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Infants' Sensitivity to Phonotactic Patterns in the Native Language

PETER W. JUSCZYK AND PAUL A. LUCE

Department of Psychology and Center for Cognitive Science, State University of New York at Buffalo, Buffalo, New York

AND

JAN CHARLES-LUCE

Department of Communicative Disorders and Sciences and Center for Cognitive Science, State University of New York at Buffalo, Buffalo, New York

There is increasing evidence that during the latter half of their first year, infants begin learning about the organization of sound patterns in their native language. The present study investigated whether American infants are sensitive to the frequency with which certain phonetic patterns appear in English words. Two types of lists of monosyllables were presented using the headturn preference procedure. High-probability lists contained items with phonetic patterns that occur frequently in English words. Low-probability lists were composed of items with phonetic patterns that appear infrequently in English words. Nine-month-olds, but not 6-month-olds, listened significantly longer to the high-probability lists. A follow-up experiment indicated that the 9-month-olds' preference for the high-probability lists occurs even when the lists are matched in terms of vowel quality. We discuss the implications of this preference for frequently appearing phonetic patterns for word recognition and the development of the mental lexicon.

Language learning depends, in large part, on the encoding and storage of representations of sound patterns of words in memory. In particular, the infant must acquire a mental lexicon consisting of phonetic representations that are sufficiently structured and detailed to eventually allow for the rapid and efficient recognition of spoken words exhibited by adults. There are at least two major tasks that infants face in learning to recognize spoken words: First, infants must learn to discriminate among the speech sounds that make up words and, second, they must learn something about the patterns of sounds in their native language. There is a growing body of evidence that demonstrates infants' early capacities for discrimination as well as their remarkable sensitivities to regularities in the sound patterns of their native language.

Infants' capacities for perceiving fine distinctions among speech sounds have now been well documented (Aslin, Pisoni, & Jusczyk, 1983; Jusczyk, in press; Kuhl, 1987). Moreover, the broad capacities that infants have for distinguishing among speech contrasts that could occur in any language appear to become more refined and tuned more specifically to native language contrasts at some time during the first year of life (Best, 1991; Best & McRoberts, 1989; Best, McRoberts, Goodell, Womer, Insabella, Klatt, Luke, & Silver, 1990; Best, McRoberts, & Sithole, 1988;

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Werker & Lalonde, 1988; Werker, Lloyd, Pegg, & Polka, 1993; Werker & Tees, 1984). Nevertheless, developing word recognition skills requires considerably more than the ability to discriminate one sound pattern from another. At a minimum, one also needs to recognize the occurrence of regular patterns in the input, along with some capacity to store these patterns and associate them with meanings.

Recent evidence suggests that infants begin to learn about regular features of native language sound patterns during the first year. At a global level of organization, there is evidence that American 9-month-olds, but not 6-month-olds, are sensitive to prosodic marking of major phrasal units in English utterances (Jusczyk, Kemler Nelson, Hirsh-Pasek, Kennedy, Woodward, & Piwoz, 1992). That infants must learn about any such prosodic marking in their native language is suggested by the fact that such marking is more apt to occur in languages for which word order is constrained (as in English) than for those that allow free word order (as in Polish). In addition, there are indications that infants around this age have begun to learn about more fine-grained features of native language sound structure. Kuhl and her colleagues (Kuhl, 1991; Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992) report that by 6 months, infants have begun to organize some native language vowel categories around prototypical instances. In particular, they are much more apt to generalize to a prototypical instance from a native language vowel category than they are to a prototypical instance from a foreign language vowel category.

Furthermore, results of several recent studies suggest that infants are sensitive to the kinds of regularities in native language input that could prove useful in segmenting words from fluent speech. One of these studies focused on sensitivity to prosodic (or suprasegmental) properties of native language words. Jusczyk, Cutler, and Redanz (1993a) found that American 9-month-olds, but not 6-month-olds, demonstrate significant listening preferences for words that follow the predominant (strong/weak) stress pattern of English words. Cutler and her colleagues (Cutler, 1990; Cutler & Butterfield, 1992; Cutler & Carter, 1987; Cutler & Norris, 1988) have noted the high proportion of words following this stress pattern in conversational speech and proposed that one could draw upon this information as a first approximation to the locus of word boundaries in fluent speech. The demonstration that by 9 months, American infants are apparently sensitive to the predominant stress pattern of English words indicates that they are well positioned to use such information to begin segmenting words from the speech stream.

Another investigation (Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993b) examined infants' sensitivity to segmental properties of native language words. Specifically, Jusczyk et al. explored when infants begin to learn about the phonotactic properties (i.e., constraints on the possible sequencing and positions of phonetic segments allowed in words) of native language words. Infants listened to lists of words from two languages (Dutch and English) that have similar prosodic characteristics but differ in their phonetic properties and phonotactic organization. Each list contained words from one language that violated the phonetic structure or phonotactic constraints in the other language. At 9 months, but not at 6 months, American infants listened significantly longer to the English lists. To investigate whether the infants responded because they had learned about phonetic and phonotactic properties of native language words, an additional experiment was conducted with both Dutch and American 9-month-olds. Both the Dutch and American 9-month-olds listened longer to the lists in their own native language. Also, Friederici & Wessels (1993) have recently demonstrated that Dutch 9-month-olds listen longer to monosyllabic words that contain sequences which are phonotactically legal within the language versus ones that are phonotactically illegal (i.e., word onset clusters vs. word offset clusters). Hence, by 9 months of age, infants have picked up some information about the phonetic patterns and phonotactic sequences in words in their native language. Knowledge about constraints on the position in which phonetic segments can appear is another potential source of information that can be tapped in locating word boundaries in fluent speech perception (Church, 1987).

