COGNITIVE SCIENCE
A Multidisciplinary Journal

Cognitive Science 45 (2021) e13022

ISSN: 1551-6709 online
DOI: 10.1111/cogs.13022

Onset Neighborhood Density Slows Lexical Access in High Vocabulary 30-Month Olds

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Received 24 April 2020; received in revised form 21 June 2021; accepted 24 June 2021

Abstract

There is consensus that the adult lexicon exhibits lexical competition. In particular, substantial evidence demonstrates that words with more phonologically similar neighbors are recognized less efficiently than words with fewer neighbors. How and when these effects emerge in the child's lexicon is less clear. In the current paper, we build on previous research by testing whether phonological onset density slows lexical access in a large sample of 100 English-acquiring 30-month-olds. The children participated in a visual world looking-while-listening task, in which their attention was directed to one of two objects on a computer screen while their eye movements were recorded. We found moderate evidence of inhibitory effects of onset neighborhood density on lexical access and clear evidence for an interaction between onset neighborhood density and vocabulary, with larger effects of onset neighborhood density for children with larger vocabularies. Results suggest the lexicons of 30-month-olds exhibit lexical-level competition, with competition increasing with vocabulary size.

Keywords: Lexicon; Language development; Vocabulary

1. Introduction

Spoken word recognition in adults involves the incremental and parallel activation of candidate words that compete for selection. One compelling source of evidence for these processes

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comes from neighborhood effects: the more similar sounding neighbors a word has (e.g., *mint, lint, dint*, etc.), the less efficiently it is recognized (see Vitevitch & Luce, 2016). Similar effects are observed when other measures of phonological relatedness are used. For example, words that have denser cohorts (i.e., words that have the same phonological onsets, e.g., *book, bike, bat*, etc.) are typically accessed more slowly than words with less dense cohorts, controlling for overall phonological neighborhood density (e.g., Magnuson, Dixon, Tanenhaus, & Aslin, 2007; Marslen-Wilson, 1987; for review see Vitevitch & Luce, 2016). Models of spoken word recognition such as TRACE (McClelland & Elman, 1986) and Shortlist (Norris, 1994) explain these effects by postulating lexical-level inhibitory connections between words.

While it is well known that variables like phonological neighborhood density influence the acquisition of new words (Carlson, Sonderegger, & Bane, 2014; Fourtassi, Bian, & Frank, 2020; Storkel, 2004; Swingley & Aslin, 2007), how phonological neighborhood properties of the lexicon affect online spoken word recognition in young children, and thus when inhibitory-level connections develop between words, is unclear. Evidence from computational modeling suggests that lexical-level inhibitory connections are not initially present in the emerging lexicon. Notably, Mayor and Plunkett (2014) used TRACE, a connectionist model of the adult model of spoken word recognition, to simulate several observations from spoken word recognition in toddlers, including graded sensitivity to a word's mispronunciations in 18-month-olds (White & Morgan, 2008). The model was not able to accommodate these findings until the authors greatly reduced inhibitory connections between words (in addition to connections between phonemes and words).

The most direct empirical evidence for neighborhood-like effects in toddler spoken word recognition comes from a pair of studies by Mani and Plunkett (2010, 2011), who investigated phonological priming effects using a modified intermodal preferential looking task. In these studies, participants first saw a single image, whose label was known to them (e.g., *bed*) and which functioned as a prime. They then saw two images (e.g., a *boot* and a *fork*), one of which was labeled (i.e., the target). On half the trials the label of the prime image and the target word had the same onset (e.g., *boot*). Mani and Plunkett (2010) found that 18-month-old infants looked proportionately *more* to the target image when the prime and target shared the same onset than when they did not. However, Mani and Plunkett (2011) found that 24-month-olds looked proportionately *less* to the target image when it shared the same onset as the prime label. In follow-up analyses, Mani and Plunkett (2011) found that the priming effect was moderated by the target word's onset neighborhood density for 24-month-olds. In particular, for these children, the difference between matching and non-matching onset primes was larger for target words from dense onset neighborhoods (e.g., many words begin with /b/) than for target words of sparser onset neighborhoods (e.g., fewer words begin with /f/). They hypothesized that in older children the target word's onset neighbors competed for selection because they were activated by the onset-matching prime.

To test this hypothesis, Mani and Plunkett (2011) conducted a second study with 24-month-old children, in which they crossed target onset neighborhood size with prime type. They also included a condition where trials were un-primed. They found that participants looked at the target from high-density onset neighborhoods proportionally less in all three conditions, including the un-primed condition. They also found that, for targets from high-density onset neighborhoods, children looked to the target proportionately less when presented with an onset matched prime than when un-primed, suggesting that the prime increased the interference due to the target word's onset neighbors.

However, several aspects of Mani and Plunkett's design complicate this interpretation. First, onset density was operationalized as a binary variable, high versus low, and the high category contained only words with a /b/ onset. To rule out the possibility that these results reflect something particular about the set of words beginning with /b/, a stronger approach would be to determine whether there are interference effects across a set of words with a range of onset neighborhood densities. Second, their dependent variable was the proportion of looks to target. While this is common for infant preferential-looking data, it does not directly reflect the relevant metric–the speed with which children recognize the target word. Other research suggests the interpretation of this dependent variable may not always be clear: While Mani and Plunkett (2011) found that phonological primes decreased looks to target among 24-month-olds, which they attribute to activation of the target's number of onset neighbors, Angulo-Chavira and Arias-Trejo (2018) found that a variation of phonological priming *increased* the proportion of looks to target amongst 30-month-olds, the opposite pattern of results from Mani and Plunkett (see Avila-Varela, Arias-Trerjo & Mani, 2021, for a similar result with children aged 18 to 24 months).[1] Third, while Mani and Plunkett (2011) argue that differences between 18- and 24-month-olds likely reflect different vocabulary sizes of the two groups, this assumes that age is a proxy for vocabulary and not other relevant variables. Thus, overall, the current evidence for the presence of neighborhood onset effects in young children and their relationship to vocabulary size is limited.

The current study aimed to address these limitations. One hundred 30-month-old children completed a looking-while-listening (LWL) task (Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998; Fernald, Zangl, Portillo, & Marchman, 2008), where we measured their lexical access to targets that were manipulated for onset neighborhood density. Importantly, we build upon the past research in three ways. First, target words were selected from nine different onset groups, allowing us to examine the effect across a range of onset neighborhoods, and rule out the effect being driven by a single onset. Testing 30-month-olds ensured that children had large enough vocabularies to include target words from several onset neighborhoods. Second, for each trial, both reaction times (RTs) and proportions were calculated, allowing a more precise examination of the speed of lexical access and how it relates to more commonly used eye-movement measures. Finally, we collected an independent measure of the children's vocabulary size in order to examine the moderating effect of vocabulary size on the slope of onset neighborhood density. Finding that this effect was moderated by vocabulary size in a sample of children older than those tested by Mani and Plunkett (2011) would provide compelling evidence that increases in vocabulary size drove the emergence of these effects.

