Journal of Child Language (2024), **51**, 217–233
doi:10.1017/S0305000923000041

ARTICLE

Relating the prosody of infant-directed speech to children's vocabulary size

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(Received 28 March 2021; revised 14 December 2022; accepted 06 January 2023)

Abstract

This study examines correlations between the prosody of infant-directed speech (IDS) and children's vocabulary size. We collected longitudinal speech data and vocabulary information from Dutch mother-child dyads with children aged 18 ($N = 49$) and 24 ($N = 27$) months old. We took speech context into consideration and distinguished between prosody when mothers introduce familiar vs. unfamiliar words to their children. The results show that IDS mean pitch predicts children's vocabulary growth between 18 and 24 months. In addition, the degree of prosodic modification when mothers introduce unfamiliar words to their children correlates with children's vocabulary growth during this period. These findings suggest that the prosody of IDS, especially in word-learning contexts, may serve linguistic purposes.

Keywords: Infant-directed speech; prosody; lexical development

Introduction

Child language acquisition during the first years of life benefits from a rich language environment. Recent literature has seen increased interest in understanding exactly which qualitative aspects of language input are relevant to children's language outcomes (Blom & Soderstrom, 2020). Infant-directed speech (IDS) is an important type of input in children's early language development. Compared to adult-directed speech (ADS), IDS is primarily characterized by its relatively exaggerated prosody (see reviews in Cristia, 2013; Soderstrom, 2007). The prosody of IDS has often been hypothesized to be beneficial to language acquisition, but whether there is a relationship between IDS prosody and children's language outcomes remains an open question. The current study set out to examine correlations between the prosody of IDS and children's concurrent vocabulary as well as longitudinal vocabulary growth. In particular, we consider the different effects of IDS prosody when mothers introduce familiar vs. unfamiliar words to children.

The role of prosodic input in children's lexical development

Extensive research suggests that prosody plays an important role in early language acquisition. Prosody is a major aspect of language and serves linguistic functions at both the word level (lexical tone and stress) and phrase level (intonation) in languages around the world. Infants are sensitive to both word and phrasal prosody from birth (e.g., Christophe, Mehler, & Sebastián-Gallés, 2001; Nazzi, Floccia, & Bertoncini, 1998), and they may use it to bootstrap lexical and morphosyntactic learning, a process known as "prosodic bootstrapping" (Gervain, Christophe, & Mazuka, 2020). The most prominent feature of IDS is its distinctive prosody, including a higher pitch, a larger pitch range, and a slower speaking rate compared to ADS. Such prosodic exaggeration is found in many languages such as American English, German, Dutch, Mandarin Chinese, and Thai (see reviews in Golinkoff, Can, Soderstrom, & Hirsh-Pasek, 2015; Soderstrom, 2007).

Researchers have proposed three functions of IDS: attracting infants' attention, conveying positive affect, and facilitating language acquisition (Spinelli, Fasolo, & Mesman, 2017). The attentional and affective functions of IDS are related to its exaggerated prosody (Cooper & Aslin, 1994; Trainor, Austin, & Desjardins, 2000; but see Singh, Morgan, & Best, 2002). However, whether the prosody of IDS serves specific linguistic functions is still a matter of much debate. In a meta-analysis, Spinelli et al. (2017) examined the role of IDS prosody in language acquisition during the first two years of life. Their results suggest that prototypical IDS prosody has a much greater effect on attentional and pre-linguistic aspects, such as eliciting vocal responses, than it does on linguistic outcomes. Prototypical IDS prosody has also been shown to facilitate children's word learning in laboratory settings, including word segmentation, word recognition, and word-to-object mapping (Ma, Golinkoff, Houston, & Hirsh-Pasek, 2011; Mani & Pätzold, 2016; Thiessen, Hill, & Saffran, 2005). This line of research compares children's word learning performance between ADS and IDS conditions. Children hear auditory stimuli that have similar speech content but are produced with either ADS or prototypical IDS prosody. However, these studies cannot fully account for the role of IDS prosody in children's lexical development. First, most of these studies tested overall effects of IDS versus ADS, and only one study has investigated which acoustic cues in IDS might support word recognition (Song, Demuth, & Morgan, 2010). Their findings suggest that slow speaking rate and vowel hyperarticulation, but not wide pitch range, significantly improved children's word recognition. Second, conclusions from these online word-learning experiments often rely on group differences instead of examining individual differences in children's prosodic input.

The quantity and quality of input show great individual variation and there is substantial research investigating the links between quantity and quality of individual mothers' language input and children's language outcomes. It is well established that the QUANTITY (e.g., number of words) of language input a child receives in early years is associated with his or her lexical development (e.g., Hart & Risley, 1995; Hoff & Naigles, 2002; Ramírez-Esparza, García-Sierra, & Kuhl, 2014). As for INPUT QUALITY, studies have shown that lexical richness, syntactic complexity, repetitiveness, and vowel

https://doi.org/10.1017/S0305000923000041 Published online by Cambridge University Press

hyperarticulation, are related to children's vocabulary size (Hartman, Bernstein Ratner, & Newman, 2017; Hoff & Naigles, 2002; Kalashnikova & Burnham, 2018; Newman, Rowe, & Bernstein Ratner, 2016).