The present study attempted to extend these previous findings by examining infants' potential sensitivity to the organization of sound patterns *within* their native language. In particular, we were interested in determining whether infants prefer sound patterns that are typical or highly probable in English, compared to patterns that—although perfectly legal and acceptable in English—are nonetheless relatively atypical or less probable. If infants prefer to listen to more typical sound patterns in the language, this would strongly suggest that early on they encode and represent detailed information about the structure of phonotactic sequences of spoken words. Given the research demonstrating that adult spoken word recognition is influenced by the structure of sound patterns and the relations among these patterns in the mental lexicon (Auer & Luce, 1993; Landauer & Streeter, 1973; Luce, Pisoni, & Goldinger, 1990; Massaro & Cohen, 1983), we were interested in examining the development of infants' sensitivity to the structure of spoken words.

In order for the frequency of certain phonetic sequences to play any role in the development of word recognition processes, infants must first attend to the way that these sequences are distributed in the input. Results of the studies reviewed above suggest that infants between 6 and 12 months develop sensitivity to a number of different aspects of native language sound structure. Thus, they respond to differences in the organization of native vs. nonnative phonetic categories (Best, 1991; Kuhl et al., 1992; Werker & Tees, 1984) and phonotactic patterns (Jusczyk et al., 1993b). Even among the sequences permitted in their native language, they appear to attend more closely to frequently occurring prosodic patterns (Jusczyk et al., 1993a). The aim of the present investigation was to determine whether infants at the beginning stage of organizing a mental lexicon are attuned to the distribution of phonetic patterns in the input.

Experiment 1

One indication that infants have detected some regular feature of native language sound patterns is that they tend to listen longer to stimulus materials embodying that feature than to ones without the feature. For example, in their study of infants' sensitivity to native language phonetic and phonotactic properties, Jusczyk et al. (1993a) found that 9-month-olds listened significantly longer to lists of items that observed the phonetic and phonotactic constraints of their native language than they did to ones which violated these constraints. We decided to employ the same measure in the present study. A trained phonetician (J.C.L.) recorded two different types of lists of monosyllabic nonwords.' One list contained nonword stimuli with frequently occurring phonetic patterns—the *high-probability* phonotactic pattern list; the other list contained nonword stimuli with infrequently occurring patterns—the *low-probability* phonotactic pattern list (see below for a complete description). To the extent that infants register information about how such sequences are distributed in the input, we expected that they would listen longer to lists containing frequently occurring phonetic patterns. Previous research using the headturn preference procedure indicated that infants first demonstrate sensitivity to properties of native language sound patterns some time between 6 and 9 months of age (Jusczyk et al., 1993a, 1993b, 1992). Accordingly, we examined whether 9-month-olds would show any tendency to prefer the lists composed of words with frequently occurring phonotactic patterns.

Method

Subjects. Twenty-four American infants of approximately 9 months of age were tested. The infants were an average age of 38 weeks, 5 days (range: 37 weeks, 0 days to 40 weeks, 3 days). Six additional infants were tested but not included for the following reasons: crying (4), failing to look for an average of 3 s to each side (1), and experimenter error (1).

Stimulus materials. Two master lists, each consisting of 120 consonant–vowel–consonant (CVC) nonwords, were constructed. One list contained high-probability phonotactic patterns and the other low-probability phonotactic patterns. Examples of the stimuli are given in Table 1 and a complete listing of all the stimuli used in the experiments is presented in the Appendix. We operationally defined phonotactic probability based on two measures: (1) positional phoneme frequency (i.e., how often a given segment occurs in a position within a word) and (2) biphone frequency (i.e., the phoneme-to-phoneme cooccurrence probability). These metrics were originally computed using the approximately 20,000 phonetic transcriptions in an on-line version of *Webster's Pocket Lexicon* (1967). All probabilities were computed based on log frequency-weighted values (Auer & Luce, 1993; Kucera & Francis, 1967). The average summed phoneme probability was .1926 for the high-probability pattern list and .0543 for the low-probability pattern list. The average summed biphone probability (e.g., the probability of a /b/ and /æ/ occurring together and of /æ/ and /t/ occurring together for /bæt/) was .0143 for the high-probability lists and .0006 for the low-probability lists.[1]

A high-probability pattern consisted of segments with high phoneme positional probabilities. For example, in the high-probability pattern /ɹIs/ ("riss"), the consonant /ɹ/ is relatively frequent in initial position, the vowel /I/ is relatively frequent in the medial position, and the consonant /s/ is relatively frequent in the final position. A high-probability phonotactic pattern also consisted of frequent segment-to-segment cooccurrence probabilities. In particular, we chose CVC phonetic patterns whose initial consonant-to-vowel cooccurrences and vowel-to-final consonant cooccurrences had high probabilities of occurrence in the computerized database. For example, for the pattern /ɹIs/, the probability of the cooccurrence /ɹ/ to /I/ was high, as was the cooccurrence of /I/ to /s/.