Based on the past research, we had two hypotheses. First, following Mani and Plunkett (2011), we hypothesized that target words coming from denser onset neighborhoods would yield slower RTs and proportionately less looking to target than targets from comparatively less dense onset neighborhoods. Second, following Mani and Plunkett (2010, 2011), we hypothesized that the onset neighborhood density effects would interact with individual differences in children's vocabulary size, such that the effect of onset neighborhood density would be greater in children with larger vocabularies.

2. Method

2.1. Participants

Data came from a cohort of children who are being followed as part of a larger longitudinal project tracking the interaction between language processing and language development from 9 months to 5 years (see Donnelly & Kidd, 2020; Kidd, Junge, Spokes, Morrison, & Cutler, 2018). Families were recruited from Canberra, a medium-sized city in Australia. Inclusion criteria for the longitudinal study were: (i) full-term (at least 37 weeks gestation) babies born with a typical birth weight (> 2.5 kg), (ii) a predominantly monolingual language environment (mean percentage of a language other than English = 2%, range: [0, 40%], mode = 0), and (iii) no history of medical conditions that would affect typical language development, such as repeated ear infections, visual or hearing impairment, or diagnosed developmental disabilities. Consistent with the demographics of the city, the sample was drawn from families of high socioeconomic status. Approximately 75% of the parents had completed a bachelor's degree or higher. Of the original 130 participants, 12 had withdrawn prior to 30 months, 16 did not complete at least one of the tasks at 30 months, and two were diagnosed with hearing loss. As a result, the present sample contains 100 children for whom sufficient data were available during the 30-month session (*mean* age = 133 weeks, *SD* = 0.937, *range* = 131:136).

2.2. Materials

2.2.1. LWL task

Participants completed a visual world LWL eye-tracking task (Fernald et al., 1998, 2008), containing 18 target words, reflecting nine different onsets (/b/, /d/, /f/, /h/, /k/, /m/, /p/, /sh/, /tr/). The 18 targets were chosen because they were highly likely to be familiar to children of this age group: According to the American English subsample of the Wordbank database (Frank, Braginsky, Yurovsky, & Marchman, 2017), the minimum proportion of 30-month-old children producing a target word was 93%.[2] Two words were selected per onset to allow variability in age of acquisition (AoA; quantified by the earliest age at which 75% of the American English sample from the Wordbank database produced the word) and frequency[3] within each onset. Doing so reduced the likelihood of confounding onset neighborhood density and the variables, which were controlled in our analyses. Each word occurred with the same distracter object twice, once on the left side and once on the right side, over the course of the experiment. See Table 1 for information on the target words and distracter words. Distracter objects were concrete nouns, highly likely to be known by participants, without restrictions on the number of syllables. Distracter images were chosen to have similar AoAs as the target words. Two images were chosen for each target and distracter image so that no image was repeated over the course of the experiment.

On each trial, the two images were presented on a 1920 × 1200 pixel screen for 6000 ms. The images were of approximately equal size and enclosed in 470 × 450 pixel boxes equal

TABLE 1
Descriptive statistics for each target and distracter word

Target Word	Distracter Image	Target Proportion	Distracter Proportion	Target AoA	Distracter AoA	Frequency Target	Onset Neighborhood Density
Ball	Apple	0.99	0.97	16	22	43,512	36
Bee	Horse	0.93	0.97	26	23	6342	36
Cake	Flower	0.93	0.97	24	24	13,336	14
Car	Book	0.99	0.97	19	19	133,571	14
Dog	Bird	0.96	0.97	18	20	52,347	7
Duck	Cow	0.97	0.95	22	23	8335	7
Fish	Balloon	0.97	0.98	22	22	41,488	7
Fork	Pillow	0.94	0.93	25	25	7742	7
Hat	Spoon	0.95	0.96	22	23	18,198	10
House	Clock	0.93	0.89	27	29	149,251	10
Milk	Chair	0.97	0.94	22	24	17,812	11
Moon	Bunny	0.93	0.92	24	24	13,959	11
Pants	Tree	0.97	0.79	26	23	12,457	27
Pig	Cheese	0.95	0.97	24	22	8307	27
Shirt	Cup	0.96	0.97	25	22	21,486	7
Shoe	Boat	0.98	0.95	18	24	26,945	7
Train*	Frog	0.97	0.94	24	26	21,766	2
Truck*	Couch	0.97	0.85	22	28	31,536	2

Note. For train and truck, /tr/ was treated as the onset, and other /tr/ onset words were counted for the onset neighborhood density measure.

distances from the center of the screen. An audio file, recorded by a female native speaker of Australian English in child-friendly natural speech, directed the child to the target image. The audio was timed so that the target word began playing at around 4000 ms. There was some variability across trials in the exact onset time of the target word, but each word's specific onset time was used to calculate RTs and proportions. The target word was introduced using one of three carrier phrases ("look at the," "where is the," or "find me the").

Four pseudo-randomized lists were created so that no target word was repeated within three trials and that the target image appeared on the same side of the screen on no more than two consecutive trials. Attention-getting fillers were played after every six trials. These were dynamic cartoons with encouraging audio (e.g., "Did you see it?!"), which aimed to keep the children engaged. Eye-tracking data was captured using a Tobii T60XL, sampling at a rate of 60 Hz. Two dependent variables were calculated: RT and proportions. RTs were calculated following the procedure from Fernald, Perfors, and Marchman (2006): On the trials in which participants were looking to the distracter image prior to the onset of the target word, we calculated the duration between the onset of the target word and the participant's first 100 ms fixation on the target between 200 and 1800 ms post onset. While previous research has extracted RTs after 300 ms, these studies have typically been done with younger children (Donnelly & Kidd, 2020; Fernald et al., 2006), and we found that doing so dropped an unacceptable number of trials (347 trials or 25% of possible trials, compared to 171% or 12% of possible trials when 200 ms was used). The proportion of looks to the target image was calculated after the onset of the target word.

2.2.2. MacArthur Bates Communicative Development Inventory (MB-CDI)

The MB-CDI: Words and Sentences (Fenson et al., 2007) was used to estimate children's vocabulary size. This is a caregiver report checklist, for which caregivers must indicate whether or not their child produces words, from a list of 682. The MB-CDI has excellent internal consistency (alpha's > .90) and test-retest reliability (r at all ages > .9), and has good concurrent reliability with laboratory-based assessments of vocabulary ($.53 < r < .73$). Following Reilly et al. (2007), some minor changes were made to a small number of words to better capture the Australian dialect, resulting in 678 items. Throughout these analyses, we used the total productive vocabulary score as our relevant vocabulary measure.

