
Phonotactic Probabilities at the Onset of Language Development: Speech Production and Word Position

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Purpose: To examine the role of phonotactic probabilities at the onset of language development, in a new language (Dutch), while controlling for word position.

Method: Using a nonword imitation task, 64 Dutch-learning children (age 2;2–2;8 [years;months]) were tested on how they imitated segments in low- and high-phonotactic probability environments, in word-initial and word-final position. The relationship between phonological representations and vocabulary development was examined by comparing children's performance with their receptive and expressive vocabularies.

Results: Segments in high-phonotactic probability environments were at an advantage in production, in both word-initial and word-final position. Significant correlations were found between vocabulary size and children's mean segment repetition accuracy for word-initial position, but not in word-final position.

Conclusion: The results indicate that phonological representations are mediated not only by children's developing vocabularies but also by the structure of children's emerging lexicons.

KEY WORDS: phonological representations, speech production, lexical development, phonotactic probability, prosody

Research has indicated that learners are sensitive to frequently occurring patterns in the ambient language (see recent overview in Werker & Curtin, 2005). These results provide evidence for statistical learning, and consequently, statistical patterns in the ambient language play a role in the development of speech perception and production abilities. In particular, research has shown that learners are sensitive to phonotactic probabilities, which express the likelihood that sounds will occur in a given environment. Phonotactic probabilities can be calculated by individual segments (positional segment frequency) and by segmental sequences (biphone frequency). For example, although Dutch allows words to end in both /f/ *lief* "sweet" and /s/ *poes* "cat," the likelihood that a word will end in /s/ is greater because there are more Dutch words ending in /s/. The context of these individual sounds can also vary. For example, there is a greater likelihood that /s/ will be preceded by /a/ than by /ε/, because there are more words in Dutch that end in /as/ than end in /εs/. Phonotactic probabilities have been found to influence speech processing (Vitevitch, 2003; Vitevitch & Luce, 1999), lexical acquisition (Storkel, 2001), word segmentation (Mattys & Jusczyk, 2001; Mattys, Jusczyk, Luce, & Morgan, 1999), developmental speech perception (Jusczyk, Luce, & Charles-Luce, 1994; Zamuner, 2003), and developmental speech production (Beckman & Edwards, 2000; Coady & Aslin, 2004; Edwards, Beckman, & Munson, 2004; Munson, 2001; Munson, Edwards, & Beckman,

2005; Munson, Kurtz, & Windsor, 2005; Stokes, Wong, Fletcher, & Leonard, 2006; Zamuner, Gerken, & Hammond, 2004; see also Coady & Evans, 2008, for a recent review). Consequently, these results have theoretical implications for models of speech processing and for the nature of phonological representations.

Sensitivities to probabilistic phonotactics have been found both in developmental speech perception and production. In perception, research has revealed that 9-month-old infants have a listening preference for non-words composed of high phonotactic probabilities versus low phonotactic probabilities (Jusczyk et al., 1994) and that infants can make use of phonotactic probabilities in speech segmentation (Mattys & Jusczyk, 2001; Mattys et al., 1999). In production, children are more accurate at producing high-phonotactic probability segments and segmental sequences (Beckman & Edwards, 2000; Coady & Aslin, 2004; Edwards et al., 2004; Munson, 2001; Munson, Edwards, & Beckman, 2005; Munson, Kurtz, & Windsor, 2005; Zamuner et al., 2004). For example, Edwards et al. (2004) found that children are better at producing frequent sequences (e.g., /kt/) than infrequent sequences (e.g., /gd/). In another study, Zamuner et al. (2004) found that children were more likely to produce segments when they occurred at the ends of high-phonotactic probability nonwords than at the ends of low-phonotactic probability nonwords (e.g., the final /d/ in *ged* vs. *chud*, respectively).

These results have been argued to support a theory of phonological representations that are mediated by frequency and lexical development. (See a recent overview in Auer & Luce, 2005, that discusses the different ways models of speech processing can capture the effects of phonotactic probabilities.) The growth of phonological representations is dependent on vocabulary development, as these representations are abstracted from the acquired lexicon. In children with typical phonological development (TD), the size of the frequency effect (FF; the difference between performance on low- vs. high-phonotactic probability items) is correlated to children's vocabulary size (e.g., Edwards et al., 2004), and this finding supports the connection between phonological representations and vocabulary development. Children with smaller vocabularies have less robust phonological representations, making it more difficult for them to parse "non-words into their constituent phonemes, and recombine the associated articulatory representations into novel vocal motor schemes... for fluent speech production" (Munson, Edwards, & Beckman, 2005, p. 62). Thus, performance on the nonword repetition task reflects the nature and development of children's categorical phonemic representations. An alternative account is that a greater effect of frequency is found with children who have smaller vocabularies, arguably because these children have less robust acoustic-auditory and/or articulatory motor

representations as compared with children with larger vocabularies. The relationship between vocabulary development and phonological representations is returned to below. The present research addresses some remaining questions about phonotactic probabilities in phonological acquisition. The specific goals were to investigate phonological representations in different word positions, to further examine the relationship between vocabulary size and phonological representations at the earliest stages of language development, and to replicate and extend research on phonotactic probabilities in the development of a new language (i.e., Dutch).

