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Neighbourhood density and word production in delayed and advanced learners

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Abstract

Purpose: This study re-examines the claim that difficulty forming memories of words comprising uncommon sound sequences (i.e. low phonological neighbourhood density words) is a determinant of delayed expressive vocabulary development (e.g. Stokes, 2014).

Method: We modelled communicative development inventory data from *N*=442, 18-month old children, with expressive lexicon sizes between zero and 517 words (median=84). We fitted a Bayesian regression model in which the production of each communicative inventory word (*N*=680) by each child was predicted by interactions between that child's expressive lexicon size and the word's (i) phonological neighbourhood density, (ii) frequency in child-directed speech, (iii) length, (iv) babiness, and (v) concreteness.

Results: Children with larger expressive lexicons were more likely to produce words comprising uncommon sound sequences than age-matched children with smaller lexicons. However, the magnitude of the interaction between expressive lexicon size and phonological neighbourhood density was modest relative to interactions between expressive lexicon size and word frequency, length, babiness, and concreteness.

Conclusion: Emphasis on a difficulty with the memorisation of low neighbourhood density words as a determinant of slow vocabulary growth may be unwarranted, and the current evidence base in this direction is not robust enough to strongly support the development of possible interventions for late talkers (e.g. Stokes, 2014).

Rates of spoken vocabulary development differ dramatically between children in the second year of life. By 18 months, children in the 95th centile (advanced learners) may produce an estimated 240 words, while same-age children below the 10th centile (so-called ‘late-talkers’) may produce fewer than five words (Alcock, Meints, & Rowland, 2017). Variance in expressive vocabulary size has been attributed to heritability, child gender, birth order, caregiver speech rate and quality, temperament, and attentional factors (Hammer et al., 2017; Rowe & Leech, 2017). Some studies into variance in expressive vocabulary size have also focussed on identifying the lexical characteristics that make a particular word easy or difficult for certain children to learn and produce. This work has addressed both semantic and phonological features, and suggests that the direction of discrepancy between delayed and advanced learners differs across these domains. In semantics, there is suggestive evidence that children in lower percentiles may be liberal learners (Beckage, Smith, & Hills, 2011). That is, the lexicons of late talkers may exhibit reduced semantic consistency. These children show a greater tendency than age-matched controls to acquire ‘oddball’ words, i.e. words that do not fit easily into existing semantic networks (though see Jimenez & Hills, 2017). With respect to phonology, however, there is evidence that children in lower expressive language percentiles are conservative learners. It has been argued that late talkers continue producing words that sound similar to many other words in the ambient language (i.e. high neighbourhood density words), when age-matched controls have started producing words comprising less common sounds (Stokes, 2010, 2014; Stokes, Kern, & Dos Santos, 2012; Takac, Knott, & Stokes, 2017). This delay has been attributed to underlying working memory deficits impeding the accurate memorisation of words from sparse phonological neighbourhoods (e.g. Stokes, 2014). Having argued that processing phonologically uncommon words is a central determinant of delayed vocabulary growth, some of these studies have suggested interventions in which clinicians identify known words from dense phonological neighbourhoods and build vocabulary by transitioning outward from this knowledge base into increasingly sparse neighbourhoods (e.g. Stokes, 2010, 2014).

The purpose of the current study is to re-examine the claim that phonological neighbourhood density is more strongly associated with word production in children with small expressive vocabularies than in children with relatively large vocabularies. We analyse communicative development inventory data similar to that used in previous studies in this area (e.g. Stokes, 2014), but adopt a methodology that avoids some of the limitations of this earlier work. For instance, previous studies have dichotomised data into 'late talker' and 'typically developing' groups. This approach reduces both statistical power and the quality of inferences that can be drawn. Data dichotomisation may be justified when analysing populations with qualitatively different profiles, such as children with and without autistic spectrum disorder. However, it is unclear whether this approach is justifiable with respect to the study of individual differences in rates of expressive vocabulary development, including late talking, given that the majority of late talkers do not show later language difficulties (Hammer et al., 2017; Rowe & Leech, 2017).

