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Phonological phrase boundaries constrain lexical access II. Infant data

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Abstract

The location of phonological phrase boundaries was shown to affect lexical access by English-learning infants of 10 and 13 months of age. Experiments 1 and 2 used the head-turn preference procedure: infants were familiarized with two bisyllabic words, then presented with sentences that either contained the familiarized words or contained both their syllables separated by a phonological phrase boundary. Ten-month-olds did not show any listening preference, whereas 13-month-olds listened significantly longer to sentences containing the familiarized words. Experiments 3 and 4 relied on a variant of the conditioned head-turning technique. In a first session, infants were trained to turn their heads for an isolated bisyllabic word. In the second session, they were exposed to the same sentences as above. Both 10- and 12.5-month-old infants turned significantly more often when the target word truly appeared in the sentence. These results suggest that phonological phrase boundaries constrain on-line lexical access in infants.

Keywords: Lexical acquisition; Segmentation into words; Prosodic boundary cues

Introduction

In recent years, it has been argued that infants may exploit phonetic, prosodic, and statistical clues in language input to extract information about word boundaries (e.g., Jusczyk, 1999; Jusczyk, Houston, & Newsome, 1999), about the grammatical category membership of words (Kelly, 1996; Shi, Morgan, & Allopenna, 1998), and about some general aspects of phrase structure (Gerken, Jusczyk, & Mandel, 1994; Hirsh-Pasek et al., 1987; Jusczyk et al., 1992). Existing research indicates both that language input provides cues to each of these aspects of structure, and that infants can exploit cues to individual levels of structure. However, the question of how infants coordinate cues to multiple levels of language structure has not yet been explored. In this article, we examine how 10- to 13-month-old infants integrate word-boundary cues with phrase boundary cues.

The claim that languages are hierarchically structured is well known with respect to syntactic structure (Bloomfield, 1933; Chomsky, 1957): words constitute phrases, phrases constitute clauses, and so forth. A corollary of this claim is that units at lower levels cannot straddle boundaries between units at higher levels: words cannot bridge phrases, nor can phrases bridge

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clauses. Parallel claims have been made with respect to the prosodic structure of language (Nespor & Vogel, 1986; Selkirk, 1980): prosodic words constitute phonological phrases, which in turn constitute intonational phrases. Consequently, prosodic words may not straddle phonological phrase boundaries. In other words, phonological phrase boundaries should always be interpreted as word boundaries. Do lexical access processes exploit this property of language? Recent results suggest that for adults, phonological phrase boundaries serve on-line to constrain lexical access (Christophe, Peperkamp, Pallier, Block, & Mehler, in press). However, whether they do so for infants early in acquisition is unknown.

In the following, we first review some recent findings on infants' use of cues in segmenting input speech. We next consider evidence on the role of cues to phonological phrase boundaries in processing of speech by both infants and adults. Then, we present four infant studies in which we manipulate cues to phonological phrase boundaries. The results of these studies show that, as early as 10 months, infants may use cues to phonological phrase boundaries to segment connected speech.

Exploiting transitional probabilities and lexical stress as cues to word boundaries

Within the past 10 years, the roles of several potential types of cues to word boundaries have been experimentally investigated (see Jusczyk, 1997; for a review). These include distributional statistics, lexical stress, phonotactics, allophonic cues, and co-articulation. We will focus here on the first two of these, because they figure in our experiments.

It has long been hypothesized that by computing the transitional probabilities between syllables or segments and using the relative strengths of these probabilities to hypothesize word boundaries, listeners (or learners) may exploit distributional regularities to extract words from continuous speech (Harris, 1955; Hayes & Clark, 1970). Goodsitt, Morgan, and Kuhl (1993) showed that 8-month-old infants were able to exploit the systematic co-occurrence of 2 syllables to infer that they were a single unit. More generally, Saffran, Aslin, and Newport (1996) demonstrated that 8-month-old infants were able to extract word-like units from a 2-min continuous stream of syllables on the basis of transitional probabilities (see also Aslin, Saffran, & Newport, 1998). Computer simulations have shown that this strategy works well on a variety of real-life corpora, using a variety of algorithms (Batchelder, 2002; Brent, 1999; Brent & Cartwright, 1996; Cairns, Shillcock, Chater, & Levy, 1997; Christiansen, Allen, & Seidenberg, 1998; Venkataraman, 2001). For example, Batchelder (2002) showed that a distributional algorithm could recognize 65% of the words in a corpus of English infant-directed speech, and 56% of the words in a corpus of Japanese speech.

Lexical stress has also been investigated as a word segmentation cue. In English, content words predominantly start with strong syllables, containing a full vowel (Cutler & Carter, 1987). Hence, positing a word boundary before strong syllables is a useful strategy for English. English-speaking adults have been shown to use this strategy in a variety of experimental tasks (e.g., Cutler & Butterfield, 1992; Norris, McQueen, & Cutler, 1995). When do infants become able to exploit this regularity of English? Jusczyk, Cutler, and Redanz (1993) showed that 9-month-old American infants, but not 6-month-olds, listen longer to lists of bisyllabic Strong–Weak (SW) words rather than to Weak–Strong (WS) words. Morgan (1996) demonstrated that by the same age, English-learning infants tend to perceive pairs of syllables as cohesive units only when they exhibit a trochaic (i.e., SW) rhythm. Furthermore, Jusczyk et al. (1999) showed that American infants are able to extract SW bisyllabic words at 7.5 months or after, but WS bisyllabic words only at 10.5 months or after. These results suggest that English-learning infants, like adults, exploit lexical stress to hypothesize word boundaries; in addition, they do so at a very early age. Finally, Morgan and Saffran (1995) showed that by 9 months, infants integrate lexical stress and distributional regularities in grouping syllables into word-like units; from this age onwards, therefore, the coincidence of these two types of cues may be an especially powerful indicator for the location of word boundaries, as simulations by Christiansen et al. (1998) confirm.

The prosodic structure of language

Theoretical accounts of the prosodic structure of spoken language (Nespor & Vogel, 1986; Selkirk, 1983) have proposed a hierarchy of elements ranging from morae and syllables to intonational phrases and utterances. Elements in the hierarchy above the prosodic word are derived from (though do not necessarily mirror) syntactic structure and serve as the domains within which particular types of phonological rules apply (Nespor & Vogel, 1986). The *intonational phrase*, which most often corresponds to whole clauses, is generally delimited by final lengthening and a pause. The *phonological phrase*, whose boundaries coincide with syntactic phrase boundaries, is characterized by final lengthening and a single pitch contour (Wightman, Shattuck-Hufnagel, Ostendorf, & Price, 1992; among others). It also exhibits greater initial strengthening (such that the first phoneme of a phonological phrase is typically more strongly articulated and potentially longer, see Fougeron & Keating, 1997; Keating, Cho, Fougeron, & Hsu, 2003), as well as reduced coarticulation between phonemes that span the boundary (see e.g., Byrd, Kaun, Narayanan, & Saltzman, 2000; Hardcastle, 1985; Holst & Nolan, 1995). Phonological phrases may incorporate material from one or more syntactic phrases, and edges of phonological phrases may not map 1-to-1 onto edges of syntactic phrases. Nevertheless, whenever there is a phonological phrase boundary, there is also a syntactic phrase boundary. For example, the sentence $[\text{He}]_{NP}$ [kicked $[\text{the ball}]_{NP}]_{VP}$ may be prosodically realized as $[\text{He kicked}]_{PP}$ $[\text{the ball}]_{PP}$. Note that here the boundary between the two phonological phrases coincides with the onset of the NP "the ball"; in English in general, as in other right-branching languages, phonological phrase boundaries coincide with the onsets of syntactic phrases. A fortiori, wherever there is a phonological phrase boundary, there must also be a word boundary.

Intonational phrase boundaries have been shown to be perceptible by young infants: Hirsh-Pasek et al. (1987) observed that infants listened longer to stimulus sets in which silences were inserted at points coincident with intonational phrase boundaries than to stimuli in which silences were non-coincident. They have also been shown to influence on-line sentence comprehension in adults (see e.g. Kjelgaard & Speer, 1999; Warren, Grabe, & Nolan, 1995). Thus, this higher level of the prosodic hierarchy seems to participate in language processing.

With respect to phonological phrases, Christophe, Dupoux, Bertoncini, and Mehler (1994) and Christophe, Mehler, and Sebastián-Gallés (2001) showed that, from very early on, infants are sensitive to prosodic cues correlated with phonological phrase boundaries. Using a High Amplitude Sucking Procedure, they observed that newborns could discriminate between two lists of bisyllabic stimuli that were extracted from French and Spanish sentences; one list contained bisyllables that belonged to a single word, whereas the second list contained bisyllables that were separated by a phonological phrase boundary. Infants' sensitivity to phonological phrase boundaries in English has also been studied with the pause-insertion technique. Jusczyk et al. (1992) showed that 9-month-olds are sensitive to syntactic phrase boundaries that correspond to phonological phrase boundaries. Gerken et al. (1994) replicated this result and showed in addition that 9-month-olds do not seem to perceive syntactic phrase boundaries, which do not correspond to phonological phrase boundaries (as in "[he # kicked] [the ball]" as opposed to "[the caterpillar] # [kicked the ball]," where # stands for the inserted pause).