The recurring observation is that children are sensitive to phonotactic probabilities in the production of nonwords. Take recent findings from Munson, Edwards, and Beckman (2005). Two groups of children participated in the study: children with TD and children with phonological disorders (PDs). Children were tested on their ability to produce low- and high-frequency sequences collapsed across initial, medial, and final position. Both TD and PD children were more accurate at producing the high-frequency sequences. They concluded that children's performance stems from vocabulary growth and the emergence of phonological representations from children's acquired lexicon. Assuming that children's perception is accurate, increased production errors on low-frequency items could stem from an inability to access stored representations accurately, from motor difficulty in producing nonwords in a novel context (e.g., Munson, Edwards, & Beckman, 2005) or from probability-based differences in how stored representations in short-term memory are reconstructed during retrieval (Gathercole, Frankish, Pickering, & Peaker, 1999).

One feature of the Munson, Edwards, and Beckman (2005) study is that children were tested on how they produced segmental sequences in different nonword positions (initial, medial, and final), although the analyses were collapsed across these different positions (see also Edwards et al., 2004, and Beckman & Edwards, 2000, where in the latter study, position is kept distinct in the analyses). Research has shown that speech perception and production abilities vary depending on the word position. Specifically, advantages are seen for initial position in infant speech perception (Jusczyk, Goodman, & Bauman, 1999; Swingley, 2005; Zamuner, 2006b) and in child language production (Jakobson, 1941/1968; Levelt, Schiller, & Levelt, 1999; cf. Kirk & Demuth, 2005). Despite the reported differences between initial and final position, children's accuracy in producing the same singleton segments in different prosodic positions has been directly compared in a few studies (cf. Beers, 1995; Kirk & Demuth, 2005). Given the asymmetry in perception and production in different positions, this leads to the first goal of the study: to investigate children's production abilities in both word-initial and word-final position. On the basis

of previous findings from development, children's overall accuracy is expected to be better in word-initial position. This last prediction is also based on acquisition data from Dutch, which indicate that children acquire segments in initial position before final position (Beers, 1995, p. 206). Two different age groups were examined to determine whether there are developmental patterns.

As noted above, a relationship between children's vocabularies and phonotactic probabilities in nonword production has been found in previous studies (e.g., Edwards et al., 2004). Children with smaller vocabularies have lower mean nonword repetition accuracy scores and show a greater difference in the FF (the difference between low- vs. high-frequency items). This finding is intuitive because if phonological representations are based on lexical representations, then the size of children's lexicons should have an impact on the nature of children's representations. An exception to this finding are the results from Zamuner et al. (2004), who found no significant relationships between children's expressive vocabulary size and mean segment repetition accuracy (MSRA) or the FF (as measured by the proportion of correct responses in high-phonotactic probability environments). Zamuner et al. suggested that these null effects may reflect the sample: Children had very similar vocabulary sizes; thus, the homogeneity of the sample may have obscured any possible relationships between vocabulary size and performance on the task. Another possibility is that because children were at the beginning stages of language production (age range = 1;8–2;4 [years;months]), their lexicons may have been so small as to obscure any possible relationships between vocabulary development and phonotactic probabilities. The findings from Munson, Edwards, and Beckman (2005), however, suggest an alternative explanation for the Zamuner et al. finding. Munson, Edwards, and Beckman found that the FF was smaller with children with more severe PD. This finding was unexpected because if PD stems from a difficulty in building phonemic representations, then children with more severe PD should have a greater FF; however, the opposite pattern was found. They suggest that these children do not have a deficit in forming phonemic representations, but rather that this finding reflects the nature of abstractions at the earliest stages of vocabulary acquisition. For example, they may be represented as general patterns of articulatory or motor gestures. In other words,

At the earliest stages of vocabulary expansion, the patterns that can be abstracted away from known words are very general schema [...] so that something that sounds like [gæʔ] might be the word shape for *cat*, *carrots*, *car*, *gobble*, and any new word that even vaguely fits that template. (Munson, Edwards, & Beckman, 2005, p. 75)

In other words, the earliest abstractions consist of general patterns without individual phonemes or phonemic contexts specified; thus, the abstractions do not capture distinctions between probability-based segments or segmental sequences. As a result, Munson, Edwards, and Beckman (2005) argued that

there should be no difference in production accuracy between high-frequency /kæ/ and lower frequency /ga/ until the child has accurate production routines for both of these sublexical patterns and can abstract a representation of the sequence from the following word context. Thus over development, the frequency-effect should have a floor as well as a ceiling. (p. 75)

Given the age of the children in the Zamuner et al. (2004) study, their phonological representations may have reflected this earliest stage, accounting for why they found no correlation between the FF and children's vocabulary size.

In the present study, I continued the examination of children at the earliest stages of language development to determine whether there is a relationship between vocabulary development and phonological representations. I further investigated this issue by looking at two different points in development and by exploring the relationship between children's performance in different prosodic positions and vocabulary development. Children's early vocabularies have been shown to have more lexical items distinguished in word-initial position than in word-final position (Zamuner, 2009). Thus, word-initial representations are potentially more robustly represented than word-final ones. On the basis of this finding, one might predict to find relationships between phonological representations and vocabulary development in word-initial position before word-final position.