2.2.3. Calculating onset neighborhood density

In addition to using the CDI to calculate each child's vocabulary size, we used the CDI to calculate onset neighborhood density. For each target in the LWL task, we calculated the number of nouns on the CDI with the same onset reported to be known by each participant. We counted the total nouns, rather than total words, to ensure we limited our analysis to words that could have plausibly occurred in the carrier phrase in the context of the task. Words were counted as onset neighbors if they had identical segments to the target word prior to the vowel (e.g., words that only contained /d/ prior to the vowel were treated as onset neighbors of /d/ words, and words that contained /tr/ prior to the vowel were treated as onset neighbors of /tr/ words). Following Mani and Plunkett (2011), we used the median of this value across participants as the onset neighborhood density measure. Onset neighborhood densities for each word are presented in Table 1.

2.3. Analytic strategy

Data were analyzed using Bayesian mixed models using STAN (STAN Development Team, 2018) and the BRMS package (Bürkner, 2018). This approach was used because Bayesian software typically contains a wider range of likelihood functions than frequentist software. For all models of RT, we used a shifted log-normal likelihood function (Rouder & Province, in press), to account for the skew and heteroscedasticity exhibited by RT data, as well as the floor of 200 ms used to calculate the RTs. When the dependent variable was the proportion of looks to target we used a beta-likelihood function with a logit link function (Smithson & Verkuilen, 2006). The beta distribution is defined between 0 and 1, exclusive, and can accommodate the heteroscedasticity common to proportions and rates. Because the beta distribution is not defined for values of 0 or 1, raw proportions were transformed using the equation in Smithson and Verkuilen (2006), which resulted in a range of .004 to .996.

All models were estimated using four chains of 5000 samples with 2500 warm-up samples. The minimum number of effective samples for any parameter was ∼ 800. All models had random effects by participant and target word. For each random factor, we included uncorrelated random intercepts and all relevant random slopes. For all models, we used BRMS's default priors for fixed effects but used slightly more informative priors ($t(3, 0, 2)$) for random effect standard deviations. These priors are more informative because they assign very little prior probability to random effect standard deviations greater than 4 or less than −4. We did this because all of our models employed link functions (log for log-normal models and the logit function for beta regressions), and random effect standard deviations greater than 4 are implausible (e.g., in the log-normal model, this would imply that individual differences in regression parameters that span four orders of magnitude).

We fit four models for both RTs and proportions, all containing several control variables. First, we fit models with a main effect for onset neighborhood density. Second, we fit a model with the interaction between onset neighborhood density and vocabulary. We then conducted a median split on vocabulary, and our third and fourth models examined the effect of onset neighborhood density for high- and low-vocabulary participants separately. For each model, we present all fixed effects estimates with 95% credible intervals. We also conducted directional hypothesis tests on the posterior distribution for parameters of substantive interest; that is, we calculated the proportion of the posterior distribution greater than or less than 0 in the hypothesized direction. Given our directional hypotheses, we expected to observe the following effects: For RTs we tested (a) the probability that the effect of onset neighborhood density was positive (i.e., longer RTs with higher onset densities) and the probability that the interaction between onset neighborhood density and vocabulary was positive. For proportions, we tested that the probability that the effect of onset neighborhood density for proportions was negative (i.e., proportionately fewer looks to target with higher onset densities) and that the probability that the interaction between onset neighborhood density and vocabulary was negative.

3. Results

All data and scripts are available online: https://osf.io/rgahv/. Table 2 presents the descriptive statistics for LWL outcomes for each word. One thing to note is that the pre-onset proportion of looks for many words is greater than 0.5, with a particularly large proportion of looks to *cake* (0.75). In general, words that attracted more pre-onset looks yielded fewer usable RTs. Therefore, prior to our main analyses, we examined looks to target during this initial window.

3.1. Pre-onset looking

To determine whether overall looks to target differed from chance in the pre-onset window, we estimated a mixed effects beta regression without any predictor variables. We included random intercepts by participant and target word. Results indicated that average looks to target differed from chance ($b = .29$, Credible Interval (CI) = 0.08: 0.51, on the logit scale; $b = .58$, CI = 0.52: 0.63 on the proportion scale).

Given these above-chance looks, it was important to determine (a) whether this could be explained by practice effects over the course of the task, and (b) whether performance in this window was related to our predictor variables, in particular onset neighborhood density and

TABLE 2
Proportion of looks to target, RTs, and number of RT trials for each target word

Target Word	Post-Onset Prop	Pre-Onset Prop	RT	*N* RT
Ball	0.72 (0.25)	0.50 (0.23)	672.18 (303.00)	81
Bee	0.80 (0.19)	0.65 (0.19)	533.65 (253.42)	48
Cake	0.90 (0.16)	0.76 (0.20)	449.39 (208.74)	23
Car	0.85 (0.19)	0.62 (0.23)	443.59 (156.26)	31
Dog	0.72 (0.24)	0.55 (0.19)	508.94 (244.63)	64
Duck	0.77 (0.23)	0.56 (0.20)	503.68 (192.50)	59
Fish	0.80 (0.19)	0.62 (0.18)	518.76 (236.81)	66
Fork	0.80 (0.19)	0.57 (0.18)	499.35 (231.82)	67
Hat	0.69 (0.24)	0.44 (0.21)	537.30 (243.02)	96
House	0.77 (0.22)	0.54 (0.22)	594.15 (335.65)	81
Milk	0.84 (0.18)	0.64 (0.18)	506.48 (195.55)	48
Moon	0.68 (0.22)	0.41 (0.19)	544.31 (227.39)	94
Pants	0.62 (0.23)	0.43 (0.18)	689.26 (336.55)	109
Pig	0.77 (0.23)	0.57 (0.19)	462.80 (208.93)	40
Shirt	0.75 (0.20)	0.52 (0.20)	513.97 (254.00)	88
Shoe	0.76 (0.25)	0.52 (.20)	536.32 (295.23)	66
Train	0.81 (0.20)	0.62 (0.21)	472.47 (207.12)	59
Truck	0.86 (0.17)	0.65(0.24)	495.79 (167.59)	52

TABLE 3
Models predicting proportion of looks to target in window prior to onset of target word

