**A Systematic Review and Bayesian Meta-Analysis of the Acoustic Features of Infant-Directed Speech**

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# **Abstract**

When speaking to infants, adults often produce speech that differs systematically from that directed to other adults. In order to quantify the acoustic properties of this speech style across a wide variety of languages and cultures, we extracted results from empirical studies on the acoustic features of infant-directed speech (IDS). We analyzed data from 88 unique studies (734 effect sizes) on the following five acoustic parameters that have been systematically examined in the literature: i) fundamental frequency (*f*o), ii) *f*o variability, iii) vowel space area, iv) articulation rate, and v) vowel duration. Moderator analyses were conducted in hierarchical Bayesian robust regression models in order to examine how these features change with infant age and differ across languages, experimental tasks and recording environments. The moderator analyses indicated that *f*o, articulation rate, and vowel duration became more similar to adult-directed speech (ADS) over time, whereas *f*o variability and vowel space area exhibited stability throughout development. These results point the way for future research to disentangle different accounts of the functions and learnability of IDS by conducting theory-driven comparisons among different languages and using computational models to formulate testable predictions.

# **Introduction**

Speaking to infants presents caregivers with a significant challenge. Because infants are not linguistically competent, older individuals modify their speech to them in a variety of ways to communicate. The ways in which caregivers produce infant-directed speech (IDS) have been widely documented, and some clear patterns have emerged across multiple languages. For example, speakers often increase their vocal pitch and pitch variability, slow down their speech, and articulate more clearly e.g., 1–3. The discovery of similar acoustic properties of IDS across so many languages and cultures strongly suggests that this speech style plays an important role in linguistic and social development 4.

In the study of signal design in humans and nonhuman animals, form-function analysis is used to understand how structural characteristics of signals are shaped by the communicative functions they serve. This approach applies well to the study of IDS 5–7. For instance, the loud, low-pitched, abrupt onset of a prohibitive yell could be designed to interrupt the behavior of a baby by exploiting the startle reflex, which quickly re-orients a target infant’s attention to the sound source 5. Similarly, approval vocalizations may induce positive emotions through raised pitch and pitch variability, faster speech, and modulated loudness reflecting speakers’ positive valence and heightened arousal 5,8,9. But communicative functions overlap and interact as the cognitive and linguistic skills of the infant develop, and their interactional affordances change 10–12.

One prominent hypothesis holds that the acoustic features of IDS may help infants learn aspects of language 4. The benefits of IDS to language development are generally attributed to its tendency to increase the clarity of the speech input e.g., 13–15. This hypothesis receives substantial support from longitudinal studies showing positive correlations between parents’ tendency to produce acoustically exaggerated vowels and speech discrimination skills 15 as well as expressive vocabulary size 13,16. Other studies show that acoustically exaggerated vowels induce more mature neural processing of vowel categories in infants 17 and faster word recognition 18. The cross-linguistic tendency for caregivers to exaggerate the differences between vowel categories might facilitate infants’ language development by increasing category separability in the speech stream. An increase in vowel category separability in speech has been shown to co-occur with a greater degree of within-category variability 19–23, which may work in parallel with separability to increase the robustness and generalizability of the categories 24–27.

The functions of IDS have been posited to exhibit change over the course of early infant development, with the speech style initially serving primarily to direct infants' attention and express affect, and later on serving more specific linguistic purposes 6. According to a form-functions analysis, these age-related changes in the functions of IDS should manifest themselves in the acoustic properties of caregivers’ speech. Despite the implications of unidirectionality in its name, however, IDS also includes feedback from infants – IDS involves reciprocity and interaction where the interdependence of infants’ active participation and caregiver responsiveness plays a crucial role 28–32. The benefits of IDS should be construed as originating in the mutual feedback loops between infant and caregiver, where infants provide an important source of feedback about which signals they prefer to attend to and interact with 28–32.

Many studies have demonstrated that infants prefer to listen to IDS over ADS 1,2,14,33–37. This preference persists when presented speech is in a foreign language 35,37, or when low-pass-filtered and containing only global prosodic information 38. Even infant-directed songs in a foreign language induce relaxation in babies 39. A recent large-scale, multi-lab replication study found that infants exhibit linear increases in their IDS preference until at least 15 months of age, the oldest age tested 35. This trajectory was similar to the findings of a meta-analysis reporting a general increase in looking times toward IDS in preverbal infants from 0 to 9 months 40. In contrast, two studies have reported that infants’ IDS preference exhibits a U-shaped pattern. Hayashi et al. 41 found that while both groups of 4-6- as well as 10-14-month-old infants paid more attention to IDS than ADS, but 7-9-month-old infants did not exhibit a preference. Similarly, Newman & Hussain 42 found a preference for IDS in 5-month-old infants, but not in 9- or 13-month-olds.

Infants’ shifting preferences for IDS over ADS over the first year of life could reflect dynamic changes in the acoustic features they attend to. For example, Panneton et al. 12 reported that 4-month-old infants listened longer to speech with a higher positive affect (i.e., relatively higher emotion content) and slowed duration, but 8-month-old infants preferred speech with normal duration and lower relative affect. Other studies examining differences in preferences have demonstrated various effects suggesting that infants, even during their first year, might be attending differentially to many aspects of IDS 8–10. For example, younger infants have been shown to preferentially attend to the intonational variability and positive affect of IDS 43,44. At this early developmental stage, the tendency for IDS to contain increased pitch variability, modulated loudness contours, and rhythmic alterations 34,45 likely serves the function of effectively communicating intentions, including getting an infant’s attention, expressing emotions and encouraging behavior 6. As infants get older and become more advanced in language development, their attention might shift toward aspects of IDS that provide linguistic information 10,11,46. If caregivers adapt the acoustic properties of their IDS to suit infants’ developmental needs, we may see systematic shifts in acoustic properties over the course of early infancy, such that exaggerated prosodic features associated with communicating intent to young infants should decline, and linguistically-relevant properties should be emphasized more for older children, including expansion of the vowel space area 6,14.

The study of IDS across cultures has a long interdisciplinary history. Early linguistic research revealed many regularities in IDS across disparate languages and cultures, as well as language-specific phenomena. In this work, many of the reported features were not acoustic but concerned phenomena such as modified morphemes and grammatical constructions as well as lexical innovations e.g., 47. Naturally, these kinds of features should vary cross-culturally, and variations were noted within villages, including features that were unique to single families, or that might spread to a few households at most. Ferguson (1964) also discussed cultural variations in attitudes toward babytalk, including its use in public and whether it was more appropriate for men or women to produce it. Other studies have shown that the frequency of speaking to infants in any manner can vary dramatically, with some cultural groups not speaking to infants very much at all 48–50. A high degree of variability in the rate of IDS use, however, does not preclude universality 51; rather, IDS may represent a continuum across cultures that exhibits cross-linguistic variability in its rate and acoustic properties. Early rejections of the universality of IDS often conflated the issues of incidence with form; that is, how often IDS occurs during interaction is separate from its acoustic features when it is actually produced. Later analyses focusing on acoustic characteristics of IDS across languages have revealed striking similarities 2,52,53. Recent large-scale studies have shown that these features occur widely, and the recognition of IDS and infant-directed song is robust 35,54. Questions regarding within- and between-culture variation are crucial to address when issues of universality are raised 51.