However, even though IDS is distinguished from ADS primarily by its exaggerated prosody, the association between prosodic quality and children's language outcomes is less studied. In fact, a recent meta-analysis, considering studies as recent as July 2017 on the links between the quantity and quality of linguistic input and children's language outcomes, did not describe a single study that focused on the role of prosody (Anderson, Graham, Prime, Jenkins, & Madigan, 2021). So far, only a few studies have examined the links between individual mothers' IDS prosody and children's language outcomes such as vocabulary size, and the findings are mixed. There is evidence to show that the percentage of time when parents use prototypical infant-directed speaking style is a significant predictor of children's concurrent speech production and later vocabulary size (Ramírez-Esparza et al., 2014). Furthermore, some specific prosodic cues have been found to be linked to children's vocabulary size. For example, Porritt, Zinser, Bachorowski, and Kaplan (2014) found that F0 range in IDS was positively correlated with 3- to 14-month-old infants' expressive vocabulary percentile scores. Raneri, von Holzen, Newman, and Bernstein Ratner (2020) recently found that a slow speaking rate in IDS at seven months predicts larger expressive vocabulary at two years of age. However, Song, Demuth, and Morgan (2018) did not find any significant correlations between the prosody of individual mothers' IDS (mean pitch and pitch range) at 17 months and children's vocabulary size at 19 or 25 months. Kalashnikova and Burnham (2018) investigated whether three components of IDS, including vowel hyperarticulation, pitch, and affect, predicted children's vocabulary size at later ages. This study took a "hyper-score" measure instead of using raw prosodic values as predictors. They measured vowel triangle areas, mean F0 of vowels, and affect scores (rated by native speakers) in IDS addressed to children at 7, 9, 11, 15, and 19 months of age, as well as in ADS. For each of the three factors, a hyper-score was obtained by dividing each mother's IDS score by their corresponding ADS score. These hyper-scores indicate the degree of modification in IDS compared to ADS for each participant mother. Their results show that only vowel hyper-scores at 9 months and beyond significantly correlate with children's expressive vocabulary size at 15 and 19 months, while neither pitch nor affect hyper-scores could predict children's vocabulary size. The authors concluded that vowel hyperarticulation, but not generally exaggerated pitch or positive affect, plays a role in lexical development.

Taken together, previous studies have yielded inconsistent results regarding whether the prosody of IDS can predict children's vocabulary size and which prosodic parameters of IDS are correlated with children's vocabulary size.

IDS prosody in word-learning contexts

In correlational studies on the relationship between IDS prosody and children's vocabulary size, prosody is often measured at the global level without taking speech context into consideration. Word-learning contexts are defined as situations in which mothers introduce unfamiliar words to children. Such contexts may be assumed to provide the most direct input for children learning novel words and are thus crucial for word learning. Recent studies have found that mothers modify their speech prosody when introducing unfamiliar words, as compared to familiar words, to children (Han, de Jong, & Kager, 2020, 2021). These prosodic modifications were cross-linguistically evident, although the specific prosodic cues that were modified varied among the languages investigated. In particular, Dutch mothers of 18- and 24-month-old children had a lower pitch and a slower articulation rate when introducing unfamiliar words compared to familiar words, while Mandarin-Chinese-speaking mothers heightened pitch for 18- month-old children and expanded pitch range for the 24-month-olds. These findings indicate that mothers not only exaggerate their prosody at a global level, they also modify their speech prosody in word-learning contexts. As such, even if the generally exaggerated prosody of IDS may not be reliably associated with children's vocabulary size, it is nonetheless still possible that the prosody of IDS in word-learning contexts may be related to children's vocabulary size. In this study, we therefore examine the relationship between the prosody of IDS in word-learning contexts and children's language outcomes.

The current study

As illustrated above, it is yet unclear whether there is a correlation between IDS prosody and children's vocabulary size. Also, no study has investigated whether IDS prosody in word-learning contexts predicts children's vocabulary size. The overarching goal of this study is to determine whether individual mothers' IDS prosody is associated with their child's vocabulary size concurrently and longitudinally. Crucially, we take speech context into consideration and examine mothers' prosody when introducing unfamiliar words to children as a predictor of children's vocabulary size. As we are specifically interested in the role of IDS in children's word learning, we opted to test children longitudinally at both 18 and 24 months, during which period children's vocabulary increases rapidly (Goldfield & Reznick, 1990) and word learning ability improves significantly (Bion, Borovsky, & Fernald, 2013).

There are two ways to measure individual differences in children's prosodic input: raw prosodic values (e.g., Raneri et al., 2020) and prosodic hyper-scores (Kalashnikova & Burnham, 2018). The raw prosodic values measure the prosody of the IDS the children hear. The hyper-scores are calculated by dividing raw IDS prosodic values by ADS values, and indicate the degree of prosodic modification in IDS compared to ADS. We use both raw prosodic values and prosodic hyper-scores as prosodic predictors and calculate these per utterance.

