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Sensitivity to Word-Final Phonotactics in 9- to 16-Month-Old Infants

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Previous research has shown that infants begin to display sensitivities to language-specific phonotactics and probabilistic phonotactics at around 9 months of age. However, certain phonotactic patterns have not yet been examined, such as contrast neutralization, in which phonemic contrasts are neutralized typically in syllable- or word-final position. Thus, the acquisition of contrast neutralization is dependent on infants' ability to perceive certain contrasts in final position. The studies reported here test infants' sensitivity to voicing neutralization in word-final position and infants' discrimination of voicing and place of articulation (POA) contrasts in word-initial and word-final position. Nine and 11-month-old Dutch-learning infants showed no preference for legal versus illegal voicing phonotactics that were contrasted in word-final position. Furthermore, 10-month-old infants showed no discrimination of voicing or POA contrasts in word-final position, whereas they did show sensitivity to the same contrasts in word-initial position. By 16 months, infants were able to discriminate POA contrasts in word-final position, although showing no discrimination of the word-final voicing contrast. These findings have broad implications for models of how learners acquire the phonological structures of their language, for the types of phonotactic structures to which infants are presumed to be sensitive, and for the relative sensitivity to phonemic distinctions by syllable and word position during acquisition.

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Acquiring language involves not only learning the language's sound inventory, but also learning the language's possible sound combinations, and where those sounds can occur within syllables and words. The term *phonotactics* or *language-specific phonotactics* refers to the legal sequencing of sounds within a given language. For example, in English words can end with /ŋ/ as in *sing* /sɪŋ/; however, no words in English begin with /ŋ/. Other phonotactic patterns are probabilistic or statistic. Phonotactic probabilities refer to the likelihood a sound will occur within a given environment. For example, although words in English end in both /t/ (e.g., *cat* /kæt/) and /ʃ/ (e.g., *fish* /fiʃ/), it is more likely that any randomly selected word in English will end in /t/ because there are more words in the English language that end in /t/.

Research on phonotactic acquisition has found that 9-month-old infants have acquired a sophisticated knowledge about the language-specific phonotactics and probabilistic phonotactics of their native language (Friederici & Wessels, 1993; Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993; Jusczyk, Luce, & Charles-Luce, 1994; Sebastián-Gallés & Bosch, 2002). However, infants must learn other types of phonotactic patterns, such as contrast neutralization. In this pattern, phonemic contrasts between segments are neutralized typically in syllable- or word-final position. For infants to acquire contrast neutralization, they must learn that whereas certain sounds are permitted in one position, in another position, the same sounds are restricted. A well-known example of contrast neutralization is voicing neutralization, where voiced obstruents are not allowed in syllable- or word-final position. Dutch is a language that restricts voiced obstruents, such that /b, v, d, z/ cannot occur at the ends of syllables or words (see Table 1). When words violate this restriction, speakers produce voiced obstruents as their voiceless counterparts. For example, the word-final voiced /d/ in *bed* is produced as a voiceless [t], that is, [bɛt]. Another typical pattern of contrast neutralization found across languages is one in which place of articulation (POA) is restricted in syllable- or word-final position. Dutch does not restrict POA in final position; therefore, /p/, /t/, and /k/ can occur initially and finally. These patterns are also illustrated in Table 1.

Knowledge of contrast neutralization is argued to be helpful in a number of tasks such as word segmentation and the acquisition of morphophonological acquisition. In word segmentation, knowing how sounds pattern within words can help the infants locate word boundaries. For example, if Dutch infants know about voicing neutralization, they might also know that a word boundary must never occur after /d/, because the latter would create a phonotactically illegal word of the language. Knowledge of contrast neutralization is also relevant for the acquisition of morphophonological alternations. Morphophonological alternations refer to phonological processes that occur between words and affixes. For example, in Dutch, voicing neutralization results in a regular change or alternation between voiceless and voiced obstruents with the addition of noun, verbal, or

TABLE 1
Dutch Contrasts in Voicing (/t/ vs. /d/) and Place of Articulation (/p/ vs. /t, d/) in Word-Initial and Word-Final Position

	Word-Initial Position			*Word-Final Position*		
Phoneme	*Transcription*	*Orthography*	*Gloss*	*Transcription*	*Orthography*	*Gloss*
p	[pɑk]	*pak*	suit	[mɛp]	*mep*	slap
t	[tɑk]	*tak*	branch	[pɛt]	*pet*	cap
d	[dɑk]	*dak*	roof	*[bɛd]	*bed*	bed

Note. *signifies an ungrammatical word form.

adjectival morpheme suffixes. The voicing contrast that is neutralized in final position reappears with the addition of this morphology. For example, the plural suffix in Dutch is /–ə/. When this suffix is added to a noun, the noun's word-final consonant is no longer in final position. Compare the /d/ that is produced as [t] in the singular *nood* [not] 'emergency,' but as [d] in the plural *noden* [nodə] 'emergencies.' Voiceless obstruents do not undergo a similar alternation, compare *noot* [not] 'nut' to *nooten* [notə] 'nuts,' where /t/ is produced as [t] in both the singular and the plural.[1] If the infant or child has knowledge about voicing neutralization, this should aid his or her acquisition of morphophonological alternations. This is possible because phonotactics and alternations are captured by the same set of language generalizations (see Pater & Tessier, 2003, for a recent review). To date, theories on morphophonological acquisition have assumed that infants are sensitive to contrast neutralization. This has been based on research showing that 9-month-old infants have knowledge of language-specific and probabilistic phonotactics. Drawing on these findings, it has been argued that the acquisition of phonotactics precedes and can aid the acquisition of morphophonological alternations (e.g., Hayes, 2004; Prince & Tesar, 2004; Tesar & Prince, in press). For example, both Peperkamp and Dupoux (2002) and Tesar and Prince (in press) argued that the first step to learning morphophonological alternations, such as the pattern described for Dutch, is to learn the phonotactics of voicing neutralization. There is a gap, however, in our knowledge of infants' sensitivity to this type of phonotactic pattern.