Researchers have now started using day-long recordings of infants e.g., 55,56 and open archives of acoustic data e.g., 57, allowing for the analysis of more ecological data to investigate infants’ linguistic and emotional development through quantitative and computational means e.g., 32. These archives provide data from diverse cultures e.g., 48 and offer new insights into the role of linguistic input on early language development. For example, US English speakers appear to produce a particularly exaggerated form of IDS relative to other speakers 2,58,59. Because such a high proportion of studies on IDS examine US English (cf. Figure 1 and Supplementary Tables 11.1-12.1 in Supplementary Information), the field may have a biased view of how IDS manifests itself, and how it may affect language development 35,58. Figure 1 shows the proportion of languages for which IDS has been analyzed compared to the total number of languages listed on the World Atlas of Language Structures 60. Although this world map suggests a considerable bias in the types of languages and cultures investigated, increasing linguistic diversity – while valuable in and of itself – is unlikely to improve our understanding of the cognitive underpinnings of IDS alone. More fine-grained, hypothesis-driven comparisons are also required 61–63, as discussed further in the Discussion. In order for such comparative approaches to be useful, we need a more careful and theory-driven analysis of the extant IDS literature and how IDS varies across infant ages, languages, experimental tasks and recording environments. It should also be noted that the participants in the studies included in this meta-analysis largely consist of female caregivers residing in Western, educated, industrialized, rich, developed countries 64. Due to the sparsity of the data on other speaker types and populations, the meta-analysis could not analyze these factors as potential sources of variability in the acoustic measures (e.g., kin vs. non-kin caregivers), as discussed further in the Discussion.

Many studies have demonstrated that caregivers exhibit age-related changes in the acoustic properties of their IDS. Here we will provide an overview of how each of the acoustic features in IDS that we investigated in our meta-analysis have been shown to change as a function of infants’ age. See Figure 2 for a summary visualization.

The most common finding in studies examining the acoustic features of IDS is that IDS utterances, on average, have higher *f*o and *f*o variability than ADS, resulting in the salient perceptual effects of perceived higher pitch and pitch variation e.g., 1,3. Interestingly, many longitudinal studies on *f*o show that caregivers decrease their overall vocal pitch to infants over the course of development 3,65–69, but findings are mixed with other studies reporting no change over time 13,70–75. Variability in *f*o shows a similar pattern. Pitch variation reflects intonational contours that provide information about speakers’ expression of affect and intentions e.g., 34,76. Longitudinal studies of *f*o variability in IDS indicate a peak before infants turn 12 months of age, with a subsequent decrease over the course of development 3,65–67,69,71,74,75,77.

The tendency for caregivers to expand their vowel space area in IDS represents one of the more subtle adaptations of speech directed to infants. The most common measure calculates the area in acoustic space encompassed by the mean formant values of the three corner vowels: /i/, /a/, and /u/. Because these three vowels represent articulatory extremes and occur in the majority of the world’s languages e.g., 78, studies focus on how caregivers adapt the acoustic-phonetic characteristics of these vowels in their IDS. Thus, vowel space area is used as a measure of how much caregivers clarify their speech to infants e.g., 16,15, although cf., 19,20,22. A majority of studies do not find evidence of any shift in vowel space area at a variety of age ranges 13,19,66,70,79–83. But some studies have shown changes over time, although there are differences in the direction of the shift 84,85.

Articulation rate measures the speed at which people speak, which can have important consequences for how easily language is processed. This is true not only for young infants, but adults as well, including second-language learners and listeners with other impairments e.g., 86. Speaking too fast can prevent proper processing, which could have effects on phonological perception, emotional communication, and other comprehension issues. Several longitudinal studies of articulation rate have shown that caregivers increase their rate of articulation (i.e., speed up speech) over the course of infant development 71,73–75. Vowel duration, lastly, plays a crucial role in phonological processing e.g., 2 as well as in modulating infant attention and facilitating language development 87. The exaggeration of the duration of vowels in IDS may make relevant phonological differences more salient to children, thereby facilitating their detection of clause and phrase boundaries 88,89. Longitudinal studies in several languages indicate that caregivers often decrease relative vowel duration differences in IDS and ADS as infants get older 16,69,90.

In the current meta-analysis, we aimed to investigate the acoustic properties of IDS across infant ages and languages, and understand these results in relation to the purported functions of IDS. We conducted this investigation by examining the influence of four moderator variables on possible acoustic differences between ADS and IDS: i) age, ii) language, iii) experimental task and iv) recording environment. The justification for each is described in brief. First, by pooling together data from the studies and quantifying the acoustic changes in IDS as a function of infant age, we can examine which of the acoustic properties of IDS change to become more similar to ADS over early infant development. Specific changes in the acoustic properties of IDS over developmental time would suggest that caregivers exhibit sensitivity to infants’ shifting socio-emotional and linguistic needs and adapt their speech accordingly. Concretely, if IDS in early development serves primarily to convey affect and only later serves a linguistic function, then we might expect to see developmental shifts in the acoustic properties that are primarily associated with linguistic facilitation (e.g., vowel space area and vowel duration). Whether these linguistic features are present from birth or become gradually more exaggerated in IDS as infants exhibit linguistic development remains an open empirical question. Over longer timescales (not covered by the studies in this meta-analysis), we would expect all of the acoustic properties of IDS to gradually become indistinguishable from those of ADS. Second, to quantify the amount of cross-linguistic variation that could be observed, we analyzed language as a moderator variable. For each acoustic variable, we provided language-specific estimates for each of the languages under investigation, as shown in Supplementary Tables 9.1-9.5 in the Supplementary Information. The data were too sparse to allow for an investigation of an interaction between infant age and the language spoken (cf. Supplementary Figure 7 in the Supplementary Information). Last, we analyzed experimental task (i.e., spontaneous vs. read speech) and recording environment (i.e., naturalistic vs. laboratory) as moderators to examine whether the studies provided commensurable measurements across different conditions.

Whether the acoustic properties of caregivers’ IDS change according to experimental task and recording environment remains an open question and an important consideration for future studies of IDS 40. A cross-tab plot showing how the acoustic measures were distributed across the conditions of task and environment is shown in Supplementary Figure 8 in the Supplementary Information. In addition to these moderator analyses, we also conducted sensitivity analyses in order to quantify the robustness of our findings and to assess the evidentiary strength for each acoustic feature in light of publication bias. We computed the worst-case effect size estimate based only on non-affirmative studies and investigated how sensitive the meta-analytic results were to a potential bias for significant results in the field.

# **Results**

**Summary of Results**

The overall results indicated a robust cross-linguistic tendency for caregivers to produce IDS with a higher pitch and pitch variability, an expanded vowel space area, a slower articulation rate, and longer vowel durations. Table 1 provides a summary of the average effect size estimates for each of the acoustic measures as well as the estimated between-study variability. The heatmap in Extended Data Figure 1 shows that the acoustic properties of IDS and ADS exhibit similar differences across languages, with some language-specificity. In the following five sections, we delve deeper into how each of the five acoustic measures are moderated by language, age, experimental task and recording environment, and assess how sensitive the results are to publication bias.

# **Fundamental frequency (*f*o)**

We combined data from studies reporting either the mean or median *f*o of utterances, as both measures indicate the central tendency of *f*o. The following hierarchical model included 262 individual reported effect size measures from 60 studies. The model with task, environment, age, and language as predictors was shown to provide a similar account of the data (stacking weight: 0.481) to the model excluding environment (stacking weight: 0.477), but a better account than the model excluding task (stacking weight: 0.014) or the model excluding task and environment (stacking weight: 0.029).

***f*o across studies**

The Bayesian hierarchical intercepts-only model of *f*o revealed an overall estimated effect size of *g* = 1.17 with 95% CrI of [0.86; 1.45], a between-languages heterogeneity of *g* = 0.34 [0.05; 0.67], a heterogeneity between studies within languages of *g* = 0.90 [0.71; 1.11], as well as a between-measures heterogeneity of *g* = 0.07 [0.00; 0.21]. A standardized mean difference of this size implies that approximately 87.9% of IDS speech samples are expected to exhibit a higher *f*o than ADS speech samples. An overview of how the studies varied with respect to the *f*o estimate is shown in the forest plot in Supplementary Figure 6.1 in the Supplementary Information. All of the studies exhibited effect size estimates on the positive scale, with only 16 of the 60 studies including the null in the lower-bound of their credible intervals.

