0.01$, 95% CI[-0.11, 0.13], $p = 0.882$), but there was a significant negative relationship

666 between infant age and post-naming analysis window length, such that younger infants'

667 looking times were analyzed using a longer post-naming analysis window ($r = -0.23$, 95%

668 CI[-0.35, -0.11], $p < .001$). We next investigated whether post-naming analysis window

669 length impacted measures of mispronunciation sensitivity.

670   When post-naming analysis window length and condition (correct pronunciation,

671 mispronunciation) were included as moderators, the moderator test was significant (QM(3)

672 $= 237.055$, $p < .001$). The estimate for the interaction between post-naming analysis

673 window and condition was small but significant ($\beta = -0.268$, SE $= 0.059$, 95% CI[-0.383,

674 -0.153], $p < .001$), showing that as the length of the post-naming analysis window

675 increased, the difference between target fixations for correctly pronounced and

676 mispronounced items (mispronunciation sensitivity) decreased. This relationship is plotted

677 in Figure 10a. When age was added as a moderator, the moderator test was significant

678 (QM(7) $= 247.485$, $p < .001$). The estimate for the three-way-interaction between

679 condition, post-naming analysis window, and age was small, but significant ($\beta = -0.04$, SE

680 $= 0.014$, 95% CI[-0.068, -0.012], $p = 0.006$). As can be seen in Figure 10b, when records

681 were analyzed with a post-naming analysis window of 2000 ms or less (a limit we imposed

682 for visualization purposes), mispronunciation sensitivity seems to increase with infant age.

683 If the post-naming analysis window is greater than 2000 ms, however, there is no or a

684 negative relation between mispronunciation sensitivity and age.

685   (Insert Figure 10 about here)

Dependent variable

As described in the Methods section, there was considerable variation across papers in whether the pre-naming phase was used as a baseline measurement (Difference Score or Pre- vs. Post) or whether the post-naming PTL was compared with a chance value of 50% (Post). Considering analyses of the dependent variables Difference Score or Pre- vs. Post produce the same result, we combined these two dependent variables into one, which we call Baseline Corrected. To our knowledge, there is no theory or evidence that explicitly drives choice of dependent variable in preferential looking studies, 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 was related to the estimated size of sensitivity to mispronunciations.

When we included both condition and dependent variable as moderators, the moderator test was significant (QM(3) = 231.004, $p < .001$). The estimate for the interaction between the type of dependent variable and condition was was significant ($\beta =$ -0.185, SE = 0.093, 95% CI[-0.366, -0.003], $p = 0.046$). As can be seen in 11, mispronunciation sensitivity was higher when the dependent variable reported was Post compared to when it was Baseline Corrected. When age was included as an additional moderator, the moderator test was significant (QM(7) = 237.51, $p < .001$). However, the estimate for the interaction between dependent variable, condition, and age was not significant ($\beta =$ -0.049, SE = 0.026, 95% CI[-0.1, 0.002], $p = 0.061$).

(Insert Figure 11 about here)

General Discussion

In this meta-analysis, we set out to quantify and assess the phonological specificity of infants' representations for familiar words and how this is modulated with development, as measured by infant age and vocabulary size. Infants not only recognize object labels when they were correctly pronounced, but are also likely to accept mispronunciations as labels

712 for targets. Nonetheless, there was a considerable difference in target fixations in response

713 to correctly pronounced and mispronounced labels, suggesting that infants show sensitivity

714 to what constitutes unacceptable, possibly meaning-altering variation in word forms,

715 thereby displaying knowledge of the role of phonemic changes throughout the ages assessed

716 here (6 to 30 months). At the same time, infants, like adults, can recover from

717 mispronunciations, a key skill in language processing.

718   Considering the variation in findings of developmental change in mispronunciation

719 sensitivity (see Introduction), we next evaluated the developmental trajectory of infants'

720 mispronunciation sensitivity. Our analysis of this relationship revealed a pattern of

721 unchanging sensitivity over infant age and vocabulary size, which has been reported by a

722 handful of studies directly comparing infants over a small range of ages, such as 18-24

723 months (Bailey & Plunkett, 2002; Swingley & Aslin, 2000) or 12-17 months (Zesiger et al.,

724 2012). The lack of age or vocabulary effects in our meta-analysis suggest that this

725 understanding is present from an early age and is maintained throughout early lexical

726 development. We note, however, that despite an increasing publication record of

727 mispronunciation sensitivity studies, fewer than half of the papers included in this

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

729 This may reflect a decreasing interest in the relationship between mispronunciation

730 sensitivity and vocabulary size and/or to invest in data collection that is not expected to

731 yield significant outcomes. Considering the theoretical implications, however, more

732 experimental work investigating and reporting the relationship between mispronunciation

733 sensitivity and vocabulary size is needed if this link is to be evaluated. Nonetheless, if we

734 are to take our results as robust, it becomes thus a pressing open question that theories

735 have to answer which other factors might prompt acquiring and using language-specific

736 phonological contrasts at such an early age.

Moderator Analyses

With perhaps a few exceptions, the main focus of many of the experiments included in this meta-analysis was not to evaluate whether infants are sensitive to mispronunciations in general but rather to investigate specific questions related to phonological and lexical processing and development. We included a set of moderator analyses to better understand these issues by themselves, as well as how they may have impacted our main investigation of infants' development of mispronunciation sensitivity. Several of these moderators include manipulations that make mispronunciation detection more or less difficult for the infant. As a result, the size of the mispronunciation sensitivity effect may be influenced by the task, especially if older infants are given more demanding tasks in comparison to younger infants, potentially masking developmental effects. Considering this, we also evaluated whether the investigation of each of these manipulations was distributed evenly across infant ages, where an uneven distribution may have subsequently heightened or dampened our estimate of developmental change.

The results of the moderator analysis reflect several findings reported in the literature. The meta-analytic effect for mispronunciation size, as measured by phonological features changed, showed graded sensitivity (Bernier & White, 2017; Mani & Plunkett, 2011; Tamasi, 2016; White & Morgan, 2008), an adult-like ability. More studies are needed to evaluate whether this gradual sensitivity develops with age, as only one study examined more than one age (Mani & Plunkett, 2011) and all others test the same age with a varying number of features (Bernier & White, 2017; Tamasi, 2016; White & Morgan, 2008). With more studies investigating graded sensitivity at multiple ages with all other facturs held constant, we would achieve a better estimate of whether this is a stable or developing ability, thus also shedding more light on the progression of phono-lexical development in general that then needs to be captured in theories and models.

Our meta-analysis showed that infants are more sensitive to changes in the sounds of

763 familiar words when they occur in an earlier position as opposed to a late position. This

764 awards support to lexical access theories that place greater importance on the onset

765 position during word recognition (i.e. COHORT; Marslen-Wilson & Zwitserlood, 1989). At

766 face value, our results thus support theories placing more importance on earlier phonemes.

767 But studies that have contrasted mispronunciations on different positions have found this

768 does not modulate sensitivity (Swingley, 2009; Zesiger et al., 2012). One potential

769 explanation is how the timing of different mispronunciation locations are considered in

770 analysis. For example, Swingley (2009) adjusted the post-naming analysis window start

771 from 367 ms for onset mispronunciations to 1133 for coda mispronunciations, to ensure

772 that infants have a similar amount of time to respond to the mispronunciation, regardless

773 of position. The length of the post-naming analysis window does impact mispronunciation

774 sensitivity, as we discuss below, and mispronunciations that occur later in the word

775 (i.e. medial and coda mispronunciations) may be at a disadvantage relative to onset

776 mispronunciations if this is not taken into account. These issues can be addressed with the

777 addition of more experiments that directly compare sensitivity to mispronunciations of

778 different positions, as well as the use of analyses that account for timing differences.

779   For several moderators, we found no evidence of significant modulation of

780 mispronunciation sensitivity. Studies that include an unfamiliar, as opposed to familiar

781 distractor image, often argue that the unfamiliar image provides a better referent

782 candidate for mispronunciation than a familiar distractor image, where the name is already

783 known. Yet, no studies have directly examined this assertion and our meta-analysis found

784 that distractor familiarity did not significantly modulate mispronunciation sensitivity.

785   Despite the proposal that infants should be more sensitive to consonant compared to

786 vowel mispronunciations (Nazzi et al., 2016), we found no difference in sensitivity to

787 consonant and vowel mispronunciations. But, a more nuanced picture was revealed when

788 further moderators were introduced. Age and native language did not modulate sensitivity

789 to consonant mispronunciations, but sensitivity to vowel mispronunciations increased with

790 age and was greater overall for infants learning Germanic languages (although this

791 increased with age for infants learning Romance languages). This pattern of results

792 supports a learned account of the consonant bias, showing that sensitivity to consonants

793 and vowels have different developmental trajectories, which depend on whether the infant

794 is learning a Romance (French, Italian) or Germanic (British English, Danish) native

795 language (Nazzi et al., 2016). TRACE simulations conducted by Mayor & Plunkett (2014)

796 reveal a relationship between vocabulary size and sensitivity to vowel-medial

797 mispronunciations, although here the authors give more weight to the role of

798 mispronunciation position, a distinction we are unable to make in our analyses.

799   Contrary to predictions made from the literature, our meta-analysis revealed that

800 studies which include target and distractor images that overlap in their onset elicit greater

801 mispronunciation sensitivity than studies who do not control for this factor. Perhaps

802 including overlap leads infants to pay more attention to mispronunciations, increasing

803 mispronunciation sensitivity. Yet, older children were more likely to receive the arguably

804 more difficult manipulation where target-distractor pairs overlapped in their onset

805 phoneme, added task demands which may reduce their ability to access the phonetic detail

806 of familiar words as argued by the PRIMIR Framework (Curtin & Werker, 2007; Werker &

807 Curtin, 2005). This imbalance in the ages tested has the potential to dampen

808 developmental differences, due to task differences in the experiments that older and

809 younger infants participated in. Further support comes from evidence that sensitivity to

810 mispronunciations when the target-distractor pair overlapped on the onset phoneme

811 increased with age. This pattern of results suggests that when infants are given an equally

812 difficult task, developmental effects may be revealed. This explanation can be confirmed by

813 testing more infants at younger ages on overlapping target-distractor pairs in the future.