In addition, evidence for a protracted density association in late talkers has previously involved the comparison of statements of statistical significance. For instance, Stokes (2014, p. 651) reports a statistically significant difference in the neighbourhood density of the expressive lexicons of typically developing children and late talkers, and a non-significant difference in the neighbourhood density of the receptive lexicons of typically developing and late talkers. It is argued that the expressive lexicons of late talkers, though not children in the normal range, are characterised by high neighbourhood density. This interpretation is, however, somewhat controversial because the difference between 'statistically significant' and 'non-significant' may not in itself be significant. This point is illustrated by Gelman and Stern (2006, p. 328), who imagine one analysis with a resulting effect estimate of 25 and a standard error of 10, and a second analysis with an effect estimate of 10 and a standard error of 10. Analysis one is significant at the 1% threshold, while analysis two is non-significant. Nevertheless, the difference between results is not itself significant, with a difference between estimates of 15 and a standard error of 14. Therefore while one result is significant and the other non-significant, the difference between outcomes may itself be of little practical importance.

To address these concerns in the current study, expressive lexicon size is modelled continuously. There is also an emphasis on estimate probability distributions rather than *p*-values. A probability distribution shows the relative plausibility of different parameter values, such as the beta (i.e. slope) coefficient in a linear regression model (McElreath, 2016). A probability distribution crossing zero would suggest that no linear relationship between variables was plausible (i.e. a horizontal regression line). A probability distribution with mass bound above zero would suggest a positive relationship between variables (i.e. a positive slope), and a probability mass bound below zero would suggest a negative relationship between variables (i.e. a negative slope). The decision to apply this methodology reflects our belief that probability distributions show uncertainty in the data better than point estimates such as *p*-values.

The first research question we address is: *Is the importance of ambient language phonological neighbourhood density as a predictor of word production moderated by expressive vocabulary size in (N=442) children aged eighteen months?* Throughout this study we are interested in whether variables such as phonological neighbourhood density are more important predictors of individual word production for children with relatively small or large expressive vocabularies. In statistical terms this means that there is an emphasis on interaction effects rather than main effects, most importantly the interaction between the child's expressive lexicon size and word phonological neighbourhood density. Evidence that children with small lexicons were more likely to produce words with high phonological neighbourhood density would be an interaction effect estimate probability distribution bound below zero. This would show that as vocabulary size increased, the strength of positive association between high neighbourhood density and word production decreased (as reported by Stokes, 2010, 2014; Stokes et al., 2012; Takac et al., 2017).

Our second research question is: *What is the strength of the interaction between expressive vocabulary size and phonological neighbourhood density as a predictor of word production relative to interactions between expressive vocabulary size and alternative variables associated with age of acquisition (i.e., word frequency, length, babiness, and concreteness)?* As described above, previous studies have claimed that difficulty processing phonologically sparse words is a central determinant of limited expressive vocabulary size (Stokes 2010, 2014). These studies have also suggested interventions on the basis of evidence from parental report data similar to that used in the current study. However, because phonological neighbourhood density has to date been considered in isolation (i.e. commonly alongside only word length and frequency), we do not currently know whether the relative strength of the association between expressive lexicon size and phonological neighbourhood density is strong enough to constitute preliminary support for this position. Previous work by Braginsky, Yurovsky, Marchman, and Frank, (2018), for instance, has demonstrated that lexical features associated with significant variance in word understanding and production when modelled in isolation may show only limited relative effects when modelled as part of a larger, more representative inventory of predictors linked with age of acquisition. With this in mind, we model the interaction between expressive vocabulary size and neighbourhood density as a predictor of word production alongside interactions between expressive vocabulary size and a range of variables previously associated with age of acquisition effects; namely, word length (in phonemes), frequency (calculated from token counts in child-directed speech), babiness (i.e. adult ratings of the relevance of words for infants and babies), and concreteness. A substantial estimate for the interaction between expressive lexicon size and phonological neighbourhood density relative to estimates for the interactions between expressive lexicon size and word length, frequency, babiness, and concreteness, would constitute preliminary evidence that low phonological neighbourhood density may be a particular problem area for some children with language delay.