## ***f*o as a function of language**

The estimates from the full model are shown in Figure 3 below. All of the point estimates for the languages under investigation appear in the positive range of effect sizes. The cross-linguistic differences between IDS and ADS in *f*o across languages thus mainly vary according to the extent to which *f*o is higher in IDS relative to ADS (cf. Supplementary Table 9.1 in the Supplementary Information for language-specific estimates and credible intervals).

## ***f*o as a function of age**

As shown in the top-right of Figure 3, the model indicated a robust effect of age—as infants’ ages increased, the difference in *f*o between IDS and ADS decreased. The estimate for the effect of age is -0.02 with 95% CrI [-0.03; 0.01], evidence ratio: 143.58, credibility: 0.99. This developmental pattern indicates that the cross-sectional data included in this meta-analysis conform to the results reported in most of the longitudinal studies (cf. Figure 2).

## ***f*o as a function of task and environment**

As shown in the middle-right plot in Figure 3, caregivers produced a greater *f*o difference between the two speech styles in experimental tasks designed to elicit spontaneous speech (estimate: 0.43 with 95% CrI [0.13; 0.74], evidence ratio: 94.54, credibility: 0.99). As shown in the lower-right-hand plot in Figure 3, recording parents in a naturalistic setting as opposed to in the laboratory shows a smaller difference between IDS and ADS in terms of *f*o (estimate: -0.48 with 95% CrI [-0.87; -0.07], evidence ratio: 36.54, credibility: 0.97).

## **Publication bias for *f*o**

The sensitivity analysis of publication bias for *f*o indicated that no amount of publication bias would be able to attenuate the effect size estimate for the credible interval to include null effects, as depicted in Supplementary Figure 10.1 in the Supplementary Information. The worst-case effect size estimate based solely on non-significant studies is 0.60 with 95% CrI [0.37; 0.83], as shown in Supplementary Figure 10.2 in the Supplementary Information. This analysis suggests that the effect size estimates might be quite robust to even severe levels of publication bias - assuming that effect size estimates of non-significant studies are representative of those of unpublished studies.

## ***f*o variability**

Some of the studies reported *f*o range (*n*=25) and others reported the standard deviation of *f*o (*n*=20). As these measures both capture change in *f*o over the course of the utterance, we grouped them together into a single category. If a study reported both measures, we used standard deviation because range consists of the difference between the highest and the lowest value, therefore being highly sensitive to even one outlier or measurement error. Therefore, standard deviation remains less sensitive to extreme values and represents the more reliable measure of the two. The effect size distributions of *f*o range and *f*o standard deviation were shown to be strongly correlated and exhibit no notable differences, as shown in Supplementary Figures 4.1-4.2 in the Supplementary Information. We extracted 223 effect sizes from 44 of the 88 studies. In this context, a positive Hedges’ *g* value signifies a higher degree of *f*o variability in IDS, and vice versa. The model with task, age, and language as predictors provided a better account of the data (stacking weight: 0.681) than the model including both task and environment (stacking weight: 0.218), the model excluding task (stacking weight: 0.017), and the model excluding both task and environment (stacking weight: 0.084).

## ***f*o variability across studies**

The Bayesian hierarchical intercepts-only model of *f*o variability showed an overall estimated difference of *g* = 0.69 with 95% CrI [0.44; 0.92] and a between-languages heterogeneity of *g* = 0.25 [0.02; 0.52], a heterogeneity between studies within languages of *g* = 0.71 [0.56; 0.88], as well as a between-measures heterogeneity of *g* = 0.11 [0.01; 0.23]. With a standardized mean difference of this size, this implies that approximately 83% of IDS speech samples would show a higher degree of *f*o variability compared to that of ADS speech samples. An overview of how the studies varied with respect to the *f*o variability estimate is shown in the forest plot in Supplementary Figure 6.2 in the Supplementary Information. The estimated effect sizes were primarily distributed on the positive scale, indicating that the studies provided evidence for greater *f*o variability in IDS than in ADS. Only one out of the 43 studies on *f*o variability had a negative effect size point estimate, which the authors posit could be a result of caregivers’ tendency to produce utterances with a higher minimum *f*o in IDS, thereby reducing the possible *f*o range 91.

## ***f*o variability as a function of language**

As shown in Figure 4 below, most of the point estimates for the languages appeared to be in the positive range of effect sizes (cf. Supplementary Table 9.2 in the Supplementary Information for language-specific estimates and credible intervals). The cross-linguistic differences between IDS and ADS in *f*o variability mainly related to the degree of exaggeration.

## ***f*o variability as a function of age**

As shown in the top-right of Figure 4, the model indicated no effects of infant age (estimate: 0.00 with 95% CrI [-0.01; 0.01], evidence ratio: 1.33 for no effect, credibility: 0.57. This suggests that *f*o variability in caregivers’ IDS remains stable even as infants become older. This is consistent with results reported in some of the longitudinal studies under investigation (cf. Figure 2).

## ***f*o variability as a function of task and environment**

The middle-right-hand plot in Figure 4 shows that caregivers spoke with higher degree of *f*o variability in spontaneous speech compared to in read speech (estimate: 0.39 with 95% CrI [0.11; 0.68], evidence ratio: 89.68, credibility: 0.99). The lower-right-hand plot in Figure 4 indicates that recording the parents in a naturalistic setting compared to in the laboratory exerted a weak negative influence on the effect size estimates (estimate: -0.22 with 95% CrI [-0.59; 0.15], evidence ratio: 5.02, credibility: 0.83).

## **Publication bias for *f*o variability**

A sensitivity analysis with a random-effects specification indicates that no amount of publication bias would be able to attenuate the effect size estimate for the credible interval to include null effects, as depicted in Supplementary Figure 10.1 in the Supplementary Information. The uncorrected worst-case estimate for the effect size based solely on non-significant studies is 0.33 with 95% CrI [0.18; 0.47], as shown in in Supplementary Figure 10.2 in the Supplementary Information.

# **Vowel space area**

33 studies reported vowel space area estimates, for a total of 107 reported effect sizes. In this context, a positive Hedges’ *g* value signifies an expansion of the vowel space area in IDS. The model with age and language as predictors was shown to provide a better account of the data (stacking weight: 0.431) than the model including environment (stacking weight: 0.250), the model including task (stacking weight: 0.193) as well as the model including both task and environment (stacking weight: 0.127).

## **Vowel space area across studies**

The Bayesian hierarchical intercepts-only model of vowel space area showed an overall estimated difference in vowel space area of *g* = 0.66 with 95% CrI of [0.34; 0.98], a between-languages heterogeneity of *g* = 0.55 [0.12; 0.97], a heterogeneity between studies within languages of *g* = 0.66 [0.43; 0.92], as well as a between-measures heterogeneity of *g* = 0.11 [0.00; 0.28]. A standardized mean difference of this size implies that approximately 74% of IDS speech samples overall will show an expanded vowel space area compared to those of ADS speech samples. An overview of how the studies varied with respect to the vowel space areaestimate is shown in the forest plot in Supplementary Figure 6.3 in the Supplementary Information. The studies were generally distributed across positive effect sizes; however, 19 of the 32 studies included the null in the lower bound of their credible intervals, and 2 of the 32 studies provided evidence for the opposite effect, namely that ADS exhibited an expanded vowel space area compared to IDS 70,92. The pooling of data from these studies on vowel space area, then, indicated a moderate effect size, with some of the studies providing conflicting results, possibly due to cross-linguistic differences, as discussed further below and in the Discussion.

## **Vowel space area as a function of language**

As shown in Figure 5, most of the point estimates for the languages appeared to be in the positive range of effect sizes (cf. Supplementary Table 9.3 in the Supplementary Information for language-specific estimates and credible intervals); however, there appears to be substantial cross-linguistic variation in the extent to which caregivers expand their vowel space area when speaking to infants.