Using phonological phrase boundaries to constrain lexical access

Recent experimental results show that French adults postulate a word boundary whenever they encounter a phonological phrase boundary (Christophe et al., in press). In a word detection task, adults were slowed by local lexical ambiguities *within* phonological phrases: the target word *chat* ("cat") was responded to more slowly in ...*son* <u>*chat grin*</u>*cheux*... ("...his grumpy cat..."), where *chagrin* is also a word, than in *son chat drogué* ("his drugged cat"), where no competitor word starts with *chad*.... In contrast, when the target word was followed by a phonological phrase boundary, participants responded equally fast in both conditions, irrespective of the following context; e.g., *chat* in [*son grand* <u>*chat*</u>] [<u>*grim*</u>*pait aux arbres*] ("his big cat climbed up trees"; potential competitor *chagrin*) vs. [*son grand chat*] [*dressait l'oreille*] ("his big cat pricked up its ears"; no competitor). This result shows that phonological phrase boundaries constrain lexical access on-line in (French) adults.

Whether infants also exploit phonological phrase boundary information to constrain lexical access has not yet been directly investigated. However, certain experiments from a recent extensive series of studies investigating the role of lexical stress in infant speech segmentation indirectly bear on this issue (Jusczyk et al., 1999). Because Jusczyk et al. (1999) did not design their stimuli to test for the relative contributions of cues to phonological phrases vs. cues to words, several plausible alternative explanations of the results cannot be ruled out. We consider these experiments in some detail here in order to make explicit the factors that must be controlled in investigating how infants coordinate cues to phrase boundaries with word-boundary cues. Jusczyk et al. (1999) familiarized 7.5- and 10.5-month-old infants with sets of sentences containing $\text{weak}_1/\text{strong}_2/\text{weak}_3$ ($W_1S_2W_3$) syllabic sequences such as *guitar is* or *beret on*. Infants' listening time was measured for bisyllables contained in the sentences vs. comparable bisyllables that they had not heard. At 7.5 months, infants listened longer to familiar S_2W_3 bisyllables (e.g., *taris*) than to unfamiliar strong–weak bisyllables. In contrast, after having been familiarized with the WS bisyllabic word (e.g., *guitar*), infants did not listen longer to sentences containing the familiarized WS bisyllable. Jusczyk et al. attributed this to an early reliance on a metrical segmentation strategy according to which strong syllables are taken to signal onsets of words. Ten-month-olds displayed the opposite pattern of behavior, thus correctly segmenting the speech sequence as adults would: they must have relied on word-boundary cues other than the stress pattern—and phonological phrase boundaries are one such candidate.

In Jusczyk et al.'s experiment 14, 10-month-olds showed no differences in listening time to familiar vs. unfamiliar S_2W_3 sequences (e.g., *taris*). These bisyllables appeared with the same regularity in the sets of familiarization sentences as did the W_1S_2 bisyllables and moreover manifested the predominant lexical stress pattern of English. Why then did 10-month-olds apparently fail to recognize them as familiar? One possible explanation is that phonological phrase boundaries sometimes intervened between the S_2 and W_3 syllables, thereby signaling an intervening word boundary. Inspection of their stimuli suggests that about 60% of the sentences used may have included phonological phrase boundaries in this key position. Jusczyk et al. note allophonic differences between familiarization sequences and test items that are at least partially consistent with this possibility. On this view, the phrase boundaries that did occur may have led 10-month-old infants to segment the trisyllabic sequences (appropriately) as $W_1S_2 + W_3$, so that the S_2W_3 test bisyllables failed to correspond to any perceived units. One potential interpretation for the above results is therefore that 10-month-olds, but not 7-month-olds, exploit phonological phrase boundaries to constrain their lexical segmentation processes.

However, other alternative interpretations cannot be ruled out. First, there were differences in the statistical relations within the W_1S_2 and S_2W_3 bisyllables. Although S_2 followed W_1 and W_3 followed S_2 with perfect regularity in the familiarization sentences (making the W_1S_2 and W_2S_3 sequences equally probable within this restricted corpus), the same is not true when one considers the entire English corpus 10-month-olds have been exposed to. In each instance, the W_3 syllable was a closed-class item (*is*, *on*, *to*, or *in*); by 10 months, as Jusczyk et al. note, infants may well have learned that these high frequency English words occur in combination with many other different words. As a consequence of the very high frequency of W_3, the mutual predictability (mutual information, Cover & Thomas, 1991) of S_2 and W_3 would not be as strong as that of W_1 and S_2 (Morgan, 1996; and Swingley, 2000; have suggested that such asymmetries in mutual information may signal word boundaries). Second, it is possible that the 10-month-olds did not segment bisyllables from the familiarization sentences but rather segmented complete trisyllabic sequences. On this view, the W_1S_2 bisyllables may have served more effectively as probes activating the stored $W_1S_2W_3$ trisyllables due to their shared onsets. There have been many demonstrations that word onsets enjoy privileged status as cues for word retrieval in adults (e.g., Allopenna, Magnuson, & Tanenhaus, 1998); it would not be surprising to discover that the same phenomenon holds true for infants.

The studies reported below were designed to explicitly test infants' reliance on phonological phrase boundaries for lexical access, with an eye toward avoiding the sorts of alternative explanations just cited. In Experiments 1 and 2, we used the now-standard version of the head-turn preference procedure originally developed by Jusczyk and Aslin (1995) for assessing infants' recognition of spoken words in fluent speech. Infants were first familiarized with tokens of two bisyllabic words (*paper* and *beacon*). They were then tested on passages made up of two types of sentences. The crucial experimental manipulation was that the bisyllables were either contained within a phonological phrase, as in (1) or they straddled a phonological phrase boundary, as in (2) (similar sentences were constructed for *beacon*).

1. [The college] [with the biggest **paper** forms] [is best]
2. [The butler] [with the highest **pay] [per**forms the most]

If infants have learned to coordinate cues to phrasal and lexical structure of input, then the presence of an intervening phonological phrase boundary should block (or at least, impede) infants' recognition of the familiar bisyllabic words. As a result, we expected longer listening times for sentences that contained the familiar bisyllabic words within a phonological phrase. In Experiments 3 and 4 we replicated the first two experiments using a conditioned head-turn procedure, which provides on-line measures of infants' speech processing.

Two features of the experimental design we used are worth noting. First, the constituent syllables of the familiarized words manifested the same lexical stress pattern and statistical relationships in both experimental conditions (with and without an intervening prosodic boundary). As a consequence, any differences between the conditions can only be due to the presence of the phonological phrase boundary. Second, two powerful cues should encourage infants to consider the bisyllabic items as single units: They have a SW pattern, and their syllables display a strong statistical relationship within the experimental corpus (whenever S_1 occurs it is followed by W_2, and vice versa). Lexical stress appears to be a powerful cue to word boundaries in English: for instance, both SW patterns and coarticulatory cues have been shown to override distributional cues (Johnson & Jusczyk, 2001; though Thiessen & Saffran, 2003; observed that distributional cues overrode stress patterns in 7-month-olds), and SW patterns have been show to override phonotactic regularities as well (Mattys, Jusczyk, Luce, & Morgan, 1999; Myers et al., 1996). Therefore, if phonological phrase boundaries are found to effectively prevent infants from considering the SW bisyllables as single units, it will follow that these prosodic boundary cues are very powerful word-boundary cues. This is consistent with our hypothesis that word segmentation strategies apply within the domain of the phonological phrase.

Experiment 1

Ten-month-old infants were first exposed to tokens of two bisyllabic words (*paper* and *beacon*), until they accumulated 30 s of attentive listening to each word. They were then tested on four different passages. In two of these passages, all sentences contained instances of one of the familiarized bisyllabic words. In the other two, all sentences contained both syllables of one of the familiarized words, separated by a phonological phrase boundary. Previous work has shown that 10-month-old infants are already proficient at segmenting words from fluent speech (e.g., Jusczyk et al., 1999) and also that they can perceive phonological phrase boundaries (e.g., Gerken et al., 1994). We therefore expected 10-month-old infants to be able to exploit phonological phrase boundaries and thus show longer listening times for sentences actually containing the familiar words.

Method

Participants

Infants approximately 10 months old were recruited from information provided by the Rhode Island Department of Health. Twenty-one infants were tested to attain the final sample of 18 infants (mean age: 10 months 14 days, range: 10 months 0 days to 10 months 30 days). Three infants were excluded for the following reasons: technical problems (1), restlessness (2).

Stimuli

Stimuli for the familiarization phase were isolated words: tokens of *paper* and *beacon.* We selected *paper* and *beacon*, two bisyllabic SW words, because the first syllables (*pay* or *bee*) are words, and the second syllables (*per* or *con*) are the beginnings of many verbs (e.g., *perform*, *perceive*, *conflict*, *confound*, and so forth). This allowed us to construct many different sentences containing either the bisyllabic words themselves or both syllables of these words separated by phonological phrase boundaries. We chose words with a SW pattern because this pattern is predominant among English content words.

The stimuli for the test phase were fluent sentences. For each target word (*paper* and *beacon*) we constructed 12 pairs of sentences such that one member of each pair contained the bisyllabic word itself while the second member contained both syllables of this word separated by a phonological phrase boundary. For Experiments 1 and 2 relying on the head-turn preference procedure, only the first six sentence pairs were used for each word. Example pairs of sentences are shown below (see Appendix for a complete list of materials).

3a. [The scandalous *paper*] [sways him] [to tell the truth].
3b. [The outstanding *pay*] [*per*suades him] [to go to France].
4a. [The owner of the *beacon*] [founded the association].
4b. [The color of the *bee*] [*con*founded the new beekeeper].

In the following, we refer to sentences like (3a) and (4a) as "*paper*-type sentences" and to sentences like (3b) and (4b) as "*pay#per*-type sentences." Sentences of each pair were matched in their prosodic structures before the target word, as well as in total number of syllables and feet and in the number of syllables before and after the target words (mean number of syllables was 14).[1] Sentences were randomly ordered in a list (together with a number of distractor sentences) and read by a female American speaker who was naive to the aim of the experiment and who was asked to read in a lively voice. After reading and recording all the sentences, the same speaker was asked to pronounce the target words in isolation. We selected one exemplar for each sentence and 6 exemplars for each word.