We have two research questions:

First, we ask whether the three prosodic parameters of individual mothers' IDS – mean pitch, pitch range, and articulation rate – predict children's concurrent vocabulary size and longitudinal vocabulary growth. Since prototypical IDS prosody has been shown to facilitate children's online word learning (e.g., Ma et al., 2011; Mani & Pätzold, 2016; Thiessen et al., 2005), we predict a correlation between the raw prosodic values and children's vocabulary size. Specifically, we predict that a higher mean pitch, a larger pitch range, and a slower speaking rate are associated with children's larger vocabulary size and vocabulary growth. Also, we predict that the prosodic hyper-scores, which indicate the extent to which mothers modify their IDS compared to ADS, are positively correlated with children's vocabulary size and vocabulary growth.

Second, as we are interested in the effect of word-learning context, we ask whether the correlations between prosody and children's language outcomes differ when mothers introduce familiar vs. unfamiliar words to their children. Since word-learning contexts in which mothers introduce unfamiliar words are immediately relevant to children's novel word learning, we predict that IDS prosody when a mother introduces unfamiliar words

https://doi.org/10.1017/S0305000923000041 Published online by Cambridge University Press

to her child will be correlated with children's vocabulary size and growth and better explain individual differences in children's vocabulary compared to IDS prosody when introducing familiar words.

Method

Participants

This study is part of a larger cross-linguistic study on Dutch and Mandarin Chinese infant-directed speech (Han, 2019). The speech data collection methods are identical to those reported in Han et al. (2020, 2021).[1] The participants were Dutch-speaking mother-child dyads who were recruited from the Utrecht Baby Lab database and were all Dutch native speakers living in the Utrecht area in the Netherlands. All children were Dutch-learning monolinguals (degree of exposure to a second language < 10%, as measured by the Multilingual Infant Language Questionnaire (Liu & Kager, 2017)). We used a longitudinal design and collected mothers' ADS and IDS speech data when their children were 18 months and 24 months. Forty-nine mother-child dyads participated when children were 18 months old (mean age of children = 18;15, age range = 18;00–18;29; girls $N = 26$; mean age of mothers = 35 years, age range = 29–44 years). Thirty-two of these mother-child dyads visited the lab again when the children were 24 months old (mean age of children = 24;18, age range = 24;00–26;30). All children were typically developing with no report of language or hearing problems. All mothers had higher education (HBO (hogescholen 'universities of applied sciences') or WO (universiteiten 'research universities') and above). All participant mothers signed informed consent forms.

Speech data collection

During each lab visit, the mother-child dyads participated in a semi-spontaneous storybook-telling task. We designed two storybooks for 18- and 24-month-old children, respectively. Each book contained seven preselected target words that were either familiar or unfamiliar to children (see Table 1 for a list of target words). The book structure was the same for the two groups – however, the five unfamiliar words were replaced with new unfamiliar words in the 24-month-old version. On each page of the picture book, a word was on the left side and an illustration including a depiction of the word was shown on the right side. No other script was provided besides the target words (see Han, 2019, p. 187 for the picture book). An additional six pages were used as fillers to make the story coherent throughout the book. We selected default familiar words on the basis of the Dutch version (N-CDI, Zink & Lejaegere, 2002) of the MacArthur-Bates Communicative Development Inventories (CDI, Fenson, Marchman, Thal, Dale, & Reznick, 2007). In contrast, the default unfamiliar words were not listed in the N-CDI. The familiar words were also more frequent than the unfamiliar words. Due to individual differences in vocabulary, the actual familiarity of the target words might vary among the child participants. Thus, after each experiment, mothers completed a checklist to determine the familiarity of words for each child. The checklist resembled the N-CDI. For each target word, we asked the

[1]The Dutch participants in Han et al. (2020, 2021) included mother-child dyads who participated longitudinally and are a subset of the participants in the current study.

https://doi.org/10.1017/S0305000923000041 Published online by Cambridge University Press

Table 1. Target words

	18 months		24 months	
Default Familiarity	Dutch	English translation	Dutch	English translation
Familiar	opa	"grandpa"	opa	"grandpa"
Familiar	appel	"apple"	appel	"apple"
Unfamiliar	eland	"moose"	emoe	"emu"
Unfamiliar	bever	"beaver"	wezel	"weasel"
Unfamiliar	walnoot	"walnut"	bamboe	"bamboo"
Unfamiliar	kasteel	"castle"	kapel	"chapel"
Unfamiliar	pompoen	"pumpkin"	jasmijn	"jasmine"

participant mother to mark whether their child had "understood" (begrijpen) or "understood and said" (begrijpen en zeggen) it before the experiment. These responses were coded as Familiarity (Familiar/Unfamiliar) and used in data analyses.

All participants were tested in a quiet room in the Utrecht Baby Lab. Before the experiment, mothers were given a few minutes to familiarize themselves with the book. The mothers were then instructed to tell the story twice, once to an adult (ADS) and once to their child (IDS). For ADS, mothers were instructed to tell the story to an experimenter (female, a Dutch native speaker), and to take into account the fact that she was a college student. For IDS, the child sat on his or her mother's lap, and the mother was instructed to tell the story to her child the way she normally would at home. The mothers were specifically told that they could use any sentences; the only requirement was to include the words given on each page. The order of the two speech registers was counterbalanced across participants. Speech data were recorded with a ZOOM H1 recorder with 16-bit resolution and a sampling rate of 44.1 kHz. Each experimental session took about 15–20 minutes. All families received a book as a gift after the experiment.