## **Vowel space area as a function of age**

As shown in the top-right of Figure 5, the model indicated no evidence for an effect of infant age. The estimate is -0.00 with 95% CrI [-0.02; 0.01], evidence ratio: 2.04, credibility: 0.66.

## **Vowel space as a function of task and environment**

As shown in the middle-right plot in Figure 5, caregivers did not seem to credibly produce a greater vowel space area in the experimental task of producing spontaneous speech (estimate: -0.16 with 95% CrI [-0.49; 0.18], evidence ratio: 3.58, credibility: 0.78). Similarly, as shown in the lower-right-hand plot in Figure 5, recording caregivers with their infants in a naturalistic setting did not appear to exert an effect on the vowel space area of caregivers’ IDS (estimate: -0.27 with 95% CrI [-0.76; 0.23], evidence ratio: 4.29, credibility: 0.81).

## **Publication bias for vowel space area**

A sensitivity analysis with a random-effects specification indicated that if moderate publication bias were present in the literature, then the effect size estimate may be closer to null effects. That is, if significant results were fourfold more likely to be published in the literature, the credible interval would include an effect size of 0.1, as shown in Supplementary Figure 10.1 in the Supplementary Information. The uncorrected worst-case estimate for the effect size based solely on non-significant studies is 0.20 with 95% CrI [-0.01; 0.42], as shown in in Supplementary Figure 10.2 in the Supplementary Information.

# **Articulation rate**

Speech production rate is generally measured in one of two ways: articulation rate excludes pause intervals, but speech rate includes them and consequently takes speaker-specific ways of conveying information (e.g., hesitations and pauses) into account 93–95. The majority of studies under investigation here (15 out of 17) reported articulation rate as opposed to speech rate. Because both of these measures capture similar acoustic information (i.e., the number of output units per unit of time), we have combined the measures in our meta-analysis. But the distinction between them should be made theoretically because a slower speech rate may signify factors in addition to a slower articulation rate (e.g., the number and duration of silent pauses) (Laver, 1994). Here, we use articulation rate to refer to this combination of measures.

The acoustic measure of articulation rate was analyzed in 17 of the 88 studies and provided 60 separate effect sizes. A negative Hedges’ *g* value in this context signifies a slower production rate in IDS. The model with task, age, and language as predictors was shown to provide a better account of the data (stacking weight: 0.999) than the model including environment (stacking weight: 0.000), the model excluding task (stacking weight: 0.001) and the model excluding both task and environment (stacking weight: 0.000)).

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## **Articulation rate across studies**

The Bayesian hierarchical intercepts-only model of articulation rate showed an overall estimated difference of *g* = -1.03 with 95% CrI of [-1.53; -0.56] and a between-languages heterogeneity of *g* = 0.38 [0.02; 1.00], a heterogeneity between studies within languages of *g* = 0.80 [0.50; 1.20], as well as a heterogeneity between measurements of *g* = 0.26 [0.04; 0.47]. With a standardized mean difference of this size, this implies that approximately 85% of IDS speech samples will show a slower rate compared to that of ADS speech samples. An overview of how the studies varied with respect to articulation rate estimate is shown in the forest plot in Supplementary Figure 6.4 in the Supplementary Information. The estimated effect sizes of the studies are distributed primarily on the negative scale, indicating that caregivers on average speak slower in IDS than in ADS; however, due to the relative sparsity of data for this acoustic measure, many of the languages include null effects in their credible intervals.

## **Articulation rate as a function of language**

As shown on the left-hand side of Figure 6, all of the effect size point estimates for the languages under investigation appeared in the negative range (cf. in Supplementary Table 9.4 in the Supplementary Information for language-specific estimates and credible intervals).

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## **Articulation rate as a function of age**

As shown in the top-right of Figure 6, the model indicated a reliable effect of infant age. The estimate for the effect of age is 0.02 with 95% CrI [0.00; 0.05], evidence ratio: 33.33, credibility: 0.97. This result shows that caregivers’ articulation rate in IDS becomes more similar to ADS over the course of infant development from 0 to 30 months.

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## **Articulation rate as a function task and environment**

As shown in the middle-right plot in Figure 6, caregivers appeared to speak faster to their infants in spontaneous speech than in read speech (estimate: 0.95 with 95% CrI [0.1; 1.73], evidence ratio: 28.34, credibility: 0.97. Conversely, the lower-right-hand plot in Figure 6 indicates that there is no evidence that recording infants outside of the laboratory affects the articulation rate in caregivers’ IDS (estimate: 0.15 with 95% CrI [-0.71; 0.96], evidence ratio: 1.66, credibility: 0.62).s

## **Publication bias for articulation rate**

A sensitivity analysis with a random-effects specification indicated that no amount of publication bias would be able to attenuate the estimate to null, as shown in Supplementary Figure 10.1 in the Supplementary Information. If moderate publication bias were present in the literature, then the effect size estimate may represent a more moderate effect; the uncorrected worst-case estimate for the effect size based solely on non-significant studies is -0.445 with 95% CrI [-0.757; -0.133], as shown in Supplementary Figure 10.2 in the Supplementary Information.

# **Vowel duration**

The acoustic measure of vowel duration was analyzed in 26 of the 88 studies, and 81 effect sizes were extracted from these studies. We should note that the vowel categories for which data were available differed markedly across studies, with some studies reporting vowel duration only for the articulatory extremes of /i/, /a/ and /u/ e.g., 81,92 and others reporting vowel duration for the full set of vowel phonemes in their language e.g., 96. In this context, a positive Hedges’ *g* value signifies a longer vowel duration in IDS compared to that in ADS, and vice versa. The model with age and language as predictors was shown to provide a better account of the data (stacking weight: 0.393) than the model including task and environment (0.154), the model including task (stacking weight: 0.242) and the model including environment (stacking weight: 0.211).

## **Vowel duration across studies**

The Bayesian hierarchical intercepts-only model of vowel duration showed an overall estimated difference of *g* = 0.48 with 95% CrI of [0.08; 0.88], a between-languages heterogeneity of *g* = 0.38 [0.03; 0.92], a heterogeneity between studies within languages of *g* = 0.43 [0.06; 0.85], as well as a between-measures heterogeneity of *g* = 0.17 [0.01; 0.38]. With a standardized mean difference of this size, this implies that approximately 70% of IDS speech samples will show a longer vowel duration to that of ADS speech samples. An overview of how the studies varied with respect to the vowel durationestimate is shown in the forest plot in Supplementary Figure 6.5 in the Supplementary Information. The majority of the effect size estimates were distributed on the positive scale, indicating that the studies show that caregivers produce vowels with a longer duration in IDS than in ADS.

## **Vowel duration as a function of language**

As shown in Figure 7, most of the effect size estimates for the languages under investigation appeared in the positive range (cf. in Supplementary Table 9.5 in the Supplementary Information for language-specific estimates and credible intervals); however, there appears to be an influence of language-specific phonological properties, as some languages exhibit substantially longer vowel durations in IDS (e.g., Mandarin Chinese), mixed results (e.g., US English and Japanese), while others indicate no durational differences between the speech styles (e.g., Swedish, Norwegian, and Danish).

## **Vowel duration as a function of age**

As shown in the top-right of Figure 7, the model indicated a moderate effect of infant age. The estimate for the effect of age is -0.02 with 95% CrI [-0.05; 0.01], evidence ratio: 6.48, credibility: 0.87. This suggests that caregivers’ vowel durations in IDS became slightly more similar to ADS as infants got older.