Low-probability phonotactic patterns consisted of CVCs with low positional phoneme probabilities and low segment-to-segment cooccurrence probabilities. For example, in the low-probability pattern /jaʊdʒ/ ("yowdge," rhymes with "gouge"), each of the segments are relatively rare in their respective positions. In addition, the cooccurrence of /j/ and /aʊ/ and the cooccurrence of /aʊ/ and /dʒ/ are also relatively infrequent. Although the low-probability patterns contained infrequent segments and transitions, none of the stimuli in either of

TABLE 1
EXAMPLES OF EXPERIMENTAL STIMULI FOR HIGH AND LOW PROBABILITY PHONOTACTIC PATTERNS FOR EXPERIMENT 1

High probability	Low probability
[ɹIs] "riss"	[jaʊʤ] "youdge"
[gɛn] "ghen"	[ʃɔʧ] "shawch"
[kæz] "kazz"	[guʃ] "gushe"

[1] The difference in the magnitudes of the phoneme and biphone probabilities reflects the fact that there are many more biphones than phonemes. Thus, biphones have a lower probability of occurrence overall than phonemes because the same total probability (i.e., 100) is divided among many more possible outcomes for the biphones than for the phonemes.

the lists contained positional phonemes or transitions that did not exist in the lexicon. Thus, all stimuli were composed of phonotactically legal sequences in English.

Equal numbers of stimuli in the high-probability master list contained one of the three vowels /I, ɛ, æ/; equal numbers of stimuli in the low-probability master list contained one of the three vowels /aʊ, ɔ, u/. The two master lists were each divided into eight lists of 15 stimuli, with each list containing an equal number of the three vowels from the master list. Altogether, we constructed sixteen lists of stimuli, eight consisting of high-probability patterns and eight consisting of low-probability patterns. The average stimulus durations of the high- and low-probability lists, measured from a digital waveform display, were 588 ms (SD = 101) and 609 ms (SD = 95), respectively.

Our probability estimates for the different list types reflect those of an adult-directed speech corpus. We also recalculated these phoneme and biphone frequencies based on a sample of child-directed speech, namely the Bernstein (1982) corpus available in MacWhinney (1991). The phoneme and biphone frequencies obtained using this child-directed speech corpus accord well with those based on the Webster's Pocket Lexicon. In particular, the average summed phoneme frequencies were .1822 and .0706 for the high- and low-probability lists, respectively. Similarly, the average summed biphone frequencies were .0095 and .0016 for the high- and low-probability lists, respectively. Thus, regardless of whether one calculates frequency estimates from adult- or child-directed speech corpora, the phoneme and biphone probabilities are substantially higher for items in the high-probability than for the low-probability phonotactic lists.

The words were recorded and digitized at a sampling rate of 10 kHz via a 12-bit analog-to-digital converter. The recordings were made in a sound attenuated room with a Shure microphone by a trained phonetician. The lists were assembled with a 1-s silent interval between successive words. Digitized versions of the lists were transferred to a PDP 11/73 computer for playback during the experiment. Four of the lists (two high- and two low-probability) were chosen for the familiarization trials; the remaining lists were used on the test trials. The ordering of the stimuli during the test trials was random, subject to the constraint that no more than three lists of the same type could occur in a row. A different random order of stimulus presentation was used for each subject.

Apparatus. A PDP 11/73 controlled the presentation of the lists and recorded the observer's coding of the infant's responses. The audio output for the experiment was generated from the digitized waveforms of the samples. A 12-bit D/A converter was used to recreate the audio signal. The output was fed through anti-aliasing filters and a Kenwood audio amplifier (KA 5700) to 7-inch Advent loudspeakers mounted on the side walls of the testing booth.

The experiment was conducted in a three-sided test booth constructed of pegboard, with panels of 4 by 6 ft on three sides and open at the back. This made it possible for an observer to look through one of the existing holes to monitor the infant's headturns. Except for a small section for viewing the infant, the remainder of the pegboard was backed with white cardboard to guard against the possibility that the infant might respond to movements behind the panel. The test booth had a red light and a loudspeaker mounted at eye level on each of the side panels, and a green light mounted on the center panel. A white curtain suspended around the top of the booth shielded the infant's view of the rest of the room. A computer terminal and response box were located behind the center panel, out of view of the infant. The response box, which was connected to the computer, was equipped with a series of buttons that started and stopped the flashing center and side lights, recorded the direction and duration of headturns, and terminated a trial when the infant looked away for more than 2 s. Information about the direction and duration of headturns and the total trial duration were stored in a data file on the computer.

Procedure. The version of the headturn preference procedure used by Jusczyk et al. (1993a) was employed in the present study. Each infant was held on a caregiver's lap. The caregiver was seated in a chair in the center of the test booth. The infant completed a 4-trial familiarization phase (two lists of each type: high- and low-probability) and a 12-trial test phase. The high-probability lists were consistently played through the loudspeaker on one side panel, and the low-probability lists through the loudspeaker on the other side panel. (The side was counterbalanced across subjects.) The familiarization phase was intended to acquaint the infant with the assigned position of each type of list. During the test phase, the infant heard six lists of each type.

Each trial began by blinking the green light on the center panel until the infant had oriented in that direction. Then, the center light was extinguished and the red light above the loudspeaker on one of the side panels began to flash.[2] When the infant made a headturn of at least 30° in the direction of the loudspeaker, the next list appropriate to that side began to play and continued until its completion or until the infant failed to maintain the 30° headturn for 2 consecutive seconds (e.g., if the infant turned back to the center or the other side or looked at the mother, the floor, or the ceiling). If the infant turned briefly away from the target by 30° in any direction, but for less than 2 s, and then looked back again, the time spent looking away was not included in the orientation time. During the familiarization trials, the red light was extinguished when the list began, but during the test trials, the light remained on for the entire duration of the trial.