Data Analysis Choices

During the coding of our meta-analysis database, we noted variation in variables relating to timing and the calculation of the dependent variable reported. As infants mature, they recognize words more quickly (Fernald et al., 1998), which may lead experimenters to shorten the length of the analysis window. We found wide variation in the post-naming analysis window which correlated negatively with infant age and influenced the estimate of mispronunciation sensitivity. Looks to the target in response to mispronunciations may be slower than in response to correct pronunciations in infants (as predicted by TRACE, Mayor & Plunkett, 2014), and those studies with longer post-naming analysis windows allow fixations to accumulate even in the presence of mispronunciations, thereby reducing the measured sensitivity to mispronunciations. In fact, the exact dynamics of fixations to mispronunciations (overall flattened versus delayed) are an ongoing topic of discussion. Returning to the analysis window length itself, we wish to raise awareness that the observed variation might seem like it indicates a so-called Questionable Research Practice where analyses are adjusted after observing the data to obtain a significant effect, which in turn increases the rate of false-positives (Gelman & Loken, 2013): a "significant effect" of mispronunciation sensitivity is found with an analysis window of 2000 but not 3000 ms, therefore 2000 ms is chosen. While we have no reason to believe that this is the cause of the observed variation, consistency or justification of chosen time windows would increase the credibility of developmental eye movement research. In addition, and even in the absence of such practices, the variation in analysis window length introduces noise into the dataset, blurring the true developmental trajectory of mispronunciation sensitivity.

The type of depedent variable calculated also moderated mispronunciation sensitivity, albeit not conclusions about its developmental trajectory. There is, to the best of our knowledge, no clear reason for one dependent variable to be chosen over another; the prevalence of each dependent variable appears distributed across ages and some authors

always calculate the same dependent variable while others use them interchangeably in

different publications. One clear difference is that both the Difference Score (reporting

looks to the target image after hearing the label minus looks in silence) and Pre vs. Post

(reporting both variables separately) dependent variables consider each infants' actual

preference in the pre-naming baseline phase, while the Post dependent variable (reporting

looks to target after labelling only) does not. Without access to the raw data, it is difficult

to conclusively determine why different dependent variable calculations influence

mispronunciation sensitivity.

Recommendations to Establish Analysis Standards

A lack of a field standards can have serious consequences, as our analyses show,

limiting our ability to draw conclusions. We take this opportunity to make several

recommendations to address the issue of varying, potentially post hoc analysis decisions.

First, 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 (see Havron, Bergmann, & Tsuji, 2020 for a primer). The

peer-reviewed form of preregistration, 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. Second, sharing data (Open Data) can allow others to re-analyze existing datasets

to both examine the impact of analysis decisions and cumulatively analyze different

datasets in the same way. Considering the specific issue of analysis time window,

experimenters can opt to analyze the time course as a whole, instead of aggregating the

proportion of target looking behavior. This allows for a more detailed assessment of

infants' fixations over time and removes the need to reduce the post-naming analysis

window. Both Growth Curve Analysis (Mirman, Dixon, & Magnuson, 2008) and

Permutation Clusters Analysis (Maris & Oostenveld, 2007; Von Holzen & Mani, 2012) offer

potential solutions to analyze the full time course. Third, 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 (see ManyBabiesConsortium, 2020 for a parallel effort). We hope the above suggestions take us one step closer to this important goal that clarifies the link between internal abilities and behavior in a laboratory study.

Conclusion

This meta-analysis comprises an aggregation of two decades of research on mispronunciation sensitivity, finding robust evidence that infants have well-specified phonological representations for familiar words. Furthermore, these representations may be well specified at an early age, perhaps before the vocabulary explosion. We recommend future theoretical frameworks take this evidence into account. Our meta-analysis was also able to confirm different findings in the literature, including the role of mispronunciation size, mispronunciation position, and infants' age and native language in sensitivity to mispronunciation type (consonant vs. vowel). Furthermore, evidence of an interaction between task demands (phonological overlap between target-distractor pairs) and infant age may partially explain the lack of developmental change in our meta-analysis.

Despite this overall finding, 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 identify issues in a particular field and play a vital role in how the field addresses such issues.

891   **References**

892 Allaire, J., Xie, Y., McPherson, J., Luraschi, J., Ushey, K., Atkins, A., … Chang, W.

893   (2018). rmarkdown: Dynamic Documents for R. Retrieved from

894   https://cran.r-project.org/package=rmarkdown

895 Altvater-Mackensen, N. (2010). *Do manners matter? Asymmetries in the acquisition of*

896   *manner of articulation features.* (PhD thesis). Radboud University Nijmegen.

897 Altvater-Mackensen, N., Feest, S. V. H. van der, & Fikkert, P. (2014). Asymmetries in

898   early word recognition: The case of stops and fricatives. *Language Learning and*

899   *Development*, *10*(2), 149–178. doi:10.1080/15475441.2013.808954

900 Aust, F., & Barth, M. (2018). papaja: Prepare reproducible APA journal articles with R

901   Markdown. Retrieved from https://github.com/crsh/papaja

902 Bailey, T. M., & Hahn, U. (2005). Phoneme similarity and confusability. *Journal of*

903   *Memory and Language*, *52*(3), 339–362. doi:10.1016/j.jml.2004.12.003

904 Bailey, T. M., & Plunkett, K. (2002). Phonological specificity in early words. *Cognitive*

905   *Development*, *17*(2), 1265–1282. doi:10.1016/S0885-2014(02)00116-8

906 Ballem, K. D., & Plunkett, K. (2005). Phonological specificity in children at 1;2. *Journal*

907   *of Child Language*, *32*(1), 159–173. doi:10.1017/S0305000904006567

908 Bergmann, C., & Cristia, A. (2016). Development of infants' segmentation of words from

909   native speech: A meta-analytic approach. *Developmental Science*, *19*(6), 901–917.

910   doi:10.1111/desc.12341

911 Bergmann, C., Tsuji, S., Piccinini, P. E., Lewis, M. L., Braginsky, M., Frank, M. C., &

912   Cristia, A. (2018). Promoting replicability in developmental research through

913   meta-analyses: Insights from language acquisition research. *Child Development*.

914   doi:10.17605/OSF.IO/3UBNC

915 Bernier, D. E., & White, K. S. (2017). What's a Foo? Toddlers Are Not Tolerant of Other

Children's Mispronunciations. In *Proceedings of the 41st annual boston university conference on language development* (pp. 88–100).

Charles-Luce, J., & Luce, P. A. (1995). An examination of similarity neighbourhoods in young children's receptive vocabularies. *Journal of Child Language*, *22*(3), 727–735. doi:10.1017/S0305000900010023

Cohen, J. (1988). *Statistical Power Analysis for the Behavioural Sciences* (2nd ed.). New York: Lawrence Earlbaum Associates.

Csibra, G., Hernik, M., Mascaro, O., Tatone, D., & Lengyel, M. (2016). Statistical treatment of looking-time data. *Developmental Psychology*, *52*(4), 521–36. doi:10.1037/dev0000083

Curtin, S., & Werker, J. F. (2007). The perceptual foundations of phonological development. In M. G. Gaskell (Ed.), *The oxford handbook of psycholinguistics* (pp. 579–599). New York: Oxford University Press. doi:10.1093/oxfordhb/9780198568971.013.0035

Feest, S. V. H. van der, & Fikkert, P. (2015). Building phonological lexical representations. *Phonology*, *32*(02), 207–239. doi:10.1017/S0952675715000135

Ferguson, C. J., & Heene, M. (2012). A vast graveyard of undead theories: Publication bias and psychological science's aversion to the null. *Perspectives on Psychological Science*, *7*(6), 555–561. doi:10.1177/1745691612459059

Fernald, A., Pinto, J. P., Swingley, D., Weinberg, A., & McRoberts, G. W. (1998). Rapid gains in speed of verbal processing by infants in the 2nd year. *Psychological Science*, *9*(3), 228–231. doi:10.1111/1467-9280.00044

Fisher, R. A. (1922). On the Interpretation of $\chi 2$ from Contingency Tables, and the Calculation of P. *Journal of the Royal Statistical Society*, *85*(1), 87. doi:10.2307/2340521

Fleiss, J. L. (1986). *The Design and Analysis of Clinical Experiments.* New York: Wiley; Sons.

Frank, M. C., Lewis, M. L., & Macdonald, K. (2016). A performance model for early word learning. *Proceedings of the Cognitive Science Society*, 2609–2614. Retrieved from https://mindmodeling.org/cogsci2016/papers/0450/paper0450.pdf

Gelman, A., & Loken, E. (2013). *The garden of forking paths: Why multiple comparisons can be a problem, even when there is no "fishing expedition" or "p-hacking" and the research hypothesis was posited ahead of time.* Department of Statistics, Columbia University. doi:10.1037/a0037714

Halberda, J. (2003). The development of a word-learning strategy. *Cognition, 87*, B23–B34.

Havron, N., Bergmann, C., & Tsuji, S. (2020). Preregistration in infant research - a primer. doi:10.31234/osf.io/es2gx

Hedges, L. V. (1981). Distribution theory for glass's estimator of effect size and related estimators. *Journal of Educational and Behavioral Statistics, 6*(2), 107–128. doi:10.3102/10769986006002107

Højen, A., Madsen, T. O., Vach, W., Basbøll, H., Caporali, S., & Blese, D. (n.d.). *Contributions of vocalic and consonantal information when Danish 20-month-olds recognize familiar words.*

Jennions, M. D., Mù, A. P., Pierre, Â., Curie, M., & Cedex, F. P. (2002). Relationships fade with time : a meta-analysis of temporal trends in publication in ecology and evolution. *Proceedings of the Royal Society of London B: Biological Sciences, 269*, 43–48. doi:10.1098/rspb.2001.1832

Leon, A. C., & Heo, M. (2009). Sample sizes required to detect interactions between two binary fixed-effects in a mixed-effects linear regression model. *Computational Statistics and Data Analysis, 53*(3), 603–608. doi:10.1016/j.csda.2008.06.010

Mani, N., Coleman, J., & Plunkett, K. (2008). Phonological specificity of vowel contrasts at 18-months. *Language and Speech, 51*, 3–21. doi:10.1177/00238309080510010201

Mani, N., & Plunkett, K. (2007). Phonological specificity of vowels and consonants in early lexical representations. *Journal of Memory and Language, 57*(2), 252–272. doi:10.1016/j.jml.2007.03.005