## **Vowel duration as a function of task and environment**

As shown in the middle-right plot in Figure 7, there appeared to be weak evidence that caregivers spoke with a greater vowel duration difference in spontaneous speech (estimate: -0.12 with 95% CrI [-0.97; 0.74], evidence ratio: 1.44, credibility: 0.58), although note that this estimate was based on only three data points for the task of read speech. The lower-right-hand plot in Figure 7 indicated that recording the infants in a naturalistic setting exerted a weak positive influence on the effect size estimates (estimate: 0.27 with 95% CrI [-0.51; 1.06], evidence ratio: 2.47, credibility: 0.71).

## **Publication bias for vowel duration**

A sensitivity analysis with a random-effects specification indicated that no amount of publication bias can attenuate the estimate to 0.1, as shown in the sensitivity plot of in Supplementary Figure 10.1 in the Supplementary Information. The uncorrected worst-case estimate for the effect size based solely on non-significant studies is 0.277 with 95% CrI [0.134; 0.417], as shown in Supplementary Figure 10.2 in the Supplementary Information.

# **Discussion**

The tendency for caregivers to modify their speech to infants represents a widespread cross-cultural and cross-linguistic phenomenon. The aims of this meta-analysis (see Introduction) were to examine how the acoustic properties of IDS i) change over the course of early infant development, ii) vary across languages, and iii) differ according to experimental task and recording environment, with an eye towards a better understanding of culturally widespread IDS communicative functions. The results confirmed that across multiple languages and cultures, IDS contains acoustic features that are distinct from ADS, and that different acoustic features operate on varying timescales. Our analysis of publication bias showed that the pattern of acoustic features in IDS would remain reliable even if a strong bias for significant results existed in the literature (although potentially with the exception of vowel space area, cf. Supplementary Figures 10.1-10.2). The findings thus provide reliable evidence that caregivers across multiple languages produce IDS with a higher *f*o, a higher degree of *f*o variability, an expanded vowel space area, a slower articulation rate, and a longer vowel duration, as summarized in Figures 3-7 and Table 1 (cf. also Supplementary Tables 9.1-9.5 in the Supplementary Information). The analyses, however, also suggested a high degree of unexplained between-study and between-language heterogeneity. Our analyses of moderators indicated that *f*o, articulation rate, and vowel duration became more similar to ADS over the course of infants’ early development, while vowel space area and *f*o variability remained stable, at least up to 25 and 36 months of age, respectively. Our analysis of the effect of experimental task revealed that spontaneous speech displayed greater differences in fo, articulation rate, and fo variability between ADS and IDS, compared to read speech.Recording environment likewise showed a reliable influence on the estimates for *f*o.

In the following sections, we discuss our findings in light of the following questions: (1) To what extent do the acoustic features of IDS change over time, and how do these findings speak to the putative functions of IDS? (2) How much do the acoustic properties of IDS vary across languages? (3) What are the sources of variation? We use these questions as an opportunity to reflect on the scientific study of IDS and to provide study recommendations that can inform theory building, modelling approaches, and future experimental and descriptive investigations.

**Changes in IDS features and their relation to functions**

The tendency for some of the acoustic features of IDS to change over the course of early development may be due to a form-functions relationship between caregivers’ acoustic production patterns and infants’ attentional allocation to certain aspects of the speech stream 10–12,46. For example, the increase in articulation rate and parallel decrease in vowel duration during development may reflect caregivers’ sensitivity to infants’ improved processing of the speech stream. Articulation rate exhibits robustness across languages (cf., Figure 6), with a universal tendency for caregivers to slow down their speech to infants. Slowed IDS likely eases the cognitive load involved in young infants’ speech and language processing e.g., 97–99. Similarly, the decrease in the utterance-global measure of *f*o in IDS may be a consequence of infants’ changing preferences to attend to this acoustic feature in the speech stream 12. Younger infants have been shown to prefer to attend to the positive affect of IDS 43,44, while older infants prefer aspects of the speech stream that provide less positive affect and more linguistically relevant information 10,11,46. Vocal pitch exhibited a high degree of robustness across languages (cf., Figure 3), supporting the notion that it is a highly salient property of IDS e.g., 1,3 and that caregivers adjust IDS acoustic properties in ways that suit infants’ developmental needs 100,101. Similarly, the cross-linguistic tendency for the acoustic properties of *f*o variability and vowel space area to remain stable throughout early infancy (cf. Supplementary Figure 6.6) suggests ongoing developmental relevance 17,18. We should note, however, that vowel space area exhibited cross-linguistic variation (cf. Figure 5), with some of the studies reporting reduced vowel separability in IDS e.g., 70,85,90,92. Both acoustic features have been implicated in facilitating language development 15,16,38,102, but whether the benefits of IDS derive mainly from its capacity to direct infants’ attention or to emphasize linguistic aspects of the speech stream (or both) remains as an important open question. We should also note that although infant age appears to exert an effect on some of the acoustic measures, the amount of available data across different age ranges varies, ranging from 0-25 months for vowel duration to 0-36 for *f*o and *f*o variability (cf. Supplementary Figure 6.6 in Supplementary Information). These results highlight the need for an expansion in the availability of data with a high density of observations across many different age ranges.

Computational evidence indicates that vowel space expansion can aid speech intelligibility 24,103–105, but beyond considerations of the information content in the speech signal 4,106, the benefits may simply be a product of the social qualities of IDS, which facilitate learning through increased infant attention 35,37 and social motivation 28,44. The question of how specific acoustic properties in IDS may facilitate aspects of infant development could be pursued with more detailed theory-driven studies of languages with distinct linguistic systems.

**Unexplained variability across studies and languages**

Our meta-analytic models revealed a substantial amount of between-study heterogeneity for each of the acoustic features, especially among the studies reporting measures of *f*o, *f*o variability and articulation rate (cf. Table 1). Some between-study heterogeneity is expected simply from random sampling error and the mathematics of estimating an effect across a large number of studies 107,108. But some of this unexplained variance may derive from the inclusion of studies that differ from one another in meaningful ways, such as in study designs, population sample characteristics, cross-linguistic diversity, and experimental methodologies 109. For example, our results indicated larger differences between the speech styles in *f*o, *f*o variability, and articulation rate for studies recording parents’ spontaneous speech as opposed to read speech (cf. Figures 3, 4, and 6). Without a complete characterization of the sources of this unexplained heterogeneity, factors influencing the generalizability of the effects remain undetermined and therefore constitute an important avenue for future research.

One source of heterogeneity could be the variability induced by cross-linguistic differences in IDS. The acoustic features of IDS were shown to vary across languages, many of which relied on a small number of datapoints and studies, and therefore exhibited substantial uncertainty (cf. Supplementary Tables 9.1-9.5 in Supplementary Information). Part of this heterogeneity and cross-linguistic uncertainty may also depend on the variability caused by subtle differences in phonological systems across languages. For example, although our results suggest a strong cross-linguistic tendency for caregivers to produce IDS with an overall slower articulation rate, Church et al. 110 found that the difference in articulation rate between Canadian English ADS and IDS to 8.5- and 11-month-old infants disappeared when utterance-final syllables were excluded, due to the phonological tendency for utterance-final syllables to be lengthened in Canadian English cf. 111 for similar results for Japanese. Similarly, substantial differences in the number and category of vowels included in our analysis of vowel duration may influence the generalizability of results in languages with other types of vowel inventories and phonological systems. Determining the influence of subtle cross-linguistic differences, such as prosodic phonology, as well as vowel inventories and phonemes, will be a fruitful area for future investigations. Although we were unable to accommodate these types of subtle phonological differences between languages in our analyses, these sources of variability highlight the need for fine-grained, theory-driven comparisons of the acoustic properties of IDS across different languages and population characteristics (e.g., gender and ethnicity) as well as careful consideration of the causal mechanisms involved 61–63.