An observer hidden behind the center panel looked through a peephole and recorded the direction and duration of the infant's headturns using a response box. The observer was not informed as to which loudspeakers played the two different types of lists. This was possible because the assignment of the versions to the left or right side was determined by the computer and not revealed to the observer until the completion of the test session. The loudness levels for the samples were set by a second assistant, who was not involved in the observations, at 72 ± 2 dB (C) SPL using a Quest (Model 215) sound level meter. In addition, both the observer and the infant's parent listened over tight-fitting closed headphones (SONY MDR-V600) to a tape recording of lists of randomly ordered and closely spaced items from both types of lists produced by the same talker who had recorded the test stimuli. This tape masks the test stimuli. Parents and observers reported that with this background they were unaware of either the location or the nature of the stimulus on the trial.[3]

[2] During the familiarization trials, the blinking red light was extinguished as soon as the infant oriented to the side and the list began to play. However, during the test trials, the blinking light remained on until the trial ended. Extensive pilot testing in previous studies (e.g., Jusczyk et al., 1992) convinced us that this was the best way to handle the lights during the procedure. Leaving the flashing light on during the familiarization trials seemed to habituate the infants to the lights, and resulted in very short orientation times during the test trials. Moreover, the infants were also less likely to complete the full set of test trials under these circumstances.

[3] To test the effectiveness of maskers in preventing the experimenter and caregiver from hearing the stimuli during the course of the experiment, Kemler Nelson, Jusczyk, Mandel, Myers, Turk, and Gerken (in press) recently completed a series of control studies with adult subjects. They found that adults sitting inside the test apparatus performed nearly flawlessly in discriminating the two types of stimuli when no auditory masker was present. Next, the same subjects were asked to perform the task once again while wearing headphones and listening to masking stimuli (played at the same sound level as used in the present study). They were told they might have great difficulty in hearing the stimuli and to use the flashing side lights as an indication of when a sample was playing. They

Results and Discussion

The amount of time that each infant oriented to the loudspeaker on each trial was recorded. The average looking time was 10.21 s (SD = 2.89 s) for the high-probability lists and 8.16 s (SD = 2.65 s) for the low-probability lists. Nineteen of the 24 infants had longer listening times for the high-probability lists. A paired t-test confirmed that the difference in orientation times to the two types of lists was significant, $t(23) = 2.73$, $p < .001$. Thus, the present results indicate that 9-month-olds do listen longer to lists having items with highly probable phonotactic patterns. The longer listening times to the high-probability lists may reflect the fact that the infants have registered something about the frequency of certain phonotactic patterns in the input. However, it is also possible that the longer listening times are not due to anything that the infants picked up about the distribution of such properties in the input but that the high-probability items are simply more interesting to listen to. If the latter is true, and experience with the input is not a major determinant of infants' listening preferences, then even younger infants, such as 6-month-olds, should listen longer to the high-probability than to the low-probability patterns.

EXPERIMENT 2

As noted earlier, there is now considerable evidence that during the first year of life infants are learning about many aspects of the organization of sound patterns in the native language. Not only do they begin learning about phonetic categories and their internal organization (Best, 1991; Kuhl et al., 1992; Polka & Werker, in press; Werker & Tees, 1984), but they also begin to demonstrate some sensitivity to the way that phonetic and prosodic patterns are organized in their native language (Jusczyk et al., 1993a, 1993b). Although many of the documented changes in sensitivity to native and nonnative language patterns appear to occur some time after 6 months of age (Best, 1991; Jusczyk et al., 1993a, 1993b; Werker & Lalonde, 1988), certain types of changes may occur even before 6 months (Jusczyk et al., 1993a; Kuhl, 1991; Kuhl et al., 1992; Polka & Werker, in press). For example, Jusczyk et al. (1993b) found that 6-month-olds are sensitive to differences in the prosodic patterns associated with native and nonnative language words. Moreover, Polka and Werker (in press) report evidence suggesting that vowel categories may undergo an earlier reorganization into language-specific categories than do consonant categories. Nevertheless, our understanding of developmental changes in speech processing capacities during infancy is incomplete. Much remains to be determined not only about the underlying mechanisms responsible for these changes (Best, 1993; Jusczyk, 1993; Kuhl, 1993; Werker & Tees, 1992), but also about when sensitivity to various aspects of native language sound structure develops. For these reasons, we decided to examine how 6-month-olds' would respond to the items on the high- and low-probability lists.

Method

Subjects. Twenty-four infants of approximately 6 months of age were tested. The infants were an average age of 26 weeks, 1 day (range: 22 weeks, 6 days to 29 weeks, 4 days). Seven additional infants were tested but not included for the following reasons: crying (4), experimenter error (1), parental interference during the procedure (1), and failing to look for an average of 3 s to each side (1).

Stimulus materials, apparatus, and procedure. These were identical to those in Experiment 1.

were told to respond on each trial even if they had to guess. With the masker present, subjects performed at chance in discriminating the two types of stimuli. Thus, the masker was effective in preventing listeners from discriminating the two types of samples.

Results and Discussion

The amount of time that each infant oriented to the loudspeaker on each trial was recorded. The average looking time was 9.72 s (SD = 3.17 s) for the high-probability lists and 10.37 s (SD = 2.99 s) for the low-probability lists. Twelve of the 24 infants had longer listening times for the high-probability lists. A paired t-test indicated that the difference in orientation times to the two types of lists was not significant, $t(23) = 1.06$, $p = .30$.

The present results indicate that, unlike 9-month-olds, 6-month-olds do not listen longer to those lists with items with highly probable phonotactic patterns. This result suggests that it is not simply the case that the items from the high-probability lists are more interesting to listen to. If so, then the 6-month-olds should have behaved like the 9-month-olds by showing significantly longer listening times to the high-probability lists. Instead, the data from these two experiments support the view that any preference for the items from the high-probability lists develops some time between 6 and 9 months of age.

