Early Language Development

Bridging brain and behaviour

Edited by

Angela D. Friederici
Max Planck Institute for Human Cognitive and Brain Sciences

Guillaume Thierry
Bangor University

John Benjamins Publishing Company
Amsterdam / Philadelphia

CHAPTER 4

Reflections on reflections of infant word recognition*

Valesca Kooijman, Elizabeth K. Johnson and Anne Cutler

1 Introduction: Reflecting the development of speech perception

The history of experimental psychology is a progression of ever more ingenious attempts to capture reflections of the processes of the mind. No mental operations can ever be observed directly. Since experimental psychology began in earnest – in Wilhelm Wundt's Leipzig laboratory in the late nineteenth century – the principal concern of experimental psychologists has been to devise methods which allow mental operations to be observed indirectly. Most commonly, these methods record the speed or accuracy of behavior for which certain mental processes are a prerequisite; more recently, the electrophysiological signals or the blood flow in the brain can be measured as mental processing occurs. Although only such indirect reflections can ever be available to us, experimental psychology has contrived to amass substantial knowledge about the processes which go on in the human mind.

Particularly challenging has been the study of the beginnings of cognitive processing. Infants in the first year of life cannot command the overt behavioral responses required in the most common adult testing procedures; it is obviously laughable to imagine nine-month-olds signaling recognition of a word by pressing a response button or giving a verbal answer. Nonetheless, as will become clear, we do now know that nine-month-olds can indeed recognize word forms. This is because the challenge of capturing reflections of early cognition has also been met: in the past four decades, highly effective covert-behavioral methodologies have been devised for studying mental operations in the infant brain.

In the area of early speech perception and the beginnings of vocabulary development, the commonest testing methodologies have used the rate or duration of simple behavioral responses, such as sucking on a pacifier or looking at a visual stimulus associated with an auditory signal, as the indirect measures of developing speech perception and processing abilities. Creative use of these testing methodologies has uncovered remarkably sophisticated speech perception skills in preverbal infants. The High Amplitude Sucking Paradigm, for example, which uses sucking rate as a dependent measure of speech preferences and discriminatory abilities, works well with infants up to two months of age (Jusczyk 1985; Sameroff 1967). Research using this paradigm has demonstrated that infants begin laying a foundation for language acquisition even before birth. Newborns prefer to listen to their mother's native tongue over other languages (e.g. English-learning infants prefer to listen to English over Spanish; Moon, Cooper and Fifer 1993). They also show recognition of voices (DeCasper and Fifer 1980) and of stories heard before birth (DeCasper and Spence 1986), and they discriminate phoneme contrasts (Eimas, Siqueland, Jusczyk and Vigorito 1971).

Of course, newborns are still far removed from linguistic competence. Their phoneme discrimination skills reflect their auditory abilities, not their use of linguistic experience; they can discriminate phonetic contrasts which do not appear in their maternal language as well as those that do (Aslin, Jusczyk and Pisoni 1998; Werker and Tees 1984; 1999). At two months of age, likewise, English-learning infants cannot yet perceive the difference between their own language and the rhythmically similar Dutch (Christophe and Morton 1998). However, speech processing skills develop rapidly during the first year of life, as research using other procedures more suited to testing older infants, such as the Conditioned Headturn Procedure and the Headturn Preference Procedure, has demonstrated. By four months, infants recognize their own name (Mandel, Jusczyk and Pisoni 1995) and discriminate between their native language and other rhythmically similar languages (Bosch and Sebastián-Gallés 1997). By five months, infants are so familiar with the prosodic structure of their native language that they can even discriminate between two dialects of their native language – thus American infants can discriminate between American and British English (Nazzi, Jusczyk and Johnson 2000). Sensitivity to language-specific vowel patterns emerges by six months of age (Kuhl, Williams, Lacerda, Stevens and Lindblom 1992), and language-specific consonant perception is well in place before infants reach their first birthday (Werker and Tees 1984; 1999). First evidence of rudimentary word segmentation and comprehension skills has been observed between six and seven and a half months of age (Bortfeld, Morgan, Golinkoff and Rathbun 2005; Jusczyk and Aslin 1995; Tincoff and Jusczyk 1999), and these skills continue to develop at an impressive rate throughout the first year of life (Hollich, Hirsch-Pasek and Golinkoff 2000; Jusczyk, Houston and Newsome 1999). In short, infant testing methodologies using simple behavioral measures such as sucking rate and looking time have revealed that the infant's world is a far cry from the "*blooming, buzzing confusion*" envisioned by William James (James 1911). Infants in fact amass considerable linguistic knowledge long before they begin to communicate with language.