Mani, N., & Plunkett, K. (2010). Twelve-month-olds know their cups from their keps and tups. *Infancy, 15*(5), 445–470. doi:10.1111/j.1532-7078.2009.00027.x

Mani, N., & Plunkett, K. (2011). Does size matter? Subsegmental cues to vowel mispronunciation detection. *Journal of Child Language, 38*(03), 606–627. doi:10.1017/S0305000910000243

ManyBabiesConsortium. (2020). Quantifying sources of variability in infancy research using the infant-directed speech preference. *Advances in Methods and Practices in Psychological Science.*

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods, 164*(1), 177–190. doi:10.1016/j.jneumeth.2007.03.024

Markman, E. M., Wasow, J. L., & Hansen, M. B. (2003). Use of the mutual exclusivity assumption by young word learners. *Cognitive Psychology, 47*(3), 241–275. doi:10.1016/S0010-0285(03)00034-3

Marslen-Wilson, W. D., & Zwitserlood, P. (1989). Accessing spoken words: The importance of word onsets. *Journal of Experimental Psychology: Human Perception and Performance, 15*(3), 576–585. doi:10.1037/0096-1523.15.3.576

Mayor, J., & Plunkett, K. (2014). Infant word recognition: Insights from TRACE simulations. *Journal of Memory and Language, 71*(1), 89–123. doi:10.1016/j.jml.2013.09.009

McClelland, J. L., & Elman, J. L. (1986). The TRACE model of speech perception. *Cognitive Psychology*, *18*(1), 1–86. doi:10.1016/0010-0285(86)90015-0

Mirman, D., Dixon, J. A., & Magnuson, J. S. (2008). Statistical and computational models of the visual world paradigm: Growth curves and individual differences. *Journal of Memory & Language*, *59*(4), 475–494. doi:10.1016/j.jml.2007.11.006

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & PRISMA Group". (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLoS Medicine*, *6*(7), e1000097. doi:10.1371/journal.pmed.1000097

Morris, S. B., & DeShon, R. P. (2002). Combining effect size estimates in meta-analysis with repeated measures and independent-groups designs. *Psychological Methods*, *7*(1), 105–125. doi:10.1037/1082-989X.7.1.105

Nazzi, T., Floccia, C., Moquet, B., & Butler, J. (2009). Bias for consonantal information over vocalic information in 30-month-olds: Cross-linguistic evidence from French and English. *Journal of Experimental Child Psychology*, *102*(4), 522–537. doi:10.1016/j.jecp.2008.05.003

Nazzi, T., Poltrock, S., & Von Holzen, K. (2016). The developmental origins of the consonant bias in lexical processing. *Current Directions in Psychological Science*, *25*(4), 291–296. doi:10.1177/0963721416655786

Rabagliati, H., Ferguson, B., & Lew-Williams, C. (2018). The profile of abstract rule learning in infancy: Meta-analytic and experimental evidence. *Developmental Science*, (October 2017), 1–18. doi:10.1111/desc.12704

Ramon-Casas, M., & Bosch, L. (2010). Are non-cognate words phonologically better specified than cognates in the early lexicon of bilingual children? *Selected Proceedings of the 4th Conference on Laboratory Approaches to Spanish Phonology*, 31–36.

Ramon-Casas, M., Swingley, D., Sebastián-Gallés, N., & Bosch, L. (2009). Vowel categorization during word recognition in bilingual toddlers. *Cognitive Psychology*, *59*(1), 96–121. doi:10.1016/j.cogpsych.2009.02.002

R Core Team. (2018). R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from https://www.r-project.org/

Renner, L. F. (2017). *The magic of matching – speech production and perception in language acquisition* (thesis). Stockholm University.

Sakaluk, J. (2016). Make it pretty: Forest and funnel plots for meta-analysis using ggplot2. [Blog post]. Retrieved from https://sakaluk.wordpress.com/2016/02/16/7-make-it-pretty-plots-for-meta-analysis/

Schwarzer, G. (2007). meta: An R package for meta-analysis. *R News*, *7*(3), 40–45. doi:10.1007/978-3-319-21416-0>

Simmons, J. P., Nelson, L. D., & Simonsohn, U. (2011). False-positive psychology: Undisclosed flexibility in data collection and analysis allows presenting anything as significant. *Psychological Science*, *22*(11), 1359–1366. doi:10.1177/0956797611417632

Simonsohn, U., Nelson, L. D., & Simmons, J. P. (2014). P-curve: A key to the file-drawer. *Journal of Experimental Psychology: General*, *143*(2), 534–547. doi:10.1037/a0033242

Skoruppa, K., Mani, N., Plunkett, K., Cabrol, D., & Peperkamp, S. (2013). Early word recognition in sentence context: French and English 24-month-olds' sensitivity to sentence-medial mispronunciations and assimilations. *Infancy*, *18*(6), 1007–1029. doi:10.1111/infa.12020

Swingley, D. (2009). Onsets and codas in 1.5-year-olds' word recognition. *Journal of*

Memory and Language, *60*(2), 252–269. doi:10.1016/j.jml.2008.11.003

Swingley, D. (2016). Two-year-olds interpret novel phonological neighbors as familiar words. *Developmental Psychology*, *52*(7), 1011–1023. doi:10.1037/dev0000114

Swingley, D., & Aslin, R. N. (2000). Spoken word recognition and lexical representation in very young children. *Cognition*, *76*(2), 147–166. doi:10.1016/S0010-0277(00)00081-0

Swingley, D., & Aslin, R. N. (2002). Lexical Neighborhoods and the Word-Form representations of 14-Month-Olds. *Psychological Science*, *13*(5), 480–484. doi:10.1111/1467-9280.00485

Tamasi, K. (2016). *Measuring children ' s sensitivity to phonological detail using eye tracking and pupillometry* (PhD thesis). University of Potsdam.

Tsuji, S., Bergmann, C., & Cristia, A. (2014). Community-Augmented Meta-Analyses: Toward Cumulative Data Assessment. *Psychological Science*, *9*(6), 661–665. doi:10.1177/1745691614552498

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software*, *36*(3), 1–48. doi:10.18637/jss.v036.i03

Von Holzen, K., & Mani, N. (2012). Language nonselective lexical access in bilingual toddlers. *Journal of Experimental Child Psychology*, *113*, 569–586. doi:10.1016/j.jecp.2011.02.002

Werker, J. F., & Curtin, S. (2005). PRIMIR: A developmental framework of infant speech processing. *Language Learning and Development*, *1*(2), 197–234. doi:10.1207/s15473341lld0102_4

White, K. S., & Morgan, J. L. (2008). Sub-segmental detail in early lexical representations. *Journal of Memory and Language*, *52*(1), 114–132. doi:10.1016/j.jml.2008.03.001

Zesiger, P., Lozeron, E. D., Levy, A., & Frauenfelder, U. H. (2012). Phonological specificity in 12- and 17-month-old French-speaking infants. *Infancy*, *17*(6), 591–609.

1066   doi:10.1111/j.1532-7078.2011.00111.x

1067   Allaire, J., Xie, Y., McPherson, J., Luraschi, J., Ushey, K., Atkins, A., … Chang, W.

1068   (2018). rmarkdown: Dynamic Documents for R. Retrieved from

1069   https://cran.r-project.org/package=rmarkdown

1070   Altvater-Mackensen, N. (2010). *Do manners matter? Asymmetries in the acquisition of*

1071   *manner of articulation features.* (PhD thesis). Radboud University Nijmegen.

1072   Altvater-Mackensen, N., Feest, S. V. H. van der, & Fikkert, P. (2014). Asymmetries in

1073   early word recognition: The case of stops and fricatives. *Language Learning and*

1074   *Development*, *10*(2), 149–178. doi:10.1080/15475441.2013.808954

1075   Aust, F., & Barth, M. (2018). papaja: Prepare reproducible APA journal articles with R

1076   Markdown. Retrieved from https://github.com/crsh/papaja

1077   Bailey, T. M., & Hahn, U. (2005). Phoneme similarity and confusability. *Journal of*

1078   *Memory and Language*, *52*(3), 339–362. doi:10.1016/j.jml.2004.12.003

1079   Bailey, T. M., & Plunkett, K. (2002). Phonological specificity in early words. *Cognitive*

1080   *Development*, *17*(2), 1265–1282. doi:10.1016/S0885-2014(02)00116-8

1081   Ballem, K. D., & Plunkett, K. (2005). Phonological specificity in children at 1;2. *Journal*

1082   *of Child Language*, *32*(1), 159–173. doi:10.1017/S0305000904006567

1083   Bergmann, C., & Cristia, A. (2016). Development of infants' segmentation of words from

1084   native speech: A meta-analytic approach. *Developmental Science*, *19*(6), 901–917.

1085   doi:10.1111/desc.12341

1086   Bergmann, C., Tsuji, S., Piccinini, P. E., Lewis, M. L., Braginsky, M., Frank, M. C., &

1087   Cristia, A. (2018). Promoting replicability in developmental research through

1088   meta-analyses: Insights from language acquisition research. *Child Development*.

1089   doi:10.17605/OSF.IO/3UBNC

1090   Bernier, D. E., & White, K. S. (2017). What's a Foo? Toddlers Are Not Tolerant of Other

Children's Mispronunciations. In *Proceedings of the 41st annual boston university conference on language development* (pp. 88–100).

Charles-Luce, J., & Luce, P. A. (1995). An examination of similarity neighbourhoods in young children's receptive vocabularies. *Journal of Child Language, 22*(3), 727–735. doi:10.1017/S0305000900010023

Cohen, J. (1988). *Statistical Power Analysis for the Behavioural Sciences* (2nd ed.). New York: Lawrence Earlbaum Associates.

Csibra, G., Hernik, M., Mascaro, O., Tatone, D., & Lengyel, M. (2016). Statistical treatment of looking-time data. *Developmental Psychology, 52*(4), 521–36. doi:10.1037/dev0000083

Curtin, S., & Werker, J. F. (2007). The perceptual foundations of phonological development. In M. G. Gaskell (Ed.), *The oxford handbook of psycholinguistics* (pp. 579–599). New York: Oxford University Press. doi:10.1093/oxfordhb/9780198568971.013.0035

Feest, S. V. H. van der, & Fikkert, P. (2015). Building phonological lexical representations. *Phonology, 32*(02), 207–239. doi:10.1017/S0952675715000135

Ferguson, C. J., & Heene, M. (2012). A vast graveyard of undead theories: Publication bias and psychological science's aversion to the null. *Perspectives on Psychological Science, 7*(6), 555–561. doi:10.1177/1745691612459059

Fernald, A., Pinto, J. P., Swingley, D., Weinberg, A., & McRoberts, G. W. (1998). Rapid gains in speed of verbal processing by infants in the 2nd year. *Psychological Science, 9*(3), 228–231. doi:10.1111/1467-9280.00044

Fisher, R. A. (1922). On the Interpretation of χ 2 from Contingency Tables, and the Calculation of P. *Journal of the Royal Statistical Society, 85*(1), 87. doi:10.2307/2340521

Fleiss, J. L. (1986). *The Design and Analysis of Clinical Experiments.* New York: Wiley; Sons.