The last goal of the study was to replicate and extend the previous findings on phonotactic probabilities in acquisition with a new language, specifically, Dutch. Whereas cross-linguistic studies of phonotactic probabilities have been conducted with adults, very little developmental research has examined children's knowledge of phonotactic probabilities in languages other than English. Cross-linguistic research is informative because it can identify what aspects of language development are biological versus environmental (Stokes & Surendran, 2005). Phonotactic patterns vary from language to language, and the acquisition of phonotactics requires a sophisticated knowledge about the sound patterns of the target language. Previous research in developmental speech perception has compared the acquisition of phonotactics in English and Dutch (Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993), and results indicated that both English- and Dutch-learning infants are sensitive to the phonotactic patterns of their respective

languages by 9 months. In production, developmental research has compared the role of frequency in English versus Dutch (Stokes & Surendran, 2005). Stokes and Surendran (2005) found that frequency has different explanatory power in accounting for children's production accuracy of initial consonants in the two languages: Frequency plays a stronger role in Dutch than in English. (Only initial position was examined.) Dutch has a phonotactic pattern of contrast neutralization in syllable-final position. Although the set of segments (voiced obstruents) /b, v, d, z/ are permitted in syllable-initial position, they are restricted and phonotactically illegal in syllable-final position (Booij, 1995). Note that English does not have this same restriction, and the same set of segments is permitted in both syllable-initial and syllable-final position. In development, Dutch-learning infants are sensitive to contrasts in word-initial position before they are sensitive to the same contrasts in word-final position, in perception (Zamuner, 2006b) and production (Beers, 1995). Given these phonotactic and developmental differences between initial and final position, one may find variation in Dutch learners' sensitivities to phonotactic probabilities in the two positions.

To test children's sensitivity to phonotactic probabilities in different positions, Dutch-learning children were presented with nonwords beginning and ending with the same segment, presented in both low- and high-phonotactic probability environments. Children were tested on their imitation accuracy using a nonword repetition task. Although the prediction is that there will be an effect of phonotactic probabilities in both positions, children's overall performance is predicted to be better in word-initial position. To investigate the relationship between vocabulary size and phonotactic probabilities in young language learners, analyses compared children's performance on the task with their receptive and expressive vocabulary scores.

Experiment

Method

Participants

Sixty-four children from monolingual Dutch-speaking homes participated in the experiment: 32 children between ages 2;2 and 2;4 ($M = 2;4.6$) and 32 children between ages 2;6 and 2;8 ($M = 2;7.27$). There was one between-subjects factor of position (initial or final), and 16 participants from each age group were randomly assigned to either condition. Participants did not have a history of speech and/or hearing impairment, as determined by parent questionnaire. Thirty-seven additional participants were tested but not included in the analysis

because they did not complete the experiment (29) or because of equipment failure (8). Parents completed the Dutch version of the MacArthur Communicative Development Inventory (N-CDI; Zink & Lejaegere, 2002). Children were recruited through the Kindertaal Lab (Child Language Lab) at the Radboud University Nijmegen, Nijmegen, the Netherlands and through the Baby Research Center of the Max Planck Institute for Psycholinguistics in Nijmegen, the Netherlands.

Materials

The stimuli consisted of 32 monosyllabic CVC nonwords, with the target segments /p, t, k, x, m, n, r, l/. Each segment occurred in four contexts, illustrated with the stimuli for the segment /p/: word-initial low-phonotactic probability environment (*peem/pim/*), word-initial high-phonotactic probability environment (*paat/pat/*), word-final low-phonotactic probability environment (*buup/bup/*), and word-final high-phonotactic probability environment (*miep/mip/*). The 32 nonwords consisted of 16 nonword pairs: 8 pairs with the same consonant in word-initial position in low- and high-phonotactic probability environments (e.g., *peem/pim/* and *paat/pat/*) and 8 pairs with the same consonant in word-final position in low- and high-phonotactic probability environments (e.g., *buup/bup/* and *miep/mip/*). A list of the nonword stimuli is presented in Table 1. Each nonword was paired with a nonce animal and presented using laminated flash cards.

The stimuli were controlled for their phonotactic probabilities, neighborhood densities, and word-likelihood ratings (see Table 2). Phonotactic probabilities were controlled for both segmental positional frequencies and biphone frequencies (low or high). Phonotactic probabilities were calculated on the log-frequency weighted counts using both type and token counts of CVC words from a Dutch speech corpus that includes adult-, child-, and infant-directed speech (van de Weijer, 1998). The phonotactic probabilities of the nonword stimuli were also

Table 1. Nonword stimuli, by word position and target segments, in low- and high-phonotactic probability (PP) environments.

Segment	Initial position		Final position	
	Low PP	High PP	Low PP	High PP
p	peem /pem/	paat /pat/	buup /bup/	miep /mip/
t	tup /tʏp/	tan /tan/	sut /sʏt/	not /not/
k	keup /køp/	kaan /kan/	feuk /føk/	daak /dak/
x	guf /xʏf/	ges /xes/	feug /føx/	naag /nax/
m	mup /mʏp/	mas /mas/	joem /jum/	daam /dam/
n	num /nym/	nes /nes/	jeun /jøn/	doon /don/
r	reup /røp/	raan /ran/	sir /sir/	ger /xer/
l	loem /lum/	laar /lar/	jeul /jøl/	gaal /xal/

Table 2. Mean phonotactic probabilities, neighborhood densities, and word-likelihood ratings of nonword stimuli, by word position, in low and high PP environments.