Another source of the between-study heterogeneity may come from intra-study participant characteristics. Low sample sizes and tight experimental controls characteristic of infant research may result in outcomes that are idiosyncratic to particular study conditions 108. Between-study differences in participant characteristics, such as gender and kinship, are thus likely to function as potential sources of unexplained heterogeneity. For example, the high prevalence of post-partum depression 112,113 and its attested effects on the prosodic properties of IDS 114–116 may affect the generalizability of the current results to these population samples. The developmental status of the infant, moreover, may also function as a potential source of heterogeneity in IDS properties, as caregivers have been shown to respond differently according to the developmental status of the infant 31,100,117. Future research exploring the effects of diverse speaker characteristics, such as depression, kinship, gender and infants’ developmental status, would provide important insights into factors affecting the acoustic properties of IDS.

In order to allow for more fine-grained temporal analyses of how acoustic features of IDS manifest themselves across early infancy, and to further explore sources of between-study variability, we encourage researchers to share participant-level data in open repositories. A cumulative approach to improving the external validity of studies can also be carried out by conducting experiments across multiple laboratories e.g., 35, affording the exploration of within-lab and between-lab variability. Because logistical constraints may hinder multi-laboratory approaches, we argue that providing access to participant-level data may represent the easiest, most practical alternative.

 Despite the finding of substantial between-study heterogeneity, we should emphasize that the studies exhibited consistency with each other; that is, the credible intervals for the results of individual studies showed substantial overlap (cf., Supplementary Figures 6.1-6.5). Moreover, our meta-analytic models included random effects by study to address the dependency among effect sizes as well as predictor variables to explain the heterogeneity between studies. In the following section, we provide a series of recommendations that will enable a better understanding of the factors moderating the acoustic properties of caregivers’ IDS.

**Recommendations for Future Research**

While solid progress has been made toward examining a wide variety of relevant aspects of IDS, we have identified various shortcomings that should be addressed in future investigations. In the following, we provide several suggestions. First, with the continued rise of day-long recordings e.g., 56 and open archives of acoustic and phonetically transcribed data e.g., 57, as well as the continued development of techniques to automatically assess and code large amounts of audio data 55,e.g., 118, future research can provide an expansion in the availability of cross-linguistic data and a high density of observations for each participant e.g., 119. These technological developments will allow for a more fine-grained resolution and comparison of how IDS differs across individuals, languages and infant ages. Second, as noted above, to further explore the functions and learnability afforded by IDS, more theory-driven comparisons across distinct linguistic systems are needed 61,63, as well as testable predictions from computational models disentangling different theoretical accounts. For example, computational models that explore the supposed learnability afforded by the acoustic properties of IDS constitute fruitful future avenues of research 105,e.g., 120,121 as do computational models of stimulus-driven attention and prominence of IDS 122 and other sensory inputs more generally 123,124. Assessing these models on data from a broad range of cultural, linguistic and sociodemographic settings would provide a more robust assessment of theoretical limitations and provide fuel for further theoretical development. Finally, adapting speech to a listener is not a unilateral phenomenon. We want to highlight the importance of considering the mutual feedback loops between infant and caregiver, with infants being an important source of information regarding which sort of signal would be most beneficial for their developmental progress 28–32. This is especially important given the substantial variability in developmental trajectories across individuals. Studies investigating the importance of the bidirectional process of adaptation between infants’ communicative signals and caregiver responsiveness on a turn-by-turn basis comprise another fruitful avenue of future work that can deliver new accounts, predictions, and data from both interactants’ viewpoints 4,13,31,90,100,125,126.

The current meta-analysis investigated the acoustic features of IDS across a variety of languages and cultures by aggregating data from three decades of research on this speech style. We found robust evidence that adults worldwide often speak to infants in ways that differ systematically from how they speak to other adults (i.e., they alter a range of acoustic features). Moreover, how caregivers speak to infants changes as a function of infants’ ages. We propose that the observed modifications in acoustic features over the course of early infancy may reflect caregivers’ dynamic sensitivity to changes in infants’ attention to specific acoustic properties in the speech stream.

Our results provide support for several findings in the literature, including the robust effects of cross-linguistic differences, infant ages, and experimental tasks. However, the precise nature of these differences remains elusive. We therefore recommend that future studies i) share participant-level data to enable analysis of individual differences and intra-study variability, ii) conduct theory-driven comparative studies of cross-linguistic differences, iii) formulate computational models on the functions and learnability afforded by IDS, as well as iv) longitudinal studies on the importance of dynamic adaptation to the developmental process.

# **Methods**

In order to obtain a comprehensive sample of the available literature on acoustic properties of IDS, we conducted a systematic literature search on PubMed and Web of Science, in line with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Guidelines 127 (cf. Supplementary Figure 1.1 and Supplementary Tables 1.2-3 in Supplementary Information). The search terms used were ("motherese" OR "baby talk" OR "child-directed speech" OR "infant-directed speech" OR "caretaker speech" OR "parentese"), with no search limits in the query in order to target studies broadly. The first systematic search was conducted independently by two of the authors (RF & EF) in June 2017 and updated by a third author (CC) in December 2021; CC screened for missed studies from before and after the date of the first systematic search. Disagreements in the screening of papers were resolved with discussions in the first phase between EF and RF and in the second phase between CC and RF; if the paper was thought to contain relevant data for the meta-analysis (see below), the paper was included for the successive phase of the review. Disagreements were therefore rare and mainly motivated by studies where relevant information was reported only in the Supplementary Information. As of December 2021, the search strategy yielded a total of 602 papers, which were manually screened for inclusion according to the following criteria: i) infants had to be typically-developing, ii) studies had to include quantification of an acoustic feature, iii) studies had to include a comparison condition with ADS, iv) the speech had to be spoken to an infant by one or both of their primary caregivers.

Based on the initial set of 602 papers, we used Connected Papers and Research Rabbit to find an additional 48 relevant studies. After excluding 54 duplicate studies, we screened the titles of 596 studies and excluded a further 302 studies that were unrelated to the current investigation. We read the abstracts of the remaining 294 studies and evaluated each with reference to the above exclusion criteria. Of the 294 papers, 175 studies had no relation to IDS, 17 studies had no comparison condition with ADS, and 15 studies examined atypical populations and had no relevant control sample of typically-developing infants to extract data on. We discuss the importance of future studies investigating more diverse speaker characteristics further in the Discussion. To the best of our knowledge, the present review of a total of 88 studies represents a comprehensive sample of the literature on IDS.

In order to assess the state of the literature and to explore the extent to which the studies build a common discourse with reciprocal references, we used the R package *bibliometrix* 128 to build coupling and direct-citation networks of the studies, as shown in Supplementary Figure 2.1 in Supplementary Information. The studies cluster together into three main groups and exhibit considerable overlap in the studies they cite. Further, they cite each other somewhat independently of the acoustic measure reported. The collection of studies investigated here, then, represents a coherent intersection of papers that builds a common discourse on a variety of relevant aspects of IDS.

## **Data Extraction**

The following meta-analyses allowed us to explore how each acoustic measure differed across infant ages, languages, experimental tasks, and recording environments. We classed the 84 relevant papers into 5 clusters based on the acoustic measure reported: i) *f*o, ii) *f*o variability, iii) vowel space area, iv) articulation rate, and v) vowel duration. If an individual study reported multiple acoustic measures, the study was included in all of the relevant clusters. It should be noted that other acoustic measures of IDS were reported in some of the studies under investigation (e.g., syllable duration (3 studies), pause duration (5 studies), and intensity (5 studies)); however, the studies provided insufficient data for meta-analysis.

In order to standardize the measures and to allow for comparison among the studies, we calculated Hedges’ *g*, an effect size variant that is preferred for small sample sizes 129. For our purposes, this effect size represents the standardized mean difference between ADS and IDS; that is, the bigger the effect size, the larger the difference between the speech styles. A positive effect size indicates that the value for IDS is greater than that for ADS, and vice versa. This implies that an acoustic property of IDS that becomes more similar to ADS over the course of development would manifest as a shift towards an effect size of zero.