We analyzed the acoustic realizations of the phonological phrase boundaries by measuring the duration of each phoneme in the bisyllabic targets (see Table 1 for means, as well as statistical tests of differences between means), using Praat software (http://www.fon.hum.uva.nl/praat/). We used the waveform to identify segments' beginnings and ends; vowels were identified by their periodicity; stops began with a closure (silent interval, zero amplitude), and ended after a burst when the periodicity of the vowel started. As expected from the literature (e.g., Gussenhoven & Rietveld, 1992; Wightman et al., 1992), we observed highly significant phrase-final vowel lengthening: thus, [eɪ] from 'p**ay**#per…' (phrase-final) was about 75% longer than [eɪ] from 'p**a**per' (word-medial). Note that this phrase-final vowel is also word final, and significant word-final vowel lengthening has also been reported in the literature (e.g., Wightman et al., 1992). Word-final lengthening was observed in the present data too: [ə] from 'pap**er**' (word-final but not always phrase-final) was longer than [ə] from 'pay#p**er**…' (word-medial; 42% lengthening on average). As expected from the literature, we also observed significant phrase-initial consonant lengthening: [p] from 'pay#**p**er…' was significantly longer than [p] from 'pa**p**er' (32% lengthening) (e.g., Christophe et al., 2001; Fougeron & Keating, 1997; Quené, 1992).

In five *pay#per*-type sentences (out of 24), we observed a short pause between the crucial words (3 *pay#-per* sentences and 2 *bee#con* sentences). Whenever there was a pause, it was impossible to measure the beginning of the closure of the following unvoiced stop consonant because it was not marked acoustically. To split the silent interval into pause and stop-closure in as objective a fashion as possible, we assigned to the stop-closure the mean duration of the other stop-closures in the same condition (either 'pay#**p**er…' or 'bee#**c**on…'). The duration of the pause was whatever remained of the silent interval. The mean duration of pauses was 133 ms

[1] Note that in most cases, a phonological phrase boundary occurred after the bisyllabic target word, *paper* or *beacon* (as in sentences 3a and 4a). This boundary may facilitate the extraction of the bisyllabic target words from fluent sentences. We thank James McQueen for pointing this out to us.

Table 1
Duration measurements for each individual segment in the Boundary and No-Boundary experimental conditions (averaging over *paper* and *beacon* sentences): mean duration in both conditions, difference between the Boundary and the No-Boundary conditions (and standard error of this difference), percentage lengthening (longest duration minus shortest duration divided by shortest duration and multiplied by 100)

	Phonological Phrase Boundary **pay [per...]**	No-Boundary **paper**	Difference		*t* test		% Lengthening
	Mean (ms)	Mean (ms)	Mean (ms)	*SE*	*t*(23)	*p*	
p	129	115	14	6.7	−1.9	.06	11.4
eɪ	198	112	86	10.0	8.6	$<10^{-6}$	76.4
p	137	104	33	4.4	7.5	$<10^{-6}$	31.9
ə	86	122	−36	5.4	6.7	$<10^{-6}$	−41.7

ə The data show significant word-final and phrase-final rhyme lengthening as well as significant word-initial consonant lengthening.

(range 82–167 ms). Phrase-final lengthening may be greater in the presence of a pause than in its absence. To check that the above results were not due solely to the few sentences, which exhibited a pause, we computed the same analysis without these five sentences, and observed very similar results (phrase-final vowel lengthening: 64%, $t(18) = 7.28$, $p < .001$; initial consonant lengthening: 32%, $t(18) = 6.4$, $p < .001$). These short pauses were carefully edited out before the experiment began so as not to leave any audible click. The edited sentences sounded perfectly natural.

To summarize these acoustic analyses, we observed that most sentences were realized without a pause at the phonological phrase boundary, but with very significant phrase-final and phrase-initial lengthening compared to the same phonemes in word-medial position. Phonological phrase boundaries in our sentences were therefore marked clearly but not by pauses.

Apparatus

Testing was conducted in a three-walled testing booth within a sound-treated laboratory room. Each beige pegboard wall of the booth was 120 cm wide. A chair was positioned at the open end of the booth where the parent sat with the infant on his/her lap. The infant sat approximately 110 cm from the front of the booth. Advent loudspeakers were located behind both side walls of the booth. At the infants' eye level, 86 cm above the floor, a yellow light was mounted on the front wall. Each of the side walls had a similar green light at the same level. A Panasonic CCTV video camera (model WV-BP330) was mounted behind the testing booth 12.3 cm above the yellow light. In a separate control room, a Panasonic monitor (WV-5410) was connected to the video camera in the testing booth. The participants were displayed on the monitor in the control room, where the experimenter judged infants' looking, pressing buttons on the mouse of a Windows computer to control the custom experimental software. The computer was equipped with a Sound-Blaster compatible soundboard connected to a Yamaha amplifier. Speech stimuli were set at conversation level (75 dB) using a Realistic sound level meter.

Procedure

The experiment consisted of two phases completed within a single session. The infant was seated on the parent's lap facing the yellow light. The parent listened to instrumental music over Bose aircraft-quality noise-cancellation headphones to mask the stimuli. Each trial began with the yellow light flashing until the experimenter judged that the infant fixated on the flashing light. At that point, this light was turned off and one of the green side lights began to flash to attract the infant's attention to the side. Side of presentation was randomized across trials, so that all stimuli occurred on both sides. After the infant turned to look at the flashing green light, the speech stimuli for that trial began to play. The sound continued to play and the green light remained on for the duration of the infant's fixation on the light. Each trial continued until the infant looked away for two seconds, or until 30 s of looking time had been accumulated during that trial. If the infant looked away, but then looked back within two seconds, the trial continued. For each trial, cumulative listening time was computed as the sum of the duration of the looks towards the blinking light.

In the familiarization phase, infants listened to lists of bisyllabic words. Side of presentation was random. Trials alternated between *paper* and *beacon* lists. The familiarization phase lasted until an infant accumulated 30 s of attentive listening to each of the familiarized words. Once the infant had exceeded 30 s of looking time with one word, all subsequent familiarization trials presented the alternate word. As soon as the infant reached 30 s of looking time with the second word, the test phase began. During the test phase, infants listened to passages composed of 6 sentences each. The order of sentences within passages was randomized on each trial. Four different passages were repeated three times each (one passage with *paper* sentences, one with *beacon* sentences, one with *pay#per* sentences, and one with *bee#con* sentences), yielding a total of 12 test trials. Passages were presented in three blocks of four passages, with the order of passages being random within each block. The experimental measure was the cumulative listening time to each type of passage.

We incorporated several refinements in HPP introduced in recent studies (Bortfeld & Morgan, 2000; Singh, Bortfeld, & Morgan, 2002; Singh, Morgan, & White, 2004). First, in all trials, speech stimuli were directly contingent on infants' looking. As soon as the infant looked away, the sound stopped. If the infant looked back within two seconds, the sound resumed and the trial continued, but if the infant continued to look away for two or more seconds, the trial ended. This modification helps infants to learn the task contingency very rapidly. Second, the amount of familiarization per stimulus set was controlled. As soon as infants had reached the familiarization criterion for one set, all subsequent familiarization trials presented the other set. This is an important control because greater familiarization may cause a familiarity preference to flip to a novelty preference (Aslin & Mehler, 2002; Hunter & Ames, 1988). Thus, if an infant accumulates highly disparate amounts of familiarization with two stimuli, the result may be a familiarity preference for one and a novelty preference for the other. Combined, these may cancel each other out. Third, to ensure that infants heard enough of the stimuli to make a decision to continue or terminate listening, we required that infants listen a minimum amount of time on each trial (2 s). If the infant failed to meet this minimum, the trial was repeated with a novel randomization of the stimuli; otherwise, the procedure advanced to the next trial.

Results and discussion

Mean listening times to each type of passage are presented in Fig. 1. A t test revealed no significant difference in listening times to the two passage types (7.0 s for both, standard error of the difference .66), $t(17) < 1$. Only 8 out of 18 infants listened longer to passages containing the actual bisyllabic words.

Contrary to our expectations, 10-month-old infants familiarized with SW bisyllabic words listened no longer to passages containing *paper*-type sentences than to passages containing *pay#per*-type sentences. This failure to find the expected pattern of results may have been due to several reasons.