We verified the developmental difference in the performance of the 6- and 9-month-olds in two ways. First, for all the infants in Experiments 1 and 2, we computed difference scores based on each infant's looking times to the high-probability lists minus those for the low-probability lists. The mean difference score was 2.05 s (SD = 2.72 s) for the 9-month-olds and -0.65 s (SD = 3.0 s) for the 6-month-olds. A t test for independent samples confirmed that the two age groups differed significantly in this respect, $t(46) = 3.26$, $p < .005$. Second, we invited the parents of the 6-month-olds to return to the laboratory when their infants were 9-months-old. Fifteen of the original 24 subjects returned and successfully completed testing. One additional infant was recruited and tested at both ages. Thus, there was a total of 16 infants in this longitudinal sample. At 6 months of age, the average looking time was 10.94 s (SD = 2.95 s) for the high-probability lists and 10.74 s (SD = 3.33 s) for the low-probability lists. This difference was not significant, $t(15) = 0.29$, $p = .77$. However, at 9 months of age, the same infants had average looking times of 10.79 s (SD = 2.97 s) for the high-probability lists and 8.38 s (SD = 2.71 s) for the low-probability lists, which is a significant difference, $t(15) = 3.31$, $p < .01$. So, by 9 months of age, these infants displayed a clear preference for the high-probability lists. A 2 (Age) × 2 (List type) ANOVA was used to compare listening preferences at 6 and 9 months of age. There was a significant main effect for List Type, $F(1,15) = 5.60$, $p < .04$, but no main effect for Age, $F(1,15) = 3.15$, $p > .05$. However, as expected there was a significant Age × List Type Interaction, $F(1,15) = 5.59$, $p < .04$, indicating a significant developmental change between 6 and 9 months. It is also interesting that the nature of the change was that listening times to the low-probability samples were shorter at the older age. This trend is in the same direction as that observed for listening times to foreign language words in the study by Jusczyk et al. (1993b). It may be indicative of a tendency for language learners at this stage to seek out regularities (or "islands of reliability") in the input.

To summarize, the results of these first two experiments show that between 6 and 9 months of age, infants begin to listen more attentively to items in which the positional phoneme probabilities and the segment-to-segment cooccurrence probabilities tend to be high. This may be an indication that, at a time when the mental lexicon is beginning to form, infants are seeking out regularly occurring sound patterns in the speech stream. However, inspection of the stimuli from both types of lists indicated that there was no overlap in the particular vowels that appeared in the items from the two different types of lists. The vowels for the items on the high-probability lists were [I, æ, ɛ], whereas the low-probability lists contained the vowels [aʊ, u, ɔ]. Perhaps what the 9-month-olds picked up about native language sound patterns has to do more with frequently occurring vowels than with frequently occurring consonants or sequences of consonants and vowels. To examine this issue, we conducted a follow-up experiment.

EXPERIMENT 3

In selecting stimuli for the first two experiments, we endeavored to create lists which differed maximally in positional phoneme probabilities as well as cooccurrence probabilities among adjacent segments. Because there are differences in the frequency with which certain vowels appear in English words, the infrequently occurring vowels are more likely to occur in items on the low-probability lists. Is it possible that infants were simply responding to vowel quality differences on the lists? Recent research by Polka and Werker (in press) and by Kuhl and her colleagues (Kuhl, 1991; Kuhl et al., 1992) suggests that infants may develop sensitivity to the nature of native language vowel categories at an earlier age than they do for consonantal categories. Could sensitivity to vowel information have played a role in the tendency for 9-month-olds to listen longer to the high-probability phonotactic lists? To examine this possibility, we constructed new lists of items in which the same five vowels [ʌ, aI, i, e, ɝ] appeared in both types of lists. If infants are truly sensitive to the overall composition of the items—and not simply to differences in vowel quality—then they should still exhibit differential listening times regardless of the fact that the vowels are identical in the two lists.

Methods

Subjects. Twenty-four infants of approximately 9 months of age were tested. The infants were an average age of 40 weeks, 4 days (range: 39 weeks, 0 days to 42 weeks, 0 days). Three additional infants were tested but not included for the following reasons: crying (2) and failing to stay centered on the caregiver's lap during the experiment (1).

Stimulus materials. The method for constructing the stimuli was the same as in Experiment 1, with one exception: The same five vowels, /ʌ, aI, i, e, ɝ/, were equally represented in both types of lists. Examples of these stimuli are given in Table 2 and a full listing of the stimuli appears in the Appendix. In the two lists, 24 stimuli contained one of the five vowels, rendering 120 total stimuli for each high- and low-probability list (5 vowels × 24 stimuli = 120 total). Based on Webster's Pocket Lexicon (1967), the average summed phoneme probabilities were .1602 and .0565 for the high- and low-probability pattern lists, respectively, and the average summed biphone probabilities were .0053 and .0009 for the high- and low-probability lists, respectively. Once again, probability estimates based on the child-directed speech corpus (Bernstein, 1982; MacWhinney, 1991) accorded well with those based on the Webster's Pocket Lexicon. Thus, the average summed phoneme probabilities were .1733 (high-probability lists) and .0873 (low-probability lists), and the average summed biphone probabilities were .0068 (high-probability lists) and .0015 (low-probability lists).

The average stimulus durations of the high- and low-probability lists, again measured from a digital waveform display, were 618 ms (*SD* = 110) and 626 ms (*SD* = 114), respectively.