When the raw means and standard deviations were reported in the papers, we calculated the effect sizes with standard formulae for Hedges’ *g* (i.e., $hedges^{'}g= \frac{mean \_{1}- mean\_{2}}{SD\_{pooled}}$), where $SD\_{pooled}=\frac{\left(n\_{1}-1\right)SD\_{1}^{2}+(n\_{2}-1)SD\_{2}^{2}}{n\_{1}+n\_{2}-2}$ , as formulated in 130 where the standard deviation of each group is weighted by its sample size, using the R package *esc* 131. For the remaining studies that did not report the raw data, the effect sizes were calculated either by using the reported *d*-values, one-sample *t*-values, or by digitally extracting the raw data from published plots using the WebPlotDigitizer application 132. In certain cases, the standard deviation of the effect size could not be calculated from the reported data or plots. In order to include these effect sizes in the meta-analysis, these missing standard deviation values (n = 110) were imputed by using multivariate imputation by chained equations based on a Bayesian linear regression model in the R package *mice* 133, as described further in S3 of the Supplementary Information. We checked that this process of multiple imputation did not bias the estimation of the overall effect size for each acoustic measure by comparing the estimates of the intercepts-only models for the imputed and non-imputed datasets. The results of these analyses are shown in Supplementary Table 3.1 in Supplementary Information. All hierarchical Bayesian models in this paper pool the results of analyses performed on the imputed datasets. In Supplementary Tables 11.1 and 12.1 in Supplementary Information (cf., Figure 1 as well), we provide more information about the size of the sample investigated for each language.

## **Hierarchical Bayesian model**

In the following meta-analyses of five acoustic features, we combined the weighted results of comparable studies and provided a pooled estimate of the overall effect sizes. We estimated and adjusted for heterogeneity in population samples and methodologies by allowing the estimate to vary by study. The hierarchical structure of the random-effects model posits that the true effect size may be study-specific and thereby accounts for repeated measures 134–136.The credible interval of the pooled estimate thus aggregates information from both within-study sampling error and between-study variance 137. The hierarchical Bayesian robust regression models were fitted to the meta-analytic data using a Student’s t-likelihood. With this type of robust regression model, longer-tailed distributions are implemented in order to reduce the influence of outliers. This method incorporates outliers without allowing them to dominate non-outlier data 138. See S5 in the Supplementary Information for a detailed account of the models and choice of priors (Supplementary Table 5.1), prior and posterior predictive checks (Supplementary Figure 5.2.1), prior-posterior update plots (Supplementary Figure 5.3.1) as well as prior sensitivity analyses for the model estimates (Supplementary Figure 5.4.1) and evidence ratios (Supplementary Figure 5.4.2) of intercept and age.

## **Moderator Analyses**

We began by building intercepts-only models in order to condition the data for each of the acoustic measures on the variance associated with individual studies. With this model, we posited that effect sizes were nested within languages and within studies. In order to quantify the within-language variability due to different studies reporting data on the same language and repeated measures within these studies, we included nested effects of study and measures within the random-effects term (i.e., (1 | Language/StudySite/measurement)). We used these three-level intercepts-only models to assess the within-language, between-study heterogeneity and report how the effect size estimates of each study deviate from the pooled effect size estimate (cf. Supplementary Figures 6.1-6.5 in Supplementary Information).

We then constructed a second model to analyze the influence of potential moderators on the variation of effect sizes across studies. This second model allowed us to explore the effect of the following predictors on each of the acoustic measures: i) infant age, ii) language, iii) experimental task and iv) recording environment, the justifications for which were described in the Introduction. We refer to this second model as the full model for the remainder of this paper.

We performed pairwise leave-one-out-information criterion-based model comparison 139 between the full model and models without each of the predictor variables. We report leave-one-out (loo) stacking weights 140 in favor of the model. Stacking weights indicate the probability that the model including the variables is better than the model without the predictor variables.

All computations were performed in R 4.2.0 141 using brms 2.17 142 and Stan 2.21 143 in R Studio 1.4 144.

For each acoustic measure, we provide the estimates from the full model and report 95% credible intervals, evidence ratios, credibility scores and loo stacking weights for each of the models. Each will be described in turn: i) credible intervals (henceforth CrI) refer to the range of values within which there is a 95% probability that the true value of the parameter is included given the assumptions of the model, ii) the evidence ratio provides the ratio of likelihood in favor of a hypothesis; that is, an evidence ratio of 5 indicates that the hypothesis is 5 times more likely than the alternative, while an evidence ratio of ‘Inf’ (infinite) suggests that all of the posterior samples are compatible with the hypothesis and not with the alternatives 142, iii) the credibility score refers to the percentage of posterior samples in the direction of the hypothesis under investigation 142, and lastly, iv) stacking weight refers to the probability that the model including a predictor provides a better model of the data than the model without the predictor 139. The estimates from the best model for each acoustic variable are reported in Supplementary Tables 9.1-9.5 in the Supplementary Information.

We chose to assess publication bias by conducting quantitative sensitivity analyses and estimating the severity of the publication bias required to attenuate the credible interval of the pooled effect size to include null values (Mathur & VanderWeele, 2020). Traditional assessments of publication bias rely on spearman rank correlations between effect size and standard error and exhibit certain limitations. These traditional methods, for example, provide binary decisions either rejecting the null hypothesis of no publication bias or not and fail to control for Type I error rates when used with standardized mean difference effect sizes and conventional variance estimates 145,146. This is especially the case when within-study sample sizes are relatively small or between-study heterogeneity is high 147. We therefore chose to assess how robust the meta-analytic estimates would be to varying assumptions of publication bias 148. These methods assume that meta-analytic studies represent samples from an underlying (possible) population of published and unpublished studies, where the probability of selection for significant studies is higher. The potential presence of publication bias is thereby assessed i) by varying assumptions as to how much more likely significant studies are to be published than non-significant studies, and ii) by calculating the amount of publication bias required to attenuate the estimates so that the evidence in favor of an effect becomes negligible. This method has limitations, such as relaxing certain distributional assumptions on the population effects and assuming that the non-significant findings available are representative of the whole population of unpublished studies 148, However, the method still offers substantial benefits over classical funnel plot methods and selection models cf., 145,146,147 for reviews. It should be noted that this method of analyzing publication bias sensitivity cannot comment on the severity of publication bias in practice, nor the opposite; rather, this analysis provides results that allow us to assess the extent to which an effect would be present even if publication bias were a severe issue in the literature. For each acoustic measure, we report the worst-case effect size estimate based solely on the non-significant studies and make sensitivity plots and significance funnel plots (cf. Supplementary Figures 10.1-10.2 in Supplementary Information).

**Data Availability Statement**

All data were accessed on PubMed and Web of Science and are available and permanantly archived in the following open repository: <https://osf.io/hc7me/>.

**Code Availability Statement**

Analysis and visualization code and a reproducible R Markdown manuscript are available and permanently archived in the following open repository: <https://osf.io/hc7me/>.

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**Author Contributions Statement**CC, RF and EF conceived of the research and extracted data from studies. CC, GB, RF and CB wrote the initial manuscript with contributions from TKP, AR & EF. CC wrote the first and second revision with contributions from RF, GB & TKP. CC and RF led statistical analyses with contributions from CB. CC wrote the computer code with contributions from RF. CC designed the figures.

**Competing Interests Statement**The authors declare no competing interests, nor any conflicts of interest with regard to the funding source for this study.