Prosodic measures

We measured the prosody of utterances containing the target words. We focus on prosody at the utterance level for the following reasons. First, previous studies on the correlations between IDS prosody and children's language outcomes often measured prosody at the utterance level (e.g., Raneri et al., 2020; Song et al., 2018; Suttora, Salerni, Zanchi, Zampini, Spinelli, & Fasolo, 2017). Song et al. (2010) also manipulated articulation rate and pitch range at the utterance level to test the effect of different prosodic cues on infant word recognition. Second, in real-word word learning settings, novel words are often embedded in an utterance. Only a small portion of words are presented in isolation when addressing children (Brent & Siskind, 2001; Han et al., 2021).

To measure the utterance prosody, a trained Dutch native speaker annotated and extracted these utterances from the audio recordings using Praat (Boersma & Weenink, 2017). An utterance boundary was defined as "any pause longer than 200ms which is preceded by an intonational phrase boundary (pauses not accompanied by an IP boundary were considered utterance internal)," following Martin, Igarashi, Jincho, and Mazuka (2016, p. 54). In total, 1927 utterances were elicited, including 1267 utterances for children at 18 months (ADS $N = 552$, Familiar $N = 173$; IDS $N = 715$, Familiar $N = 247$) and 660 utterances for those at 24 months (ADS $N = 286$; Familiar $N = 96$; IDS $N = 374$, Familiar $N = 134$).

We extracted the following prosodic measures for the target utterances: articulation rate (syllables/s), mean F0 (in semitones (st)[2]), and F0 range (Maximum F0 – Minimum F0, in semitones (st)). The pitch values were extracted automatically using a Praat script and checked manually for doubling and halving errors. For articulation rate, a Dutch native speaker transcribed and manually counted the numbers of phonological syllables for each of the target utterances. Another coder counted the numbers of syllables for 10% of the recordings. The intercoder reliability was 0.93 (percentage of agreement). All prosodic measurements were averaged by Register (ADS/IDS) and Familiarity (Familiar/ Unfamiliar) for each mother.

Vocabulary size

All mothers completed the N-CDI: *Woorden en Zinnen* (Zink & Lejaegere, 2002) online twice: once when children were 18 months old and once at 24 months. Raw scores of receptive vocabularies were used for data analyses.

Statistical analysis

We conducted a series of multiple regression analyses to examine whether the prosody of mothers' IDS is correlated with children's vocabulary size concurrently or longitudinally and which prosodic parameters significantly predict children's vocabulary. Forty-nine participants were tested at 18 months (girls $N = 26$), and 32 of the participants were tested again at 24 months (girls $N = 19$). We consider two types of prosodic predictors: raw prosodic values and prosodic hyper-scores. For each type of prosodic predictor, we performed three sets of multiple regression analyses: concurrent correlations at 18 months, concurrent correlations at 24 months, and longitudinal correlations over this time period.

(1) Concurrent correlations at 18 months. Specifically, we examine whether there were concurrent correlations between the prosodic predictors at 18 months and children's vocabulary size at 18 months. For this analysis, we include speech data from all 49 participants. Six participants were excluded due to missing vocabulary information, resulting in a total of 43 participants in the final analyses.

(2) Concurrent correlations at 24 months. Here we examine whether there were concurrent correlations between the prosodic predictors at 24 months and children's vocabulary size at 24 months. For this analysis, we include the 32 participants who participated at both ages, of which 5 participants were excluded due to missing vocabulary information at 24 months, resulting in a total of 27 participants in the final analyses.

(3) Longitudinal correlations between the prosodic predictors at 18 months and children's vocabulary at 24 months. In particular, we examine whether there were longitudinal correlations between the prosodic predictors at 18 months and children's

[2]Following Kitamura, Thanavishuth, Burnham, & Luksaneeyanawin (2002), F0 range (Hz) was transformed to Semitones (st) using the formula: Semitones = $12*\log_2$(maximum F0/minimum F0). Mean F0 (Hz) was transformed to Semitones (st) using the formula: $12\log_2$(Mean F0/50).

https://doi.org/10.1017/S0305000923000041 Published online by Cambridge University Press

vocabulary size at 24 months. For this analysis, we also only include the 32 participants who participated at both ages, of which 5 were excluded due to missing vocabulary information at 24 months, resulting in a total of 27 participants in the final analyses. For this analysis, the effect of individual differences in vocabulary size was accounted for by including children's vocabulary size at 18 months as a predictor in the model.[3]

The multiple regressions were done in the R environment (R Core Team, 2018) using the lm() function. The outcome variables were children's receptive vocabulary at either 18 months or 24 months. The predictor variables were raw prosodic values and prosodic hyper-scores. Before building each model, we detected outliers by visual inspection of scatter plots and capped them at the 5th percentile (for outliers below the lower limit) and the 95th percentile (for outliers above the upper limit). For each model, we started by including all the predictors and their interactions with Familiarity[4] and then used the "stepAIC" function of the MASS package (Venables & Ripley, 2002) to reduce the model by selecting variables with a significance level of 5% (direction was set to "backward").