First, infants may have failed to detect the familiarized word forms when they recurred in fluent speech. Previous research has shown that infants are capable of detecting SW words in fluent speech from 7.5 months onwards (Jusczyk et al., 1999), but the long sentences that we used here may have excessively taxed infants' processing resources, especially because targets always appeared in sentence-medial positions. Second, it is possible that, for reasons extraneous to present concerns, in

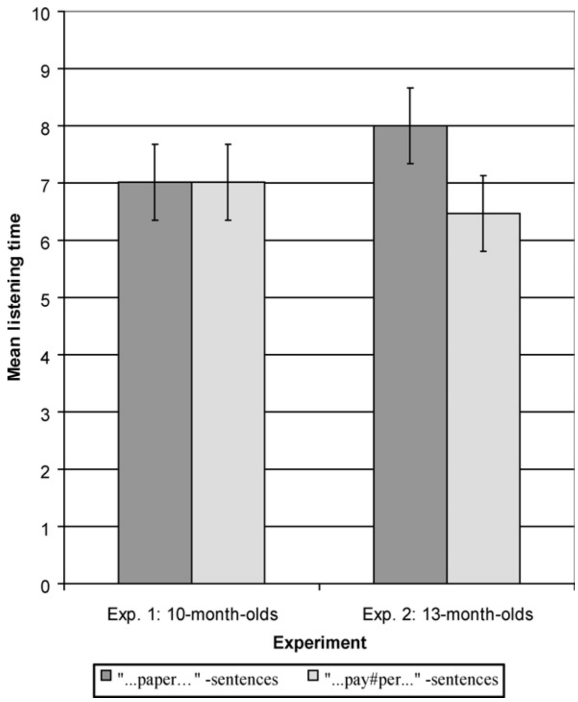

Fig. 1. Results from Experiments 1 and 2: mean listening time (seconds) for sentences containing the bisyllabic word (*paper*-sentences, dark-gray bars) and sentences in which it straddled a phonological phrase boundary (*pay#per*-sentences, light-gray bars). Error bars represent the standard error of the difference.

the absence of experience infants may have preferred the sentences in which phonological phrase boundaries intervened between the two syllables of the targets. Familiarization with the targets may have served to counteract this preference, resulting in a null effect. Third, it is possible that the difference between the two types of passages used here was not sufficiently salient for 10-month-old infants to notice spontaneously. The difference between sentence types was rather subtle, since the same two syllables were present in all sentences and only phrasal prosody distinguished between them. Nevertheless, previous work suggests that 10-month-old infants are sensitive to phonological phrase boundaries (Gerken et al., 1994). To test whether the prosodic distinctions in our stimuli were excessively subtle, we replicated Experiment 1 with slightly older infants.

Experiment 2

Experiment 2 aimed at replicating Experiment 1 with 13-month-old infants. By 13 months, infants typically have receptive vocabularies of approximately 50 words (Fenson et al., 1994) and are producing their first words. These phenomena indicate that, by this age, infants' segmentation abilities are more advanced.

Method

Participants

Infants approximately 13 months old were recruited from information provided by the Rhode Island Department of Health. Twenty-three infants were tested to attain the final sample of 18 infants (mean age: 13 months 8 days, range: 12 months 24 days to 13 months 26 days). Five infants were excluded for the following reasons: technical problem (1), drowsiness (1), restlessness (3).

Experimental design, stimuli, apparatus, and procedure

The experimental design, stimuli, apparatus and procedure were identical to those used in Experiment 1.

Results and discussion

Mean listening times to each type of passage are presented in Fig. 1. A *t* test revealed that 13-month-old infants listened longer to passages containing *paper*-type sentences that to passages containing *pay#per*-type sentences (8.0 s vs. 6.5 s, standard error of the difference .5), $t(17) = 2.9$, $p < .01$. Fifteen of 18 infants listened longer to passages with *paper*-type sentences (binomial $p < .01$). A joint analysis of Experiments 1 and 2 revealed that the performance of 13-month-olds (mean difference score = 1.5 s) was significantly different from that of 10-month-olds (mean difference score = .0 s), $t(35) = 1.8$, $p < .05$ (1-tail). Moreover, significantly more 13-month-olds than 10-month-olds listened longer to *paper*-type sentences, $\chi^2(1) = 5.90$, $p < .05$.

Thirteen-month-old infants who were familiarized with two bisyllabic words, *paper* and *beacon*, listened longer to fluent passages with *paper*-type sentences than to passages with *pay#per*-type sentences. This result indicates that infants readily identified the familiarized bisyllabic words when they were embedded within fluently spoken sentences, in keeping with previous studies of infant word recognition (e.g., Jusczyk & Aslin, 1995; Jusczyk et al., 1999). This also shows that the prosodic marking of phonological phrases was sufficient for infants to exploit: infants apparently did not consider both syllables of the bisyllables separated by a phonological phrase boundary as good instances of the familiarized bisyllabic words. Possibly, infants may also be able to exploit simple word boundaries, even if these were not marked through special allophonic, phonotactic, or lexical stress cues, but solely through prosodic cues (i.e., modifications of segments duration, pitch, and coarticulation similar to those marking phonological phrase boundary, but of lesser magnitude). Even though the present experimental design does not allow us to address this question, recent experimental data by Johnson (2003), suggests that this is the case at 12 months of age. Johnson observed that infants familiarized with passages containing both syllables of a SW word (e.g., 'ruby' in 'rue bequest') did not listen longer to that SW word during test, whereas they did when they had been familiarized with passages containing the SW word itself (no acoustic measurements are presented). Future work should address the question of whether or not phonological phrase boundaries are used earlier by infants, or more reliably, than simple word boundaries.

Taken together, the results of Experiments 1 and 2 suggest that infants' ability to exploit phonological phrase boundaries in segmenting words from fluent speech might emerge sometime between 10 and 13 months (although it remains possible that younger infants have difficulty in detecting words in the middle of long sentences). Existing work on infants' sensitivity to phonological phrase boundaries demonstrates that such boundaries are detected by nine months (Gerken et al., 1994); it is possible that the ability to exploit such boundaries would appear only after some lag. On the other hand, it is possible that the results of Experiment 1 underestimate younger infants' abilities. In the head-turn preference procedure, the presence of a preference necessarily implies the ability to discriminate; however the reverse is not true. As Aslin, Pisoni, and Jusczyk (1983) have pointed out, in preference techniques, what serves to maintain the infant's interest in the task is the stimuli themselves. Thus, a loss (or lack) of interest in the stimuli may mask discriminative abilities.

In the conditioned head-turning technique (CHT), infants are trained to turn when they hear a particular auditory stimulus; if they turn at the appropriate time, an interesting visual event occurs. Thus, in CHT, the reinforcer and the stimuli are separate, so that results (or lack of results) cannot be attributed to the intrinsic interest of the stimuli. In addition, in CHT, infants' responses are time-locked to particular stimuli, whereas in HPP, the dependent measure (differences in looking time) represents a global response to opposed stimulus sets. These attributes suggest that CHT may provide a more sensitive index of infants' speech processing abilities. Accordingly, we set out to replicate Experiment 1 using CHT to see whether 10-month-olds are indeed incapable of exploiting phonological phrase boundaries. Before doing so, however, to establish comparability of results obtained with HPP and CHT, we replicated Experiment 2 using the latter procedure.

Experiment 3

In this experiment, we used a conditioned head-turn procedure to provide an on-line measure of infants' word detection. Infants participated in two experimental sessions. During an initial training session, infants learned to turn their head upon hearing a particular word. One group of infants was trained on a bisyllabic target (either *paper* or *beacon*); a second group was trained on a monosyllabic target that matched the first syllable of one of the bisyllabic targets (either *pay* or *bee*). During the test session, infants heard fluent sentences containing or not these targets (the same sentences that were used in Experiments 1 and 2). Some sentences contained the bisyllabic target itself (*paper* or *beacon*), while others contained both its syllables separated by a phonological phrase boundary (e.g., [the outstanding *pay*] [*per*suades him...]). We expected infants trained on bisyllabic targets to turn their head more often when the targets did not straddle a phonological phrase boundary than when they did.

Infants from the monosyllabic group were tested on the same sentences, and were expected to show the reverse pattern of results, turning more often for '*pay*#per-sentences' that actually contain the target word *pay* than for '*pa*per-sentences' that contain a syllable homophonous to the target word. Note, however, that phonological phrase boundaries should be *sufficient*, though not *necessary*, for locating word boundaries. Indeed, most phonological phrases contain more than one word, so that many word boundaries do not coincide with a phonological phrase boundary. Monosyllabic targets either immediately preceded a phonological phrase boundary (when the associated bisyllable straddled the boundary, '...*pay*] [persuades...]') or constituted one syllable of a continuing prosodic group (...*pa*per...). Although the presence of a phonological phrase boundary located just after the targets might aid infants in segmenting the target from the sentences, the absence of such a boundary should not preclude them from doing so. We therefore expected a smaller difference between sentence types for infants trained on monosyllabic targets.

Method

Participants

Infants approximately 12.5 months old were recruited from information provided by the Rhode Island Department of Health. In the bisyllabic target group, 49 infants were tested to attain the final sample of 24 infants (mean age at the first session: 12 months 6 days, range: 11 months 24 days to 12 months 22 days); in the monosyllabic target group, 30 infants were tested to attain the final sample of 16 infants (mean age at the first session: 12 months 9 days, range: 11 months 18 days to 12 months 28 days). Infants were excluded for the following reasons: technical problems (3), failure to meet the predetermined training criterion within 30 trials in the initial session (9), difficulties scheduling the subsequent testing session within a 3–10 days period (6), crying or restlessness during training (14) or during test (7).

Stimuli

The same stimuli as in Experiments 1 and 2 served for this experiment. Stimuli for the first session were isolated words: tokens of *paper* and *beacon* for the bisyllabic group, and tokens of *pay* and *bee* for the monosyllabic group (monosyllabic targets were recorded at the same time as bisyllabic targets). The stimuli for the test session were fluent sentences, some containing the bisyllabic word itself (e.g., '..*paper*...')while others contained both syllables of this word separated by a phonological phrase boundary (e.g., [the outstanding *pay*] [*per*suades him...]). The full sets of 12 sentence pairs (for both *paper* and *beacon*) were used in this experiment. In addition, 26 distractor sentences that did not contain either the target words or their constituent syllables were included. These were matched with the test sentences in mean number of syllables, and had been recorded at the same time as the test sentences. As mentioned above, five *pay#per*-type sentences exhibited short pauses between the crucial words; these pauses were not excised from the stimuli used here.