[1]Some research has shown that when Dutch word-final voiced /d/s are produced as [t] there is incomplete voicing neutralization (Warner, Jongman, Sereno, & Kemps, 2004). However, there are no studies that have demonstrated incomplete neutralization in spontaneous speech. The final /n/ of the plural suffix /-ən/ is typically not produced in this context. Note that although voicing neutralization in Dutch is best captured as restricted to voicing in syllable-final position, we refer to the restriction in word-final position given that the experiments presented in this article look only at word-final position.

Various studies have demonstrated that infants are sensitive to language-specific phonotactics and probabilistic phonotactics, so this assumption may be accurate. However, previous studies have not directly tested infants' knowledge of neutralization phonotactics. In the case of Dutch voicing neutralization, this requires knowledge of how voicing (or the set of voiced obstruents) is restricted in a specific position. Additionally, contrast neutralization typically occurs at the ends of syllables or words; therefore, infants' acquisition of contrast neutralization is dependent on their ability to perceive contrasts in final position. Thus, we take as a starting point an examination of infants' perception in final position. We then turn to a closer examination of the types of phonotactic patterns that have been tested in previous studies.

Contrast neutralization typically occurs in syllable- or word-final position; therefore, the acquisition of this type of phonotactic pattern is dependent on infants' ability to perceive or track the distribution of segments in final position. However, there is evidence that infants are less sensitive to contrasts that occur in word-final position as compared to word-initial position. Jusczyk, Goodman, and Bauman (1999) tested infants' sensitivities to the same segments versus varying segments in initial versus final position. Nine-month-old infants preferred lists of nonwords that shared common word-initial consonants to lists of nonwords with varying word-initial consonants. However, infants at the same age had no preference for commonalities in word-final consonants. Position within multisyllable words has also been shown to affect discrimination. Trehub (1974) found that infants' discrimination of a voicing contrast was better between the first and second syllable of a bisyllabic word ([apa] vs. [aba]) than between the second and third syllable of a trisyllabic word ([atapa] vs. [ataba]). Similarly, Karzon (1985) tested 1- to 4-month-old infants on their discrimination of [ra] versus [la]. Whereas infants were able to discriminate the syllables in isolation, when the same syllables were between the first and second syllable of a trisyllabic word ([marana] vs. [malana]), infants could only discriminate the contrast if the target syllables had exaggerated stress and increased amplitude and length. Thus, these studies illustrate that infants' perception is poorer in noninitial position.

One of the few studies to test and find successful discrimination of contrasts in word-final position was Jusczyk (1977). Using the high-amplitude sucking paradigm, Jusczyk found that English-learning 2-month-old infants were able to discriminate the word-final /d/–/g/ contrast in *bad* versus *bag* and the word-final /m/–/g/ contrast in *bam* versus *bag*. Similarly, Eilers, Wilson, and Moore (1977) found that 6- to 8-month-old English-learning infants were able to discriminate syllable-final voicing contrasts between /t/–/d/ and /s/–/z/. In English, one of the primary cues for voicing is the length of the preceding vowel—vowels are longer before voiced obstruents. Infants were only able to perceive the voicing contrast when these vowel length cues were present combined with voicing cues for the final consonant. In sum, some studies have shown that infants are poorer at discrimination in noninitial position, whereas other studies have found that infants are able to perceive contrasts in final position. This suggests that a closer

examination is needed of the previous studies on phonotactic acquisition to determine what patterns have been tested in various positions throughout the word.

In the literature on the acquisition of language-specific phonotactics and probabilistic phonotactics, one recurring finding is that infants are sensitive to the order or likelihood of occurrence of segmental sequences or clusters. For example, Friederici and Wessels (1993) found that 9-month-old Dutch-learning infants have a language-specific preference for legal versus illegal onset and offset clusters. Similarly in Jusczyk et al. (1993), English-learning and Dutch-learning 9-month-old infants were tested on their preference for either English or Dutch word lists. Importantly, the English and Dutch word lists contained phonemes found in both languages, but differed only in the legal sequencing of these sounds in word-initial, word-medial, and word-final position. For example, although English and Dutch have both /v/ and /l/, only Dutch allows words to begin with /vl/ clusters. Results were that English-learning infants had a significant preference for the English word lists, but Dutch-learning infants' preference for the Dutch word lists only approached significance. This might reflect the types of stimuli used in the English versus Dutch word lists. Based on the authors' description of the stimuli, the Dutch word lists contained consonant clusters not found in English (see previous example), and the English word lists contained primarily singleton segments not found in specific positions in Dutch.[2] For example, only English words can begin with schwa or end in voiced obstruents. Therefore, Dutch-learning infants may have only approached significance because the English word lists were distinguished from Dutch by singleton segments. It is also possible that infants in both language groups were able to distinguish the word lists based on other phonetic differences between English and Dutch. For example, although the vowels are in principle the same in both languages according to the International Phonetic Alphabet, there are differences in quality (acoustic patterns that reflect the ways in which vowels are articulated), quantity (vowel length), and vowel reduction (changes in vowel quality and quantity that occur between stressed and unstressed syllables) between the two languages (Colin & Mees, 1984).