Parameter	Model 1		Model 2	
	M	CI	M	CI
Intercept	.30	(.06 : .55)	.30	(.06 : .55)
Repetition	–.09	(–.20 : .02)	–.09	(–.19 : .02)
Trial Number	.21	(–.40 : .84)	.22	(–.40 : .84)
Log Frequency	–1.19	(–29.34 : 26.62)	–1.28	(–28.66 : 26.00)
Vocab	.00	(–.05 : .06)	.00	(–.05 : .06)
AoA	.63	(–7.07 : 8.52)	.69	(–6.95 : 8.21)
Onset Density	–.21	(–2.38 : 2.03)	–.20	(–2.35 : 1.93)
Onset Density * Vocab			–.07	(–.56 : 43)

Note. M represents posterior mean; CI represents 95% credible interval.

its interaction with vocabulary. Therefore, we ran two additional beta regressions, predicting the proportion of looks to target in this window from vocabulary, frequency, onset neighborhood density, trial number, and a dummy-coded variable indicating whether the present trial was the first or second trial containing the target word (which we call *repetition* from here). We included all possible (uncorrelated) random slopes, by participant and target. Model 1 included only main effects for onset neighborhood density and vocabulary, and model 2 contained both main effects and their interactions. Parameter estimates and credible intervals for all predictors are presented in Table 3. As can be seen, there was no evidence that onset

TABLE 4
Models predicting RT from onset neighborhood density and control variables

	Model 1		Model 2		Model 3		Model 4	
	M	CI	M	CI	M	CI	M	CI
Intercept	6.30	(5.83 : 6.77)	6.30	(5.85 : 6.76)	6.36	(5.73 : 7.02)	6.07	(5.54 : 6.58)
Repetition	–.01	(–.10: .08)	–.01	(–.10 : .08)	–.07	(–.20 : .06)	.06	(–.06 : .17)
Frequency	3.64	(–4.57 : 12.53)	3.59	(–4.52 : 12.17)	2.52	(–9.77 : 14.73)	.64	(–3.56 : 5.55)
Target Prop	–.86	(–1.75 : .00)	–.86	(–1.74 : –.01)	–1.46	(–2.67 : –.22)	–.17	(–1.12 : .78)
Part Target Prop	–.19	(–.49 : .10)	–.20	(–.50 : .10)	.03	(–.42: .48)	–.46	(–.87 : –.06)
Duration	.01	(–.06: .07)	.01	(–.06 : .07)	–.01	(–.11 : .09)	.03	(–.05 : .11)
Vocabulary	–.08	(–.13 : –.02)	–.09	(–.14 : – .03)	.06	(–.15 : .26)	–.06	(–.16 : .01)
AoA	1.36	(–1.39 : 4.40)	1.36	(–1.33 : 4.39)	1.42	(–2.41 : 5.76)	.47	(–1.87 : 2.90)
Onset Density	.51	(–.20 : 1.22)	.56	(–.15 : 1.28)	.76	(–.25 : 1.77)	.15	(–.65 : .95)
Onset Density * Vocab			.36	(–.05 : .76)				

Note. M represents posterior mean; CI represents 95% credible interval.

neighborhood density or its interaction with vocabulary were related to the proportion of looks in this window. There was, however, evidence that participants looked to the target image more on their second instance than their first, suggesting a practice effect (proportion of posterior probability $< 0 = 0.05$). Therefore, we included this variable as a predictor variable in our main analyses.

3.2. *Post-onset looking*

For both RTs and proportions, we fit mixed effects models, including an interaction between (centered) onset neighborhood density and (centered) vocabulary (both divided by 100 to make coefficients more easily interpretable). We also included the following control variables: repetition, the logarithm of lemma frequency (centered), word duration (in milliseconds, centered), AoA (centered and divided by 100), and two additional variables to account for differential proportion of looks to target in the pre-onset window: (i) Target Proportion, the average proportion of looks to the target in the pre-onset window averaged across participants, and (ii) Participant Target Proportion, the average looks to the target in the pre-onset window within participants. Including both of these allowed us to control for (a) features of the stimuli that cause it to attract more attention across all participants as well as (b) individual participant's idiosyncratic preferences for particular objects.

3.2.1. *Reaction times*

Parameter estimates for all four models of RTs are presented in Table 4. Model 1 included the main effects of both vocabulary and onset neighborhood density. The mean posterior estimate for onset neighborhood density was positive, suggesting slower reaction times for words from denser onset neighborhoods. Moreover, a test of the directional hypothesis that this effect was positive revealed that 92% of the posterior distribution was positive. This effect