Results

Descriptive statistics

Table 2 shows descriptive statistics of the raw prosodic values of IDS and hyper-scores at 18 months. Table 3 shows descriptive statistics of the raw prosodic values of IDS and hyper-scores at 24 months. Supplementary Figures 1-6 show scatter plot matrices of correlations (Pearson correlation coefficients) between all predictors (raw prosodic values and prosodic hyper-scores) and children's receptive vocabulary.

The outcome measure was children's receptive vocabulary. Children's vocabulary increased significantly from 18 months (M = 247, SD = 103, range = 101–473) to 24 months (M = 529, SD = 90, range = 352–670).

Correlations between the raw prosodic values and children's vocabulary size

We first examined whether the raw prosodic values of mothers' IDS could predict children's concurrent vocabulary at 18 and 24 months as well as children's vocabulary growth between these two ages. Regression analyses revealed that, for the 18-month-old group, the final model showed no significant correlation between the raw prosodic values and children's vocabulary[5] (see Supplementary Figure 1). Similarly, the final model for the concurrent correlations at 24 months was not significant[6] (see Supplementary Figure 2). There was no remaining predictor in the final models.

For the longitudinal correlations between the raw prosodic values of IDS at 18 months and children's vocabulary growth between 18 and 24 months (see Supplementary Figure 3), the results of the regression analyses (Table 4) showed two significant predictors for children's vocabulary at 24 months in the final model: utterance mean F0 and children's vocabulary at 18 months. This model accounted for 73.6% of variance in

[3]For example, this could be calculated in R as follows: lm(vocabulary_24m ~ vocabulary_18m + Familiarity * (articulation_rate + mean_F0 +F0_range)).

[4]An example of the R codes is: lm(vocabulary ~ Familiarity * (articulation_rate +mean_F0 + F0_range))

[5]Final model: Vocabulary_18m ~ 1.

[6]Final model: Vocabulary_24m ~ 1.

https://doi.org/10.1017/S0305000923000041 Published online by Cambridge University Press

Table 2. Means and standard deviations (*SD*s) of raw prosodic values of IDS and hyper-scores in 18 months (*N = 43*)

		Raw prosodic values		Hyper-scores	
Prosodic measures	Familiarity	*M*	*SD*	*M*	*SD*
Articulation rate	Familiar	4.99	0.76	0.95	0.16
	Unfamiliar	4.57	0.66	0.92	0.15
Mean F0	Familiar	29.14	2.51	1.11	0.10
	Unfamiliar	28.29	2.18	1.09	0.10
F0 range	Familiar	15.22	3.33	1.05	0.31
	Unfamiliar	15.37	3.68	1.10	0.33

Table 3. Means and standard deviations (*SD*s) of raw prosodic values of IDS and hyper-scores in 18 and 24 months (who participated longitudinally) (*N* = 27)

Age		18 months				24 months			
Prosodic measures		Raw prosodic values		Hyper-scores		Raw prosodic values		Hyper-scores	
	Familiarity	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Articulation rate (syllables/s)	Familiar	4.91	0.73	0.95	0.16	5.08	0.75	0.98	0.15
	Unfamiliar	4.50	0.72	0.91	0.15	4.65	0.54	0.92	0.10
Mean F0 (st)	Familiar	29.53	2.82	1.12	0.10	28.69	2.88	1.12	0.15
	Unfamiliar	28.27	2.37	1.09	0.11	27.44	1.21	1.07	0.10
F0 range (st)	Familiar	15.12	3.47	1.00	0.32	15.83	4.70	1.14	0.50
	Unfamiliar	16.00	3.34	1.11	0.29	14.94	3.68	1.05	0.30

Table 4. Regression model for longitudinal correlations between raw prosodic values at 18 months and children's vocabulary growth (*N* = 43)

	Estimate	*SE*	*t*	*p*
(Intercept)	134.24	86.07	1.56	0.125
18m Vocabulary	0.76	0.07	11.19	<0.001***
Familiarity (Unfamiliar)	−84.71	64.68	−1.31	0.200
Mean F0	9.87	2.68	3.68	<0.001***
F0 range	−5.20	2.81	−1.85	0.070
Familiarity (Unfamiliar): F0 range	6.36	4.04	1.57	0.122

*Notes. *p < .05; **p < .01; ***p < .001.*

https://doi.org/10.1017/S0305000923000041 Published online by Cambridge University Press

Table 5. Regression model for correlations between vocabulary at 18 months and vocabulary at 24 months ($N = 27$)

	Estimate	*SE*	*t*	*p*
(Intercept)	358.05	19.17	18.68	<0.001***
18m Vocabulary	0.71	0.07	9.66	<0.001***

*Notes. *p < .05; **p < .01; ***p < .001.*

children's vocabulary at 24 months ($R^2 = 0.736$, $F(5, 48) = 26.71$, $p < 0.001$). Compared to a model with only vocabulary at 18 months as a predictor (Table 5) ($R^2 = 0.642$, $F(1, 52) = 93.31$, $p < 0.001$), this model explained 9.35% more of the variance. When excluding the non-significant predictors in the final model, we found that children's vocabulary at 18 months ($\beta = 0.73$, $SE = 0.07$, $t = 10.89$, $p < 0.001$) and mean F0 ($\beta = 8.89$, $SE = 2.54$, $t = 3.50$, $p < 0.001$) significantly predicted children's vocabulary at 24 months ($R^2 = 0.711$, $F(2, 51) = 62.9$, $p < 0.001$). Compared to the model with only vocabulary at 18 months as a predictor (Table 5) ($R^2 = 0.642$, $F(1, 52) = 93.31$, $p < 0.001$), adding mean F0 improved the model by explaining 6.94% more of the variance. These results suggest that a higher mean F0 at 18 months significantly predicts children's vocabulary growth between 18 and 24 months.