Method

This study was pre-registered with the Open Science Framework on 19th October 2018. A pre-registration protocol, R code, and all data required to re-run the analysis are available via the associated project page: https://osf.io/p8ax4/. The study was unfunded and undertaken as part of the first author's PhD. We declare no conflict of interest.

Database and sample

To answer the questions above, we used parental report data collected using the MacArthur-Bates communicative development inventory, words and sentences version (MCDI-WS; Fenson et al., 2007). The reason for using this data is that similar data were used in previous work which argued that a protracted neighbourhood density effect characterises the expressive lexicons of late talkers (i.e. children in low percentiles) (e.g. Stokes, 2010, 2014). We wanted to test whether this claim stands when using a different statistical approach and controlling for other variables (e.g. babiness and concreteness). The MCDI-WS comprises a checklist of words and phrases, but note that our analysis looked only at words. During administration, caregivers are asked to tick the boxes adjacent to items that their child is able to say. These responses (0 = does not produce; 1 = produces) for 680 words and 442 children form our dependent variable.

We accessed MCDI-WS data for 442 American English-learning children from the wordbank database using the wordbankr package in R (Braginsky, Yurovsky, Frank, &

Kellier, 2018; Frank, Braginsky, Yurovsky, & Marchman, 2017; R Core Team, 2016). We selected the American English data because these were well sampled within wordbank. We selected the 18-month subset of the American English data because this was the best-sampled age group, and also because the existing work reporting protracted density effects has looked at a comparable age range (e.g. Stokes, 2010, 2014). Gender was not reported for 119 children, while 148 children were identified as female and 175 children were identified as male. Figure 1 shows the distribution of expressive lexicon sizes across children.

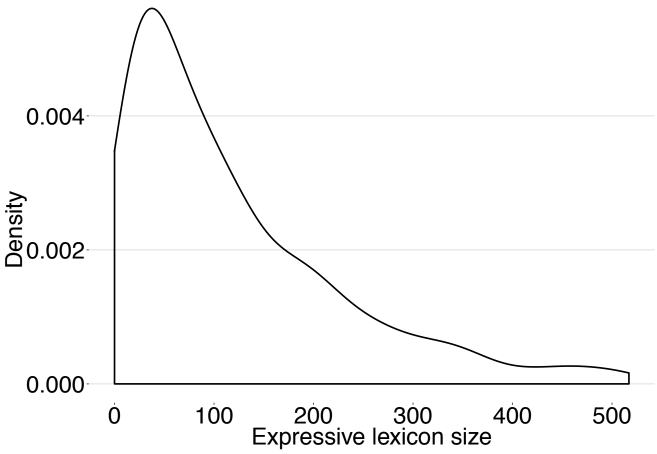

Figure 1. Density distribution of expressive lexicon sizes for 442 American English-learning children aged 18 months.

Figure 1 confirms that the sample showed the substantial individual differences in expressive lexicon size typical of their age (Alcock et al., 2017). The median lexicon size was 84 words (*M*=118 words), with a range of zero to 517 words. Ten children in the 442-participant sample had expressive lexicons of fewer than five words, and would be considered late talkers under a ≤10^{th} centile criterion (e.g. Dale et al., 1998).

Predictor variables

We aimed to predict whether each child produced each MCDI-WS word using a range of lexical variables in interaction with the child's expressive vocabulary size. The inventory of lexical variables we used was selected by reference to work by Braginsky et al. (2018), who found substantial effects for word length, frequency, babiness, and concreteness. We expanded this predictor inventory by adding phonological neighbourhood density, operationalised as the number of words in a given corpus that can be formed from a target word through one phoneme in addition, deletion, or substitution (Luce & Pisoni, 1998). Predictors, data sources, and minimum- and maximum-value example words from the MCDI-WS are shown in Table 1.