Apparatus

Infants were tested in a sound-treated laboratory room. An experimenter in an adjoining room monitored the infant's behavior via a Panasonic closed circuit television (CCTV) system. Trial duration, stimulus presentation, and delivery of reinforcement were controlled by custom designed software running on a PC compatible equipped with a Zefiro acoustics ZA-2 sound board. Stimuli were presented through an Onkyo P-301 pre-amplifier connected to an Onkyo M-504 amplifier and an Electrovoice Sentry 100A loudspeaker located in the testing room with the infant.

Two smoked Plexiglas boxes containing mechanical toys that provided reinforcement were located under the loudspeaker. Four TV screens, playing Dumbo cartoons and situated under the Plexiglas boxes could also provide reinforcement when the child was afraid or bored with the mechanical toys.

Procedure

The experiment consisted of three main phases: shaping, criterion, and test. The shaping and criterion phases were completed in an initial training session; the test phase was completed during a second session. The sessions were separated by a maximum of 10 days.

Throughout both sessions, infants were seated on their parents' laps at a small table. An assistant seated directly across from the infant maintained the infant's attention at midline by displaying and manipulating an assortment of toys. A loudspeaker and the motorized animals that provided reinforcement were located 90° from midline on the infant's left, about 1.5 m away; a video camera was located directly above the loudspeaker. Another experimenter in the control room observed the infant on a video monitor and judged whether the infant looked into the camera. Throughout all sessions, parent, assistant and experimenter listened to music over noise-cancellation headphones.

The outside experimenter initiated trials by pressing a button when infants' attention was focused at midline. When the infant turned its head toward the loudspeaker, the outside experimenter pressed another button to signal a head-turn. The experimenter served as sole judge of whether the infant turned its head during trials, and the computer delivered reinforcement if it was an appropriate head-turn (i.e., to a target word).

The Training Session comprised the Shaping and the Criterion phases. During this session, infants heard a background word which was played continuously, presented at a comfortable listening level (68 dB SPL-b) with 1000 ms inter-stimulus interval, and occasionally replaced by three repetitions of the target word, allowing for a response window of 4 s. Infants were taught to turn their head toward the loudspeaker whenever they heard the target word. Infants from the bisyllabic group heard the words *paper* and *beacon* and infants from the monosyllabic group heard the words *pay* and *bee*. For each infant, one of the words served as target and the other one as background (half the infants from the bisyllabic group heard *paper* as target and the other half heard *beacon* as target; similarly, half the infants from the monosyllabic group heard *pay* as target and the other half heard *bee* as target). For example, if an infant was taught to turn its head for *paper*, the background word *beacon* was played continuously and replaced by three repetitions of the target word *paper* when a trial occurred. Only head-turns occurring while the target word was being played were reinforced. During the shaping phase, all trials were change trials. Initially, the target word was presented at a level 12 dB greater than the background word to elicit orienting head-turns. The intensity difference between target and background words was decreased by 4 dB whenever the infant responded correctly to a change trial, until both stimuli were presented at equal intensity levels. When the infant failed to turn on three consecutive trials, the sound level increased by 4 dB. The shaping phase continued until 30 trials were completed (in this case, the experiment was terminated) or until the infant turned its head on two consecutive trials with the target sound level at the background level.

At this point, the Criterion phase (second phase of the Training Session) began. This phase was similar to the Shaping phase, except that trials were either change trials or no-change trials (50% of each, randomly selected by the computer). Infants were tested until they had reached the predetermined criterion of responding correctly on seven out of eight consecutive trials (by turning on change trials and not turning on no-change trials). When an infant failed on three consecutive trials (change and no-change trials), retraining trials were introduced, following the same schedule as during Shaping, until the infant turned correctly on two consecutive trials with equal intensity. Infants not reaching criterion within 40 trials were excluded from further participation; infants who reached criterion returned for the test session, 3–10 days later.

The Testing Session began with a review phase, including a maximum of ten trials and requiring four head-turns: the background and the target words were presented sentence-finally in short sentences (e.g., "Look at the beacon!"). Initially, the intensity of the target words within the sentences was raised by 12 dB; this was gradually lowered, following each head-turn, until it was equal to the background intensity level. Following this, the test phase began. Infants heard 24 experimental sentences (either the *paper* and *pay#per* sentences, or the *beacon* and *bee#con* sentences, depending on the target word on which the infant was trained) and 26 distractor sentences, presented in random order, for a 50-trial session. Infants were reinforced when they turned within a period of 3 s beginning with the onset of the target word, and reinforcement was presented for 2.5 s. During the test phase, review trials were presented when infants failed to turn on three target trials, or after a break. Review trials were presented until the infant turned at least twice (once with a sound level 4 dB greater than background, and once at the same level).

During the test session, infants were reinforced when they turned their head to the target word: thus, infants from the bisyllabic group who were trained with the word *paper* were reinforced when they turned for *paper* but not when they turned for *pay#per*, while infants from the monosyllabic group who were trained with *pay* were reinforced for *pay#per* but not for *paper*.

Results and discussion

An ANOVA was conducted on the percentages of head-turns during target experimental sentences, with participants as the random variable. There were two between-subjects factors, Group (bisyllabic vs. monosyllabic) and Material (counterbalancing factor: *beacon/bee* vs. *paper/pay*), as well as one within-subject factor, Condition (no-boundary vs. boundary). The ANOVA revealed a main effect of Group, $F(1,36) = 13.3, p < .001$, as well as a main effect of Condition, $F(1,36) = 35.1, p < .001$. Crucially, there was a significant cross-over interaction between Group and Condition, $F(1,36) = 165$, $p < .001$. This interaction derived from the fact that infants in the bisyllabic group turned more often in the no-boundary than in the boundary condition (80.6% vs. 25.1%), $F(1,22) = 182, p < .001$, whereas infants in the monosyllabic group showed the reverse pattern (48.6% vs. 81.8%), $F(1,14) = 33.1$, $p < .001$. The counterbalancing factor Material showed no main effect and did not interact with any of the other factors (see Fig. 2).

We also computed an A′ (non-parametric version of the d′) for each infant, using the number of hits, misses, false alarms, and correct rejections (Grier, 1971). For infants in the bisyllabic group, the mean A′ was .85

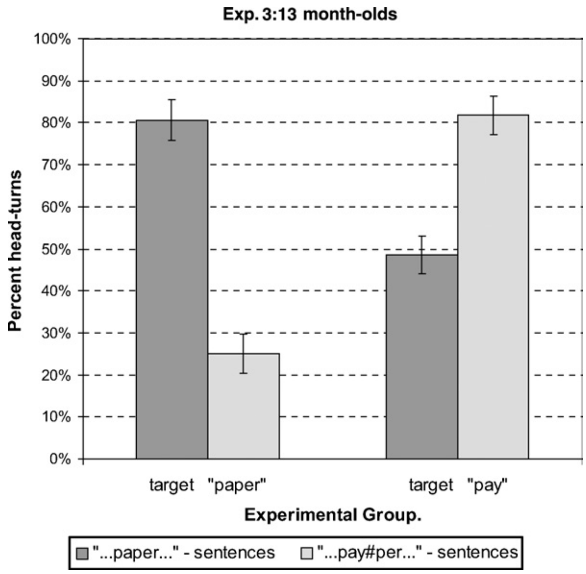

Fig. 2. Results from Experiment 3: percentage of head-turns for 12.5-month-old infants in the bisyllabic group (left-hand bars, target word, e.g., *paper*) and in the monosyllabic group (right-hand bars, target word, e.g., *pay*). Infants heard sentences containing the bisyllabic word (*paper*-sentences, dark-gray bars) and sentences in which it straddled a phonological phrase boundary (*pay#per*-sentences, light-gray bars).

(SE = .02), a value which was significantly higher than .5, the chance level, $t(23) = 16.7$, $p < .001$. For infants in the monosyllabic group the mean A′ was somewhat lower (which stems from the fact that the number of false alarms was higher, that is head-turns to *paper* when *pay* was the target) with a mean of .74 (SE = .05) but nevertheless significantly above chance, $t(15) = 4.7$, $p < .001$.

Twelve-and-a-half-month-old infants who were trained to detect a bisyllabic target word turned significantly more often when they heard the target word than when they heard its constituent syllables separated by a phonological phrase boundary. In contrast, infants who were trained to detect a monosyllabic word turned significantly more often for sentences containing the monosyllabic target word itself than when it was a part of a word. Importantly, the behavior of both groups was significantly different: There was a significant interaction between Group and Condition. This significant interaction means that infants from the bisyllabic group did not respond more often to *paper* sentences than to *pay#per* sentences because of some uncontrolled properties of *paper* sentences (which would trigger higher response rates), but rather because the phonological phrase boundary effectively reduced infants' detection of *paper* in *pay#per* sentences. Thus, the presence or absence of a phonological phrase boundary constrained infants' lexical access.

Note that we strongly predicted a difference between sentence types for infants in the bisyllabic group, while we expected a smaller difference in the other direction for infants in the monosyllabic group: this is the pattern of results that we observed. Since a phonological phrase boundary always signals a word boundary, it should be impossible (or, very unlikely) to access a "word" that straddles a phonological phrase boundary. In contrast, the absence of a phonological phrase boundary does not imply the absence of a word boundary: most phonological phrases contain more than one word and many word boundaries do not coincide with phonological phrase boundaries. As a consequence, we strongly expected infants trained on *paper* to turn their head significantly more often for *paper* sentences than for *pay#per* sentences: and we observed a 55.5% difference between conditions. The prediction was less strong for infants trained on *pay*, since this syllable was present within a phonological phrase in both types of sentences. The advantage for *pay#per* sentences was that the target word was followed by a phonological phrase boundary, which may make it easier to segment. Congruent with our expectations, we observed a 33.2% difference between conditions for infants in the monosyllabic group, which is significantly smaller than the 55.5% observed for infants in the bisyllabic group, $F(1,36) = 10.4$, $p < .01$ (another way of testing this is by comparing the A′ for both groups, .85 for the bisyllabic group vs. .74 for the monosyllabic group, $t(39) = 2.4$, $p < .02$).