Together these results suggest that there were no significant concurrent correlations between any of the raw prosodic values and children's vocabulary size at either 18 months or 24 months, but a higher mean pitch of IDS at 18 months significantly predicted children's larger vocabulary growth between 18 and 24 months. As the main effect of Familiarity was not significant, nor was there any significant interaction between Familiarity and prosodic predictors, this conclusion holds for the prosody of IDS when it contains both familiar and unfamiliar words.

Correlations between the prosodic hyper-scores and children's vocabulary size

We used multiple linear regression to test if articulation rate hyper-score, mean F0 hyper-score, and F0 range hyper-score significantly predicted children's concurrent vocabulary size and vocabulary growth. For the 18-month-old group, two outliers were capped at the 95th percentile before we built the model. The final model ($R^2 = 0.06$, $F(4, 81) = 1.32$, $p = 0.26$) showed that the effect of Familiarity ($\beta = 244.34$, $SE = 136.34$, $t = 1.79$, $p = 0.077$) and the interaction between Familiarity and utterance articulation rate ($\beta = -258.08$, $SE = 143.73$, $t = -1.80$, $p = 0.076$) approached significance (see Supplementary Table 1 and see Supplementary Figure 4). Since we were specifically interested in the differential relations between prosody and vocabulary depending on Familiarity, we conducted further multiple regressions on Familiar and Unfamiliar hyper-scores respectively. The final model for Familiar hyper-scores had no significant predictors[7]. However, the final model for Unfamiliar hyper-scores (Table 6) showed that the effect of F0 range hyper-score approached significance, though the overall regression was not significant ($R^2 = 0.09$, $F(2, 40) = 1.99$, $p = 0.15$).

For the concurrent correlations between the prosodic hyper-scores and children's vocabulary at 24 months, three outliers were capped at the 95th percentile before we built

[7]Final model: Vocabulary_18m ~ 1.

https://doi.org/10.1017/S0305000923000041 Published online by Cambridge University Press

Table 6. Regression model for concurrent correlations between Unfamiliar hyper-scores (HS) at 18 months and children's vocabulary size at 18 months ($N = 43$).

	Estimate	*SE*	*t*	*p*
(Intercept)	237.84	18.00	13.21	<0.001***
Articulation rate HS	−157.85	105.55	−1.50	0.14
F0 range HS	−128.06	69.78	−1.84	0.074

*Notes. *p < .05; **p < .01; ***p < .001.*

the model. The final model ($R^2 = 0.19$, $F(6, 45) = 1.77$, $p = 0.128$) showed a significant effect of Familiarity ($\beta = 899.37$, $SE = 391.06$, $t = 2.30$, $p = 0.026$), and a significant effect of F0 range hyper-score ($\beta = 98.14$, $SE = 38.27$, $t = 2.56$, $p = 0.014$). Also, we found that the interaction between Familiarity and articulation rate hyper-score approximates significance ($\beta = -424.46$, $SE = 223.59$, $t = -1.90$, $p = 0.064$), and there was an approximately significant interaction between Familiarity and mean F0 hyper-score ($\beta = -467.70$, $SE = 241.81$, $t = -1.94$, $p = 0.058$) (see Supplementary Table 2 and see Supplementary Figure 5). As with the 18-month-old group, we explored the correlations for Familiar and Unfamiliar hyper-scores. The final model for Familiar hyper-scores showed no significant predictors[8]. However, the final model for Unfamiliar hyper-scores (Table 7) ($R^2 = 0.37$, $F(3, 21) = 4.05$, $p = 0.020$) showed three significant predictors: articulation rate hyper-score, mean F0 hyper-score, and F0 range hyper-score[9]. These results suggest that the degree of mothers' prosodic modification in IDS when introducing unfamiliar (but not familiar) words significantly predicts children's vocabulary size at 24 months. Specifically, the degrees of slowing down articulation rate, lowering mean pitch, and expanding pitch range in word-learning contexts were correlated with children's larger vocabulary size.

For the longitudinal correlations, the final model (Supplementary Table 3) showed a significant interaction between Familiarity and F0 range hyper-score ($\beta = 125.19$, $SE = 54.25$, $t = 2.31$, $p = 0.025$) (see Supplementary Figure 6). Thus, we further explored the correlations for Familiar and Unfamiliar hyper-scores. For Familiar hyper-scores, our final model revealed that only vocabulary size at 18 months ($\beta = 0.71$, $SE = 0.11$, $t = 6.70$, $p < 0.001$) significantly predicted children's vocabulary at 24 months, while no prosodic hyper-scores remained significant in this model ($R^2 = 0.64$, $F(1, 25) = 44.86$, $p < 0.001$). For the Unfamiliar hyper-scores, our final model (Table 8) revealed two significant predictors for children's vocabulary size at 24 months: children's vocabulary size at 18 months as well as F0 range hyper-score at 18 months. These two predictors accounted for 71.6% of children's vocabulary at 24 months ($R^2 = 0.716$, $F(2, 24) = 30.29$, $p < 0.001$). Compared to a model with only vocabulary at 18 months as a predictor ($R^2 = 0.642$, $F(1, 52) = 93.31$, $p < 0.001$), adding the utterance F0 range unfamiliar hyper-score as a predictor improved the model by explaining 7.41% more of the variance, suggesting that the degree of expanding pitch range in IDS compared to ADS specifically in

[8]Final model: Vocabulary_24m ~ 1.