Another representative study is that of Mattys and Jusczyk (2001), who tested infants' ability to segment nonwords that were preceded or followed by either good phonotactic cues or poor phonotactic cues to word boundaries (see also Mattys, Jusczyk, Luce, & Morgan, 1999). Good and poor were defined by clusters that were associated with across-word boundaries and within-word boundaries, respectively.[3] This study by definition then, also looked at infants' ability to

[2]It is impossible to create English word lists with clusters that are legal English clusters but illegal Dutch clusters. This is because Dutch has a larger set of permissible clusters than English.

[3]This task does not necessarily require knowledge of probabilistic phonotactics. Infants may succeed on this task using more language-general knowledge or more general perceptual abilities. For example, a between-word boundary cluster used in the experiment was /ng/ and a within-word boundary cluster was /ŋg/. Across languages, nasals typically share POA with the following consonant

segment words using knowledge of the sequential ordering of segments or clusters. These findings do not necessarily extend to voicing neutralization in Dutch because this involves singleton segments, and a contrast between segments that is neutralized, both /t/ and /d/ map to [t].

Dutch voicing neutralization also requires knowledge of phonotactic patterns in different positions within words. When we look closer at studies that have controlled for position, we see that infants have shown sensitivity to language-specific phonotactics and probabilistic phonotactics in both word-initial and word-final position (Friederici & Wessels, 1993; Mattys & Jusczyk, 2001; Sebastián-Gallés & Bosch, 2002). For example, Friederici and Wessels (1993, Experiment 5) found that 9-month-old Dutch-learning infants prefer phonotactically legal offset clusters to phonotactically illegal offset clusters, when embedded in running speech. For example, lists of legal offsets such as /mig diNT mig/ were preferred over illegal offsets such as /mig feBR mig/. The latter cluster was defined as illegal because BR is not a possible word-final cluster in Dutch. It is an open question as to whether infants are sensitive to phonotactics, which restrict singleton segments in final position. Studies showing sensitivity to phonotactics with singleton segments include those such as Jusczyk et al. (1994) in which infants at 9 months showed a preference for nonwords composed of high phonotactic probabilities over low phonotactic probabilities. This study, however, did not control for position. Therefore, infants may have distinguished the nonword lists based purely on the patterns found in word-initial position. Moreover, there are no studies that have illustrated infants' sensitivity to language-specific phonotactics or probabilistic phonotactics limited to singleton segments in final position.

Lastly, recent research on phonotactic acquisition has looked at infants' ability to track the distribution of phonemes in an attempt to understand the types of phonotactic patterns infants can learn and to understand what learning mechanism allows infants to extract regularities from the input. Chambers, Onishi, and Fisher (2003) tested 16.5-month-old infants' ability to acquire novel phonotactic regularities. Infants were familiarized to lists of nonwords with unique sets of consonants in initial and final position. During test, infants were presented with novel words that shared the phonotactic restrictions with the familiarized nonwords

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(Jun, 2004); therefore, /ŋg/ is a better within-word boundary cluster because both /ŋ/ and /g/ have velar POA, compared to /ŋg/ in which the /n/ is coronal and the /g/ is velar. The possibility that infants may rely on more language-general knowledge also applies to the stimuli used in Friederici and Wessels (1993), and Sebastián-Gallés and Bosch (2002). For example, Friederici and Wessels (1993) created phonotactically illegal stimuli by putting phonotactically legal offsets (/rt#/) onto the beginning of words. Cross-linguistically, syllables typically conform to the sonority sequencing principle (e.g., Clements, 1990), and consequently, onset clusters tend to rise in sonority and offset clusters tend to fall in sonority. The /r/ is more sonorant than /t/; therefore, the onset cluster /#rt/ is less preferred as an onset than /#tr/. The former cluster violates the more language-general sonority sequencing principle—though note that in some languages like Russian, these types of syllables are still possible.

(legal), or novel words in which the initial and final consonant sets were juxtaposed (illegal). Infants showed a preference for the illegal nonwords, illustrating that they had acquired the phonotactic pattern or consonant distributions during training (see Saffran & Thiessen, 2003, Experiment 2 and 3, for similar studies). Although these studies require infants to track the position of phonemes, the effects could be driven solely by infants' ability to detect patterns in word-initial position (as also noted by Saffran & Thiessen, 2003, p. 489). Therefore, these studies do not address whether infants are able to track whether certain segments are restricted in final position, which is a necessary component of contrast neutralization.