Measure	Initial position		Final position	
	Low PP M (SD)	High PP M (SD)	Low PP M (SD)	High PP M (SD)
Segmental positional probabilities				
Type	0.206 (0.018)	0.241 (0.009)	0.189 (0.021)	0.227 (0.009)
Token	0.202 (0.014)	0.235 (0.009)	0.187 (0.013)	0.237 (0.008)
Bi-phoneme probabilities				
Type	0.001 (0.003)	0.021 (0.008)	0.003 (0.004)	0.0124 (0.005)
Token	0.006 (0.005)	0.019 (0.004)	0.004 (0.005)	0.016 (0.004)
Neighborhood densities				
Type	3.63 (1.92)	140.00 (4.96)	1.38 (1.99)	8.75 (1.67)
Token	650.00 (68.86)	2847.75 (2461.21)	12.75 (320.07)	2066.63 (1709.95)
Word-likelihood ratings				
	2.73 (0.37)	4.10 (0.35)	2.63 (0.28)	3.64 (0.72)

calculated using the CELEX lexical database (Baayen, Piepenbrock, & Gulikers, 1995) and had comparable phonotactic probabilities. Because one of the experimental conditions compared children's production of segments in word-initial versus word-final position, it was important to ensure that the phonotactic probabilities of the stimuli were similar for the two positions. Otherwise, a significant effect of position or interaction could stem from differences in the phonotactic probabilities of the nonword stimuli rather than reflecting position. Items analyses were performed using a repeated measures analysis of variance (ANOVA), with phonotactic probabilities (low or high) as a within-items factor and position (initial or final) as a between-items factor. Separate analyses were run for type and token counts, and for segmental positional frequencies and biphone frequencies. Across the four analyses, there was a consistent significant main effect for phonotactic probabilities: type segmental positional frequencies, $F(1, 14) = 82.18, p < .001, \eta_p^2 = .85$; token segmental positional frequencies, $F(1, 14) = 268.59, p < .001, \eta_p^2 = .95$; type biphone frequencies, $F(1, 14) = 48.43, p < .001, \eta_p^2 = .78$; and token biphone frequencies, $F(1, 60) = 118.12, p < .001, \eta_p^2 = .89$. There was one main effect of position. For type counts using segmental positional frequencies, phonotactic probabilities were higher for items in word-initial position: type segmental positional frequencies, $F(1, 140) = 6.02, p < .05, \eta_p^2 = .30$. There were two significant Phonotactic Probabilities \times Position interactions. The first was with token counts using segmental positional frequencies: token segmental positional frequencies, $F(1, 14) = 10.30, p < .01, \eta_p^2 = .42$. Post hoc analyses determined that low-phonotactic probability items were significantly lower in word-final position than in word-initial position, $F(1, 14) = 4.88, p < .05, \eta_p^2 = .26$. The second was for type counts using biphone frequencies: type biphone frequencies, $F(1, 14) = 5.59, p < .05, \eta_p^2 = .29$. Post hoc analyses determined that

the high-phonotactic probability items were significantly higher for word-initial position than for word-final position, $F(1, 14) = 6.03, p < .05, \eta_p^2 = .30$. Although there were some significant Phonotactic Probabilities \times Position interactions, these findings were not consistent across the analyses. The only constant difference between the items was their phonotactic probabilities.

There is a positive correlation between phonotactic probabilities and neighborhood densities (Vitevitch, Luce, Pisoni, & Auer, 1999). *Neighborhood densities* refer to words created by adding, deleting, or substituting a word's or nonword's phonemes (Luce, Pisoni, & Goldinger, 1990). The stimuli were also controlled for their neighborhood densities, both type and token counts (see Table 2). The stimuli were analyzed using a repeated measures ANOVA to determine whether there were fewer or more neighbors for low- and high-phonotactic probability items, respectively. Separate analyses were run for type and token counts. For type counts, there was a significant effect of neighborhood density, $F(1, 14) = 59.67, p < .001, \eta_p^2 = .81$, and a significant effect of position, $F(1, 14) = 15.63, p < .001, \eta_p^2 = .53$. There were more neighbors for the high-phonotactic probability nonwords and more neighbors for items in the word-initial position. For token counts, there was the same significant effect of neighborhood density, $F(1, 14) = 20.23, p < .001, \eta_p^2 = .59$. Thus, as seen in other studies, there is a correlation with the present experimental stimuli between phonotactic probabilities and neighborhood densities. Vitevitch (2003) argued that, "When lexical representations are used to process spoken stimuli, effects of neighbourhood density are observed. When sublexical representations are used to process spoken stimuli, effects of phonotactic probability are observed" (p. 488). Studies of adult speech processing have found that neighborhood densities influence lexical processing. In tasks using nonwords, sublexical representations

or phonotactic probabilities influence performance (Vitevitch, 2003; Vitevitch & Luce, 1998, 1999). As the present research examined children's nonword production, it is assumed that children's phonological representations are the primary factor effecting their performance; however, to date, parallel studies have not yet been conducted with children looking at the relative effects of neighborhood density and phonotactic probabilities.