We also evaluated whether the CHT word-detection method may provide individual results. As mentioned above, an A′ was computed for each infant (Grier, 1971). To determine what A′ score measured performance that was significantly above chance, we conducted a Monte Carlo simulation. One million 24-trial (half target, half control) sequences were generated based on random responding, an A′ score was computed for each, and the distribution of obtained A′ scores was evaluated. Our simulation showed that A′ scores of .755 or greater occurred by chance in less that five percent of the sequences. We focused this analysis on infants from the bisyllabic group, since in this group we had a clear prediction that infants should orient to *paper*-type sentences but not to *pay#per*-type sentences. We observed that 20 out of 24 infants performed significantly above chance (23 out of 24 infants showed a difference in response rate in the expected direction and had an A′ above .5, one had a difference of 0 exactly and therefore an A′ of .5). It thus appears that the word-detection technique used in Experiment 3 is very reliable: a vast majority of infants demonstrated their ability to extract bisyllabic words from continuous speech and to exploit phonological phrase boundaries.

These results confirm and extend those of Experiment 2: they show that 12.5-month-old infants recognize a bisyllabic SW word embedded in sentences and that they can distinguish such a target from both its constituent syllables separated by a phonological phrase boundary. In addition, the experimental design with two groups of infants (bisyllabic and monosyllabic) ensures that infants' response pattern cannot be due to intrinsic properties of experimental sentences (a feature that was absent from Experiment 2). Thus, we confirm the conclusion that twelve-and-a-half-month-old infants can exploit the presence of phonological phrase boundaries to infer the presence of word boundaries and therefore to extract words from fluent speech.

Experiment 4

Experiments 2 and 3 both demonstrated that 12.5-month-old infants exploit prosodic boundaries to constrain lexical access. Our hypothesis was thus fully confirmed with this age group. In Experiment 1, in contrast, 10-month-old infants did not show any preference for any type of sentence. As we argued above, the CHT word-detection technique may be a more sensitive technique than the head-turn preference procedure to test infants' word recognition abilities. Our next step, therefore, was to replicate Experiment 3 with 10-month-old infants.

Method

Participants

Infants approximately 10 months old were recruited from information provided by the Rhode Island Department of Health. There were two groups of infants. In the bisyllabic condition, 52 infants were tested to attain the final sample of 24 infants (mean age at the first session: 9 months 30 days, range: 9 months 21 days to 10 months 10 days), and in the monosyllabic condition, 27 infants to attain the final sample of 16 infants (mean age at the first session: 10 months 4 days, range: 9 months 26 days to 10 months 12 days). Thirty-nine infants were excluded for the following reasons: difficulties scheduling the subsequent testing session within a 3–10 days period (5), technical problems (5), failure to meet the predetermined training criterion within 30 trials in the initial session (14), crying or restlessness during training (14) or during test (7).

Experimental design, stimuli, apparatus, and procedure

The experimental design, stimuli, apparatus, and procedure were identical to those used in Experiment 3.

Results and discussion

A $2 \times 2 \times 2$ Group by Material by Condition ANOVA was conducted on the percentage of head-turns during target experimental sentences, with participants as the random variable. The ANOVA revealed a main effect of Group, $F(1,36) = 13.7$, $p < .001$ as well as a main effect of Condition, $F(1,36) = 25.9$, $p < .001$. Crucially, there was a significant interaction between Group and Condition, $F(1,36) = 33.6$, $p < .001$. This interaction derived from the fact that infants from the bisyllabic group turned their head more often in the no-boundary than in the boundary condition (48.6% vs. 15%), $F(1,22) = 48.7$, $p < .001$, whereas infants from the monosyllabic group showed a tendency in the reverse direction (41.6% vs. 48.5%), $F(1,14) = 2.3$, $p > .1$. The counterbalancing factor Material showed no main effect and did not interact with any of the other factors (see Fig. 3).

As before, we also computed an A′ for each infant (Grier, 1971). For infants in the bisyllabic group, the mean A′ was .74 ($SE = .04$), a value which was significantly higher than .5, the chance level, $t(23) = 5.8$, $p < .001$. For infants in the monosyllabic group the mean A′ was .53 ($SE = .05$) and not significantly different from chance, $t(15) < 1$.

As in Experiment 3, 10-month-old infants who were trained to respond to a bisyllabic target word turned their head significantly more often when they heard the target word itself than when they heard its constituent syllables separated by a phonological phrase boundary. Ten-month-old infants who were trained to respond to a monosyllabic word turned their head slightly more often for sentences containing the monosyllabic target word than when it was a part of a word but, unlike in Experiment 3, this difference did not reach significance.

These results show that 10-month-old infants, like 12.5-month-old infants, can exploit the presence of

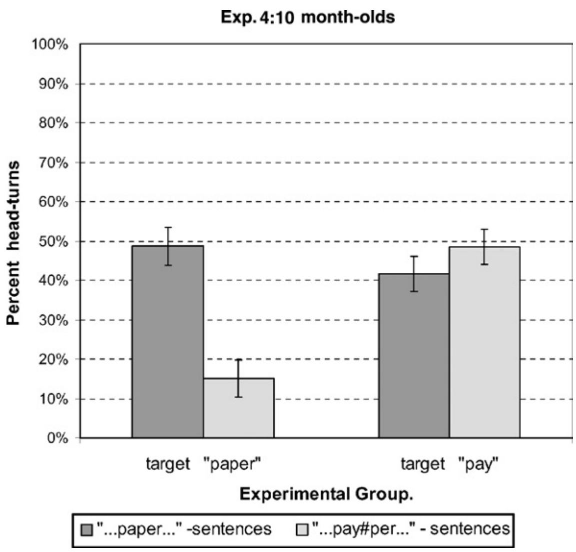

Fig. 3. Results from Experiment 4: percentage of head-turns for 10-month-old infants in the bisyllabic group (left-hand bars, target word *paper*) and in the monosyllabic group (right-hand bars, target word *pay*). Infants heard sentences containing the bisyllabic word (*paper*-sentences, dark-gray bars) and sentences in which it straddled a phonological phrase boundary (*pay#per*-sentences, light-gray bars).

phonological phrase boundaries to infer the presence of word boundaries and therefore to extract words from fluent speech. Again, we observed a greater difference between sentence types for infants from the bisyllabic group (33.6%) relative to infants from the monosyllabic group (6.9% in the other direction). This suggests that the presence of a phonological phrase boundary drastically reduces the activation of words that straddle it, while the absence of a phonological phrase boundary does not imply the absence of a word boundary.

We evaluated whether the CHT word-detection method provides individual results at 10 months of age, again focusing the analysis on infants from the bisyllabic group, where we had a clear prediction that infants should orient to *paper*-type sentences but not to *pay#per*-type sentences. We observed that 17 out of 24 infants of 10 months had an A′ above .755, and therefore performed significantly above chance (21 out of 24 infants showed a difference in response rate in the expected direction, 3 showed a difference in the reverse direction).

A comparison between Experiments 3 and 4 revealed that 13-month-old infants performed better than 10-month-olds: The hit rate was higher for older infants, both for bisyllabic target words (80.6% for 12.5-month-olds vs. 48.6% for 10-month-olds), $F(1,44) = 47.7$, $p < .001$ in a joint ANOVA, and for monosyllabic target words (81.8% vs. 48.5%), $F(1,28) = 30.1$, $p < .001$.[2] There was also a significant three-way interaction between Age, Condition, and Group, indicating that older infants performed significantly better than younger infants, $F(1,72) = 24.2$, $p < .001$; in other words, the crucial Condition by Group interaction, showing that infants exploited prosodic information to constrain lexical access, was of greater magnitude for older than for younger infants. In addition, a comparison of mean A′ revealed significantly better performance for older infants than for younger infants (.85 vs. .74, $t(47) = 2.5$, $p < .02$, for the bisyllabic groups; .74 vs. .53, $t(31) = 2.9$, $p < .01$, for the monosyllabic groups). These analyses indicate continuing improvement in segmentation ability between the ages of 10 and 12.5 months.

The results of Experiment 4 thus show that 10-month-old infants, just like 13-month-olds, are already able to exploit phonological phrase boundaries to infer word boundaries. This result contrasts with what we observed in Experiment 1. This discrepancy must come from the difference in experimental techniques, since we used the very same stimuli in both experiments. Two possibilities exist: either the CHT technique as we used it in Experiment 4 is more sensitive than the HPP technique as we used it in Experiment 1; Or, some feature of the CHT technique used in Experiment 4 lead us to overestimate infants' performance at this age. One obvious candidate is that infants in the CHT task are reinforced for turning their head towards the target word. Since reinforcement must be continued throughout the procedure, this raises the question of what should be reinforced during the test trials (issues of selective reinforcement do not arise in HPP). We chose to administer reinforcement only for target-containing sentences, and not for foil-containing sentences. As a result, infants might have learned during the test phase which sentences they had to respond to and which sentences they should not respond to. If this were the case, infants' performance should improve as the test phase unfolds, either through an increase in hit rate, a decrease in false alarm rate, or both.

To test these predictions, we conducted split-third analyses of hit rate, false alarm rate, and hit rate minus false alarm rate (since there were 24 test trials, split-third analyses were computed on blocks of 8 trials each). The data are shown in Table 2.