Frank, M. C., Lewis, M. L., & Macdonald, K. (2016). A performance model for early word learning. *Proceedings of the Cognitive Science Society*, 2609–2614. Retrieved from https://mindmodeling.org/cogsci2016/papers/0450/paper0450.pdf

Gelman, A., & Loken, E. (2013). *The garden of forking paths: Why multiple comparisons can be a problem, even when there is no "fishing expedition" or "p-hacking" and the research hypothesis was posited ahead of time.* Department of Statistics, Columbia University. doi:10.1037/a0037714

Halberda, J. (2003). The development of a word-learning strategy. *Cognition, 87*, B23–B34.

Havron, N., Bergmann, C., & Tsuji, S. (2020). Preregistration in infant research - a primer. doi:10.31234/osf.io/es2gx

Hedges, L. V. (1981). Distribution theory for glass's estimator of effect size and related estimators. *Journal of Educational and Behavioral Statistics, 6*(2), 107–128. doi:10.3102/10769986006002107

Højen, A., Madsen, T. O., Vach, W., Basbøll, H., Caporali, S., & Blese, D. (n.d.). *Contributions of vocalic and consonantal information when Danish 20-month-olds recognize familiar words.*

Jennions, M. D., Mù, A. P., Pierre, Â., Curie, M., & Cedex, F. P. (2002). Relationships fade with time : a meta-analysis of temporal trends in publication in ecology and evolution. *Proceedings of the Royal Society of London B: Biological Sciences, 269*, 43–48. doi:10.1098/rspb.2001.1832

Leon, A. C., & Heo, M. (2009). Sample sizes required to detect interactions between two binary fixed-effects in a mixed-effects linear regression model. *Computational Statistics and Data Analysis, 53*(3), 603–608. doi:10.1016/j.csda.2008.06.010

Mani, N., Coleman, J., & Plunkett, K. (2008). Phonological specificity of vowel contrasts at 18-months. *Language and Speech, 51*, 3–21. doi:10.1177/00238309080510010201

Mani, N., & Plunkett, K. (2007). Phonological specificity of vowels and consonants in early lexical representations. *Journal of Memory and Language, 57*(2), 252–272. doi:10.1016/j.jml.2007.03.005

Mani, N., & Plunkett, K. (2010). Twelve-month-olds know their cups from their keps and tups. *Infancy, 15*(5), 445–470. doi:10.1111/j.1532-7078.2009.00027.x

Mani, N., & Plunkett, K. (2011). Does size matter? Subsegmental cues to vowel mispronunciation detection. *Journal of Child Language, 38*(03), 606–627. doi:10.1017/S0305000910000243

ManyBabiesConsortium. (2020). Quantifying sources of variability in infancy research using the infant-directed speech preference. *Advances in Methods and Practices in Psychological Science.*

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods, 164*(1), 177–190. doi:10.1016/j.jneumeth.2007.03.024

Markman, E. M., Wasow, J. L., & Hansen, M. B. (2003). Use of the mutual exclusivity assumption by young word learners. *Cognitive Psychology, 47*(3), 241–275. doi:10.1016/S0010-0285(03)00034-3

Marslen-Wilson, W. D., & Zwitserlood, P. (1989). Accessing spoken words: The importance of word onsets. *Journal of Experimental Psychology: Human Perception and Performance, 15*(3), 576–585. doi:10.1037/0096-1523.15.3.576

Mayor, J., & Plunkett, K. (2014). Infant word recognition: Insights from TRACE simulations. *Journal of Memory and Language, 71*(1), 89–123. doi:10.1016/j.jml.2013.09.009

McClelland, J. L., & Elman, J. L. (1986). The TRACE model of speech perception. *Cognitive Psychology*, *18*(1), 1–86. doi:10.1016/0010-0285(86)90015-0

Mirman, D., Dixon, J. A., & Magnuson, J. S. (2008). Statistical and computational models of the visual world paradigm: Growth curves and individual differences. *Journal of Memory & Language*, *59*(4), 475–494. doi:10.1016/j.jml.2007.11.006

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & PRISMA Group". (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLoS Medicine*, *6*(7), e1000097. doi:10.1371/journal.pmed.1000097

Morris, S. B., & DeShon, R. P. (2002). Combining effect size estimates in meta-analysis with repeated measures and independent-groups designs. *Psychological Methods*, *7*(1), 105–125. doi:10.1037/1082-989X.7.1.105

Nazzi, T., Floccia, C., Moquet, B., & Butler, J. (2009). Bias for consonantal information over vocalic information in 30-month-olds: Cross-linguistic evidence from French and English. *Journal of Experimental Child Psychology*, *102*(4), 522–537. doi:10.1016/j.jecp.2008.05.003

Nazzi, T., Poltrock, S., & Von Holzen, K. (2016). The developmental origins of the consonant bias in lexical processing. *Current Directions in Psychological Science*, *25*(4), 291–296. doi:10.1177/0963721416655786

Rabagliati, H., Ferguson, B., & Lew-Williams, C. (2018). The profile of abstract rule learning in infancy: Meta-analytic and experimental evidence. *Developmental Science*, (October 2017), 1–18. doi:10.1111/desc.12704

Ramon-Casas, M., & Bosch, L. (2010). Are non-cognate words phonologically better specified than cognates in the early lexicon of bilingual children? *Selected Proceedings of the 4th Conference on Laboratory Approaches to Spanish Phonology*, 31–36.

Ramon-Casas, M., Swingley, D., Sebastián-Gallés, N., & Bosch, L. (2009). Vowel categorization during word recognition in bilingual toddlers. *Cognitive Psychology*, *59*(1), 96–121. doi:10.1016/j.cogpsych.2009.02.002

R Core Team. (2018). R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from https://www.r-project.org/

Renner, L. F. (2017). *The magic of matching – speech production and perception in language acquisition* (thesis). Stockholm University.

Sakaluk, J. (2016). Make it pretty: Forest and funnel plots for meta-analysis using ggplot2. [Blog post]. Retrieved from https://sakaluk.wordpress.com/2016/02/16/7-make-it-pretty-plots-for-meta-analysis/

Schwarzer, G. (2007). meta: An R package for meta-analysis. *R News*, *7*(3), 40–45. doi:10.1007/978-3-319-21416-0>

Simmons, J. P., Nelson, L. D., & Simonsohn, U. (2011). False-positive psychology: Undisclosed flexibility in data collection and analysis allows presenting anything as significant. *Psychological Science*, *22*(11), 1359–1366. doi:10.1177/0956797611417632

Simonsohn, U., Nelson, L. D., & Simmons, J. P. (2014). P-curve: A key to the file-drawer. *Journal of Experimental Psychology: General*, *143*(2), 534–547. doi:10.1037/a0033242

Skoruppa, K., Mani, N., Plunkett, K., Cabrol, D., & Peperkamp, S. (2013). Early word recognition in sentence context: French and English 24-month-olds' sensitivity to sentence-medial mispronunciations and assimilations. *Infancy*, *18*(6), 1007–1029. doi:10.1111/infa.12020

Swingley, D. (2009). Onsets and codas in 1.5-year-olds' word recognition. *Journal of*

Memory and Language, *60*(2), 252–269. doi:10.1016/j.jml.2008.11.003

Swingley, D. (2016). Two-year-olds interpret novel phonological neighbors as familiar words. *Developmental Psychology*, *52*(7), 1011–1023. doi:10.1037/dev0000114

Swingley, D., & Aslin, R. N. (2000). Spoken word recognition and lexical representation in very young children. *Cognition*, *76*(2), 147–166. doi:10.1016/S0010-0277(00)00081-0

Swingley, D., & Aslin, R. N. (2002). Lexical Neighborhoods and the Word-Form representations of 14-Month-Olds. *Psychological Science*, *13*(5), 480–484. doi:10.1111/1467-9280.00485

Tamasi, K. (2016). *Measuring children 's sensitivity to phonological detail using eye tracking and pupillometry* (PhD thesis). University of Potsdam.

Tsuji, S., Bergmann, C., & Cristia, A. (2014). Community-Augmented Meta-Analyses: Toward Cumulative Data Assessment. *Psychological Science*, *9*(6), 661–665. doi:10.1177/1745691614552498

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software*, *36*(3), 1–48. doi:10.18637/jss.v036.i03

Von Holzen, K., & Mani, N. (2012). Language nonselective lexical access in bilingual toddlers. *Journal of Experimental Child Psychology*, *113*, 569–586. doi:10.1016/j.jecp.2011.02.002

Werker, J. F., & Curtin, S. (2005). PRIMIR: A developmental framework of infant speech processing. *Language Learning and Development*, *1*(2), 197–234. doi:10.1207/s15473341lld0102_4

White, K. S., & Morgan, J. L. (2008). Sub-segmental detail in early lexical representations. *Journal of Memory and Language*, *52*(1), 114–132. doi:10.1016/j.jml.2008.03.001

Zesiger, P., Lozeron, E. D., Levy, A., & Frauenfelder, U. H. (2012). Phonological specificity in 12- and 17-month-old French-speaking infants. *Infancy*, *17*(6), 591–609.

1241   doi:10.1111/j.1532-7078.2011.00111.x

Table 1
Summary of all papers. Age: mean age (in months). Vocabulary: Comp = comprehension, Prod = production. Distractor Familiarity: Fam = Familiar, Unfam = Unfamiliar Target Overlap: O = onset, M = medial, C = coda. Mispronunciation Size: number of features changed; commas indicate separate comparison, dashes indicate an aggregated range. Mispronunciation Position: O = onset, M = medial, C = coda. Mispronunciation Type: C = consonant, V = vowel, T = tone. A slash separator indicates no distinction was made; the stimuli and unspec. indicates that the value was unspecified in the paper

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

Table 2
Summary of the 5 moderator tests, including effect estimates for effects and critical interactions.