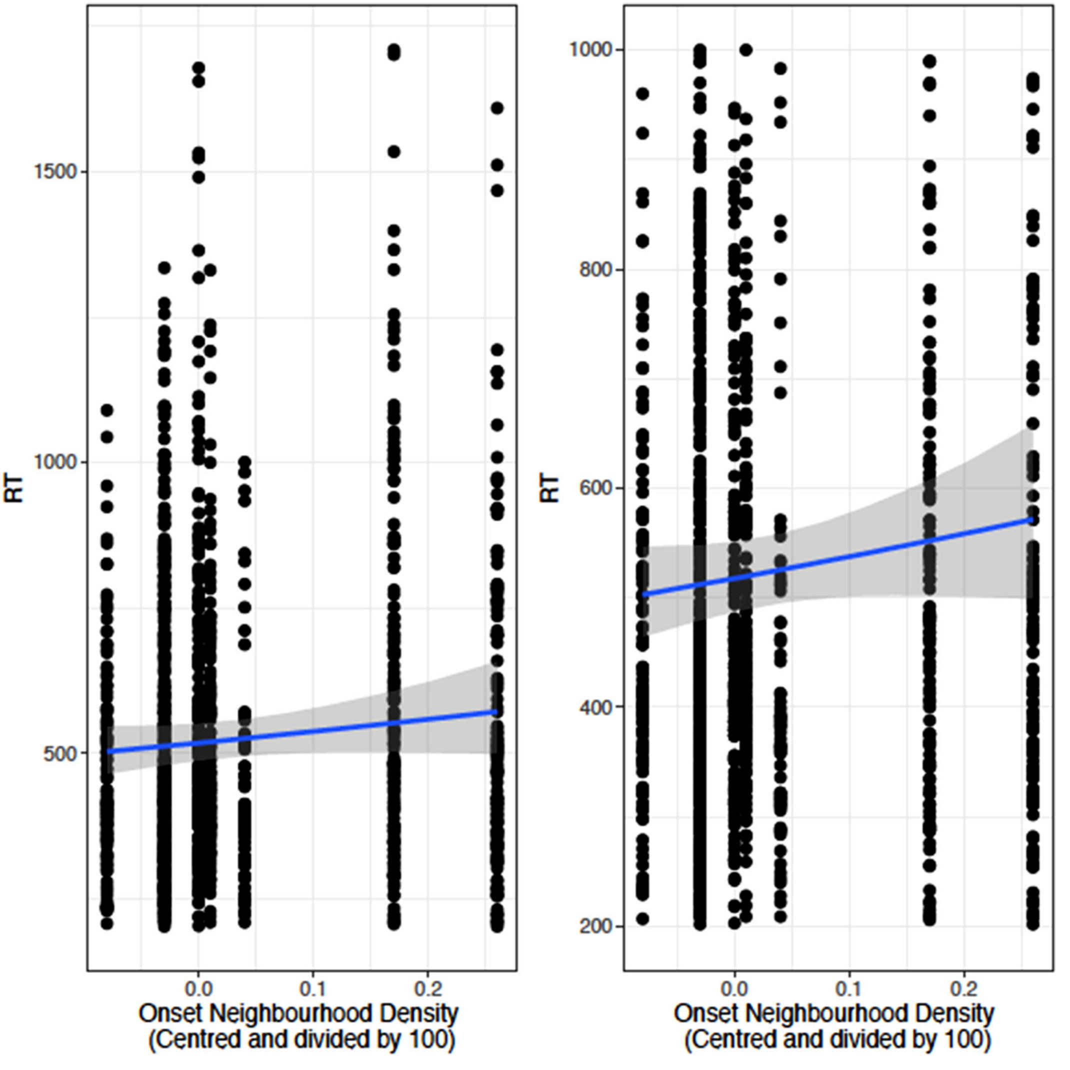

Fig. 1. Main effect of onset neighborhood density on RT from Model 1 with RTs for individual trials. The left plane plots the effect with all data points. Because we have plotted individual data points, rather than means, there is a great deal of variability between data points. The left pane displays the effect of onset neighborhood density with all data points displayed. The right pane shows the same effect with the y-axis reduced, to zoom in on the effect.

is visualized in Fig. 1. Model 2 additionally included the interaction between onset neighborhood density and vocabulary. The main effect of onset neighborhood density was similar to that in Model 1 and this effect was larger for high vocabulary children. For the main effect of onset neighborhood density, corresponding to its slope for participants with vocabulary sizes at the median, 94% of its posterior distribution was above 0. For the interaction, 96%

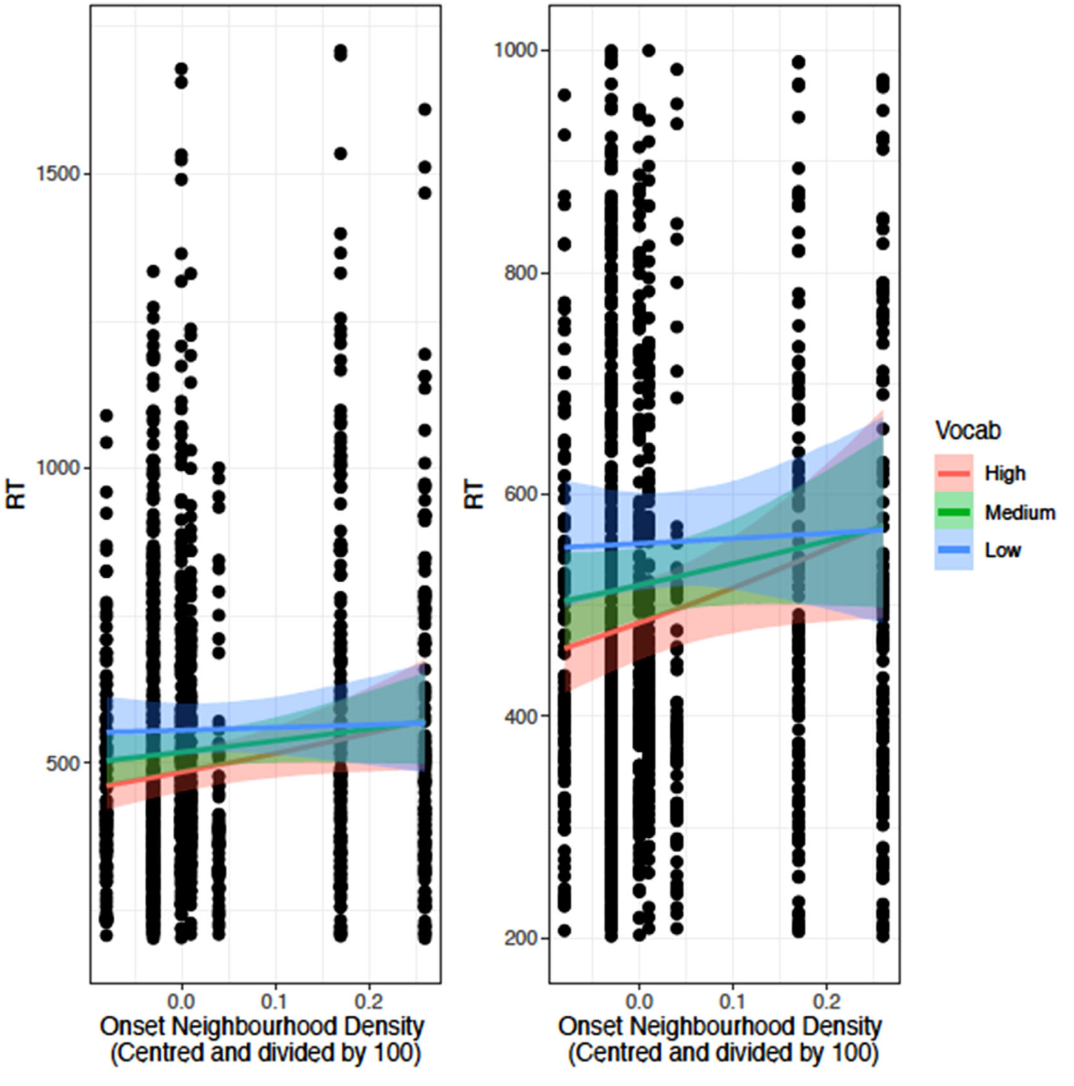

Fig. 2. Interaction between onset neighborhood density and vocabulary from Model 2 with RTs for individual trials. The left plane plots the effect with all data points. Because we have plotted individual data points, rather than means, there is a great deal of variability between data points. The left pane displays the effect of onset neighborhood density with all data points displayed. The right pane shows the same effect with the y-axis reduced, to zoom in on the effect.

of its posterior distribution was above 0, indicating a reliable interaction between these two variables. The latter effect is visualized in Fig. 2.