Although previous studies have looked at various types of phonotactic patterns, there are no studies that have specifically looked at infants' knowledge of contrast neutralization. Dutch provides a way of examining the acquisition of this type of phonotactic pattern because it has voicing neutralization. Experiment 1 assesses Dutch-learning infants' preference for legal versus illegal voicing phonotactics in word-final position. Given that voicing neutralization in Dutch occurs in final position, the remaining experiments look at Dutch-learning infants' discrimination of different phonemic contrasts in word-final and word-initial position. Experiment 2 assesses the discrimination of the same voicing contrasts in Experiment 1 as compared to the discrimination of POA contrasts in word-final position. Experiment 3 assesses discrimination of the same voice and POA contrasts in word-initial position. Finally, Experiment 4 assesses discrimination of voicing and POA contrasts in word-final position in older infants.

EXPERIMENT 1

Given the gaps in current knowledge on infants' sensitivity to neutralization phonotactics, we set out to test the acquisition of voicing neutralization with Dutch-learning infants. The prediction was that infants' sensitivity to language-specific phonotactics and probabilistic phonotactics would extend to voicing neutralization. Therefore, we predicted that infants should have a preference for legal voicing phonotactics over illegal voicing phonotactics. This is based on previous studies that have shown preferences for legal phonotactics (e.g., Friederici & Wessels, 1993). To test infants' sensitivity to voicing neutralization, infants were presented with nonwords ending in voiceless versus voiced obstruents. As only voiceless obstruents are permitted word-finally, we predicted that infants should show a preference for these stimuli; however, even if infants show a preference for the nonwords ending in voiced obstruents, this would also show that infants were able to discriminate the stimuli. Although we expected that infants would display knowledge of voicing phonotactics around 9 months, it is possible that the acquisition of neutralization comes at a later stage in development because it requires a more sophisticated knowledge of phonotactics. Infants must learn that

while the contrast is present and legal in word-initial position, in word-final position the contrast is neutralized. Given this possibility, we tested both 9- and 11-month-old infants.

Method

Participants. Two groups of infants participated in the experiment: 9- and 11-month-old infants. All infants were from Dutch monolingual speaking homes. Thirty infants were between the ages of 9.01 and 9.25 months (M = 9.21 months). Twelve additional infants were tested but not included in the analysis due to parent interference (n = 2), equipment failure (n = 2), fussiness (n = 1), and not enough data because three or more trials were less than 2 sec (n = 7). Thirty-one infants were between the ages of 11.07 and 11.27 months (M = 11.13 months). Eleven additional infants were tested but not included in the analysis due to fussiness (n = 2), three or more test trials were less than 2 sec (n = 8), and looking times were 3 *SD* from the mean (n = 1). Infants were recruited through the Baby Research Center of the Max Planck Institute for Psycholinguistics in Nijmegen, The Netherlands.

Materials. The stimuli consisted of 20 monosyllabic nonwords ending in voiceless obstruents (legal) and 20 ending in voiced obstruents (illegal). The nonwords were matched on all features except the voicing of their syllable-final (word-final) obstruents. A full list of stimuli can be seen in the Appendix. The stimuli were recorded in a soundproof booth and produced by a native speaker of Dutch who had training in phonetics. The stimuli were chosen with the help of four native Dutch speakers, all phonologists. The same native speakers reported that the voiceless–voiced distinction on the nonwords was very salient. The average length between short and long vowels in Dutch is 100 msec and 200 msec, respectively (Nooteboom, 1972). Although infants learning Dutch can distinguish this length contrast (Dietrich, Swingley, & Werker, 2004), the vowel length difference in our stimuli was much shorter. Vowels preceding voiced obstruents were on average 21 msec longer than vowels preceding voiceless obstruents. Acoustic analyses of the stimuli showed that the voiced stimuli had significantly longer vowels than the voiceless stimuli experiment, $t(19) = -2.09$, $p < .01$. However, we predict that infants cannot distinguish these small vowel-length differences. With the pairs ending in stops, the voiced stimuli had significantly longer voicing in the consonant than the voiceless stops, $t(9) = -6.22$, $p < .001$, and a significantly greater proportion of voicing during closure duration with the voiced stimuli than the voiceless stops, $t(9) = -19.37$, $p < .001$. From these stimuli, eight legal and eight illegal lists of nonwords were made. Each list contained 20 nonwords in different randomized orders. Nonwords were separated with 500-msec pauses. The length of the legal nonword lists was 20.66 sec and the length of the illegal nonword lists was 21.3 sec.

Procedure. The headturn preference procedure was used in this study (Kemler Nelson et al., 1995). Infants were held on a caregiver's lap facing a three-paneled booth. At the front center of the booth was a green light, and on the left and right were red lights and mounted loudspeakers. When the infant oriented toward the center green light, the trial would begin. The green light was then extinguished, and the light above the left or right loudspeaker would begin flashing. When the infant oriented toward the flashing light, a nonword list would begin playing. This would continue until the sound file was completed, or the infant looked away for 2 sec. Looking times less than 2 sec were not included in the analysis. Infants were given 12 trials (6 trials of each type). The order of the legal and illegal nonword trials was randomized. Both the caregiver and the experimenter listened to masking music during the experiment.