TABLE 2
EXAMPLES OF EXPERIMENTAL STIMULI FOR HIGH AND LOW PROBABILITY PHONOTACTIC PATTERNS FOR EXPERIMENT 3

High probability	Low probability
[ʧʌn] "chun"	[jʌʃ] "yush"
[taIs] "tyce"	[ʃaIb] "shibe"
[kik] "keek"	[giθ] "geeth"
[vet] "vate"	[θeʤ] "thage"
[mɝn? "mern"	[ʧɝg] "cherg"

Apparatus and procedure. These were identical to those in Experiment 1.

Results and Discussion

The amount of time that each infant oriented to the loudspeaker on each trial was recorded. The average looking time was 7.12 s (SD = 1.95 s) for the high-probability lists and 6.13 s (SD = 2.21 s) for the low-probability lists. Eighteen of the 24 infants had longer listening times for the high-probability lists. A paired t-test indicated that the difference in orientation times to the two types of lists was significant, $t(23) = 2.39, p < .03$). Consequently, even when the vowel quality was equated across the two types of lists, 9-month-olds still listened significantly longer to the high-probability lists.[4] Thus, it appears that the primary determinant of the longer listening times to the high-probability lists has to do with some sensitivity to distributional properties of phonetic patterns in the input.

Although the results of the present experiment rule out the possibility that the longer listening times for the high-probability phonotactic lists might have been based on vowel quality differences alone, they do not allow us to say whether the primary determinant of the preferences is phoneme frequency or phone-to-phone cooccurrence probability. This is because the frequency with which particular consonants appeared on each type of list was not fully controlled, i.e., the list types still differed in the frequency with which certain classes of consonants appeared. Balancing the two types of lists fully in terms of phoneme frequency is not a trivial matter because the most frequently appearing phones are also the most likely to occur in high probability phone-to-phone sequences. Moreover, because our objective is to investigate how infants respond to phonotactically legal patterns in the input, the range of possible stimulus materials is further restricted, making it difficult to create sufficient numbers of stimuli that differ greatly in phone-to-phone probability but are completely balanced with respect to phoneme frequency. Still, the aspect of phoneme frequency that we did control in the present experiment, vowel quality, is the one that appears to be the most perceptually salient to infants (Kuhl et al., 1992; Polka & Werker, in press).

General Discussion

The present results fit well with the growing body of evidence that infants in the first year are discovering many facets of the sound structure of their native language. The first indication that during the first year infants are moving from language-general to language-specific perceptual capacities came from studies noting a decline at around 9 months of age in the ability to discriminate certain nonnative phonetic contrasts (Werker & Tees, 1984). Although there are indications that sensitivity to all nonnative contrasts does not necessarily decline at the same rate (Best et al., 1988), the loss of sensitivity has been shown to occur for a variety of contrasts (Best, 1993; Werker & Polka, 1993).

At the same time that these changes in the discrimination of nonnative contrasts are occurring, there is evidence that infants are becoming attuned to various aspects of the organization of native language sound patterns. This is manifested in a number of different domains. For instance, studies of speech production in infants from 9 months of age onward indicate that babbling behavior drifts increasingly in the direction of native language vowel (de Boysson-Bardies, Halle, Sagart, & Durand, 1989; de Boysson-Bardies, Sagart, & Durand, 1984) and consonant (de Boysson-Bardies & Vihman,

[4] Although, the size of the difference in listening times to the two types of lists appeared to be smaller in the present experiment than in Experiment 1, suggesting that vowel quality differences may also have contributed to the outcome of the earlier experiment, an analysis comparing the listening times for these experiments suggested this was not the case. We compared the mean difference scores to the high- and low-probability lists for each subject from Experiment 1 with those from Experiment 3. A t test for independent samples indicated no significant differences in the size of the effect across these two experiments $t(46) = 1.52, p = .14$).

1991; de Boysson-Bardies, Vihman, Roug-Hellichius, Durand, Landberg, & Arao, 1992) categories. There is also evidence for the influence of language-specific prosodic patterns on the babbling of infants between 5 and 10 months of age (Levitt, 1993; Levitt & Wang, 1991). Moreover, the sound structure of the native language also has an impact on infants' perceptual processing of speech during the first year. Thus, between 6 and 9 months, American infants develop some sensitivity to prosodic marking of phrasal units (Jusczyk et al., 1992) and to the predominant stress patterns of native language words (Jusczyk et al., 1993a). Furthermore, it is not only suprasegmental features of native language input that begin to influence perceptual processing. There is evidence that infants are learning about the fine-grained features of native language sound patterns. For example, there is some evidence, even at 6 months, that suggests that the internal structuring of vowel categories reorganizes to reflect those of the native language (Kuhl, 1991; Kuhl et al., 1992). Furthermore, between 6 and 9 months, infants show definite preferences for listening to words which observe the phonetic and phonotactic constraints of their native language (Jusczyk et al., 1993b). The present results extend these last findings by showing that infants at this age are also sensitive to the distribution of phonotactic patterns in the input.

The finding that infants are registering information about the way that phonetic patterns are distributed in fluent speech is interesting in light of earlier discussions of when such knowledge might be attained. For instance, Whorf (1956) believed that this kind of information is achieved quite late in the process of language acquisition, as the following quote illustrates:

> . . . the structural formula for words of one syllable in the English language looks rather complicated; yet for a linguistic pattern it is rather simple. In the English speaking world, every child between the ages of two and five is engaged in learning the pattern expressed by this formula, among many other formulas. By the time the child is six, the formula has become ingrained and automatic; even the little nonsense words the child makes up conform to it. . . . (Whorf, 1956, pp. 223–224)

Subsequently, Messer (1967) investigated the acquisition of Whorf's formula in a study with nursery school children. He found evidence that these children (who had attained a mean age of 3.7 years) had already absorbed this formula for the way in which sounds can be strung together to generate possible English words. Judging from the present results and those of Jusczyk et al. (1993b), the first steps toward learning the formula actually begin during the latter half of the first year.