Table 1

Independent variables, data sources, and minimum- and maximum-value examples.

Variable	Source(s)	Examples
Child directed speech frequency	Fenson et al. (2007); Fernald, Marchman, and Weisleder (2013); Thal, Marchman, and Tomblin (2013)[1]	Min: *downtown* Max: *you*
Length, in phonemes	Balota et al. (2007)	Min: *a* Max: *cockadoodledoo*
Adult babiness rating: [1] 'not associated with babies' to [10] highly 'associated with babies'	Perry, Perlman, and Lupyan (2015)	Min: *donkey* Max: *baby*
Concreteness rating: [1] 'abstract' to [5] 'concrete'	Brysbaert, Warriner, and Kuperman (2014)	Min: *would* Max: *apple*
Phonological neighbourhood density	Balota et al. (2007)	Min: *aeroplane* Max: *boo*

Child-directed speech frequencies for each MCDI-WS word were calculated from American English transcripts in the wordbank database, before being transformed to log frequencies. We limited raw counts to transcripts in which speech from caregivers, siblings, or researchers was directed at children aged between 16 and 20 months of age. Word length was calculated

[1] See http://wordbank.stanford.edu/contributors 'American English' for a full list of contributors.

in number of phonemes. Babiness and concreteness ratings from adults were retrieved from separate databases, each of which has been used in previous work by Braginsky et al. (2018). Finally, phonological neighbourhood density counts for each MCDI-WS word were retrieved from the English Lexicon project. We used the un-weighted measure of phonological neighbourhood density excluding homophones given the apparent preference for this criterion in the related literature (e.g. Stokes, 2014, Storkel, 2009).

We assessed multicolinearity risk (i.e. the possibility that high predictor correlation may distort estimates) by fitting a simple binomial regression model in which word production was predicted by each variable listed in Table 1 as a main effect and then calculating variance inflation factors (VIFs) using the car package in R (John et al., 2017). VIFs were low, with a maximum of 2.01 for the word length variable, suggesting that multicolinearity was not a significant issue.

The rates of missing data for each predictor variable were: 0% for expressive lexicon size, 0% for word length, 3.68% for child-directed speech frequency, 13.82% for babiness rating, 4.12% for concreteness rating, and 4.26% for phonological neighbourhood density. We imputed missing values using predictive mean matching via the mice (multivariate imputation by chained equations) package in R (Buuren & Groothuis-Oudshoorn, 2011). We then confirmed that the imputed values were plausible through strip plot visualisation, a process that can be repeated using the associated R code. All predictors were then scaled in order to make model fitting more efficient and to simplify the comparison of estimates.

Analysis

We used the brms package in R (Burkner, 2017) to fit a Bayesian multiple logistic regression model in which MCDI-WS item production was predicted by each variable listed in Table 1 in interaction with each child's expressive vocabulary size. Child id was used as a grouping variable. We set a weakly informative prior across β parameters (a normal distribution centred on zero with a standard deviation of three), which we expected to be overwhelmed by the large number of observations (i.e. *N*=442 caregiver responses for 680 words=300,560 observations). This model fitted successfully, with an adequate number of effective samples, stationery and well-mixing chains, rhats uniformly at 1, and credible posterior predictive checks (see R code for analytics).

Results

A complete summary of model estimates (including main effects) is presented in Table A1 of the Appendix. Figure 2 shows probability distributions for the interaction between each lexical predictor and expressive vocabulary size (see Appendix for main effect estimates). A positive estimate, to the right of the grey line, indicates that as expressive vocabulary size increased, children were more likely to produce words with higher values of the associated variable. A negative estimate, to the left of the grey line, indicates that as expressive vocabulary size increased, children were more likely to produce words with lower values of the associated variable.