Results and Discussion

A repeated measures analysis of variance (ANOVA) was used with voicing (legal or illegal) as the within-subjects factor, and age (9 or 11 months) as the between-subject factor. There was no main effect for voicing, $F(1, 59) = 1.11$, $p = .30$ (looking times: legal $M = 9.35$ sec, $SD = 3.08$ sec; illegal $M = 9.71$ sec, $SD = 3.29$ sec), no main effect for age, $F(1, 59) = 0.82$, $p = .37$ (looking times: 9 months $M = 9.87$ sec, $SD = 3.14$ sec; 11 months $M = 9.20$ sec, $SD = 3.21$ sec), and no significant Voicing × Age interaction, $F(1, 59) = 1.03$, $p = .32$. These negative results were not expected given previous findings that have shown that 9-month-old infants have acquired knowledge about language-specific phonotactics and probabilistic phonotactics.

EXPERIMENT 2

There are a number of explanations for why infants did not show sensitivity to voicing neutralization. This might be due to (a) the position where voicing neutralization occurs, (b) the saliency of the voicing contrast, (c) learning, and (d) the nature of the phonotactic pattern tested. These possible accounts are tested in Experiment 2, which looks at infants' discrimination of the voicing contrast (t–d) and POA contrasts (p–t and p–k) in word-final position. We now turn to a discussion of these four accounts and how Experiment 2 addresses these possibilities. Before turning to this discussion, it is useful to review Table 1, which illustrates the Dutch voicing and POA contrast in word-initial position, the lack of a voicing contrast in word-final position, and the presence of a POA contrast in word-final position.

The first possible explanation is that infants did not perceive the pattern in Experiment 1 because the contrast occurs in word-final position. Previous research

has demonstrated that infants are less sensitive to patterns in word-final position as compared to word-initial position (Jusczyk et al., 1999). If positional factors account for the null results in Experiment 1, we predict that infants will also not discriminate the voice or POA contrasts in Experiment 2. Second, it is possible that infants may not be sensitive to voicing neutralization because the pattern involves a voicing contrast, which might be perceptually less salient than other types of contrasts. The saliency account predicts that infants will discriminate the POA contrasts, but not the voicing contrast in word-final position. Third, infants may have already learned that Dutch has no voicing contrast in word-final position. Therefore, they might have ignored the voicing contrast, as it is not a relevant contrast. Given this possibility, we tested infants' ability to perceive the voicing contrast in word-final position as compared to POA contrasts in word-final position that do occur in the language. If learning accounts for the null result in Experiment 1, we predict that infants will discriminate the POA contrast, but not the voicing contrast. Lastly, it is possible that no preference for voicing phonotactics was found because of the nature of the phonotactic pattern. Although voiced obstruents are restricted in position, they do occur in the language; therefore, knowledge about the phonotactics of contrast neutralization requires a more sophisticated knowledge of phonotactics than tested in previous studies. Regardless of whether infants have learned the phonotactic pattern, one might still predict that infants are able to discriminate legal versus illegal voicing phonotactics. This possibility is tested by looking at infants' ability to discriminate legal versus illegal voicing contrasts as compared to legal POA contrasts. To summarize, the first account predicts that infants will not discriminate voice or POA contrasts in word-final position, the second and third accounts predict that infants will discriminate only the POA contrasts, and the fourth account predicts that infants will discriminate both the voice and POA contrasts. We tested infants at 10 months, as this age group was between the 9- and 11-month-old age groups tested in the first two experiments.

Method

Participants. Fifty-four infants from Dutch monolingual speaking homes were tested, between the ages of 10.03 and 10.30 months (M = 10.23 months). Thirty-three additional infants were tested but not included in the analysis due to experimental error (n = 2), parent interference (n = 7), not completing the experiment due to fussiness or crying (n = 8), and no habituation (n = 16).

Materials. The stimuli consisted of multiple tokens of nonwords that were contrasted in word-final position for voicing ([kɛt] vs. [kɛd]), POA between labials and coronals ([kɛp] vs. [kɛt]), and POA between labials and velars ([tɛp] vs. [tɛk]). The stimuli were recorded and chosen the same way as in Experiment 1.

Acoustic analyses of the voicing contrast in word-final position showed that the tokens of [kɛd] had significantly longer vowels (on average 40 msec longer), significantly longer voicing in the consonant, and a significantly greater proportion of voicing during closure duration than tokens of [kɛt]. A habituation list and test list was made for each nonword. Each list contained 13 unique tokens. Tokens were separated with 500-msec pauses.

Procedure. A modified habituation procedure was used in this study (see Werker, Cohen, Lloyd, Casasola, & Stager, 1998). Infants were held on a caregiver's lap facing a large television screen. Each trial was preceded by a flashing red light. When the infant looked at the light, it was extinguished and the trial would begin. During the pretest and posttest trials, infants heard multiple tokens of the nonword [nem] paired with a visual waterwheel (see Werker et al., 1998). During habituation and test trials, infants heard multiple tokens of the relevant nonword, paired with a checkerboard with a colorful moving array. When the trial was complete, the red flashing light would be displayed again.