Moderator	Moderator Test	Interaction Terms	Hedges' *g*	SE	95 CI	*p*-value
Misp. size	QM(1) = 59.618, *p* < .001		-0.403	0.052	[-0.505, -0.301]	< .001
	QM(3) = 140.626, *p* < .001	Age	0.009	0.006	[-0.002, 0.02]	= 0.099
Misp. position	QM(3) = 172.935, *p* < .001	Condition	-0.146	0.064	[-0.271, -0.02]	= 0.023
	QM(7) = 176.208, *p* < .001	Condition * Age	0.018	0.018	[-0.017, 0.053]	= 0.314
Misp. type	QM(3) = 141.83, *p* < .001	Condition	0.043	0.079	[-0.111, 0.198]	= 0.584
	QM(7) = 149.507, *p* < .001	Condition * Age	0.041	0.018	[0.005, 0.076]	= 0.026
	QM(7) = 154.731, *p* < .001	Condition * Language Family	-0.841	0.28	[-1.39, -0.292]	= 0.003
	QM(15) = 181.174, *p* < .001	Condition * Language Family * Age	0.344	0.078	[0.191, 0.496]	< .001
Distractor overlap	QM(3) = 48.551, *p* < .001	Condition	0.199	0.215	[-0.222, 0.619]	= 0.354
	QM(7) = 68.485, *p* < .001	Condition * Age	0.092	0.038	[0.017, 0.166]	= 0.016
Distractor familiarity	QM(3) = 102.487, *p* < .001	Condition	0.038	0.138	[-0.233, 0.309]	= 0.783
	QM(7) = 106.262, *p* < .001	Condition * Age	-0.02	0.035	[-0.089, 0.049]	= 0.574
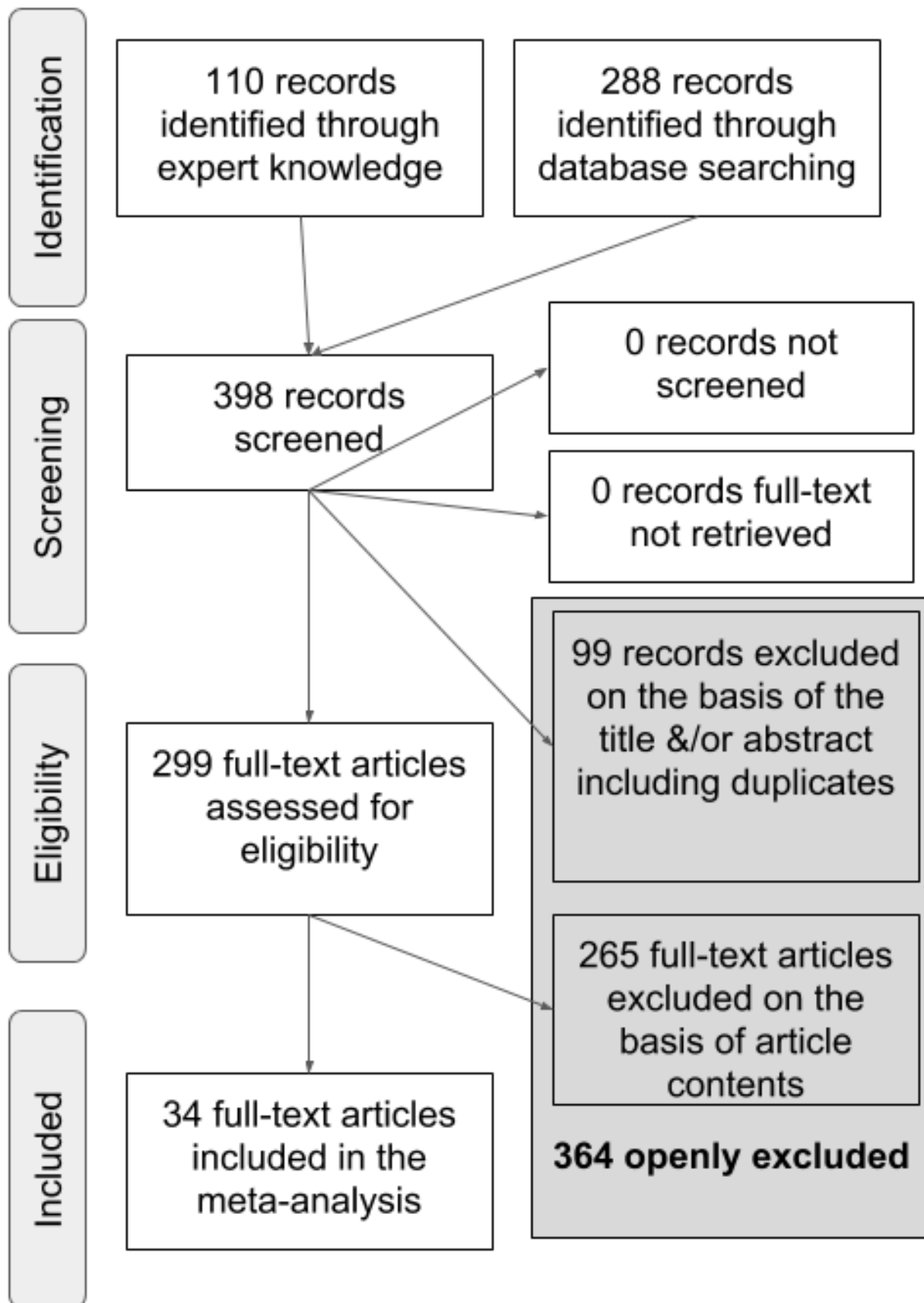
Figure 1. A PRISMA flowchart illustrating the selection procedure used to include studies in the current meta-analysis.
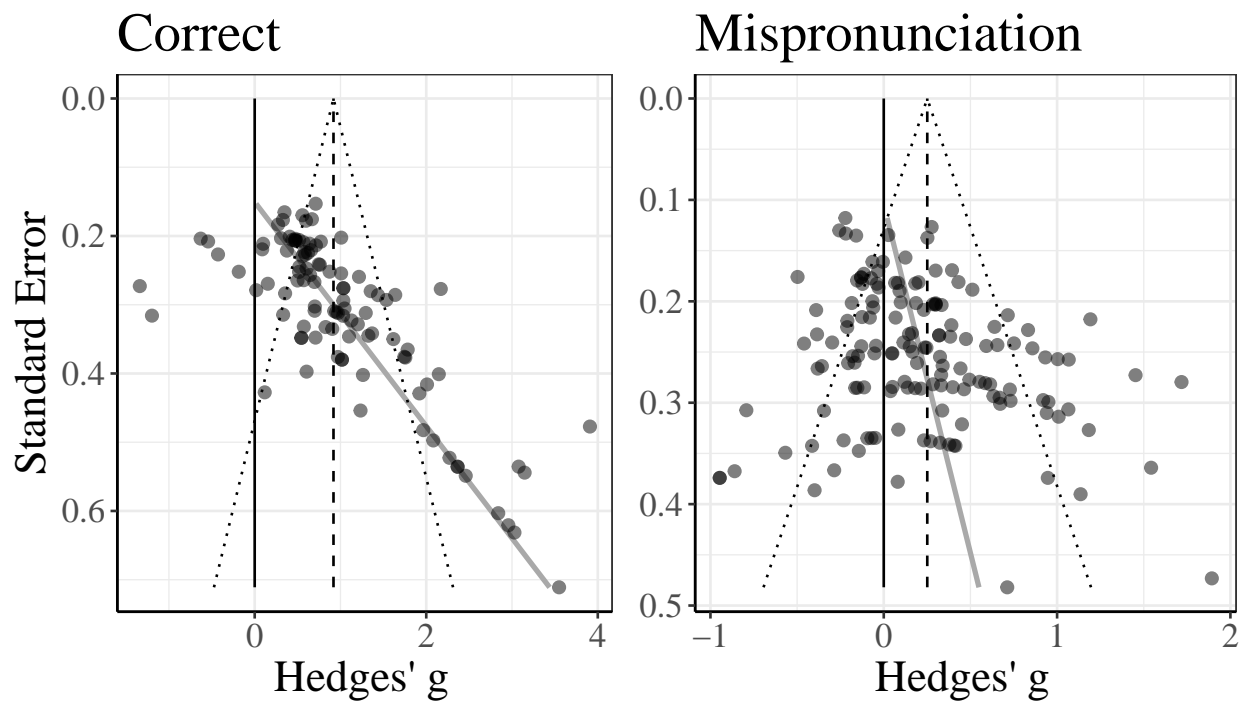