Finally, the stimuli were controlled for their word-likelihood ratings. Nonwords composed of high phonotactic probabilities are scored higher on ratings of word likelihood (Treiman, Kessler, Knewasser, Tincoff, & Bowman, 2000). Fifteen adult speakers of Dutch were asked to rate the nonwords on a scale ranging from 1 to 7, based on how much they sounded like possible Dutch words. The word-likelihood ratings for the stimuli can be seen in Table 2. The stimuli were compared for ratings on the basis of phonotactic probabilities and position, and a significant effect of phonotactic probabilities was found. Items with high phonotactic probabilities were rated as more wordlike than items with low phonotactic probabilities, $F(1, 14) = 73.68, p < .001, \eta_p^2 = .84$. There were no other significant effects. Across the three analyses of the stimuli (phonotactic probabilities, neighborhood densities, and word-likelihood ratings), the only reliable pattern was that high-phonotactic probability nonwords had higher frequencies, greater neighborhood densities, and higher word-likelihood ratings. There were some effects of position, with higher phonotactic probabilities and higher neighborhood densities for the word-initial stimuli, although these effects were not consistent across all of the analyses.

Procedure. Children were individually tested at the Kindertaal Lab (Child Language Lab) at the Radboud University Nijmegen. Children started with three practice trials and were asked for spontaneous or imitated productions of three known animals (e.g., *schaap* "sheep"). The purpose of the practice trials was to familiarize children with the task. Children were then shown pictures of nonce animals using laminating flash cards. The experimenter explained to the child that his or her job was to repeat the names of the new animals. The experimenter then said the name of the animal, "*Dit is een buup* (This is a buup)." The experimenter was a native speaker of Dutch and naïve to the purpose of the study. Experimental sessions were recorded using a Sony DCR-TRY 460 Digital 8 Camcorder, and an external Shure SM58 high-quality professional dynamic microphone was positioned in front of or near the child. Sessions were digitized and transcribed by the same experimenter, using waveforms viewed in Audacity, a free digital audio editor. A second transcriber who was also a native speaker of Dutch, naïve to the purpose of the study, and blind to the original transcriptions, also checked the sessions. The two transcribers then agreed on all items that were used in

the analyses. Only children's first response was used in the analyses. The order of the stimuli was prerandomized, and each child was tested on the same prerandomized order.

Coding. Following Zamuner et al. (2004), responses were coded into different bins, based on broad phonetic transcriptions of the target word-initial or word-final segments (production of nontarget segments was not evaluated). Correct target segments were coded as Correct Response; errors and omissions of the target segment were coded as Incorrect Response; no imitation produced for the target word was coded as No Response; and responses for which children produced real words rather than the target nonword were coded as Real Word Response (this included responses for which target segments were produced correctly and incorrectly). With a subset of the responses coded as Correct Response, Incorrect Response, and Real Word Response, children also made errors in producing nontarget segments. These errors were not considered in the analyses. The criterion for real-word coding was based on whether the word occurred in the van de Weijer corpus, a corpus of infant-, child-, and adult-directed speech (van de Weijer, 1998). Analyses are presented with Real Word Responses excluded because there is a greater likelihood for phoneme substitutions to result in real words in initial position as compared with final position. This is because there are more Dutch words that contrast in initial position than in final position (Ziegler & Goswami, 2005). There were an unequal number of No Responses for each child; therefore, analyses were based on the proportion of Correct Responses (out of eight).

Results

A repeated measures ANOVA was used, with phonotactic probabilities (low or high) as the within-subject factor and position (initial or final) and age (younger or older) as the between-subjects factors. Children's MSRA in the different conditions is given in Table 3. There was a main effect of phonotactic probabilities, $F(1, 60) = 35.83, p < .001, \eta_p^2 = .37$. Forty-two children were more accurate at repeating the target segments in the high-phonotactic probability nonwords compared with 8 children who were more accurate at repeating the target segments in the low-phonotactic probability nonwords. There was no main effect for position and no Phonotactic Probabilities \times Position interactions. There was a significant main effect of age, $F(1, 60) = 7.08, p < .01, \eta_p^2 = .11$. Older children repeated more correct responses for the target segments. Finally, there was a significant Age \times Position interaction, $F(1, 60) = 8.55, p < .01, \eta_p^2 = .13$. Planned comparisons using one-way ANOVAs were performed to determine the effect of position with the two age groups. There was

Table 3. Mean segment repetition accuracy (out of 8), by position, age, and PP environments.

Age	Initial position		Final position	
	Low PP M (SD)	High PP M (SD)	Low PP M (SD)	High PP M (SD)
Younger	4.69 (1.69)	6.30 (1.59)	5.79 (1.88)	6.96 (0.96)
Older	6.77 (0.93)	7.61 (0.64)	5.96 (1.53)	6.63 (1.58)

a statistically significant effect of position only with the older age group, $F(1, 30) = 4.92, p < .05$, and although it approached significance, there was no significant effect of position with the younger group, $F(1, 30) = 3.77, p = .06$.