The experiment began with a pretest trial. Following this, the experiment had two phases: a habituation phase and a test phase. During habituation, the infant would hear multiple tokens of a single word. Habituation criterion was reached when infants' average looking time was 65% less than the average looking time across the first three trials, based on a sliding block criterion. Following Bosch and Sebastián-Gallés (2003), infants were tested on two "same" test trials (consisting of new tokens of the word presented during habituation), and two "switch" test trials, and the order of the same and switch trials was kept constant. Infants were habituated to a maximum of 16 habituation test trials. Infants who did not habituate were not included in the analysis. The experiment ended with a posttest trial that was identical to the pretest trial. Looking times between the pretest trial and posttest trial were compared to assess whether infants were attending to the task at the end of the experiment. Both the parents and the experimenter listened to masking music during the experiment.

Results and Discussion

The experimental sessions were digitized and coded offline. Looking times to pretest and posttest trials were compared. There was no significant difference in looking times to pretest and posttest trials, signifying that infants were attending to the task at the end of the experiment, $t(53) = 0.58$, $p = .56$. A repeated measures ANOVA was used with trial type (same or switch) as the within-subjects factor, and contrast (voice[t–d], place[p–t], or place[p–k]) as the between-subject factor. There was no main effect of trial type, $F(1, 51) = 0.18$, $p = .68$ (looking times: same $M = 6.21$ sec, $SD = 2.22$ sec; switch $M = 6.03$ sec, $SD = 2.74$ sec), no main effect for contrast, $F(2, 51) = 0.80$, $p = .48$ (looking times: voice[t–d] $M = 5.68$

sec, SD = 2.77 sec; place[p–t] M = 6.45 sec, SD = 2.07 sec; place[p–k] M = 6.21 sec, SD = 2.57 sec), and no Trial Type × Contrast interaction, $F(2, 51) = 0.52$, $p = .60$. The results suggest that infants' lack of sensitivity to voicing phonotactics is not due to the nature of the contrast tested, the saliency of voicing, or learning. Rather, the results suggest that positional factors played a role because neither the legal versus illegal voicing phonotactics, nor the legal POA contrasts in word-final position were discriminated by infants at the same age group.

EXPERIMENT 3

The results from Experiment 2 suggest that infants' lack of sensitivity to the phonotactics is partly due to the position in which the contrast appears. However, if the methodology used in Experiment 2 were not sensitive enough to replicate past findings, the results would be difficult to interpret. Therefore, we tested whether infants can perceive the same voicing and POA contrasts in word-initial position as found in previous studies using different methodologies (Eimas, 1974; Eimas, Siqueland, Jusczyk, & Vigorito, 1971).

Method

Participants. Thirty-six infants from Dutch monolingual speaking homes were tested, between the ages of 10.00 and 10.30 months (M = 10.14 months). Twenty-two additional infants were tested but not included in the analysis due to experimental error ($n = 4$), parent interference ($n = 7$), not completing the experiment due to fussiness or crying ($n = 3$), and no habituation ($n = 8$).

Materials. The stimuli consisted of multiple tokens of nonwords that were contrasted for voicing in word-initial ([tɔs] vs. [dɔs]), and POA word-initial between labials and coronals ([pɔs] vs. [tɔs]). Tokens were chosen to reflect the Dutch voicing contrast in word-initial position (prevoiced vs. voiced stops). The stimulus lists were created in the same way as in Experiment 2.

Procedure. The procedure was the same as in Experiment 2.

Results and Discussion

Digitizing and coding was the same as in Experiment 2. There was no significant difference in looking times to pretest and posttest trials, $t(35) = -0.69$, $p = .50$. A repeated measures ANOVA was used with trial type (same or switch) as the within-subjects factor, and contrast (voice or place) as the between-subject factor.

There was a main effect of trial type, $F(1, 34) = 10.36$, $p = .003$, $\eta_p^2 = .23$ (looking times: same = 5.59 sec, $SD = 2.05$ sec; switch = 6.87 sec, $SD = 2.28$ sec), no main effect of contrast, $F(1, 34) = 0.04$, $p = .85$ (looking times: voice = 6.29 sec, $SD = 2.54$ sec; place = 6.17 sec, $SD = 1.94$ sec), and no Trial Type × Contrast interaction, $F(1, 34) = 0.08$, $p = .79$. Planned comparisons (two-tailed paired t tests) were performed to assess infants' discrimination in each contrast condition. Infants tested on the voicing contrast in word-initial position showed significant discrimination, $t(17) = -2.25$, $p < .05$ (looking times: same = 5.59 sec, $SD = 2.28$ sec; switch = 6.98 sec, $SD = 2.66$ sec), as did infants tested on the POA contrast in word-initial position, $t(17) = -2.34$, $p < .05$ (looking times: same = 5.58 sec, $SD = 1.85$ sec; switch = 6.76 sec, $SD = 1.9$ sec). The results illustrate that infants were able to perceive the same voicing and POA contrasts in word-initial position, which they were not able to discriminate in word-final position. Moreover, Experiment 3 replicated earlier results using a different methodology; therefore, the methodology used in Experiment 2 was appropriate.

EXPERIMENT 4

Although previous studies have shown that infants are less sensitive to patterns in word-final position (Jusczyk et al., 1999), learners must acquire the patterns in final position to become fluent language users. In many languages, crucial grammatical information occurs at the ends of words, such as plural suffixes on nouns. Moreover, in a language like Dutch, it is necessary that at some point in development learners are able to perceive POA contrasts in word-final position because there are minimal pairs that contrast in the language with POA (see Table 1). As a final test, we looked at older infants' ability to perceive voicing and POA contrasts in word-final position.