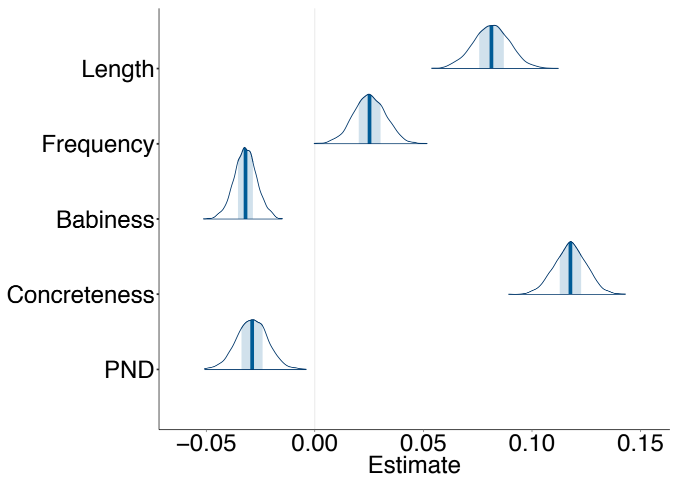

Figure 2. Predictor and expressive vocabulary size interaction effect probability distributions. The dark blue central line is the estimate mean, the light blue region is the 50% probability interval, and the distribution tails cover the 90% probability region.

From top to bottom (*y*-axis, Figure 2), children with larger expressive vocabularies were more likely to produce long words, as measured in phonemes (β =0.08; lower 95% credible interval=0.06; upper 95% credible interval=0.10). They were also more likely to produce words that occurred frequently in caregiver speech addressed to children between 16 and 20 months of age (β =0.03; lower 95% CI=0.01; upper 95% CI=0.04). Children with larger expressive lexicons were more likely than children with smaller lexicons to produce words with low babiness ratings (β =-0.03; lower 95% CI=-0.04; upper 95% CI=-0.02). They were also more likely to produce words with high concreteness ratings, with this being the most substantial effect (β =0.12; lower 95% CI=0.10; upper 95% CI=0.13). Finally, and with central importance to the current study, children with larger expressive lexicons were more likely than children with smaller expressive lexicons to produce words that were phonologically similar to few words in the ambient language (β =-0.03; lower 95% CI=-0.04; upper 95% CI=-0.01). Stated differently, high phonological neighbourhood density was more strongly associated with word production in children who could produce few words. Like all the observed estimates this interaction effect showed no probability distribution across zero. Importantly, however, the relative magnitude of the estimate for the interaction between expressive vocabulary size and phonological neighbourhood density was modest relative to interactions between expressive vocabulary size and other lexical predictors in the inventory. The neighbourhood density interaction effect was comparable to that of word frequency and word babiness, but substantially smaller in magnitude than the observed interactions with word length and concreteness. Thus it is impossible to single out low neighbourhood density as a primary factor leading to delayed vocabulary development.

Discussion

The current study examined whether the association between phonological neighbourhood density and word production was stronger in children with small or large expressive lexicons. Research Question 1 was: *Is the importance of ambient language phonological neighbourhood density as a predictor of word production moderated by expressive vocabulary size in children aged eighteen months?* Results from parental report based on 442 children suggest that the association between phonological neighbourhood density and word production is moderated by expressive vocabulary size. The direction of the reported estimate accords with previous work on early density effects. Children with small productive lexicons were more likely to produce words with high phonological neighbourhood density (e.g. Stokes, 2014; Storkel, 2004). The interaction appears reliable, with a probability distribution bound below zero (β=-0.03; lower 95% CI=-0.04; upper 95% CI=-0.01).