**Tables**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Acoustic Feature** | **No. of Studies** | **No. of ES** | **Average Effect Size** | **ER** | **Study SD** | **Robust****Predictors** |
| ***f*o** | 60 | 262 | 1.19 [0.81; 1.58] | Inf | 0.91 [0.72; 1.14] | Language, Age, Task, Environment |
| ***f*o Variability** | 44 | 202 | 0.46 [0.21; 0.71] | 817.18 | 0.76 [0.60; 0.95] | Language, Task |
| **Vowel Space Area** | 33 | 84 | 0.81 [0.44; 1.16] | 1799 | 0.61 [0.41; 0.86] | Language |
| **Articulation Rate** | 17 | 60 | -1.11 [-1.80;-0.39] | 390.3 | 0.74 [0.42; 1.19] | Language, Age, Task |
| **Vowel Duration** | 26 | 81 | 0.51 [0.16; 0.86] | 67.7 | 0.50 [0.12; 0.92] | Language, Age |

**Table 1. A summary of the results for the best models for each acoustic variable. ES refers to Effect Sizes. ER refers to Evidence Ratio. Inf means that all posterior samples are in the direction of the hypothesis. The average effect size refers to the average effect size across infant ages and languages in the best model for the acoustic measure.**

**Figure Legends**

*Figure 1: World map of IDS data. This plot provides a coarse overview of languages for which IDS has been analyzed. It compares the languages included in this meta-analysis to the languages listed on the World Atlas of Language Structures (WALS) 60. Data extracted from:* [*https://github.com/cldf-datasets/wals*](https://github.com/cldf-datasets/wals)*. Each point represents a language, the color of which indicates whether the language is included in this meta-analysis, and the size of which indicates the cumulative sample size. It should be noted that the represented languages may not be accurate in terms of exact positions on the map and that WALS includes languages with very small speaking communities (e.g., the vast number of languages in USA).*

*Figure 2: An overview of the findings from longitudinal studies 3, 13, 65-69, 70-75, 77, 79-85, 90 for each of the acoustic features. The x-axis indicates infant age in months, while the colors indicate whether the acoustic feature exhibits an increase (orange) or decrease (teal) or no change (purple) over the course of the ages investigated. Studies are sorted by the main conclusion regarding any feature change.*

*Figure 3. Panel showing model estimates for a total of 3401 participants across 60 studies investigating 33 distinct languages. The panel consists of i) A plot of effect size estimates for fo according to language (left). The centres of the error bars (orange points) indicate the posterior effect size estimate for each language pooled across studies. The error bars provide the 95% credible interval and the grey points are the raw effect size data). The size of the points is proportional to the inverse of the standard error of the effect size (i.e., the larger the point, the smaller the standard error). ii) A spaghetti plot showing 100 posterior model predictions for the effect size estimates for fo as a function of age (top right). iii) A plot showing the distribution of effect size estimates across experimental tasks (middle-right). The orange points indicate the posterior effect size estimate for each experimental condition. The error bars provide the 95% credible interval and the grey points are the raw effect size data). The size of the points is proportional to the inverse of the standard error of the effect size (i.e., the larger the point, the smaller the standard error). iv) A plot showing the distribution of effect size estimates across recording environments (bottom-right). The orange points indicate the posterior effect size estimate for each recording condition. The error bars provide the 95% credible interval and the grey points are the raw effect size data). The size of the points is proportional to the inverse of the standard error of the effect size (i.e., the larger the point, the smaller the standard error).*

*Figure 4. Panel showing model estimates for a total of 3006 participants across 44 studies investigating 34 distinct languages. The panel consists of i) A plot of effect size estimates for fo variability according to language (left). The centres of the error bars (orange points) indicate the posterior effect size estimate for each language pooled across studies. The error bars provide the 95% credible interval and the grey points are the raw effect size data). The size of the points is proportional to the inverse of the standard error of the effect size (i.e., the larger the point, the smaller the standard error). ii) A spaghetti plot showing 100 posterior model predictions for the effect size estimates for fo variability as a function of age (top right), iii) A plot showing the distribution of effect size estimates across experimental tasks (middle-right). The orange points indicate the posterior effect size estimate for each experimental condition. The error bars provide the 95% credible interval and the grey points are the raw effect size data). The size of the points is proportional to the inverse of the standard error of the effect size (i.e., the larger the point, the smaller the standard error). iv) A plot showing the distribution of effect size estimates across recording environments (bottom-right). The orange points indicate the posterior effect size estimate for each recording condition. The error bars provide the 95% credible interval and the grey points are the raw effect size data). The size of the points is proportional to the inverse of the standard error of the effect size (i.e., the larger the point, the smaller the standard error).*

*Figure 5. Panel showing model estimates for a total of 1702 participants across 33 studies investigating 30 distinct languages. The panel consists of i) A plot of effect size estimates for vowel space area according to language (left). The centres of the error bars (orange points) indicate the posterior effect size estimate for each language pooled across studies. The error bars provide the 95% credible interval and the grey points are the raw effect size data). The size of the points is proportional to the inverse of the standard error of the effect size (i.e., the larger the point, the smaller the standard error). ii) A spaghetti plot showing 100 posterior model predictions for the effect size estimates for vowel space area as a function of age (top right), iii) A plot showing the distribution of effect size estimates across experimental tasks (middle-right). The orange points indicate the posterior effect size estimate for each experimental condition. The error bars provide the 95% credible interval and the grey points are the raw effect size data). The size of the points is proportional to the inverse of the standard error of the effect size (i.e., the larger the point, the smaller the standard error). iv) A plot showing the distribution of effect size estimates across recording environments (bottom-right). The orange points indicate the posterior effect size estimate for each recording condition. The error bars provide the 95% credible interval and the grey points are the raw effect size data). The size of the points is proportional to the inverse of the standard error of the effect size (i.e., the larger the point, the smaller the standard error).*

*Figure 6. Panel showing model estimates for a total of 976 participants across 17 studies investigating 17 distinct languages. The panel consists of i) A plot of effect size estimates for articulation rate according to language (left). The centres of the error bars (orange points) indicate the posterior effect size estimate for each language pooled across studies. The error bars provide the 95% credible interval and the grey points are the raw effect size data). The size of the points is proportional to the inverse of the standard error of the effect size (i.e., the larger the point, the smaller the standard error). ii) A spaghetti plot showing 100 posterior model predictions for the effect size estimates for articulation rate as a function of age (top right), iii) A plot showing the distribution of effect size estimates across experimental tasks (middle-right). The orange points indicate the posterior effect size estimate for each experimental condition. The error bars provide the 95% credible interval and the grey points are the raw effect size data). The size of the points is proportional to the inverse of the standard error of the effect size (i.e., the larger the point, the smaller the standard error). iv) A plot showing the distribution of effect size estimates across recording environments (bottom-right). The orange points indicate the posterior effect size estimate for each recording condition. The error bars provide the 95% credible interval and the grey points are the raw effect size data). The size of the points is proportional to the inverse of the standard error of the effect size (i.e., the larger the point, the smaller the standard error).*

*Figure 7. Panel showing model estimates for a total of 1411 participants across 26 studies investigating 11 distinct languages. The panel consists of i) A plot of effect size estimates for vowel duration according to language (left). The centres of the error bars (orange points) indicate the posterior effect size estimate for each language pooled across studies. The error bars provide the 95% credible interval and the grey points are the raw effect size data). The size of the points is proportional to the inverse of the standard error of the effect size (i.e., the larger the point, the smaller the standard error). ii) A spaghetti plot showing 100 posterior model predictions for the effect size estimates for vowel duration as a function of age (top right), iii) A plot showing the distribution of effect size estimates across experimental tasks (middle-right). The orange points indicate the posterior effect size estimate for each experimental condition. The error bars provide the 95% credible interval and the grey points are the raw effect size data). The size of the points is proportional to the inverse of the standard error of the effect size (i.e., the larger the point, the smaller the standard error). iv) A plot showing the distribution of effect size estimates across recording environments (bottom-right). The orange points indicate the posterior effect size estimate for each recording condition. The error bars provide the 95% credible interval and the grey points are the raw effect size data). The size of the points is proportional to the inverse of the standard error of the effect size (i.e., the larger the point, the smaller the standard error).*

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