Method

Participants. Twenty-four infants from Dutch monolingual speaking homes were tested, between the ages of 15.11 and 16.27 months (M = 16.04 months). Twelve additional infants were tested but not included in the analysis due to parent interference ($n = 4$), not completing the experiment due to fussiness or crying ($n = 3$), and no habituation ($n = 5$).

Materials. The materials were a subset of those used in Experiment 2: a voicing contrast in word-final position ([kɛt] vs. [kɛd]), and a labial-coronal POA contrast in word-final position ([kɛp] vs. [kɛt]).

Procedure. The procedure was the same as in Experiment 2.

Results and Discussion

Digitizing and coding was the same as in Experiment 2. There was no significant difference in looking times to pretest and posttest trials. A repeated measures ANOVA was used with trial type (same or switch) as the within-subjects factor, and contrast (voice or place) as the between-subject factor. The effect of trial type on looking time was marginally significant, trial type, $F(1, 22) = 3.91$, $p = .06$ (looking times: same = 6.53 sec, $SD = 2.94$ sec; switch = 7.82 sec, $SD = 2.90$ sec), no main effect of contrast, $F(1, 22) = 0.07$, $p = .8$ (looking times: voice = 7.04 sec, $SD = 2.33$ sec; place = 7.30 sec, $SD = 3.52$ sec), and no Trial Type × Contrast interaction, $F(1, 22) = 1.54$, $p = .79$. Planned comparisons were performed to assess infants' discrimination in each contrast condition. Infants tested on the voicing contrast in word-final position did not show significant discrimination, $t(11) = -0.65$, $p = .65$ (looking times: same = 6.80 sec, $SD = 2.13$ sec; switch = 7.28 sec, $SD = 2.59$ sec); however, infants tested on the labial-coronal POA contrast in word-final position did show significant discrimination, $t(11) = -2.59$, $p < .05$ (looking times: same = 6.26 sec, $SD = 3.65$ sec; switch = 8.35 sec, $SD = 3.21$ sec). The results suggest that at an older age, positional factors alone cannot account for infants' discrimination in final position. Infants were able to discriminate the POA contrast, but not the voicing contrast. Infants may perceive the POA contrast because it is more salient than the voicing contrasts (combined with positional factors), or infants may have learned that Dutch has no voicing contrast in word-final position and as a result, they may have ignored the voicing contrast.

GENERAL DISCUSSION

The findings suggest that infants' knowledge of phonotactics is not as sophisticated as previously assumed. Nine- and 11-month-old Dutch-learning infants did not display knowledge of legal versus illegal voicing phonotactics in word-final position. Moreover, Dutch-learning infants at 10 months did not show evidence of discriminating voicing or POA contrasts in word-final position, although they were able to discriminate the same voice and POA contrasts in word-initial position. By 16 months, infants were able to discriminate the POA contrast in word-final position, but still unable to discriminate the voice contrast. There are three broad implications that can be drawn from these findings for models of how learners acquire the phonological structure of their language, for the types of phonotactic structures that we assume infants are sensitive to at different ages, and for how syllable- and word-position effects emerge during acquisition. Although the implications of these studies are based in part on null results, they are nevertheless suggestive.

At the start of the study, we set out to explore the acquisition of voicing neutralization. Importantly, learnability models that account for how phonology is

acquired assume that infants have acquired knowledge of contrast neutralization within the first year, and that this knowledge can be utilized in the acquisition of morphophonological alternations. The results from Experiment 1, however, suggest that further studies are needed to pinpoint when infants learn neutralization phonotactics. Not only is phonotactics a broad term, but languages differ in how contrasts are neutralized. For example, whereas in Dutch, voicing is neutralized in final position, an interesting parallel occurs in the Lac Simon dialect of Northern Algonquin, in which voicing is neutralized in initial position (Iverson, 1982). This provides an interesting test case for positional effects in the acquisition of voicing neutralization. Presumably the Lac Simon alternation would be easier to acquire because it involves word-initial position, even though it is less common across languages to have neutralization in initial position.[4] Further studies looking at acquisition in different languages will be informative in determining the types of phonotactic knowledge that infants acquire at different stages of development.

The findings reported here were unexpected given previous research showing that 9-month-old infants are sensitive to language-specific phonotactics and probabilistic phonotactics. This leads to the second implication of these findings. We noted in the introduction that previous results have largely been based on infants' sensitivity to segmental sequencing, whereas this study looked at singleton segments. This difference might also account for why infants do not show a preference or discrimination for patterns of singleton segments in word-final position as seen in this research or in Jusczyk et al. (1999). The phonotactic pattern tested in this research is also very different than those tested in previous studies: Experiment 1 looked at contrast neutralization, whereas previous studies have looked at language-specific phonotactics and probabilistic phonotactics. To acquire the pattern of Dutch voicing neutralization, infants must learn that the voicing contrast is restricted to a specific position. Although some studies have attempted to test whether infants can track segmental distributions in different positions (Chambers et al., 2003; Saffran & Thiessen, 2003), no studies have tested whether infants can track segmental restrictions in a specific position, as in the case of voicing neutralization in Experiment 1. This type of phonotactic pattern might not be acquired until later in infancy or even in early childhood. A recent study investigated children's productive knowledge of voicing neutralization and morphophonological alternations (Zamuner, Kerkhoff, & Fikkert, 2005). Children were presented with novel plurals with /t/ or /d/ (e.g., *slatten* [slɑtə] or *sladden* [slɑdə]) and asked to produce singulars, which should always end in [t] due to voicing neutralization (e.g., [slɑt]. Children produced significantly more