Examination of the 10-month-old data shows no significant difference across the three thirds of the experiment, whether on hit rate, false alarm rate, or the difference between them (all three $F(2,44) < 1$). In fact, performance is remarkably stable throughout the experiment. Looking at these data a bit differently, there are significant differences between hits and false alarms in all three thirds of the test sessions (all three $p < .001$). Examination of the 13-month-old data shows the same results (no significant difference across the three thirds of the experiment, all three $F(2,44) < 1$), except that the hit rate tends to decline (non-significantly) across

[2] The false alarm rate was also greater for older infants, significantly so in the bisyllabic group only (25% vs. 15%, $t(46) = 2.5$, $p < .02$ for the bisyllabic groups; 48.5% vs. 41.5%, $t(30) = 1.5$, $p = .15$ for the monosyllabic groups). This 10% increase in the false-alarm rate between 10 and 12.5 months of age (in the bisyllabic group) is hard to interpret because infants may turn their head in this condition for three independent reasons: (1) by chance; (2) because the first syllable of "paper" was heard (similarity with the target); and (3) because they failed to perceive/exploit the phonological phrase boundary between "pay" and the following verb. As a consequence, the difference between 12.5- and 10-month-olds may be due to three reasons: (1) An increase in by-chance responses, which may be due to a greater restlessness in the older infants, who seem to display a greater tendency to check what happens in the reinforcement area; (2) an increase in infants' willingness to identify words even in the presence of incomplete information; or (3) a greater tendency for older infants to overlook the phonological phrase boundary, and think that they heard "paper" upon hearing "pay#per." The last two interpretations are not very plausible given that older infants perform better in the word-detection task. However, in order to disentangle these interpretations, we need to incorporate some additional conditions in future experiments: a "baseline false alarm" condition to measure by-chance head-turns to words which are completely different from the target word "paper" (e.g., "banjo"); and a "word-beginning catch trial" condition to measure spurious head-turns to bisyllabic words starting with "pay" (e.g. "payment").

Table 2
Split-third analysis of Experiments 3 and 4, bisyllabic groups: percent hits, percent false alarms, and difference between them are shown for each third of the test session

10-month-old-infants (Experiment 4)	1st Third	2nd Third	3rd Third	Total
% Hits (*SE*)	48.4 (4.8)	45.1 (5.7)	50.6 (5.6)	48.6 (3.2)
% False Alarms (*SE*)	16.0 (4.2)	14.4 (4.1)	14.4 (4.6)	15.1 (3.0)
%H − %FA	32.4*	30.7*	36.2*	33.5*
$t(23)$	4.5	5.5	4.6	7.2
13-month-old-infants (Experiment 3)	**1st Third**	**2nd Third**	**3rd Third**	**Total**
% Hits (*SE*)	84.9 (4.7)	81.1 (4.1)	74.2 (5.8)	80.6 (3.3)
% False Alarms (*SE*)	21.3 (4.6)	26.9 (4.4)	21.0 (4.0)	25.5 (2.7)
%H − %FA	63.6*	54.2*	53.2*	55.1*
$t(23)$	10.9	9.0	7.3	13.5

Infants' performance is significantly better than chance in each third of the experiment (the difference between %Hits and %False Alarms is significantly greater than 0), and it does not improve over time.
* $p < .001$.

the test session for the older infants, probably due to boredom with the task.

There is thus no indication that selective reinforcement of target-containing trials exerts even marginal effects on the results. There is, however, one additional possibility: infants might learn on the basis of one or two non-reinforced false alarm trials not to turn to *bee#-con* or *pay#per*. This possibility seems highly unlikely for two reasons. First, half of the 10-month-olds did not false-alarm at all during the first third of the experiment; these 12 infants nevertheless averaged a hit rate of 54% ($SE = 6.7$). It is thus not the case that at least one false alarm is necessary for infants to behave better than chance. Second, in other studies with conditioned head-turning, Morgan (1998) has found that high rates of false alarms may be maintained in the presence of selective reinforcement. In these studies, 13- and 14-month-olds were trained on monosyllables and tested on sentences that contained either the target form (e.g., /rIn/), an ''inflected'' version of the target form (plural, /rInz/), or a variant of the target form that cannot be morphologically linked to it (/rIns/). Only responses to the target form were reinforced. Nevertheless, infants showed high rates of false alarms to the ''inflected'' version (/rInz/), and these rates were maintained across the test session.

Overall, there is no indication that infants' performance in CHT experiments was artificially boosted up by selective reinforcement of target-bearing sentences. It thus seems that CHT was more sensitive than HPP, at least when used with the experimental designs that we selected.

General discussion

The experiments reported in this paper suggest that both 10- and 13-month-old infants are able to exploit phonological phrase boundaries to extract words from whole sentences. Experiments 1 and 2 relied on the head-turn preference procedure, while Experiments 3 and 4 relied on a variant of the conditioned head-turning technique. With both experimental techniques, 13-month-old infants showed a good ability to interpret phonological phrase boundaries as natural word boundaries: They did not access lexical items comprising pairs of syllables that spanned such a boundary (Experiments 2 and 3). For 10-month-old infants, the conditioned head-turn procedure indicated that they were also able to exploit phonological phrase boundaries to constrain lexical access (even though their overall performance was significantly worse than that of 13-month-old infants). In the head-turn preference procedure, however, they did not behave as if they spontaneously noticed the difference between sentence types (Experiment 1).

In all four experiments, word-level cues to word boundaries were identical in both experimental conditions: The same syllables occurred adjacently in the same order (100% transitional probability between *pay* and *per* or *bee* and *con*) and they always exhibited a SW pattern. These two powerful word-boundary cues lent strong cohesiveness to the *pay* and *per* (or *bee* and *con*) syllables in our sentences. Nevertheless, when a phonological boundary intervened between the syllables, infants typically did not regard these pairs of syllables as plausible word candidates. These results strongly suggest that lexical access processes occur within the domain of phonological phrases.

Methodological considerations

Below, we consider the theoretical implications of our results. First, however, we wish to discuss methodological aspects of the experimental techniques that we used and compare their advantages and disadvantages.

The Head-turn Preference Procedure, one variant of which was used in Experiments 1 and 2, is at present the predominant technique used in studies of infant speech processing. There are several reasons for this: HPP is relatively easy to administer, can be used with a wide range of ages, and usually has low levels of subject loss (for example, in 11 studies with 7.5-month-olds in Jusczyk et al., 1999; subject loss averaged 21%, whereas in four studies with 10.5-month-olds, it averaged 16%).

The conditioned head-turn word-detection technique used in Experiments 3 and 4 provides a valuable supplement to HPP. First, the word-detection technique yields quantitative results, so that it is well suited to the fine-grained comparison of multiple groups of infants. For example, comparison of Experiments 3 and 4 showed a significant improvement in word-detection rate between 10- and 12.5-month-old infants (from about 50 to 80% hit rate), as well as a significant improvement in the ability to exploit phrasal prosody to constrain lexical access (as evidenced by the significant 3-way interaction between age, condition, and group).

Second, word-detection is an on-line method in which the infants' responses are time-locked to the occurrence of particular stimulus events. This affords direct measurement of infants' speech processing. Although we did not do so here, it is possible to measure response latencies, which may be as informative as response rates (Morgan, 1994, 1996; Swingley & Fernald, 2002; Swingley, Pinto, & Fernald, 1999). Item-by-item results may allow experimenters to correlate particular cues in the stimuli with infants' response patterns. Because individual subjects contribute multiple data points, several factors may be manipulated within subjects. Moreover, multiple data points for each infant allowed us to compute individual statistics; for example, in the bisyllabic group in Experiment 3 we observed that 20 out of 24 infants performed better than chance.

To be sure, the word-detection technique is not without drawbacks. It is a fairly difficult procedure to administer. Infants' attention is intentionally divided between toys shown at midline and speech stimuli presented to one side; maintaining an appropriate balance requires exquisite sensitivity and coordination between experimenters. Levels of subject loss are higher than in HPP: in Experiments 3 and 4, loss averaged about 50%. Since most subjects were lost either during the first session or between sessions, it is not the case that the procedure 'selected' those infants who were able to succeed in the test phase (which might have led to underestimating the age at which the average infant is able to perform the task). However, the first session may well have served to 'select' infants who were willing to actively participate in a language-related experiment. It may be that these infants paid more attention to the speech stimuli delivered during the experiment than the average infant involved in an HPP experiment (where a lesser level of attention suffices to complete the experiment). This may be one of the reasons why CHT appeared to be more sensitive than HPP in our experiments.

In summary, both HPP and the CHT word-detection technique have advantages and disadvantages. Together, they yield a stronger pattern of results than either could alone. However, as we ask increasingly sophisticated questions about infants' spoken language processing, it will become more and more important to compare findings to those in the extensive existing literature on adult spoken word recognition. To do so, we must have comparable measures of behavior. The CHT word-detection paradigm is one step in this direction, since it furnishes data comparable to word monitoring in adults (see Christophe et al., in press). Another promising avenue of research comes from recent work showing that eye-tracking methods, which have been used in studies of adult language processing (e.g., Allopenna et al., 1998; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995), may be adapted for use in referential tasks with toddlers and older infants (e.g., Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998; Swingley & Aslin, 2000). Such a technique, if tailored for younger infants in non-referential tasks, has the potential to combine the strengths of both HPP and CHT.