Thus despite the fact that the processes of speech perception are not directly observable, indirect reflections of these processes in infancy have proven highly informative. As the title of this chapter suggests, we compare and evaluate the various methods in current use; we also argue that new (electrophysiological) methods in combination with older (behavioral) methods open the way to further insights. We draw our examples from research on the segmentation of continuous speech into its component words.

2 The word segmentation problem

Hearing speech as a string of discrete words seems so effortless to adults listening to their native language that it is tempting to suspect that the speech signal unambiguously informs us where one word ends and the next begins. However, listening to an unfamiliar language or examining a spectrogram easily dispels this illusion. When we listen to an unfamiliar language, words seem to run together in an impossibly fast manner; it is only in our own language that segmenting streams of speech into their component words is so easy. But in fact words run together in any language. Nazzi, Iakimova, Bertoncini and de Schonen, this volume, make this point with a French example; our Figure 1 illustrates it with a Dutch eight-word sentence: *Die oude mosterd smaakt echt niet meer goed* 'that old mustard really doesn't taste good any more'. There are several silent portions in the speech stream, but even where these happen to occur between words, they have not arisen from pauses between the words: each such point just represents the closure of the speaker's mouth as a stop consonant (/d/, /t/, /k/, or the glottal stop separating successive vowels) has been uttered. The eight words are not demarcated by recurring word-boundary signals of any kind. This utterance was in fact spoken slowly and carefully in a manner associated with infant-directed speech; most utterances in our everyday experience, however, proceed even faster and weld the separate words even more closely together than we see here.

Why is it so easy to hear words in our native language? As it turns out, there are a myriad of cues to word boundaries which listeners can call upon, but these cues are probabilistic rather than fully reliable; furthermore, and most importantly, they are language-specific. Adults therefore exploit multiple cues for identifying word boundaries in fluent speech, and the cues they use are determined by their native language experience (Cutler 2001). An example of a language-specific cue for word segmentation is lexical stress in English. Since the majority of English content words begin with a stressed syllable (Cutler and Carter 1987), English listeners are biased towards perceiving stressed syllables as word onsets (Cutler and Butterfield 1992). English listeners who tried to apply this strategy towards the segmentation of spoken French, Polish or Japanese, however, would have little luck extracting words from the speech stream.