Figure 2. Funnel plots for object identification, plotting the standard error of the effect size in relation to the effect size. The black line marks zero, the dashed grey line marks the effect estimate, and the grey line marks funnel plot asymmetry.
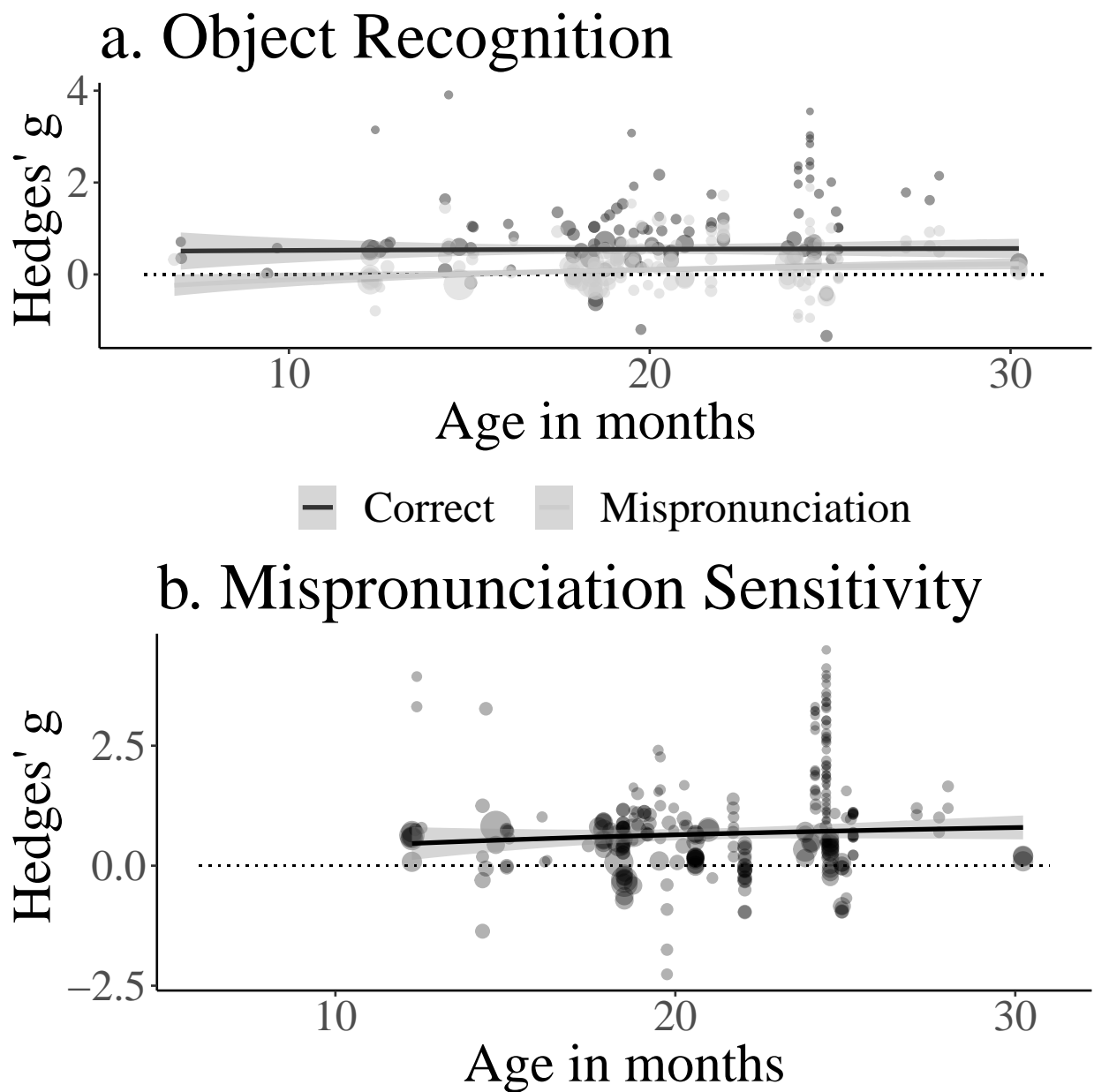
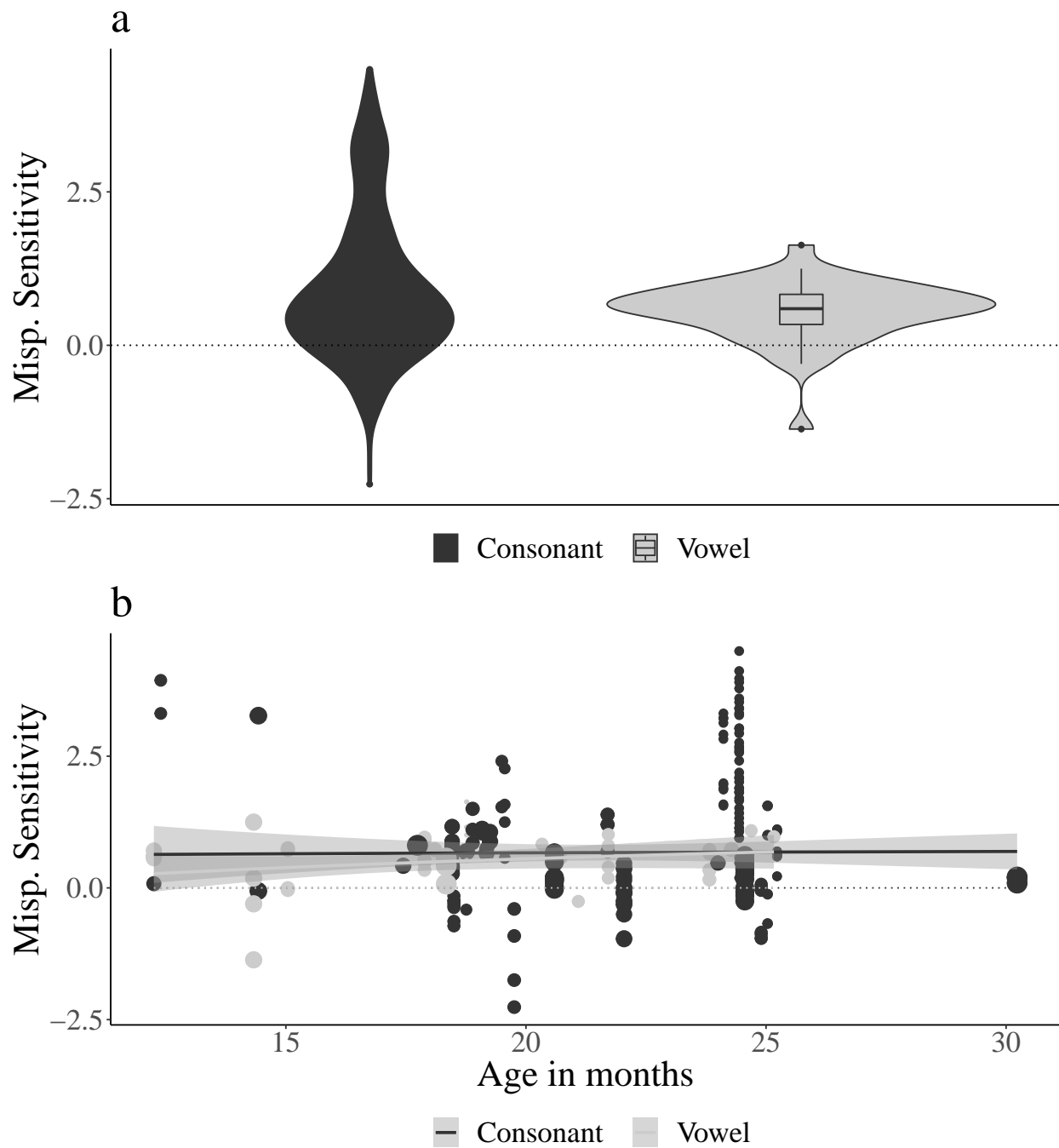*Figure 3.* Panel a: Effect sizes for correct pronunciations (orange) and mispronunciations (blue) by participant age. Panel b: Effect sizes for mispronunciation sensitivity within subject group and study (correct - mispronunciations) by participant age. For both panels, point size depicts inverse variance and the dashed line indicates zero (chance).
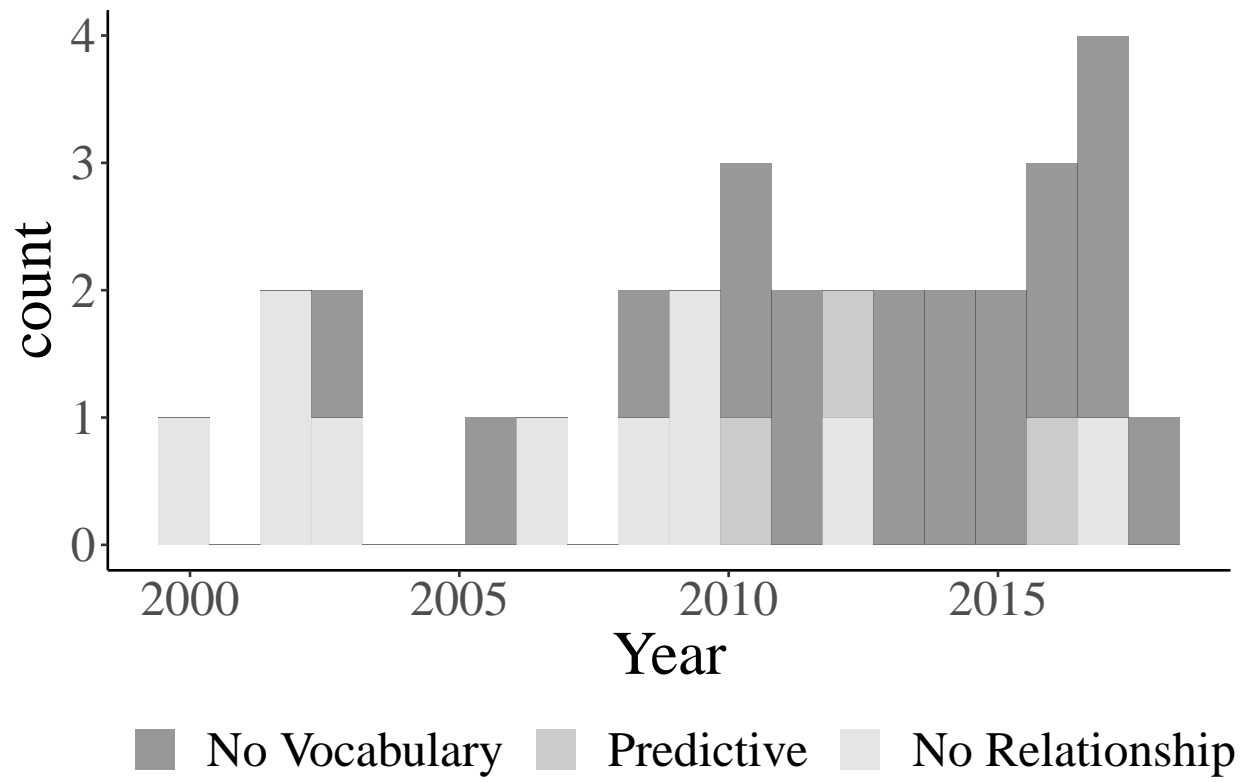
Figure 4. Counts of studies included in the meta-analysis as a function of publication year, representing whether the study did not measure vocabulary (orange), did measure vocabulary and was reported to predict mispronunciation sensitivity (blue), or did measure vocabulary and was reported to not predict mispronunciation sensitivity (green).
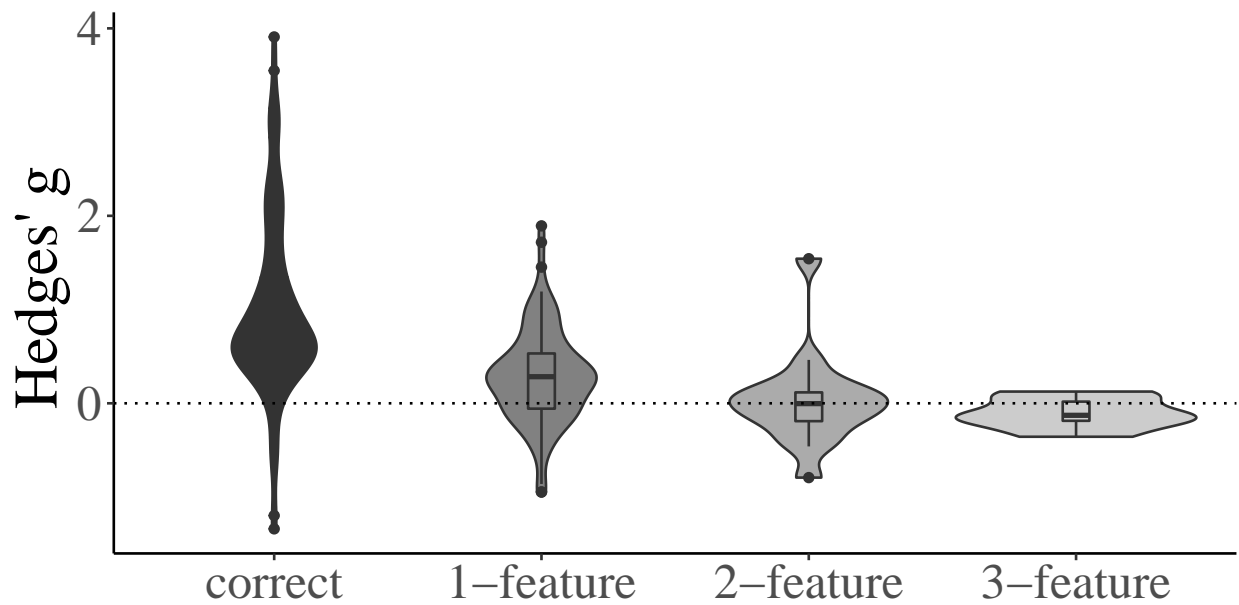
Figure 5. Effect sizes for correct pronunciations, 1-, 2-, and 3-feature mispronunciations.
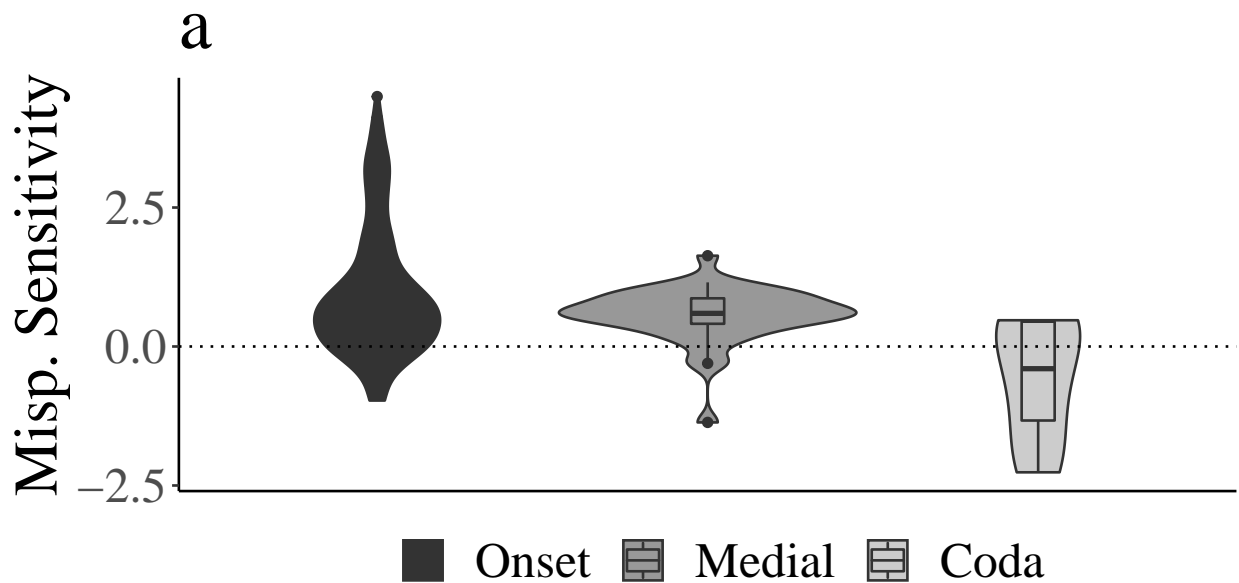
Figure 6. Effect sizes for mispronunciation sensitivity within subject group and study (correct - mispronunciations) for mispronunciations on the onset, medial, and coda positions. The dashed line indicates zero (chance).