Theoretical implications: lexical access, universality, and acquisition of syntax

As noted earlier, our results show that lexical access processes occur within the domain of phonological phrases. Let us spell out the implications of this conclusion for models of lexical access. Segmentation procedures can be sorted into two main categories: on the one hand, "lexical segmentation" strategies, in which segmentation is a by-product of word recognition (a strategy called "serendipitous segmentation" by Cutler, 1990); on the other hand, "prelexical segmentation" strategies exploit bottom-up cues (such as prosodic boundaries, allophonic or lexical stress cues, as reviewed in Introduction) that are extracted from the speech signal without reference to lexical items. In terms of lexical acquisition, "lexical segmentation" strategies require initial reliance on isolated lexical items, and continuing reliance on known lexical items, as is the case for instance in the INCDROP model proposed by Brent and Siskind (2001). In contrast, "prelexical segmentation" strategies can be generally exploited by infants as soon as they have learned the relevant properties of some words and their boundaries in their native language (it has often been proposed that infants first rely on utterance boundaries, which are clearly marked by silent pauses, to learn about these properties). In adults, there is good experimental evidence that both types of strategies are exploited, and it makes sense to think that they are both exploited in infants as well (recent evidence indicates that early use of lexical segmentation may be restricted to a handful of highly familiar items, such as the infant's own name, see Rathbun, Bortfeld, Morgan, & Golinkoff, 2002).

The question arises as to the type of relationship between these two strategies in the course of lexical access. Two opposing views may be spelled out: on the one hand, lexical segmentation could be the main process, with prelexical segmentation cues being called upon only when lexical segmentation failed. In that view, prelexical segmentation would be used initially only for long utterances that do not contain known lexical items, and would be used less and less as children grow up and increase their lexicons. On the other hand, prelexical segmentation cues may be computed at the same time as lexical recognition takes place, and directly influence lexical activation and recognition. The relative influence of prelexical segmentation relative to lexical segmentation would depend on the strength of the prelexical cues (highly predictive of a word boundary or not) as well as on the strength of the lexical items involved (well-known and frequent lexical item or not). In our experiments, we used an experimental design in which both the prelexical and the lexical segmentation cues were very powerful: thus, words should not straddle phonological phrase boundaries, and we used well-marked phonological phrase boundaries. But also, the target word (either *paper* or *beacon*) had been presented many times in the experimental setup: between 60 and 200 repetitions in the word-detection technique, and infants were reinforced for responding to the target word; roughly 30 repetitions for the head-turn preference procedure. The target word was thus in a good position to ensure adequate lexical segmentation. Still, in these conditions, we found that infants typically did not access the target word when its syllables straddled a phonological phrase boundary. It thus seems that at least in some instances, purely bottom-up cues to segmentation, such as those provided by phrasal prosody, may suffice to constrain lexical access.

Second, we may wonder to what extent our results would generalize to other languages. They have been obtained with American infants listening to American sentences. Some recent adult experiments suggest that they might also obtain in French. Christophe et al. (in revision) showed that phonological phrase boundaries constrain on-line lexical access in French adults listening to French sentences that either did or did not contain a local lexical ambiguity, with a design exactly parallel to the one used in the present studies. Similarly, in Korean, Choi and Mazuka (2003) observed that both 3-year-old and adults were able to use phonological phrase boundaries to resolve lexical ambiguities (using an off-line task). In addition, phonological phrases are thought to exist in all languages of the world (Nespor & Vogel, 1986; Selkirk, 1984), and prosodic cues to phonological phrases have been measured in several unrelated languages (e.g., Barbosa, 2002 for Brazilian Portuguese; de Pijper & Sanderman, 1994 for Dutch; Fisher & Tokura, 1996 for Japanese; Rietveld, 1980 for French; and Wightman et al., 1992 for English). As a result, phonological phrases are potentially available universally for lexical acquisition, even though the exploitation of boundary cues may be language-specific.

Third, phonological phrase boundaries may provide some information as to the syntactic structure of sentences (Gerken et al., 1994; Morgan, 1986). It has often been claimed that prosodic structure may help bootstrap syntactic acquisition (Gleitman & Wanner, 1982; Hirsh-Pasek et al., 1987; Jusczyk, 1997; Morgan & Demuth, 1996; Nespor, Guasti, & Christophe, 1996). Phonological phrase boundaries systematically coincide with boundaries of syntactic constituents (even though the reverse is not true, see Introduction); as a result, some syntactic constituents are prosodically marked.

This information can be exploited in two different ways: on the one hand, to constrain distributional analyses of the speech input. Thus, function words and morphemes tend to occur at the edges of syntactic phrases, and therefore also at the edges of phonological phrases: their position within phonological phrases may thus be one of the cues that distinguish function words from content words (Morgan, Shi, & Allopenna, 1996; Shi et al., 1998). Infants could compile a list of the syllables that occur at the beginning and end of prosodic units, storing the most frequent syllables in a separate list, and subsequently identifying these syllables as closed-class items when encountered at the borders of a prosodic unit (see Shady, 1996; and Shafer, Shucard, Shucard, & Gerken, 1998; for evidence that 11-month-old English infants already know some of the function words of English). As soon as a list of function words is established, infants could strip off those very frequent syllables when encountered at the borders of prosodic units and identify the rest of the string as a content word (''function word-stripping'' strategy).

On the other hand, phonological phrase boundaries may also be exploited directly by infants to constrain on-line syntactic analysis. Prosody may be a cue to syntactic structure (Gerken et al., 1994; Morgan, 1986), since phonological phrase boundaries coincide with syntactic boundaries.[3] Note that prosody in itself provides no cue to the labeling of constituents (into, e.g., Noun Phrase, Verb Phrase, etc.). However, prosodic information may

[3] Some adult experiments show that intonational phrase boundaries are exploited on-line to resolve temporary syntactic ambiguities (see e.g., Kjelgaard & Speer, 1999; Schepman & Rodway, 2000). Recent experimental evidence suggests that phonological phrase boundaries may also be exploited by adults to constrain syntactic analysis (Millotte & Christophe, 2003).

be used in conjunction with function words to perform an initial segmentation and labeling of sentences into syntactic constituents. Thus, the sentence "the little boy is running fast" may be initially perceived as [the xxx]$_{NP}$ [is xxx]$_{VP}$, where the boundaries are given by prosody and the labeling is given by the function words (assuming infants managed to learn broad categories of function words, see Höhle, Weissenborn, Kiefer, Schulz, & Schmitz, 2004, for evidence at 16 months in German). Simultaneous access to both function words and phonological phrase boundaries may thus allow young children to start constructing rough syntactic analyses for the sentences they hear, even before they know the meaning of many content words (Christophe, Guasti, Nespor, Dupoux, & van Ooyen, 1997). In fact, such a skeleton of a syntactic structure may be what is needed to help in learning the meaning of words (Gleitman, 1990).

Conclusion

In this article, we presented converging evidence from two experimental techniques showing that American infants as young as 10 months of age spontaneously interpret well-marked phonological phrase boundaries as word boundaries. This indicates that word-finding processes apply primarily within the domain of phonological phrases and, hence, that lexical segmentation must be constrained by at least some bottom-up, prelexical cues. Infants integrate word-boundary cues with phrase boundary cues by subordinating the former to the latter: hierarchical prosodic structure governs processing by infants as well as adults.

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Appendix. Experimental material

Pairs of sentences with paper:

1. The outstanding pay persuades him to go to France.
   The scandalous paper sways him to tell the truth.
2. My friend says that smaller pay perpetuates unhappiness.
   The girl found the meager paper petulant and annoying.
3. The wealthy tycoon with all the pay pursued his rivals.
   The young man who often reads the paper sued the lady.
4. The girl with piles of pay perfumed the smelly house.
   The burning piles of paper fumed through every room.
5. After he was promoted, his increased pay permuted into that of his bosses.
   Although he was conservative, his revised paper muted the reply of his colleagues.
6. The abrupt increase in pay pertained to his fine work.
   The quite sudden rise in paper tainted her good mood.
7. The man with the least pay perspires constantly.
   The church with the most paper spires is heavenly.
8. The butler with the highest pay performs the most.
   The college with the biggest paper forms is best.
9. She thought the beautiful pay permitted all the dolls.
   She put the beautiful paper mittens on the doll.
10. Such little pay perturbed her big family.
    The tiny paper turban flew off the man's head.
11. Our friend worked consistently but her awful pay perplexed us.
    We built a model hockey stadium and used paper Plexiglas.
12. A pumpkin farmer with lots of pay perceives his improving yields.
    A coffee filter is like a paper sieve to remove the grounds.

Pairs of sentences with *beacon*:

1. The plastic decorative bee contained the sparkling necklace.
   The very large and ugly beacon tainted the beautiful skyline.
2. We saw the yellow bee constrained with the weight of its load.
   The person with the beacon strained to transmit the message.
3. The girl watched the little bee controlling all the rose pollen.
   The fisherman saw the beacon rolling in the foggy bay.
4. The color of the bee confounded the new beekeeper.
   The owner of the beacon founded the association.
5. She was surprised to discover the bumble bee confused about flowers.
   It was amusing to see the overheated beacon fusing to the ice.
6. The vicious bee confronted all the angry crowd.
   The striped beacon fronted on the rocky shore.
7. The glowing bee conserved its breath for its flight around the flowers.
   The glowing beacon served as light for the sailors in the harbor.
8. He had the yellow bee concealed again to prevent the girls from stealing.
   He had the ancient beacon sealed again to stop the new lens from cracking.
9. He told us it was the old man that the bee contended with.
   She explained that the girl with the glowing beacon tended it.
10. The bumble bee confounded the study and upset us.
    The golden beacon found by the lake really surprised her.

11. The wasps buzzed around the light, and the pesky bee conflicted with them.
    The stars sparkled in the sky, and the glowing beacon sparkled with them.
12. The pesky birds stole the pollen that the enormous bee converted.
    My brother Fred watched as Mary set the gigantic beacon vertical.

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