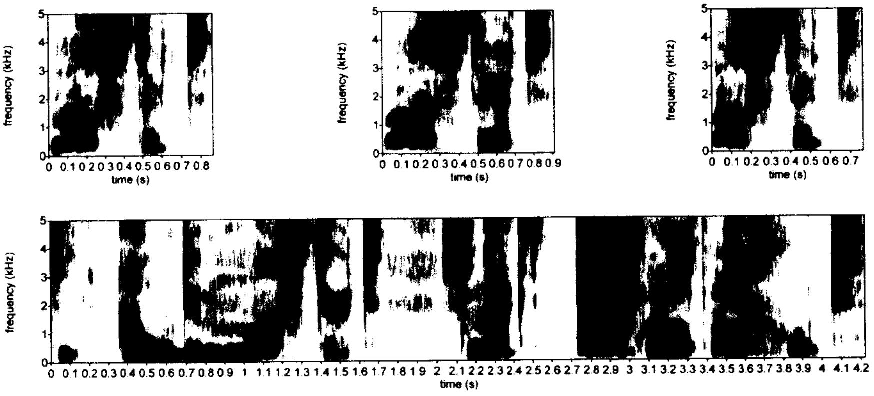

Figure 1. Above, three spectrograms of the Dutch word *mosterd* 'mustard', produced in isolation in a manner associated with infant-directed speech; below, a sentence *Die oude mosterd smaakt echt niet meer goed* 'That old mustard really doesn't taste good any more', produced in the same manner. The displays represent frequency on the vertical axis against time on the horizontal axis, with greater energy represented by darker color. It can be seen that the three word tokens differ in duration, from about 750 ms to about 900 ms, and also differ in spectral quality. The word *mosterd* in the sentence begins at about 0.78 on the time line and finishes at about 1.75

Segmenting words from speech is a trivial task for adults because they have had years of experience listening to their native language. Learning how to find words for the first time, however, presents a much bigger challenge. Moreover, it is a very important skill to learn in the first year of life, as is clear from Newman, Bernstein Ratner, Jusczyk, Jusczyk, and Dow's (2006) demonstration that relative ability to recognize discrete words in continuous speech before age one is directly predictive of vocabulary size at age two. It has been proposed that infants might solve the word segmentation problem by first learning words in isolation, and then subsequently recognizing these words in fluent speech (Bloomfield 1933; Brent 1999). But the speech which infants hear in the first year of life consists predominantly of multiword utterances (Morgan 1996; van de Weijer 1998; Woodward and Aslin 1990), so it seems unlikely that hearing words in isolation could constitute the full explanation for how language learners first begin segmenting words from speech. It seems more likely that the onset of word segmentation is fueled by developing knowledge about the typical sound pattern of words, i.e., by exploitation of language-specific probabilistic cues like typical stress patterns. As the next section describes, there is now a good deal of evidence supporting this account.

3 The headturn preference procedure and early word segmentation

The development of the Headturn Preference Procedure (HPP) brought about great advances in understanding of when infants begin segmenting words from speech. Before the HPP was in widespread use, evidence from language production led researchers to conclude that four-year-olds still had not completely solved the word segmentation problem (Chaney 1989; Holden and MacGinitie 1972; Huttenlocher 1964; Tunmer, Bowey and Grieve 1983). At the same time, however, most studies of early syntactic development assumed that two- and three-year-olds were perceiving speech as a string of discrete words. In retrospect, this assumption does not seem unwarranted, especially since it seems only logical that children would need to learn to segment words from speech before they could build a large enough vocabulary to communicate their thoughts verbally. In other words, research on infant word segmentation lagged behind research on, for instance, phoneme and language discrimination.

One reason for the relative lag is that studying word segmentation presents methodological challenges. First, long stretches of speech must be presented. Second, there must be a measure of recognition rather than simply of discrimination or preference. The earliest widely-used infant testing methodologies, such as the High Amplitude Sucking Procedure and the Visual Fixation Procedure, were unsuited to the study of word segmentation because they offered no recognition measure.

The first use of HPP was in a test of four-month-olds' preferences concerning adult- versus infant-directed speech (Fernald 1985). In Fernald's experiment, infants sat facing forward on a parent's lap in the middle of a three-sided booth. A light was mounted at eye level in the center of each of the three walls of the booth. Speakers were hidden behind the lights on the two side walls; infant-directed speech (IDS) was played from one speaker and adult-directed speech (ADS) from the other. The green light on the front panel blinked at the onset of each trial. Once infants oriented towards the green light, it would immediately stop blinking and both of the side lights would begin blinking. Depending on which light the infants turned towards, they would hear either IDS or ADS. Headturns were observed by an experimenter out of view of the infant. Fernald *et al.* found that infants turned to the side from which IDS was played more often than they turned to the side from which ADS was played. Accordingly, they inferred that four-month-olds preferred to listen to IDS over ADS.