To understand the nature of this interaction, we re-parameterized the posterior distribution from Model 2 to estimate the slope of onset neighborhood density at varying levels of vocabulary. When vocabulary size was fixed at one standard deviation below the mean (415 words),

TABLE 5
Models predicting the proportion of looks to target after the onset of the target word

	Model 1		Model 2		Model 3		Model 4	
	M	CI	M	CI	M	CI	M	CI
Intercept	–.84	(–1.38 : –.34)	–.85	(–1.40 : –.34)	–.90	(–1.46 : –.35)	–.74	(–1.44 : –.10)
Repetition	.00	(–.09 : .10)	.00	(–.09 : .10)	.10	(–.02 : .23)	–.10	(–.23 : .03)
Frequency	.86	(–9.21 : 9.85)	.89	(–9.11 : 10.57)	.78	(–3.56 : 5.74)	–1.17	(–14.32 : 11.01)
Target Prop	2.45	(1.54 : 3.43)	2.45	(1.53 : 3.44)	2.43	(1.44 : 3.45)	2.35	(1.17 : 3.64)
Target Part Prop	1.29	(1.02 : 1.56)	1.29	(1.02: 1.56)	1.27	(.91 : 1.63)	1.27	(.87: 1.66)
Vocabulary	.01	(–.04 : .07)	.01	(–.05 : .07)	.07	(–.13: .27)	–.01	(–.10 : .09)
AoA	–1.28	(–4.80 :1.72)	–1.29	(–4.63 : 1.72)	–.21	(–2.65: 2.40)	–2.11	(–6.59 : 1.98)
Onset Density	–.55	(–1.28 : .23)	–.53	(–1.27 : .23)	–.38	(–1.14 : .40)	–.73	(–1.74 : .31)
Onset Density * Vocab			.11	(–.24 : .46)				

Note. M represents posterior mean; CI represents 95% credible interval.

the slope for onset neighborhood density was small and its credible interval greatly overlapped with 0 ($b = .11$, CI $= -0.73$: 1.0, posterior prob $= 0.60$). When vocabulary size was fixed to the sample mean (524 words), the effect of onset neighborhood density was larger, with much more of its credible interval covering positive values ($b = .51$, CI $= -0.21$: 1.24, posterior prob $= 0.92$). When vocabulary size was fixed at one standard deviation above the mean (635 words), the effect of onset neighborhood density was larger still, and its credible interval did not overlap with 0 ($b = .90$, CI $= 0.05$: 1.73, posterior prob $= 0.98$). Thus, Model 2 suggests that the effect of onset density was larger for children with larger vocabularies and that this difference was reliably different from 0 for children with the largest vocabularies. To contextualize these effects, we compared the vocabulary sizes above to the American sample of the Wordbank database. Notably, a vocabulary size of 415 words falls between the 50th and 75th percentiles of vocabulary scores for 24-month-olds (316 and 454 words, respectively). This suggests that the lowest-vocabulary children in our experiment were comparable to the 24-month-olds in Mani and Plunkett (2011).

We then examined the effects of onset neighborhood density for high and low vocabulary participants separately (defined as participants with vocabularies larger and smaller than 545 words). Model 3 considered only high vocabulary participants and revealed a positive effect of onset neighborhood density; 94% of the posterior distribution for this coefficient was positive. Model 4 considered only the low vocabulary group and revealed a positive effect of onset neighborhood density with 60% of the posterior distribution positive. Overall, these results suggest that onset neighborhood density slowed lexical access but that this effect was limited to higher vocabulary children.

3.2.2. Proportions

Parameter estimates from all models of proportions are presented in Table 5. Model 1, which included the main effect of onset neighborhood density and a main effect of vocabulary, yielded a negative effect of onset neighborhood density on proportions, and 93% of

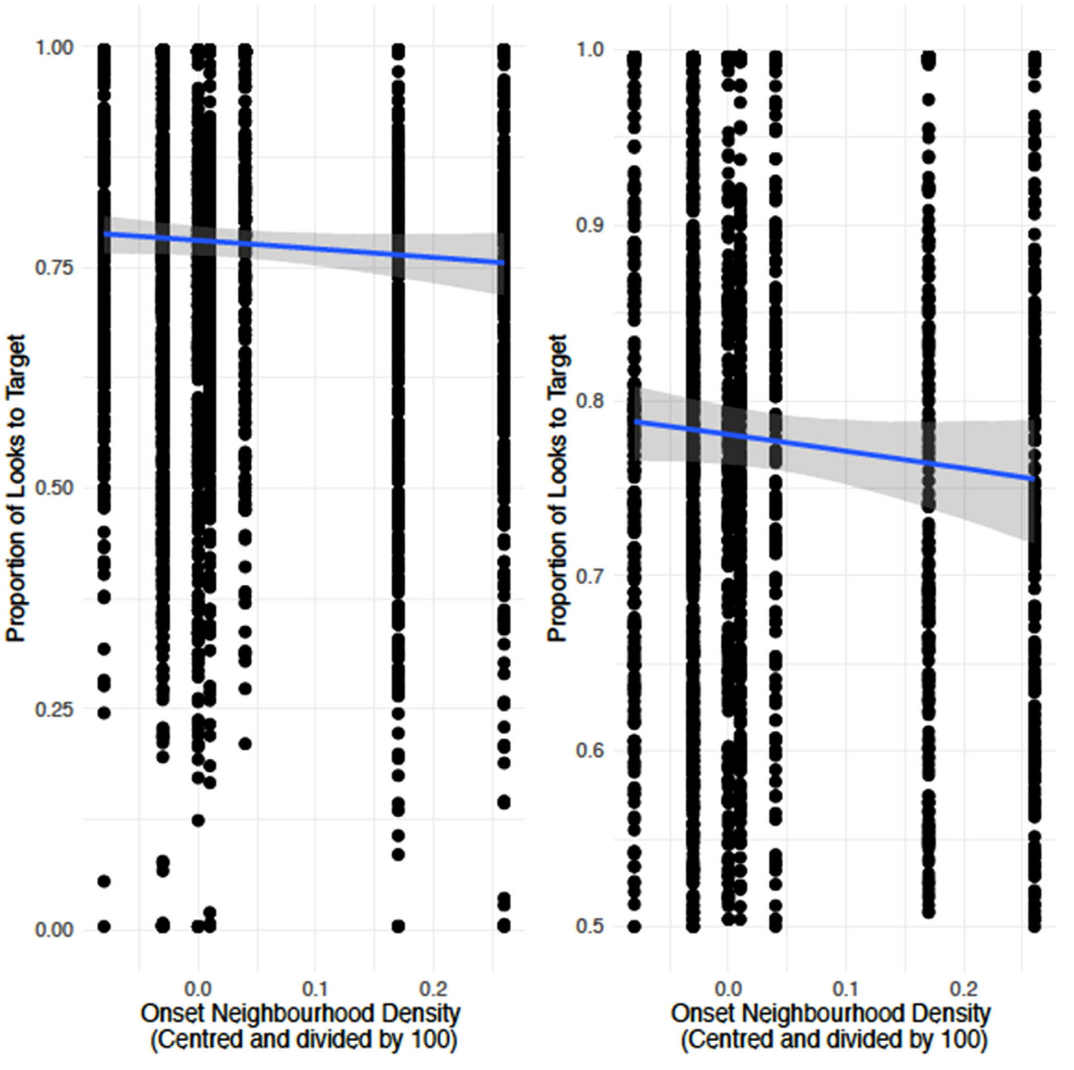

Fig. 3. Main effect of onset neighborhood density on the proportion of looks to target from Model 1 with proportions for individual trials. The left plane plots the effect with all data points. Because we have plotted individual data points, rather than means, there is a great deal of variability between data points. The left pane displays the effect of onset neighborhood density with all data points displayed. The right pane shows the same effect with the y-axis reduced, to zoom in on the effect.