We also considered the strength of the interaction between expressive vocabulary size and neighbourhood density relative to interactions between expressive vocabulary size and word length, frequency, babiness, and concreteness. These variables have shown substantial age of acquisition effects in previous work (e.g. Braginsky et al., 2018). Research Question 2 asked; *What is the strength of the interaction between expressive vocabulary size and phonological neighbourhood density as a predictor of word production relative to interactions between expressive vocabulary size and alternative variables associated with age of acquisition (i.e., word frequency, length, babiness, and concreteness)?* None of the estimates for interactions between expressive vocabulary size and the selected lexical variables crossed zero, suggesting reliable effects for all secondary predictors. Furthermore, the pattern of estimates for these predictors resembled those reported in work by Braginsky et al. (2018), who looked at interactions with age rather than interactions with lexicon size. For instance, our analysis showed that larger lexicons comprised more words with high CDS frequency (e.g. function words potentially omitted in early development such as *if, is,* and *that*), high concreteness (e.g. a substantial number of common nouns in addition to typically early-learned onomatopoeia and routine words such as *meow, moo, hello, bye, no*), and low babiness ratings (e.g. *glasses, stove, salt*). Recovering the reported age-related trajectories using age-matched participants serves as a reminder that the development of children in the lower percentiles we looked at was delayed though not deviant. That is, the composition of low-percentile children's lexicons in our analysis appears comparable to that of younger children in the normal range reported by Braginsky et al. (2018). Similarly, these results suggest that when discussing changes in the importance of a predictor variable, vocabulary size is a better indicator of development than age (e.g. Ainsworth, Welbourne, & Hesketh, 2016). High phonological neighbourhood density, for instance, becomes a less important predictor of word production when expressive vocabulary size rather than age per se increases.

Despite a probability distribution bound below zero signalling a reliable effect separable from other predictors, the strength of the estimate for the interaction between expressive vocabulary size and phonological neighbourhood density was modest relative to interactions between expressive vocabulary size and the other lexical variables we considered in our model (see Table 1). The magnitude of the phonological neighbourhood density interaction was comparable to interactions between expressive vocabulary size and word babiness and frequency. Much stronger estimates were seen for interactions between expressive vocabulary size and word length (larger lexicons comprised longer words, in number of phonemes) and concreteness. In short, the neighbourhood density interaction estimate did not stand out, with other lexical characterises similarly or more strongly associated with variance in expressive lexicon size.

A large number of experimental, naturalistic, and computational studies have demonstrated that phonology matters in word learning (e.g. Hogan, Bowles, Catts, & Storkel, 2011; Hoover, Storkel, & Hogan, 2010; Schwartz & Leonard, 1982; Stokes, 2010; Storkel, 2002, 2004, 2006, 2009; Storkel & Lee, 2011). For instance, children are more likely to recall words from dense phonological neighbourhoods at delayed test. They are also more likely to memorise and accurately produce non-words that contain sounds already in their expressive lexicons. Such experimental results suggest that the reported high phonological similarity advantage in early word learning is not an epiphenomenon but a substantive and separable effect. However, when it comes to identifying lexical characteristics that help explain the variance observed in expressive vocabulary development, previous studies reliant on parental report data may have overestimated the importance of the high neighbourhood density association in smaller lexicons by excluding important alternative predictor variables (e.g. Stokes, 2010, 2014; Stokes et al., 2012). Other factors leading to an overestimation of the importance of phonological neighbourhood density may be data dichotomisation and an emphasis on statements of statistical significance. A large number of environmental (Hammer et al., 2017; Rowe & Leech, 2017) and lexical variables (e.g. word frequency, length, babiness, and concreteness) are associated with variance in rates of expressive vocabulary growth. Placing central emphasis on a difficulty processing uncommon word phonology on the basis of the current or similar data may therefore be unwarranted.

Limitations

Following previous studies in this area, we analysed data from the MacArthur-Bates communicative development inventory, words and sentences version (MCDI-WS). One general limitation with repeating this correlational approach is that we cannot discuss causality. In other words, we cannot say *why* high phonological similarity appears to continue to be a more important predictor of word production for children in low language percentiles. Prior work has linked a general, early neighbourhood density advantage to undeveloped phonemic representation capacity (e.g. Storkel, 2002, 2004). This work has also linked a reported protracted density association in late talkers to memory deficits such as those sometimes identified in language-impaired children (e.g. Gathercole & Baddeley, 1990; as in Stokes, 2014). In each case, it is argued that children may find it more difficult to form detailed memories of words containing sounds that occur infrequently in the ambient language. While word comprehension is possible despite underspecified lexical representations, accurate word production is not, leading to a heightened density effect in the expressive lexicons of young and language-delayed children. While prior correlational studies in this area have argued that findings similar to our own corroborate this causal account (e.g. Stokes, 2010, 2014; Stokes et al., 2012; Takac et al., 2017), the validity of any causal account can only be determined on the basis of experimental data.