Figure 7. Panel a: Effect sizes for mispronunciation sensitivity within subject group and study (correct - mispronunciations) for consonant and vowel mispronunciations. Panel b: Effect sizes for mispronunciation sensitivity within subject group and study (correct - mispronunciations) for consonant and vowel mispronunciations by age. For both panels, point size depicts inverse variance and the dashed line indicates zero (chance).
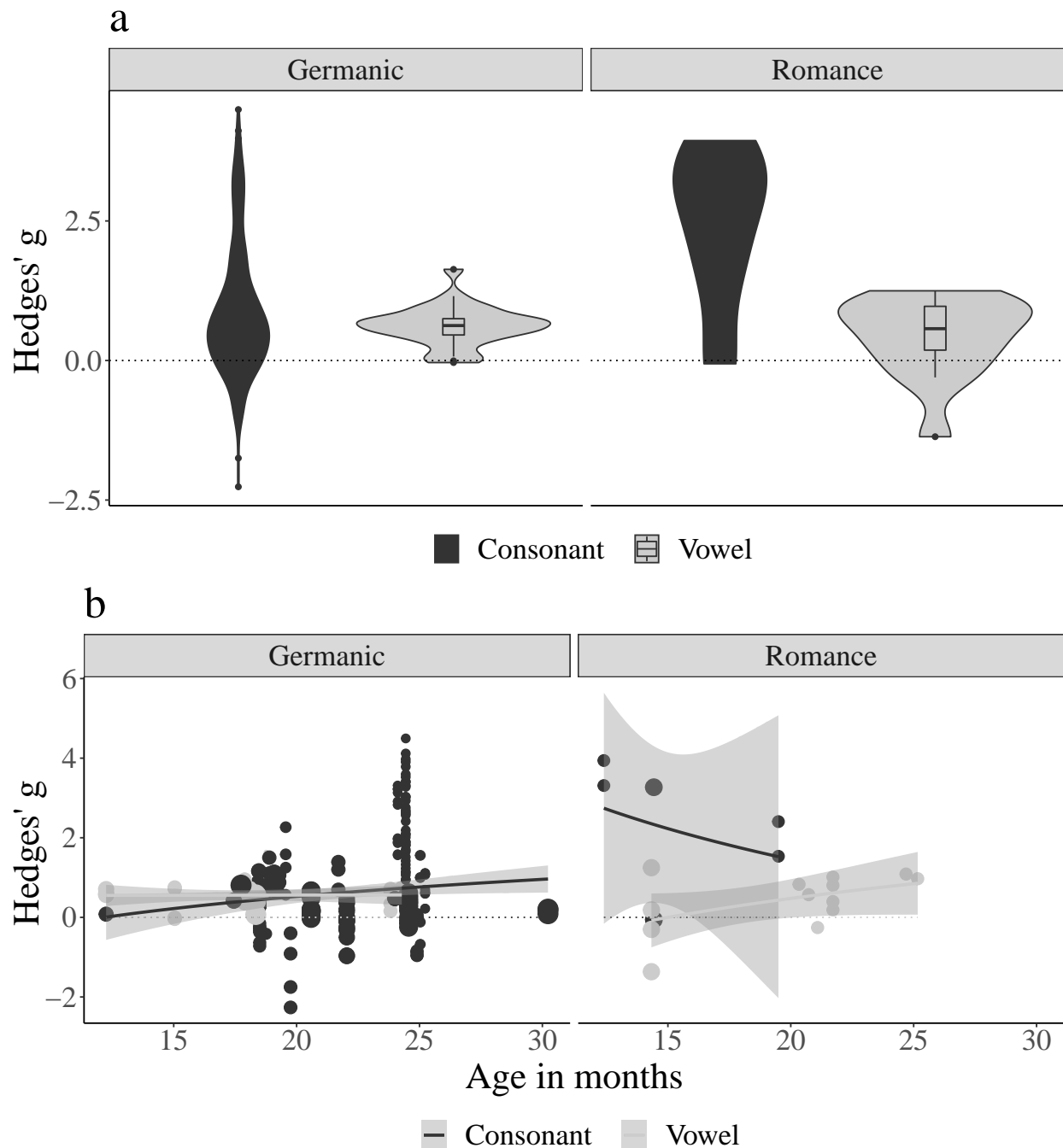
Figure 8. Panel a: Effect sizes for mispronunciation sensitivity within subject group and study (correct - mispronunciations) for consonant and vowel mispronunciations for infants learning a Germanic (left) or a Romance (right) native language. Panel b: Effect sizes for mispronunciation sensitivity within subject group and study (correct - mispronunciations) for consonant and vowel mispronunciations for infants learning a Germanic (left) or a Romance (right) native language by age. For both panels, point size depicts inverse variance and the dashed line indicates zero (chance).
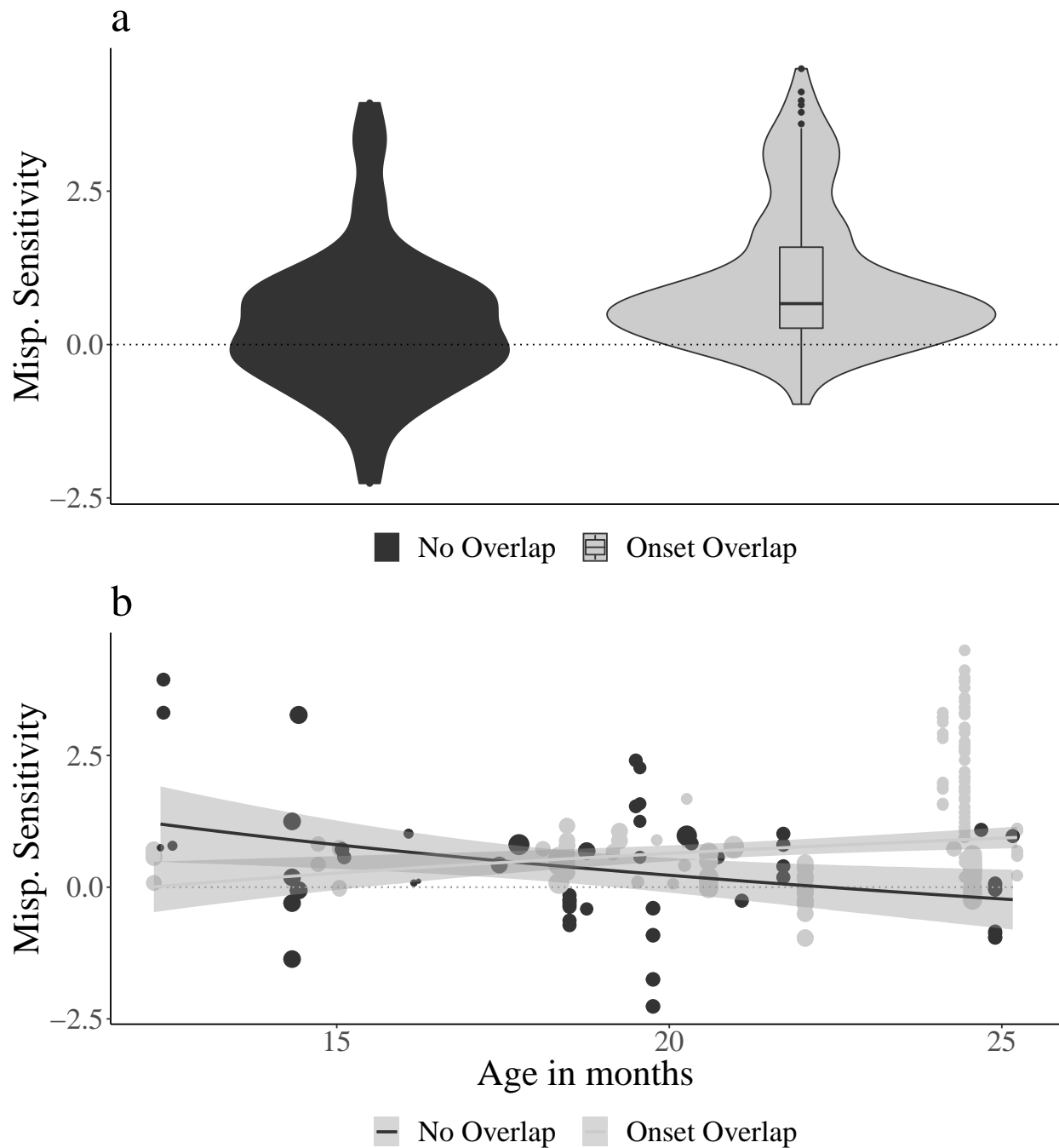
Figure 9. Panel a: Effect sizes for mispronunciation sensitivity within subject group and study (correct - mispronunciations) for target-distractor pairs with onset overlap or no overlap. Panel b: Effect sizes for mispronunciation sensitivity within subject