its posterior distribution was negative. This effect is visualized in Fig. 3. Model 2 included an interaction between onset neighborhood density and vocabulary. The effect of onset neighborhood density was negative; however, its interaction with vocabulary was positive, with the credible interval containing 0 and with 74% of its posterior distribution negative. This effect is visualized in Fig. 4. Model 3 considered only high vocabulary children and produced a negative coefficient for onset neighborhood density (with 84% of its posterior

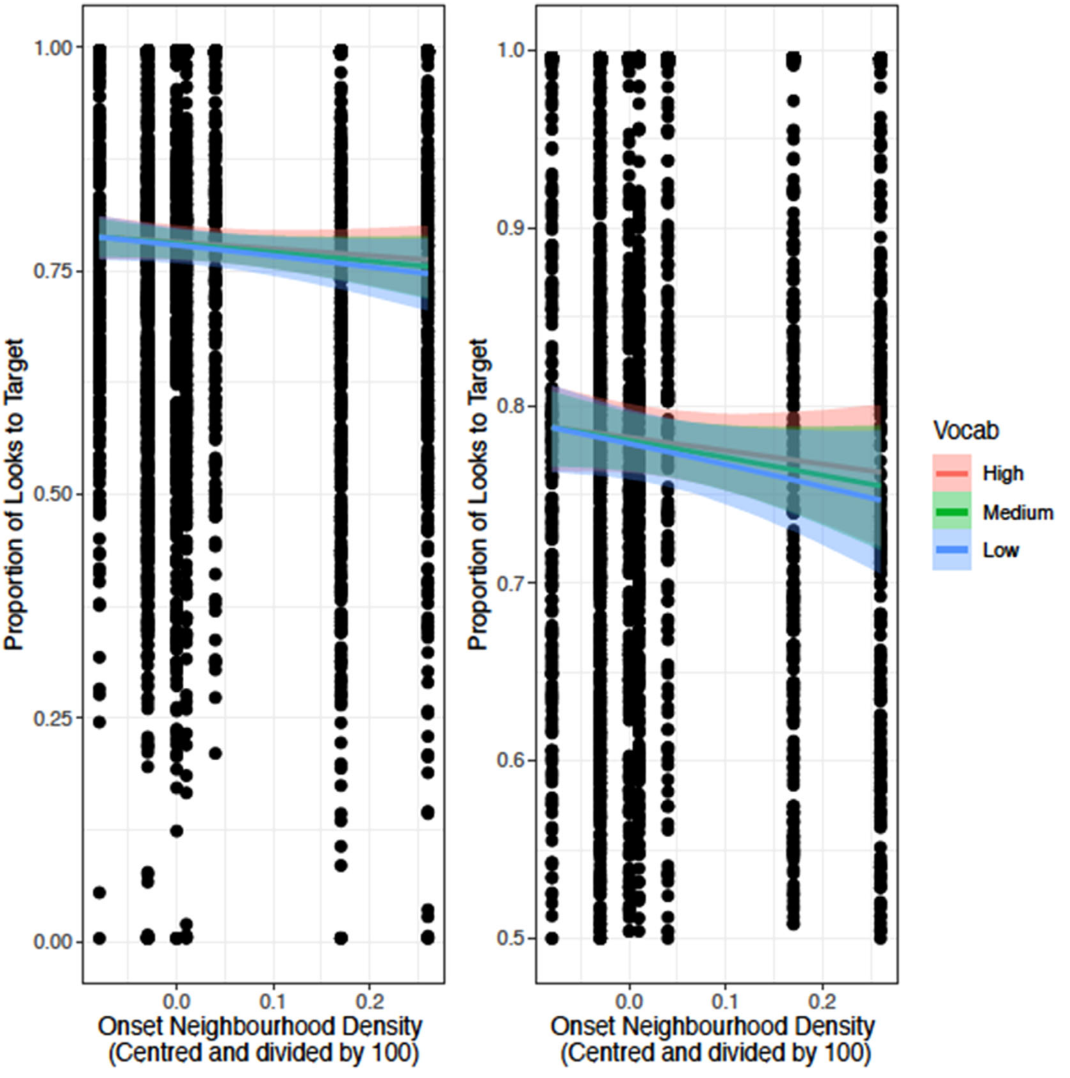

Fig. 4. Interaction between onset neighborhood density and vocabulary from Model 2 with proportions for individual trials. The left plane plots the effect with all data points. Because we have plotted individual data points, rather than means, there is a great deal of variability between data points. The left pane displays the effect of onset neighborhood density with all data points displayed. The right pane shows the same effect with the y-axis reduced, to zoom in on the effect.

distribution in the negative range). Model 4 considered only low vocabulary children and found a negative coefficient (with 93% of its posterior distribution in the negative range). Thus, there was moderate evidence that onset neighborhood density reduced the proportion of looks to the target word and no evidence that this effect was not moderated by vocabulary.

4. Discussion

The current study aimed to determine whether there were inhibitory effects of onset neighborhood density on spoken word recognition in toddlers and whether this effect was larger for individuals with larger vocabularies. Consistent with our hypotheses, we found moderate evidence of an inhibitory effect of onset neighborhood density, which was moderated by vocabulary size. The results are consistent with similar past research by Mani and Plunkett (2011), whose observation of age-based differences in inhibitory processes are thus most likely attributable to individual differences in lexical knowledge acquired over developmental time.

Our results build on previous work in several ways. First, by operationalizing onset neighborhood density as a continuous variable, rather than a factor, we demonstrated that these effects cannot be attributed to the particular characteristics of a set of words beginning with /b/. Second, by using reaction times as a dependent measure, we demonstrated clearly that onset neighborhood density slows lexical access as similar measures do in adults (Vitevitch & Luce, 2016). Critically, we observed this effect even after controlling for several theoretically substantive (frequency, vocabulary size, duration) and methodological variables (proportion of looks to the target prior to the onset of the target word), strongly supporting the inference that this effect specifically reflects onset neighborhood density and not correlated lexical variables.