Lexical analyses. To examine the relationship between vocabulary size and phonological representations, children's receptive and expressive vocabulary scores, as measured by the N-CDI, were correlated to their MSRA and to the FF (the difference between target segments repeated accurately in low- and high-phonotactic probability environments). Table 4 presents correlations separated by position (word initial and word final) between children's age (in days, collapsed between the two age groups), their receptive and expressive raw vocabulary scores, as measured by the N-CDI, and their performance on the task, as measured by the MSRA and the FF. Results from the correlation analyses indicated that age and both measures of vocabulary size are related to children's MSRA, but only in word-initial position. There were no correlations in word-final position. Age was also significantly correlated to children's expressive and receptive vocabulary scores (age and expressive: $r^2 = .38, p < .01$; age and receptive: $r^2 = .34, p < .01$), but again only for word-initial position. Given the significant correlations in word-initial position, but no significant correlations in word-final position, a test was also done to determine whether the effect of position was due to differences in

Table 4. Correlations between receptive and expressive raw vocabulary (raw scores N-CDI), age, mean segment repetition accuracy (MSRA), and the frequency effect (FF), separated by word position.

Variable	Initial position		Final position	
	MSRA	FF	MSRA	FF
Age	.50**	-.18	-.03	-.28
Raw vocabulary score, N-CDI				
Receptive	.60***	-.01	-.14	.10
Expressive	.62***	.10	.16	-.11

Note. N-CDI = Dutch Communicative Development Inventory.

** $p < .01$. *** $p < .001$.

ages or vocabulary sizes between the participants tested on word-initial and word-final position, as position was a between-subjects variable. The effect of position was tested using one-way ANOVAs. There were no significant differences between the children who were tested in word-initial versus word-final position, in either their ages, $F(1, 63) = 0.01, p = .98, \eta_p^2 = .01$; their receptive vocabulary scores, $F(1, 63) = 0.24, p = .63, \eta_p^2 = .01$; or their expressive vocabulary scores, $F(1, 63) = 0.04, p = .85, \eta_p^2 = .01$. Although age and vocabulary size are both related to language development, previous research has shown that children's vocabulary scores are a greater predictor of language development than chronological age (Edwards et al., 2004). Given that there were significant correlations between age and vocabulary size, and significant correlations between age and vocabulary size and children's performance on the task (in word-initial position), hierarchical regression analyses were run to determine the relative significance of each variable, over and beyond the predictive value of the other variable, and results are summarized in Table 5 (Regressions 1–4 for word-initial position, and Regressions 5–8 for word-final position). The dependent variable was children's MSRA (separated for word-initial and word-final positions), and with receptive or expressive vocabulary scores

Table 5. Summary of hierarchical regression analyses of variables predicting mean segment repetition accuracy (MSRA), separated by word position.

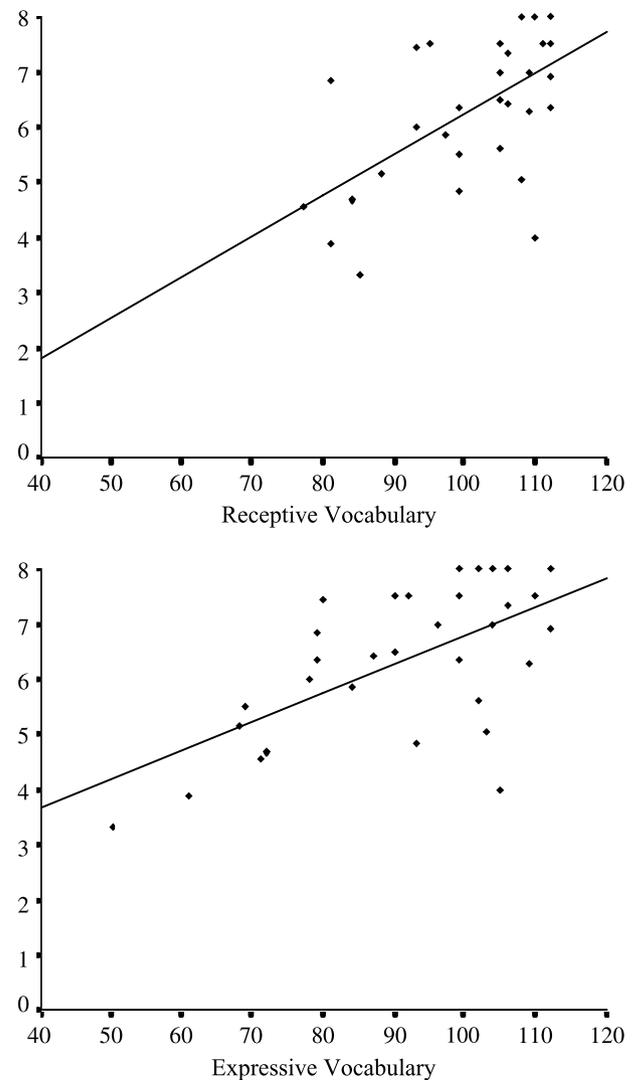
Position	Step variable	R	R ²	ΔR ²	p
Initial	Regression 1 (N = 32)				
	Receptive	.59	.34	.34	.001
	Receptive, Age	.61	.37	.02	.30
	Regression 2 (N = 32)				
	Age	.49	.24	.24	.005
	Age, Receptive	.61	.37	.13	.02
	Regression 3 (N = 32)				
	Expressive	.62	.39	.39	.001
Final	Regression 4 (N = 32)				
	Age	.49	.24	.24	.005
	Age, Expressive	.64	.41	.17	.007
	Regression 5 (N = 32)				
	Receptive	.14	.02	.02	.46
	Receptive, Age	.14	.02	.01	.92
	Regression 6 (N = 32)				
	Age	.03	.01	.01	.89
	Age, Receptive	.14	.02	.02	.47
	Regression 7 (N = 32)				
Expressive	.16	.03	.03	.39	
Expressive, Age	.16	.03	.01	.81	
Regression 8 (N = 32)					
Age	.03	.01	.01	.89	
Age, Expressive	.16	.03	.03	.39	