[4]As one reviewer noted, because voicing in Lac Simon only occurs in final position, it is possible that learners of Lac Simon would first incorrectly learn that voicing is not contrastive in the language.

singulars for plural nonwords with /t/ (e.g., *slatten*) than /d/ (e.g., *sladden*). That is, children were better at producing singulars when they were not required to draw on knowledge of voicing neutralization. For words with /d/, children gave almost all plural responses (e.g., *one sladden*). This suggests that children do not have a robust knowledge of voicing neutralization, even as late as 3 years of age. We do not know, however, whether these children have learned their language-specific voicing phonotactics. The tasks used were very different: Infants in Experiment 1 were tested on their preference for legal versus illegal voicing phonotactics and children in the Zamuner et al. (2005) study were tested on their productive knowledge of voicing neutralization. Further studies are needed with older infants and young children to test their knowledge of voicing phonotactics independent from their knowledge of morphophonological alternations (e.g., see Broersma, 2005, who found that adult speakers of Dutch can correctly categorize the English voicing contrast in word-final position).

Lastly, the findings are interesting because they point to positional effects in the acquisition of phonotactics. As noted in the introduction, studies that have found infants' sensitivity to language-specific phonotactics and probabilistic phonotactics in word-final position are also the studies that have tested infants' knowledge of the sequential ordering of segments rather than looking at segmental restrictions in a specific position. The failure to find a preference for legal voicing phonotactics in Experiment 1 suggests that previous findings do not extend to infants' knowledge of neutralization phonotactics, which typically occurs in syllable- or word-final position. Aside from studies of phonotactics, the majority of studies have focused primarily on infants' sensitivity to contrasts in word-initial or word-medial position. Those studies that have looked at both find that infants' ability to perceive patterns in final position are worse than in other positions.

One remaining issue is the discrepancy between Jusczyk (1977), which found that 2-month-old infants could discriminate the word-final contrast between /d/–/g/ in *bad* and *bag*, and this study, in which 10-month-old infants did not discriminate the word-final contrast between /p/–/t/ in *kep* and *ket* or /p/–/k/ in *tep* and *tek*. This discrepancy might reflect the vowel used in the studies (/æ/ versus /ɛ/, respectively). Some vowels (e.g., /a/; Smits, Ten Bosch, & Collier, 1996) provide more information about the POA of adjacent consonants as compared to other vowels. The difference between the two studies might also reflect the difficulty of perceiving voicing and the potentially greater ease of discriminating POA contrasts with voiced segments. In Jusczyk's study the POA contrast was made on voiced stops, whereas in this study the POA contrast was on voiceless stops. Alternatively, the young infants in Jusczyk's study may have discriminated the stimuli based on purely auditory cues, whereas the older infants in this study may have approached this task using a phonetic mechanism (Jusczyk, 1997). This same possibility might account for why 6- to 8-month-old infants in the Eilers et al. (1977) study were able to discriminate the word-final voicing contrast. Recall that infants were only able to discriminate the contrast when both voicing cues

and vowel length cues were present. English-learning infants may attend to the voicing and vowel length cues, whereas the Dutch-learning infants may not attend to these cues. (The vowel length cues in the Eilers et al. study were considerably longer. In the pairs that were discriminated, vowel length differences ranged from ~80 msec to 150 msec.) The results presented here illustrate that more studies are needed to test other contrasts in word-final position at different times in development. Positional effects such as those found in this article might reflect infants' developing lexical representations and lexical processing. Word onsets have an advantage in word recognition partly due to their perceptual saliency and more consistent production as compared to word-final position, where contrasts are less salient, produced with more variability, and are less likely to be produced in a canonical form (Gow, Melvold, & Manuel, 1996; Greenberg, Carvey, Hitchcock, & Chang, 2003; Manuel, 1991).

In summary, we have identified several implications from these findings for models of learnability on phonological acquisition, for the types of phonotactic structures to which infants are sensitive, and for potential positional effects in the acquisition of phonotactics. We have demonstrated that previous studies showing infants' sensitivity to language-specific phonotactics and probabilistic phonotactics does not necessarily extend to other phonotactic patterns, especially given the fact that contrast neutralization typically occurs in syllable- or word-final position. Thus, more studies are needed on phonotactic acquisition to help us determine the nature of and the potential limitations of infants' knowledge of phonotactics.

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APPENDIX

Experiment 1 and 2: Dutch Nonwords Ending in Phonotactically Legal Voiceless Obstruents and Phonotactically Illegal Voiced Obstruents

Voiceless	bɑp, bɪf, bɪp, dep, fit, fet, fot, fus, kaf, kɛs, mif, mɪt, nes, nip, nøt, paf, pop, tɛs, tɪf, tus
Voiced	bɑb, bɪv, bɪb, deb, fid, fed, fod, fuz, kav, kɛz, miv, mɪd, nez, nib, nød, pav, pob, tɛz, tɪv, tuz