The knowledge that infants develop about the organization of sound patterns in the native language has potentially important implications for language acquisition at a number of different levels of linguistic organization (Gerken, 1991; Gleitman, Gleitman, Landau, & Wanner, 1988; Jusczyk & Kemler Nelson, in press; Morgan, Meier, & Newport, 1987; Peters, 1983). However, the fact that infants are sensitive to the distribution of phonotactic patterns in the input may have particular relevance to the development and organization of the mental lexicon. Studies of word comprehension in language learners have reported that comprehension of the first words begins some time between 8 and 10 months of age (Benedict, 1979; Huttenlocher, 1974)—within the same general period that sensitivity is developing to frequently occurring phonotactic patterns. Investigations of the early stages of word learning have typically focused on factors influencing the acquisition of meaning (Clark, 1991; Markman, 1991; Waxman, 1991). Not much attention has been given to the role of sound properties in determining how and when new words are added to the mental lexicon. However, in discussing factors that contribute to words in a child's productive vocabulary, Vihman (1993) has raised the possibility of an "articulatory filter" that renders certain adult speech patterns especially salient or memorable. The articulatory filter reflects the child's own favored speech production patterns in babbling. Is it possible that something similar exists with respect to patterns that are prominent in infants' perceptual experience? For example, might infants also attend to and encode information about a regularly occurring sound pattern even in the absence of a clear referent to attach it to? In this case, the sound pattern might serve as a place holder or slot in the lexicon for a meaning to be attached to at some subsequent time.

One interesting implication of the present results for the growth and organization of the mental lexicon is that if attention to frequently occurring phonetic patterns in the input biases the acquisition of lexical items in some way, then this might actually lead the learner to build up areas of the lexicon in which a high concentration of phonetically similar lexical neighbors is likely. This is because high-probability phonotactic patterns tend to be associated with dense lexical neighborhoods (Landauer & Streeter, 1973; Luce et al., 1990). One potential drawback of building up dense neighborhoods in the lexicon first is that a more detailed representation of a particular item is necessary in order to distinguish it from its near neighbors. On the other hand, the acquisition of sound patterns in densely populated neighborhoods may facilitate attention to the fine-grained differences in phonetic structure (see Charles-Luce & Luce, 1990), a capability that underlies adults' rapid and efficient word recognition skills. Indeed, the acquisition of sound patterns probably involves a complex interplay between the tendency to attend to more frequently occurring patterns and the subsequent need for more detailed discrimination among those patterns once they have been stored in memory. A more detailed account and general model (WRAPSA) of how word recognition skills may develop from early speech perception capacities is presented elsewhere (Jusczyk, 1992, 1993a).

Finally, let us consider some of the implications that the present findings have for understanding word recognition processes. There is a growing body of evidence that adults make use of phonotactic probabilities and constraints in recognizing spoken words (Auer & Luce, 1993; Cole & Jakimik, 1980; Eukel, 1980; Massaro & Cohen, 1983; McClelland & Elman, 1986; Messer, 1967; Wannemacher & Sawusch, 1989; Wannemacher & Sawusch, 1990; Wannemacher & Sawusch, 1991; see also Clements & Keyser, 1983). Auer and Luce have demonstrated that both segmental and cooccurrence probabilities affect adults' speed of processing of spoken words. In particular, they demonstrated that words with high segment-to-segment transitions are processed more quickly than words with less frequent transitions. They argued that when listeners perceive spoken words, they map a path through a multidimensional acoustic–phonetic space. Paths in this space that are frequently traversed (i.e., those corresponding to words with high cooccurrence probabilities) should be most easily recognized, as was in fact the case. The present results demonstrating infants' preference for high-probability patterns may be a direct consequence of the relative ease of processing of highly probable phonotactic patterns.

As noted earlier, Church (1987) has suggested that knowledge of constraints on the positions in which certain phonetic segments can appear could facilitate the segmentation of words in fluent speech. Certainly, one prerequisite for this process is that the perceiver has some sensitivity to the patterning of phones in the input. Although they do not speak to the issue of whether infants use information about phonetic patterning to help in determining word boundaries, the present results at least show that infants are beginning to learn about the distribution of phonetic patterns. Moreover, there is evidence from a recent investigation (Jusczyk & Aslin, 1993) that 7½-month-olds have some rudimentary capacity to recognize a particular word (e.g., "cup") when it occurs in a sentential context. One subject for future research is to

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determine what role, if any, sensitivity to phonetic patterns plays in this process.

In conclusion, the present study provides a further indication that during the latter half of their first year, infants are learning about the structure and organization of native language sound patterns. Not only are infants capable of distinguishing between native and nonnative sound patterns (Jusczyk et al., 1993b), but they also seem to be drawn to the kinds of sound patterns that are apt to occur frequently in native language words. Sensitivity to the distribution of these patterns may well influence not only learning about the phonotactic and phonological organization of the native language, but also the development of word recognition capacities and the organization of the mental lexicon.

Appendix

Stimulus materials for Experiments 1 and 3 for HIGH and LOW probability phonotactic patterns.