[9]The significance level was 0.025 after Bonferroni correction. The *p*-value for the Utterance F0 range HS was significant, while the *p*-values for Articulation rate HS and Mean F0 HS were nearly significant; thus, the results for the latter two measures should be interpreted cautiously.

https://doi.org/10.1017/S0305000923000041 Published online by Cambridge University Press

Table 7. Regression model for concurrent correlations between Unfamiliar hyper-scores (HS) at 24 months and children's vocabulary size at 24 months ($N = 25$[10])

	Estimate	*SE*	*t*	*p*
(Intercept)	1183.10	292.18	4.05	<0.001***
Articulation rate HS	−389.51	173.99	−2.24	0.036*
Mean F0 HS	−435.63	183.59	−2.37	0.027*
F0 range HS	159.27	57.93	2.75	0.012*

*Notes. *p < .05; **p < .01; ***p < .001.*

Table 8. Longitudinal correlations between Unfamiliar hyper-scores (HS) and children's vocabulary growth between 18 and 24 months ($N = 25$)

	Estimate	*SE*	*t*	*p*
(Intercept)	339.17	26.23	12.93	0.001***
18m Vocabulary	0.76	0.10	7.70	0.000***
F0 range HS	110.76	44.25	2.50	0.020*

*Notes. *p < .05; **p < .01; ***p < .001.*

word-learning contexts significantly predicted children's vocabulary growth between 18 and 24 months[11].

Taken together, these regression analyses found no correlation between prosodic hyper-scores when introducing familiar words and children's vocabulary size, either concurrently or longitudinally. However, the prosodic hyper-scores, specifically for the unfamiliar words, showed significant correlations with children's vocabulary size, both concurrently at 24 months and longitudinally.

Discussion and conclusions

The goal of this study was to examine the relationship between IDS prosody and children's concurrent vocabulary as well as longitudinal vocabulary growth. Crucially, we focused on the role of speech context and distinguished between the prosody of IDS when mothers introduce unfamiliar vs. familiar words. To measure the prosodic quality of IDS, we included two types of predictors: (1) raw prosodic values, indicating the prosody children hear; and (2) prosodic hyper-scores, which indicate the degree of prosodic modification in IDS compared to ADS. Our main findings are I two parts.

First, we found that a higher mean pitch of IDS at 18 months significantly predicted children's vocabulary growth between 18 and 24 months regardless of whether mothers were introducing familiar or unfamiliar words to children. Across languages, prototypical IDS is characterized by a higher pitch, including Dutch (Benders, StGeorge, & Fletcher, 2021; Golinkoff et al., 2015; Han et al., 2021). Our results support the view that a higher

[10]Two participants were excluded as they did not have Unfamiliar hyper-scores at 24 months. Same for Table 8.

[11]The results for F0 range HS were statistically significant after Bonferroni correction was applied.

https://doi.org/10.1017/S0305000923000041 Published online by Cambridge University Press

mean pitch in IDS at the global level is beneficial to children's lexical development. The high pitch of IDS may directly facilitate children's language acquisition. Alternatively but not exclusively, as a higher pitch has been shown to attract children's attention (Fernald & Simon, 1984) and convey positive affect (Singh et al., 2002; Trainor et al., 2000), it is also possible that the high pitch of IDS simply serves to attract infants' attention to linguistic input and thus only INDIRECTLY facilitates language acquisition. There has been some evidence to suggest that F0 range and articulation rate in IDS may be positively correlated with children's vocabulary size (Porritt et al., 2014; Raneri et al., 2020). However, our findings only show that individual variations in pitch level is a significant predictor for children's vocabulary, while pitch range and speaking rate are not found to be significant predictors. We do not rule out the possibility that these factors can still be associated with children's vocabulary size. So far, studies on the links between prosodic quality and children's vocabulary are few and the findings are mixed. More research should be done in order to conclude which specific prosodic cues are critical to children's lexical development.

Second, our results demonstrate that the prosodic hyper-score when mothers introduced unfamiliar words to children significantly predicted children's concurrent vocabulary size and future vocabulary growth. Here, prosodic hyper-scores indicate the DEGREE of prosodic modification in IDS compared to ADS. Using these predictors, Kalashnikova and Burnham (2018) found no significant correlations between the mean F0 hyper-scores and children's vocabulary size. Our analyses show no significant correlations between Familiar hyper-scores and children's vocabulary size – neither concurrently nor longitudinally. By contrast, the unfamiliar hyper-scores are correlated with children's concurrent vocabulary size at 24 months, and the unfamiliar hyper-scores at 18 months significantly predict children's vocabulary growth in the next 6 months. Specifically, the significant predictors for children's concurrent vocabulary size at 24 months are a smaller articulation rate hyper-score, a smaller mean pitch hyper-score, and a larger pitch range hyper-score. In other words, when introducing unfamiliar words to 24-month-old children, mothers who had a relatively slower speaking rate, a lower pitch, and a larger pitch range compared to the same measures in ADS had children who had a larger vocabulary size. Also, longitudinal correlations reveal that a larger pitch range hyper-score at 18 months significantly predicts children's larger vocabulary growth between 18 and 24 months. Together these results suggest that the degree of mothers' prosodic modification in IDS specifically in word-learning contexts may facilitate children's lexical development.