group and study (correct - mispronunciations) for target-distractor pairs with onset overlap or no overlap by age. For both panels, point size depicts inverse variance and the dashed line indicates zero (chance).
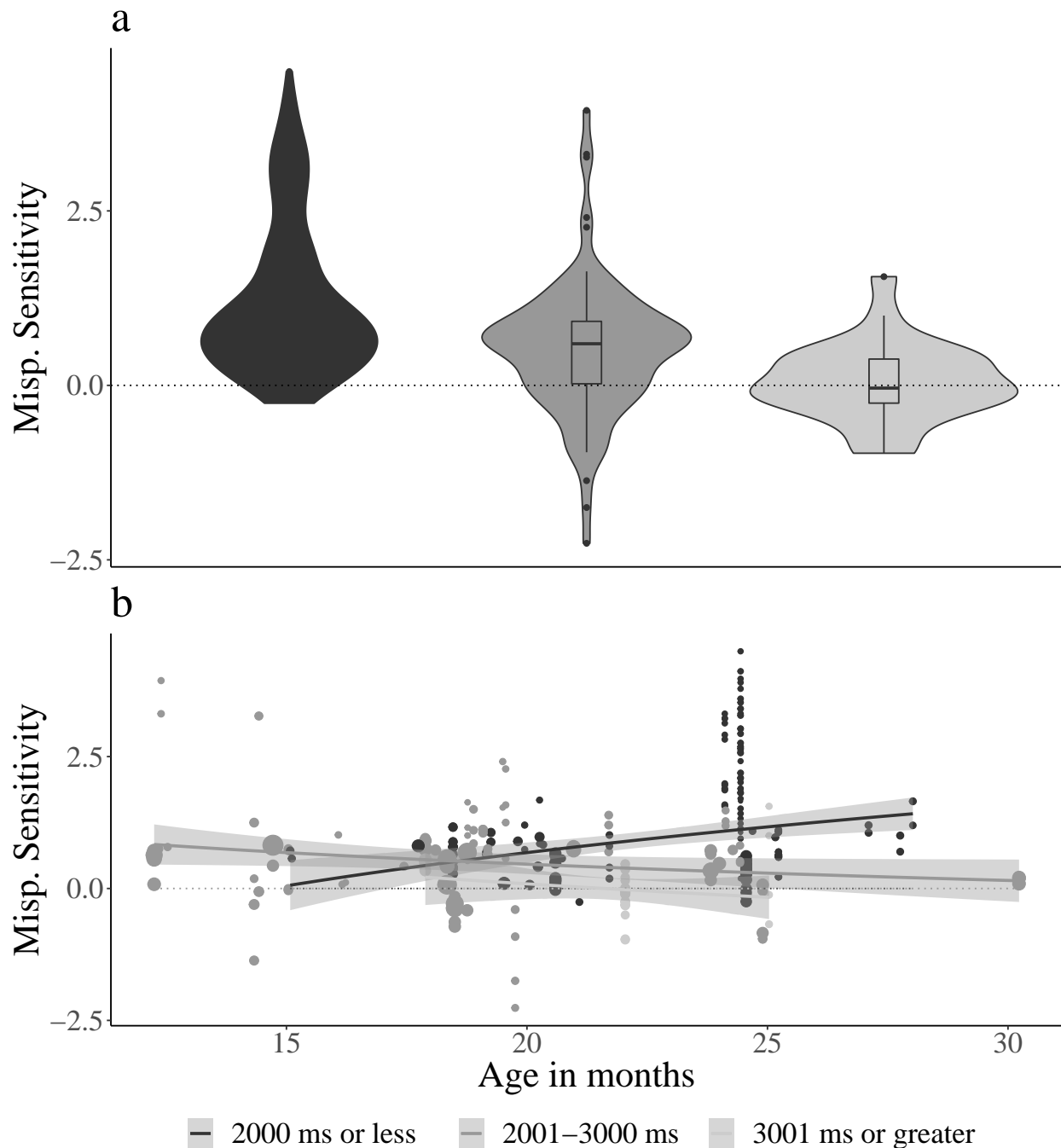
Figure 10. Effect sizes for the different lengths of the post-naming analysis window: 2000 ms or less (orange), 2001 to 3000 ms (blue), and 3001 ms or greater (green). Although length of the post-naming analysis window was included as a continuous variable in the meta-analytic model, it is divided into categories for ease of viewing. Panel a plots mispronunciation sensitivity aggregated over age, while panel b plots mispronunciation sensitivity, within subject group and study (correct - mispronunciations), as a function of age. The lines plot the linear regression and the gray shaded area indicates the standard error.
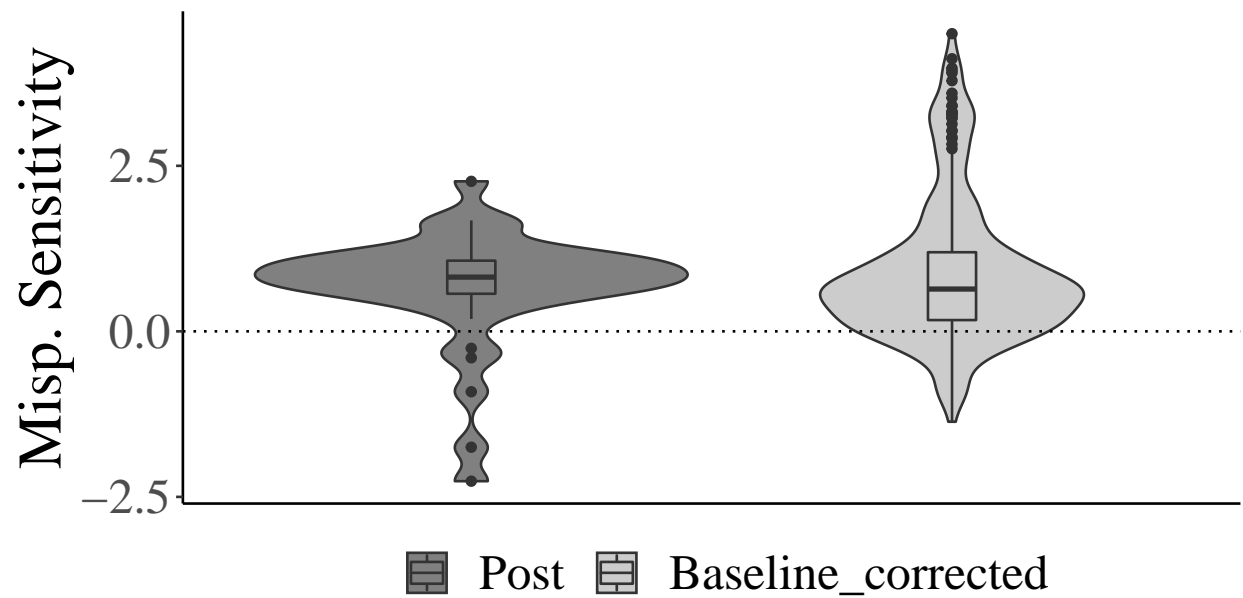
Figure 11. Effect sizes for the different types of dependent variables calculated: Post (orange), Post vs. Pre (blue), and Difference Score (green). Panel a plots mispronunciation sensitivity aggregated over age, while panel b plots mispronunciation sensitivity, within subject group and study (correct - mispronunciations), as a function of age. The lines plot the linear regression and the gray shaded area indicates the standard error.