In this version of HPP, the dependent measure was how often infants turned to the left versus right. In the first HPP study of word segmentation (Myers, Jusczyk, Kemler Nelson, Luce, Woodward and Hirsch-Pasek 1996), the procedure was modified so that all stimulus types were played equally often from the left and right speaker, and the dependent measure was length of orientation time to speech from one side versus the other. The contrast in this study was between passages containing pauses inserted within words versus pauses inserted between words. Eleven-month-olds listened longer to the latter type of speech. Based on the assumption that infants prefer to listen to natural- over unnatural-sounding speech samples (see Jusczyk 1997, for review), this study suggested that 11-month-olds have some concept of where word boundaries belong in speech. But this is not the best test of word segmentation abilities, since it is possible that the infants had simply noticed the unnatural disturbance of the pitch contour.

A better test of infants' word segmentation skills was devised by Jusczyk and Aslin (1995), who further modified HPP by adding a familiarization phase prior to the test phase (see also Kemler Nelson, Jusczyk, Mandel, Myers, Turk and Gerken 1995). During the familiarization phase of Jusczyk and Aslin's study, 7.5-month-olds listened for 30 seconds to isolated repetitions of each of two words: *dog* and *cup* or *bike* and *feet*. In the test phase immediately following this familiarization, infants' length of orientation to test passages containing *dog*, *cup*, *bike*, and *feet* was measured. Infants familiarized with *bike* and *feet* listened longer to test passages containing *bike* and *feet*, while infants familiarized with *cup* and *dog* listened longer to passages with *cup* and *dog*. Six-month-olds tested with the same procedure and stimuli failed to demonstrate any listening preferences.

Jusczyk and Aslin accordingly concluded that infants begin segmenting words from speech some time between six and 7.5 months of age. Numerous subsequent segmentation studies with the two-part version of HPP have supported this finding (see Jusczyk 1999, and Nazzi *et al.*, this volume, for reviews).

In combination, these HPP studies have provided clear evidence that production studies underestimate the rate of development of infants' word segmentation ability. Production studies were inadequate to study early word segmentation for several reasons. First, they required a verbal response, which limited researchers to testing children who could already speak. Second, the tasks used to test children's ability to hear word boundaries were often quite complicated (e.g. repeating the words in an utterance in reverse order). The difficulty of these tasks is very likely to have masked younger children's ability to segment words from speech. Word segmentation abilities develop in the course of initial vocabulary building, and studies with the HPP have allowed us to see that.

4 Advantages and disadvantages of behavioral word segmentation measures

The HPP has many strengths as a testing methodology for research on word segmentation. First, it allows long stretches of speech to be presented in either the familiarization or test phase of the experiment; this is obviously an essential prerequisite for studying fluent speech processing. Indeed, recent studies have shown that HPP also works well with fluent speech in both familiarization and test phases (Soderstrom, Kemler Nelson and Juscyk 2005; Seidl and Johnson, forthcoming). Second, the dropout rate in HPP is relatively low compared to other testing methodologies. Third, HPP yields less variable data than some other methods, since looking-time measures are often based on 12 to 16 trials, rather than the two or four test trials commonly used, for example, in the Visual Fixation Procedure (however, see Houston and Horn 2007, for discussion of an adapted version of the Visual Fixation Procedure allowing multiple test trials and providing results which are arguably suitable for individual subject analysis). Fourth, HPP is widely applicable; although it may be best suited for testing children between six and nine months of age, it has been shown to work well with children as young as four months or as old as 24 months. This is certainly useful, considering the protracted development of word segmentation abilities (e.g., see Nazzi, Dilley, Jusczyk, Shattuck-Hufnagel and Jusczyk 2005). Fifth and finally, HPP does not require that infants be trained to focus on any particular aspect of the speech signal. Rather, in contrast to procedures like the Conditioned Headturn Procedure (CHT), it provides a measure of what infants naturally extract from the speech signal.