The two prosodic measures reflect different aspects of individual differences in prosodic input. The results on the raw prosodic values suggest that the generally high pitch, as a characteristic of prototypical IDS, may benefit lexical development. However, when zooming into the word-learning contexts, prosodic hyper-scores, which indicate the degree of prosodic modification, become better predictors for children's vocabulary size and growth. Taken together, the findings on the two measures highlight the importance of distinguishing between the global prosody and prosody in word-learning contexts in this line of research.

Han et al. (2020, 2021) found that Dutch mothers had a slower articulation rate and a lower mean pitch when introducing unfamiliar words to their 18- and 24-month-old children. Here, we found that a slower articulation rate and a lower F0, which Dutch mothers used when introducing unfamiliar words (at group level), were concurrently correlated with vocabulary size at 24 months. It should be noted that there are two interpretations for these concurrent correlations, First, as illustrated above, we could interpret our results as supporting the potential facilitative effects of IDS prosody on children's lexical development. However, an alternative account for these concurrent correlations could be that mothers adapt their IDS prosody when introducing unfamiliar words according to children's vocabulary knowledge. For example, the concurrent correlation results at 24 months show that mothers spoke slower, had a lower word pitch, and expanded F0 range in IDS compared to ADS when introducing unfamiliar words to children with a relatively larger vocabulary. In other words, mothers fine-tune their speech prosody when introducing unfamiliar words to children, taking children's vocabulary size into consideration. Thus, longitudinal correlations between IDS at 18 months and children's vocabulary growth provide stronger evidence for the facilitative effects of prosody on children's language development.

Even though modifying pitch range does not seem to be a strategy that Dutch mothers use to differentiate familiar and unfamiliar words at group level (Han et al., 2020), findings from the current study suggest that individual differences in the degree of F0 range expansion in word-learning contexts may play a role in children's lexical development. Similar to mean pitch, pitch range expansion has been shown to be a main means of attracting and maintaining infants' attention (Fernald & Kuhl, 1987). It is possible that expanding pitch range, especially when introducing unfamiliar words, may draw children's attention to facilitate the novel sound to object mapping.

In this study, we focus on IDS prosody at the utterance level. As the reviewers pointed out, it would be interesting to examine whether prosody at word level or utterance level is a better predictor for children's vocabulary size. Indeed, both the unfamiliar words and the utterances containing the unfamiliar words may be crucial in word-learning contexts. As the first study to systematically investigate the relationship between IDS prosody in word-learning contexts and children's language outcomes, our data did not allow us to further examine this question. We made a design choice to focus our analyses at the utterance level in this study (see 'Prosodic measures' for more discussion) in line with previous research on IDS prosody (e.g., Porritt et al., 2014; Raneri et al., 2020; Song et al., 2018). Future studies could also include prosodic measures at the word level and examine whether the results hold across the two levels.

Here, we contrasted raw prosodic values of IDS and hyper-scores that use ADS as a baseline to show the relative degree of prosodic modification in IDS. As one reviewer pointed out, a discrepancy between familiar and unfamiliar words in IDS could be another way to measure how mothers highlight unfamiliar words compared to familiar words. Such analyses might not be feasible with our current experimental design, as the intrinsic word prosody and word frequency differ between our preselected target words and there were individual differences in children's vocabulary knowledge. A recent study by Shi, Gu, and Vigliocco (2022) used familiar words as a baseline. Their findings show that English-speaking mothers' degree of mean pitch modification for unknown words relative to known words predicted children's immediate word learning and vocabulary size a year later.

In this study, we show that the prosodic quality of IDS is related to children's language outcomes. Our findings contribute to an understanding of the function of IDS prosody in children's lexical development. These findings support the view that the prosody of IDS at a global level plays a significant role in language acquisition. In addition, the degree of prosodic modification in word-learning contexts is specifically important to lexical development. Our findings emphasize the importance of input quality in word-learning contexts.

Acknowledgments. We thank Lisanne Geurts and Karlijn Kouwer for their help with data collection and annotation. We are grateful to all the families who participated in this study. We also acknowledge the editor and anonymous reviewers for their valuable comments and suggestions. This work was partly supported by Shanghai Planning Project of Philosophy and Social Sciences (2020EYY001).

Supplementary Materials. To view supplementary material for this article, please visit http://doi.org/10.1017/S0305000923000041.

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Cite this article: Han, M., De Jong, N.H., & **Kager, R.** (2024). Relating the prosody of infant-directed speech to children's vocabulary size. *Journal of Child Language* **51,** 217–233, https://doi.org/10.1017/S0305000923000041