and age as predictor variables. As there were no significant results with word-final position, these analyses are not discussed further. In word-initial position, receptive vocabulary scores and age accounted were significantly related to MSRA ($R = .61$), $F(2, 29) = 8.46$, $p < .001$, and accounted for 37% of the variance. When receptive vocabulary scores was the first variable (Regression 1), it accounted for 34% of the variance in MSRA, $F(1, 30) = 15.75$, $p < .001$, and age accounted for only an additional 2% of the variance, which was not significant, $F(1, 29) = 1.11$, $p = .30$. In Regression 2, age was entered first and accounted for 24% of the variance in MSRA, $F(1, 30) = 9.35$, $p < .01$, with receptive vocabulary scores accounting for an additional 13% significant variance, $F(1, 29) = 6.00$, $p < .05$. Similar outcomes were found with expressive vocabulary scores and age, which were significantly related to MSRA in word-initial position ($R = .64$), $F(2, 29) = 10.16$, $p < .001$, and accounted for 41% of the variance. When expressive vocabulary scores was the first variable (Regression 3), it accounted for 39% of the variance in MSRA, $F(1, 30) = 19.01$, $p < .001$, and age accounted for only an additional 2% of the variance, which was not significant, $F(1, 29) = 1.19$, $p = .29$. In Regression 4, age was entered first and accounted for 24% of the variance in MSRA, $F(1, 30) = 9.35$, $p < .01$, with receptive vocabulary scores accounting for an additional 17% significant variance, $F(1, 29) = 8.59$, $p < .01$. Regressions 1–4 illustrate that children’s age does not account for any significant amount of variance in children’s MSRA, beyond what is accounted for by children’s receptive or expressive vocabulary scores, as found by Edwards et al. (2004). The relationship between MSRA in word-initial position and children’s receptive and expressive vocabularies is plotted in Figure 1. A parallel set of analyses was done, with the FF as the dependent variable rather than the MSRA. Results were also separated by position (word initial and word final). No significant effects were found.

General Discussion

There are three specific ways this research adds to researchers’ understanding of PD and how learners are sensitive to statistical patterns in the ambient language. First, the results established that phonotactic probabilities influenced children’s MSRA in nonwords, both word-initial and word-final position, and there was no significant difference in the effect of phonotactic probabilities in the two positions. Second, there were consistent relationships between children’s vocabulary size and their MSRA in word-initial position but not in word-final position. However, there were no significant relationships between any variables and the size of the FF. Lastly, the results replicated and extended previous

Figure 1. Mean segment repetition accuracy in word-initial position plotted against receptive vocabulary (top panel) and expressive vocabulary (bottom panel; raw scores of the Dutch version of the MacArthur Communicative Development Inventory). Results collapsed across age. $N = 32$.



findings on phonotactic probabilities from English by Zamuner et al. (2004) to the acquisition of Dutch.

Returning to the initial goals of this research, one novel component of the present study is that it considers the relationship between word position and phonological representations by comparing children’s ability to produce the same segments in word-initial and word-final positions. Differences have been reported in developmental speech perception and production for initial position as compared with final position (Jakobson, 1941/1968; Jusczyk et al., 1999; Levelt et al., 1999; Storkel, 2002; Swingley, 2005; Zamuner, 2006b). The present results

add to researchers' understanding of this asymmetry, as older children's MSRA was significantly better in word-initial position. Although there were no significant interactions between phonotactic probabilities and position, other, more sensitive measures might reveal significant interactions between position and how children produce different probability-based segments, segmental sequences, and/or segmental contrasts. Recall from the analyses of the experimental stimuli that there were some significant Phonotactic Probabilities \times Position interactions. However, these findings were not consistent across the analyses, and because there was no significant main effect of position, it is unlikely that this could account for the findings.

The second goal was to look at the onset of vocabulary development. Recall the recent findings from Munson, Edwards, and Beckman (2005), who found that children with severe PD have a relatively small FF. Their interpretation of this finding was that children with severe PD are at a stage of vocabulary development in which phonological representations are general and do not capture distinctions between segments or segmental sequences. One study that looked at the early stages of vocabulary development (age range = 1;8–2;4) and phonotactic probabilities in nonword production (Zamuner et al., 2004) found no significant relationships between children's expressive vocabulary sizes and the MSRA or the FF. This potentially supports Munson, Edwards, and Beckman's theory; however, the homogeneity of children's vocabularies in the Zamuner et al. (2004) study may have obscured any possible relationships between vocabulary size and performance on the task. The present study expanded on previous findings by examining the relationships between phonotactic probabilities and the earliest stages of vocabulary development, with two age groups: 2;2–2;4 and 2;6–2;8.