Experiment 1: HIGH

ɹIs ɹIn lIs fIs bIs dIt tIs wIs vIs
sIm nIs gIs ɹIz ʤIs ɹIv ʧIs ʃIs dIz
øIs dIv jIs zIs mIm sIz vIn ɹIʃ ɹIø
pIm ɹIð fIk dIʤ ɹIʒ dIø mIp vIl
nIn dIð gIn dIʒ sIʤ sɛɹ sɛs ɹɛl nɛn
ɹɛs sɛm pɛl gɛn dɛs ʧɛn ʃɛn pɛs
sɛp mɛk kɛl sɛv lɛl ɹɛm hɛs sɛg vɛl
dɛm tɛt sɛb kɛs vɛɹ fɛs mɛm pɛm
tɛm ɹɛp vɛs kɛk sɛŋ sɛʧ sɛð sɛʃ
fɛk sɛʒ dɛp sæn hæn kæk læn mæl
gæn ʧæn bæl wæn ʃæn kæŋ kæg ɹæl
jæn øæn zæn kæz tæl læl hæs fæl
kæø kæð kæʒ dæl fæs pæb pæg mæb
pæv mæv dæs læt næl bæp væs ʧæl
pæz mæz pæʤ

Experiment 1: LOW

jaʊʤ ʃaʊʤ ʤaʊʤ jaʊʧ vaʊʤ vaʊʤ
ʃaʊʧ jaʊø ʤaʊʧ naʊʤ ʃaʊø laʊʤ
ʤaʊø jaʊz jaʊɹ gaʊʧ jaʊʧ jaʊd ʃaʊz
naʊʧ ʤaʊz vaʊø ʃaʊd gaʊø ʤaʊɹ
ʤaʊd laʊʧ taʊʤ naʊø ɹaʊʤ gaʊz
faʊʤ laʊø jaʊt paʊʤ baʊʤ vaʊɹ gaʊd
gaʊɹ ʃaʊl taʊʧ naʊd jɔø jɔʧ ʃɔø ʃɔʧ
øɔø øɔʧ ʧɔø ʧɔʧ jɔb ʃɔb øɔb ʧɔb
nɔø jɔʃ ʃɔʃ øɔʃ ʧɔʃ nɔb ʃɔz gɔø
gɔʧ jɔŋ ʧɔz ɹɔʧ jɔd ʃɔŋ jɔg ʃɔd
ʃɔg ʧɔŋ øɔg ʧɔg ʧɔd gɔb nɔŋ nɔd
ɹɔʃ bɔø bɔʧ dɔø zuʃ zuð ʧuʃ zuʒ
wuð ʧuð ʃuð ʧuʒ wuʒ ʃuʒ guʃ zuø
puʃ fuʃ zuv guð fuð guʒ ʧuø ʃuø ʧuv
puð wuv ʃuv wuø fuʒ puʒ ʤuð guø
ʤuʃ guv muʃ fuv zub muð fuø huʃ
huð muʒ huʒ

Experiment 3: HIGH

fʌl ʧʌn mʌb sʌʃ tʌl sʌʤ hʌs ʤʌn
dʌs sʌz sʌg kʌk sʌv ɹʌl sʌd lʌn
pʌm bʌl pʌl sʌt mʌn sʌs sʌl kʌn
taIs daIp vaIɹ vaIk baIs faIk ɹaIɹ
maId haIs saIb vaIt ʤaIn saIv ʧaIn
saIp saIm gaIn paIt saIs daIt saIk
saIl baIn haIn kis ʧin kik ɹig sig
øin fik kit pim fis vin ɹiz bis siv
dik nin hin bil dis dit fin ɹit ɹis
ɹin vet ɹeb meb keb seb mep ges
wes hes sep peb ɹem nes tes pep
lel hen pem ked sed nen ten pek
ses dɝs mɝn sɝz fɝt tɝt sɝg pɝv
vɝn pɝb mɝs kɝm sɝp pɝd fɝs
bɝs kɝn sɝd sɝl sɝm sɝk pɝn sɝt
sɝn sɝs

Experiment 3: LOW

ðʌʃ ðʌʤ jʌʃ ðʌʧ øʌʃ jʌʤ ʧʌʃ øʌʤ
jʌʧ ʧʌʤ øʌʧ ʃʌʤ wʌʃ ʧʌʧ ʃʌʧ
ðʌz wʌʤ ðʌg ðʌv jʌz wʌʧ ðʌd øʌz
ʧʌz ðaIð ʃaIð ʤaIð ʧaIð gaIð ðaIz
ðaIb ʤaIz ðaIv ʃaIb ʧaIz waIð ðaIm
naIð kaIð ðaIp ʃaIv ʧaIb ʃaIm ʃaIP
gaIb ʤaIm ʤaIp faIð ðiʃ ðið jiʃ giʃ ziʃ
jið zið gið ðiø jiø ziø giø ðiʧ
jiʤ ziʤ jiʧ ziʧ ʧiʃ ʧið giʤ ðig
giʧ jig zig øeʒ øeð øeø øeg ʤeʒ
ʤeð ʧeʒ ʧeð ʤeø ʃeʒ øeʤ ʃeð ʧeø
ʃeø ʤeg ʧeg ʃeg ʤeʤ øez ʧeʤ
veʒ ʃeʤ veð geʒ jɝz jɝø ʃɝø jɝg
ʃɝz ʧɝø ʧɝz ʃɝg jɝʧ ʧɝg nɝø
nɝz ʃɝʧ lɝø ʃɝʤ øɝø lɝz jɝp ʧɝʤ
nɝg gɝg ʤɝø øɝz jɝv

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