Like all infant testing methodologies, HPP has a few disadvantages too. As with other methods, it is hard to say whether performance in the laboratory is accurately representative of performance in the real world, where visual and auditory distractions are plentiful (see however, Newman 2005). HPP is ill-suited to the study of individual variation, because a typical HPP study requires multiple subjects. Infants can become bored with the HPP procedure, and re-testing a child with the same procedure is not advisable. Finally, HPP looking times do not reflect the temporal nature of the processing involved. This is of particular importance to the case of word segmentation.

In adult word segmentation research, the temporal course of word processing has played an important role in understanding how words are recognized. Reaction time studies have revealed that many word candidates are simultaneously activated, and then compete for recognition (Norris, McQueen and Cutler 1995). The competition process is further modulated by explicit segmentation procedures which can be language-specific (e.g., attention to rhythmic structure; Cutler and Butterfield 1992) or universal (e.g., rejection of activated words which would leave isolated consonants unaccounted for in the signal; Norris, McQueen, Cutler and

Butterfield 1997; Cutler, Demuth and McQueen 2002). But HPP effectively only tells us whether word segmentation has occurred, not how rapidly it has occurred. Evidence for the temporary activation of spurious word candidates, or information about the precise timing of online segmentation, cannot be found with HPP. Thus although we know that twelve-month-olds also fail to segment word candidates which would leave isolated consonants unaccounted for (Johnson, Jusczyk, Cutler and Norris 2003), the results of this study – summarized in Figure 2 – tell us only that segmentation has occurred in one condition and not in the other; they tell us nothing about the relative speed of word recognition which was addressed in the adult studies, let alone about the relative segmentation success for individual words in the passages or the performance of individual listeners.

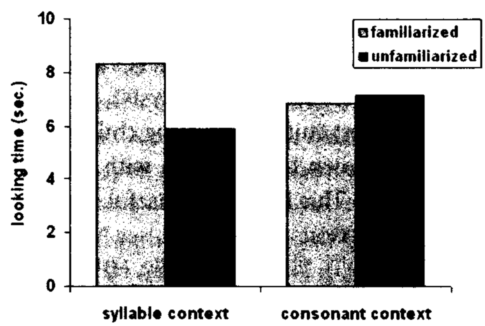

Figure 2. Mean looking times for 12-month-old infants in the HPP study of Johnson *et al.* (2003) to passages containing embedded words which were familiarized versus unfamiliarized, separately for conditions where the embedding context was a whole syllable (e.g., *win* in *winsome* or *window*, *rest* in *caressed* or *fluoresced*) versus an isolated consonant (e.g., *win* in *wind* or *whinge*, *rest* in *dressed* or *breast*). Each test passage contained five occurrences of the crucial word in five different embedding contexts. Each mean is an average over 40 participants

It would certainly be advantageous if the fine-grained temporal course of word segmentation could also be studied in younger infants, who are just beginning to use their newly acquired knowledge about the sound structure of their native language to extract word forms from speech. Two procedures which appear more temporally sensitive than HPP each have limitations. First, eye-tracking procedures (Fernald, Pinto and Swingley 2001; Swingley, Pinto and Fernald 1999) certainly offer a window onto the temporal course of children's processing; however, these procedures can only be used with children who already have a lexicon in place, which makes them unsuitable for early segmentation research. Second, the Conditioned Headturn (CHT) Procedure, in which infants are trained to turn to a puppet box for reinforcement each time they hear a target word, can also be used to test infants' extraction of words from fluent speech. In CHT studies on phoneme discrimination, target words or syllables were embedded in a list of other words, all spoken in isolation (Werker, Polka and Pegg 1997), but more recently, infants have been trained to respond to target words embedded in utterances (Dietrich 2006; Gout, Christophe and Morgan 2004), and Gout *et al.* have claimed that CHT provides a more sensitive measure of word segmentation capabilities than HPP.