A second limitation of the current analysis is that the MCDI-WS data tells us nothing about production variability. A disclaimer on the front page of the inventory addressed to caregivers reads: "If your child uses a different pronunciation of a word (for example, 'raffe' instead of 'girraffe' or 'sketti' instead of 'spaghetti'), mark the word anyway" (Fenson et al., 2007, p. 1). Prior work in this area has, however, argued that production accuracy stabilises over time, and that words from dense neighbourhoods are first produced most accurately (e.g. McLeod & Hewett, 2008; Sosa & Stoel-Gammon, 2012). It is therefore probable that children in lower percentiles not only produce fewer words than age-matched peers, but also that they are less accurate and more variable in their productions, particularly with respect to phonologically uncommon words (i.e. words from sparse neighbourhoods). Given the binary outcome variable used (i.e. 'produces' or 'does not produce'), we were unable to examine associations between the selected predictors and accuracy and variability in word production. However, it would be informative to repeat the current analysis using a similar inventory with graded response options (e.g. 0='does not produce'; 1='produces poorly', 2='produces adequately', 3='produces well'), or by calculating the accuracy and variability of transcribed phonological words (e.g. McLeod & Hewett, 2008; Sosa & Stoel-Gammon, 2012).

Future research should examine whether the results reported here generalise to different age ranges and populations, including clinical populations and children learning different languages. Such studies would improve our current understanding of individual differences in the importance of high phonological neighbourhood density as a cue to early word production.

Conclusion

A number of studies have used correlational data to argue that difficulty processing phonologically uncommon words is a central determinant of delayed expressive vocabulary development (e.g. Stokes, 2010, 2014; Stokes et al., 2012). Applying a revised methodology to comparable data we found that high phonological neighbourhood density was a reliable predictor of early word production and that this effect appears necessarily protracted in language-delayed children. However, the magnitude of this estimate relative to other known predictors of word acquisition was modest. Therefore, the claim that a difficulty acquiring low phonological neighbourhood density words is a central determinant of delayed expressive vocabulary growth may be unwarranted. The existing parental report evidence of a protracted density association in late talkers is not robust enough to support the development of possible interventions (e.g. Stokes, 2010, 2014). Experimental data is required to explore this line of inquiry further, and to determine the validity of any associated causal account.

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Appendix

Table A1

Model summary showing term (main effects and interactions), estimate, standard error (Std. error), and lower (L) and upper (U) 95% confidence intervals (CI).

Term (main effects)	Estimate	Std. error	L-95% CI	U-95% CI
Intercept	-2.23	0.02	-2.28	-2.19
SD of random intercepts	0.45	0.02	0.41	0.48
Length	-0.19	0.01	-0.21	-0.16
Vocabulary size	1.27	0.02	1.23	1.32
Frequency	0.58	0.01	0.56	0.60
Babiness	0.33	0.01	0.32	0.34
Concreteness	0.78	0.01	0.77	0.80
Neighbourhood density	0.07	0.01	0.05	0.09

Term (interactions)	Estimate	Std. error	L-95% CI	U-95% CI
Length: Vocabulary	0.08	0.01	0.06	0.10
Frequency: Vocabulary	0.03	0.01	0.01	0.04
Babiness: Vocabulary	-0.03	0.01	-0.04	-0.02
Concreteness: Vocabulary	0.12	0.01	0.10	0.13
Neighbourhood density: Vocabulary	-0.03	0.01	-0.04	-0.01