In the present study, a significant relationship was found between children's receptive and expressive vocabulary sizes and their MSRA in word-initial position but not in word-final position. Thus, the null results from the Zamuner et al. (2004) study may have stemmed from their sample, or because they only tested word-final position. As with previous examinations with young children (Zamuner et al., 2004), no significant relationships were found between the FF and children's receptive or expressive vocabulary size. In the present study, children were tested on how they produce the same segment with different phonotactic probability environments (e.g., the /p/ in /pim/ vs. /pat/), whereas compared with previous studies, children were tested on how they produced different segmental sequences (e.g., /pw/ in /pwagab/ vs. the /tw/ in /twæket/, and the /gd/ in /dogdet/ vs. the /kt/ in /tæktut/; Munson, Edwards, & Beckman, 2005, p. 65). Therefore, even though there was overlap in the previous

studies' stimuli for what segments were tested, the present study was more restricted because the exact same segments were embedded in low- and high-phonotactic probability environments (see also Gathercole et al., 1999, for similar stimuli). This difference might be one reason for why no relationship was found between the FF and children's vocabulary sizes.

The last goal was to examine the role of phonotactic probabilities in the acquisition of a new language, specifically, Dutch. Studies of phonological acquisition tend to concentrate on similarities across languages, but recent work has begun to focus on the differences in phonological acquisition. Studies of this nature have addressed what patterns in acquisition are universal (based on limitations in the perception and production of language) and what patterns in acquisition are language specific (Demuth, 2006; Edwards & Beckman, 2008). The present research further establishes that phonotactic probabilities play a role in the phonological acquisition of Dutch. The significant result in word-initial position in Dutch was expected given the findings from Stokes and Surendran (2005), who, in a comparison of production accuracy for initial consonants in Dutch and English, found that frequency has more explanatory power in Dutch. The results in word-final position were somewhat unexpected given developmental differences in Dutch learners' sensitivities to contrasts in initial and final position (Zamuner, 2006b) and because Dutch has different phonotactic patterns in syllable-initial versus syllable-final position (Booij, 1995). The present results show convergence on the effects of phonotactic probabilities across the development of languages that have different phonotactic distributions (i.e., English compared with Dutch).

Together, these results provide new insights into the nature of children's developing phonological representations. As with previous studies, probability-based differences were found in children's ability to produce nonwords, but the results also revealed a relationship between vocabulary development and position in children's phonological development (as measured by the MSRA). One possibility for this relationship is linked to the phonological structure of children's emerging vocabularies. Recent examinations of the phonological neighbors in English and Dutch children's early vocabularies have shown that there is a higher proportion or density of lexical items that contrast in word-initial position (e.g., rhyme neighbors as in /bot/ *boot* "boat" and /rot/ *rood* "red") as compared with word-final position (e.g., lead neighbors /bot/ *boot* "boat" and /bom/ *boom* "tree") (De Cara & Goswami, 2002; Zamuner, 2006a, 2009). In other words, the clustering of phonological neighborhoods in children's early vocabularies differs depending on word position (similar clustering is found in the adult

vocabulary; however, children's early lexicons have been shown to have significantly different patterns, e.g., more rhyme neighbors than has been found in the adult language; Zamuner, 2009). As it is argued that phonological representations are abstracted from the acquired lexicon, these findings from children's neighborhood densities could predict one to find differences for phonological representations on the basis of word position. Specifically, if there are more lexical items that contrast in word-initial position, then phonological representations from word-initial position should be more developed. Given the structure of phonological neighbors in children's early vocabularies (De Cara & Goswami, 2002; Zamuner, 2006a, 2009), and the significant relationship between vocabulary development and the MSRA in initial position, these results provide further support for the theory that phonological representations emerge from children's developing lexical representations. This relationship is most likely bidirectional. As children's lexicons develop with an emerging phonological structure, this in turn impacts their developing phonological representations. However, as children's phonological representations develop, these can help support the acquisition of specific lexical items. In fact, phonotactic probabilities, neighborhood densities, and word-likelihood ratings are correlated with one another, which is a limitation of the present study. Further large-scale longitudinal work may be able to tease apart some of these factors, as Maekawa and Storkel (2006) found various effects of phonotactic probabilities, neighborhood densities, and lexical frequency in accounting for children's first word productions. Maekawa and Storkel argued that the influence of these factors changes across development (emergentist coalition model; Hirsh-Pasek, Golinkoff, & Hollich, 2000).

The relationship between phonological representations and the emerging lexicon is captured in Processing Rich Information from Multidimensional Interaction Representations (PRIMIR), a present model of developmental speech perception (Werker & Curtin, 2005). The relevant aspect of the model is its ability to capture the emergence of phonological representations from generalizations made across dense, meaningful words. Phonological representations in PRIMIR are able to capture context sensitivity, such as different positions within the word (see also Pierrehumbert, 2003). Moreover, because representations are exemplar based and the result of statistical learning, representations capture and reflect probability-based information. In this model, young language learners will have richer phonological representations for different word positions, and for different probability-based segments or segmental sequences. Accordingly, as found in this study, a relationship is found between vocabulary size and children's MSRA for word-initial position, and segments in high-phonotactic probability items are produced more accurately than segments

in low-frequency environments in both word positions. Future research should continue to examine the relationship between children's phonological representations and the structure of children's emerging vocabularies, in languages with similar and with different vocabulary structures. These studies will help further define the nature of children's emerging phonological and lexical representations, as begun in this research.

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