Although the dependent measure in CHT is usually not the speed of initiating a headturn but the probability of making one, this method almost approaches an online measure, and it clearly has the potential to provide a useful convergent measure of early word segmentation. But CHT has a notoriously high dropout rate, and it typically requires two highly experienced experimenters to run the procedure. Given the skills needed to run CHT, procedural differences between laboratories could affect results. Moreover, while HPP's familiarization phase is arguably a laboratory instantiation of natural parental repetitions, CHT's phase of training infants to attend to a specific word could be seen as less ecologically valid.

Online reflection of infant speech perception is, however, available from non-behavioral methods; in particular, electrophysiological methods have been used to study infant speech processing for over 30 years (Molfese, Freeman and Palermo 1975). As we argue in the following section, these methods now offer new insights into word segmentation in infancy too.

5 ERPs as a reflection of early word segmentation

Kooijman, Hagoort and Cutler (2005) recently adapted infant Event-Related Brain Potential (ERP) measures to the study of word segmentation. Compared with the behavioral techniques just reviewed, a much clearer case can be made that this measure succeeds in reflecting the temporal course of infant word processing. In contrast to HPP and CHT, the dependent measure in ERP studies is not a behavioral response, but an electrophysiological signal produced by the brain. There are both pros and cons to the use of a brain response rather than an explicit behavior as a measure of word recognition. On the one hand, behavioral measures may be rather conservative reflections of word segmentation. When a predicted behavior is not observed in HPP or CHT, researchers can conclude that word recognition has not occurred. But it is conceivable that the infant may have recognized the word but just failed to indicate so in the way we expect. This is why null results can be so difficult to interpret in behavioral studies such as HPP (see Aslin and Fiser 2005, for discussion). Although ERP measures are also only an indirect reflection of the mental operations we wish to reveal, the behavioral measures require that neural activity be translated to behavior while ERPs arguably tap the neural activity on which the behavior is founded. On the other hand, note that it is possible that the neural activity underlying a measured behavioral response may go undetected in a particular ERP measurement situation (Kutas and Dale 1997).

Electroencephalography (EEG) measures the electrical signals generated by cortical, and to a lesser degree subcortical, areas of the brain. In a typical cognitive ERP experiment, a task is presented to the participant during continuous EEG recording. A marker, usually time-locked to the onset of stimulus presentation (but sometimes also to the offset, or to the participant's response) is linked to the EEG signal. Recorded EEG signals given different stimulus types are extracted and averaged for each condition to calculate ERPs. (For a detailed description of EEG, see Luck 2005). Although there are different ways to use the EEG signal as a measure of cognitive processes, ERP measurement is currently the most commonly used testing method.

Significant increases in knowledge of the pros and cons of ERP measurement have been achieved in the past decade. Many laboratories use ERPs to investigate language processing, and quite a few have now turned to the use of ERPs to study language development. In adults, ERPs have been used for a considerable number of years as a measure of language processing and several ERP components have been well described. For example, the N400 has been shown to be related to semantic information processing (Federmeier and Kutas 1999; Kutas and Federmeier 2000), and grammatical information processing has been shown to be reflected by the Early Left Anterior Negativity (Friederici, Hahne and Mecklinger 1996) and the SPS/P600 (Hagoort, Brown and Osterhout 1999). Studies on adult ERP reflections of word segmentation are limited: Sanders and Neville (2003) tested N100 modulation as a signature of adult word boundary recognition, and proposed this early component as an index of word segmentation; Snijders, Kooijman, Hagoort and Cutler (in press) studied word segmentation in Dutch with an ERP repetition paradigm, and found significant segmentation delay in foreign listeners with no knowledge of Dutch, as compared to adult native speakers of Dutch.