We found strong evidence that the effect of onset neighborhood density was larger for children with larger vocabulary sizes when RTs were used as the dependent variable. This is consistent with the conclusion of Mani and Plunkett (2011) that inhibitory lexical connections emerge as vocabulary size increases. Moreover, given that our sample was 6 months older than Mani and Plunkett's, the fact that the slope was not reliably different from 0 for children with the lowest vocabulary strongly suggests that vocabulary size, and not age, is the driving factor in the emergence of these sorts of dynamics.

Taken together, our results provide strong evidence to suggest that known mechanistic processes that influence adult lexical access, in this case, word-level inhibitory connections emerge early in ontogeny, demonstrating that the emerging lexicon likely contains process-based architectural similarities to the mature (i.e., adult-like) state once a critical mass of vocabulary is acquired. For adult-oriented theories of lexical processing (e.g., McClelland & Elman, 1986; Norris, 1994), this means that one can assume a degree of continuity between the developing and adult state (lexicon size notwithstanding; Mayor & Plunkett, 2014). Our findings also complement recent results from the study of semantic neighborhood density on lexical access in infants in toddlers (Borovsky & Peters, 2019; Borovsky, Ellis, Evans, & Elman, 2016; Wojcik & Saffran, 2019). For example, Borovsky and Peters (2019) found an interaction between vocabulary size and semantic neighborhood density amongst 21-month-olds on the proportion of looks to target in the LWL task. Intriguingly, they found that low-vocabulary 21-month-olds recognized words from semantically dense categories more efficiently than those from semantically less dense categories, but high-vocabulary 21-month-olds did not vary across these conditions. The broad generalization is that the structure of children's lexicon significantly influences lexical access.

Taken with these findings, our results place an important constraint on the large current research focused on lexical processing as a predictor of individual differences in language outcomes (e.g., Egger, Rowland, & Bergmann, 2020; Fernald et al., 2006; Marchman & Fernald, 2008). An important conceptual limitation of this work is that it is conducted largely without a working theoretical model of the lexicon (see Donnelly & Kidd, 2020); it implicitly assumes a largely unidirectional and linear relationship between knowledge and lexical processing speed (i.e., faster RTs are always better). Our results, as well as the literature described above, indicate that there are subtle item-based influences on lexical access that are inconsistent with this assumption but which fit with what we know about adult lexical access. While it is clear that lexical processing is subject to individual differences and faster processing is related to language both concurrently and longitudinally, we recommend that future theoretical development of the concept of lexical processing takes into account that infants are developing toward the (well-described) adult state. A productive research effort would be to understand better how online processing both depends upon and begets linguistic knowledge over development, thereby laying down the architectural properties of the future adult lexicon.

We did not observe an interaction between onset neighborhood density and vocabulary when proportions were used as the dependent variable. This may reflect the limitations of using proportions as a dependent variable for this age group. While proportions are commonly used in the LWL task at a young age (Lany, Giglio, & Oswalt, 2018), given that the RTs on the LWL task decrease with age (Donnelly & Kidd, 2020; Fernald et al., 1998; Fernald et al., 2006), proportions may become less reliable as they are affected by where the participant looks after fixating on the target word. This is consistent with the fact that Mani and Plunkett (2011) and Angulo-Chavira and Arias-Trejo (2018) found that phonological primes had the opposite effect on the proportion of looks to target in a preferential looking task (see also Avila-Varela et al., 2021).

Several limitations of this study warrant discussion. First, while using the LWL task allowed us to calculate RTs and was a strength of the present study, this task necessarily results in a great deal of missing data. Notably, given that participants looked to some target images at above-chance levels prior to the onset of the target word, there was more missing data for some target words than others. While we determined that the proportion of pre-onset looks to target was not related to onset neighborhood density, vocabulary, or their interaction, and included many relevant controls in our analyses of RTs and proportions, future research should aim to minimize the number of missing trials and ideally keep the number of missing trials balanced across items (Egger et al., 2020). In particular, while the AoA of non-target images was controlled for, the frequency was not. Therefore, differences in frequency across distracter items could explain differences for preferences across items prior to the onset of the target word.

Second, we used children's productive vocabulary as a measure of vocabulary and to calculate onset neighborhood density. We did so because collecting item-level data regarding children's receptive vocabulary is quite challenging for children older than 18 months. Given that receptive vocabulary is likely the more relevant measure, and we know of no research comparing onset neighborhood density measures calculated using production and comprehension data, this may be seen as a limitation. However, we note that the two scores are likely strongly related (the correlation between the two scores in the American English sample on Wordbank is 0.63). Moreover, psychometric modeling suggests that productive vocabulary checklists have better measurement properties than receptive vocabulary checklists (Frank, Braginsky, Yurovsky, & Marchman, 2021, Chap. 4). Thus, we are confident that using productive vocabulary as measured by the MB-CDI accurately and reliably reflects the makeup of the children's larger lexicon. Third, our control measure of frequency was based on adult corpus data, not child corpus data. The extent to which these metrics align is unclear, and no doubt there will be some differences. This may explain why there was no effect of frequency in our data.

5. Conclusion

In the current study, we found that vocabulary size moderates the effect of onset neighborhood density on lexical access in 30-month-olds. This suggests that children with larger productive vocabularies experience more lexical interference than children with smaller vocabularies. These results are consistent with empirical findings and simulation results (Mani & Plunkett, 2011; Mayor & Plunkett, 2014), suggesting that the emergence of inhibitory lexical connections early in language development is driven by increases in vocabulary size. These results suggest continuity between the processes mediating lexical access in young children and adults and suggest an important constraint on models of the relationship between lexical processing efficiency and other aspects of language development.

Acknowledgments

This research was supported by the Australian Research Council (CE140100041: CI Kidd). We thank all the families for participating, Lauren Morrison and Amanda Piper for help with data collection, and two anonymous reviewers for helpful comments.

Open access funding enabled and organized by Projekt DEAL.

Notes

1 Note, however, that Angulo-Chavira and Ariajs-Trejo (2018) did not report analyses separately for more or less dense onset-neighborhoods.
2 We used American norms to choose the targets because not enough Australian data exist to reliably estimate the same metric. The lexical differences between the standard forms of the two dialects are minimal, and we do not expect them to influence our results.
3 Frequencies came from the Corpus of Contemporary American English: https://www.wordfrequency.info/freeList.asp?s=y

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