Although we as yet know relatively little about the ERP components of language processing in infants, this field of research is developing rapidly (for recent reviews, see Friederici 2005; Kuhl 2004). Note that EEG is particularly suitable for use with difficult subject groups such as young children because it is an easy non-invasive procedure and does not require the subject to perform an overt task. The use of so-called EEG caps, i.e. caps containing a number of electrodes on fixed positions, has further increased the utility of EEG with infants. Some research has already addressed the development of ERP components. Pasman, Rotteveel, Maassen and Visco (1999) investigated the development of the N1/P2 complex in children, and showed that this response to tones does not reach mature levels until about

14–16 years of age. The Mismatch Negativity response (Cheour, Alho, Ceponiené, Reinikainen, Sainio, Pohjavouri, Aaltonen and Näätänen 1998) has been claimed to be a stable component that can be found in both adults and very young infants (though see Dehaene-Lambertz and Pena 2001); considerable changes do however occur during development (Cheour *et al.* 1998). More recently, in some laboratories the development of the N400 component has been investigated as a representation of early word meaning; for example, Friedrich and Friederici (2004; 2005) observed an N400-like semantic incongruity effect in 14- and 19-month-olds.

Kooijman *et al.*'s (2005) study on early word segmentation was the first to use an ERP paradigm to test infants under a year of age on continuous speech input. Kooijman *et al.* devised an ERP-compatible adaptation of the familiarization-and-test HPP procedure of Jusczyk and Aslin (1995), described above. Since no headturns or other behavioral responses are required in an ERP study, or even desired because of possible movement artifact, Kooijman *et al.*'s study involved no lights, and speech signals did not change source location. Infants heard, in a familiarization phase, ten tokens of the same bisyllabic word. Immediately following the familiarization, infants listened to eight randomized sentences making up the test phase. Four of these sentences contained the familiarized word, while the other four contained an unfamiliar bisyllabic word. Comparison of the ERP to the familiar and unfamiliar target words in the test phase sentences is then the measure of word segmentation. The words and sentences were spoken in a lively manner typical of infant-directed speech; the speech samples in Figure 1 are three examples of the word *mosterd* 'mustard' from a familiarization phase in this study, and one of the sentences containing this word from a test phase. There were 20 blocks of familiarization plus test phase; ERP requires such a high number of experimental blocks because an acceptable signal-to-noise ratio can only be attained with many trials per condition, and the dropout of trials per infant can be quite high due to movement artifacts. Table 1 shows an example block.

Table 1. Example of an experimental trial in the ERP study of Kooijman *et al.* (2005)

Familiarization: Ten repetitions of mosterd

Test:
Die oude mosterd smaakt echt niet meer goed.
That old mustard really doesn't taste so good any more.
Voor soep is de dikke mosterd ook te gebruiken.
The thick mustard can also be used for soup.
De oude pelgrim maakt een reis naar Lourdes.
The old pilgrim is travelling to Lourdes.
De pelgrim is niet blij met de openbaring.
The pilgrim is not happy about the revelation.
Bij de jonge mosterd past een goed stuk kaas.
A nice piece of cheese is good with with the young mustard.
Met verbazing keek de dikke pelgrim naar het beeld.
The fat pilgrim looked at the statue in amazement.
Dankzij die jonge pelgrim kon de vrouw toch mee.
Thanks to the young pilgrim, the woman came along after all.
De mosterd wordt verkocht bij elke slager.
The mustard is sold at every butcher's.

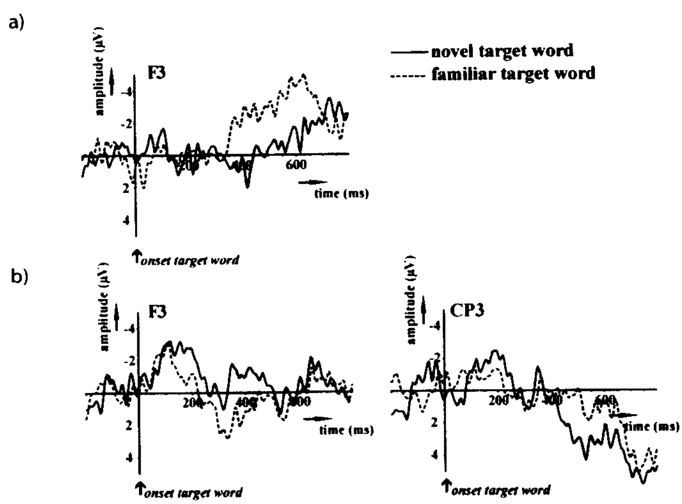

Figure 3. Mean ERPs to familiarized and unfamiliarized words in sentences; (a) 10-month-old listeners, electrode position F3; (b) seven-month-olds listeners, electrode positions F3 and CP3. Negativity is plotted upwards. The grey areas indicate the time windows showing a statistically significant difference between the two conditions

Twenty-eight normally developing ten-month-old Dutch-learning infants were tested using this procedure. The results, shown in the upper panel of Figure 3, revealed a clear difference between the waveforms generated by the familiar and the unfamiliar words in the form of a negative-going ERP response to the familiar words only, with a left lateral distribution. This effect occurred about 350 ms after word onset, indicating that word segmentation has begun as early as halfway through the word. That is, infants do not need the whole word to initiate word segmentation. These results nicely show how ERP methodology can be used to complement and extend earlier findings of word segmentation (specifically, demonstrations of word segmentation by Dutch-learning infants with the Jusczyk and Aslin procedure by Kuijpers, Coolen, Houston and Cutler 1998, and Houston, Jusczyk, Kuijpers, Coolen and Cutler 2000). The millisecond level of precision of this measure gives insight into online processes and offers a new window on developmental word segmentation.

In addition to the study with ten-month-old infants, Kooijman and colleagues also used the same ERP paradigm to test for word segmentation in seven-month-old infants (Kooijman, Hagoort and Cutler, submitted). The results of this study are summarized in the lower panel of Figure 3. Two ERP effects differentiating familiar and unfamiliar words were found with this younger age group: an early positive effect with a frontal distribution, starting at about 350 ms; and a later negative effect with a left lateral distribution, starting at about 480 ms. The words in the sentences had an average duration of 720 ms; so even about halfway into the word, seven-month-olds too show some indication of word recognition.

It is particularly interesting to compare the seven-month-old and the ten-month-old ERP data. The differential responses to familiar versus unfamiliar words, as well as the early onset of the ERP effect, show the groups to be responding similarly: both seven- and ten-month-olds initiate an early response of word segmentation. But the distribution of the effects shows the groups to be different. It could thus be that the effect has different underlying sources in the two age groups. This is a tempting conclusion to draw, since cognitive development has obviously progressed between seven and ten months of age. But such a conclusion could be premature, as physical and neural development has to be considered as well. Neural development is not complete at birth; it continues for years, indeed well into the second decade of life. Especially dendritic growth and pruning, and cortical folding, continue into the first year of life (Mrzljak, Uylings, Van Eden and Judas 1990; Uylings 2006). To what extent these changes affect the EEG is as yet unknown. In addition, physical changes in the skull, that is, the closing of the fontanels, continues until well into the second year of life. Flemming, Wang, Caprihan, Eiselt, Haueisen and Okada (2005), in a simulation study, found that a hole in the skull would have a large effect on the EEG signal. All these changes in neural and physical development may thus have an effect on the distribution and polarity of ERP results, so that caution is warranted in interpreting differences between different age groups. Nonetheless, the timing information of ERPs, and the comparison between different conditions, allow us to be confident that the similarity between groups – the clear evidence of early segmentation by both seven- and ten-month-olds – is real.

6 Parallel measures: A preliminary account

Both HPP and ERP, it is clear, provide valuable views of word segmentation in preverbal infants. HPP delivers a behavioral reflection of segmentation even at this young age, and ERP offers an online measure of segmentation skills with high temporal precision. In an attempt to combine the advantages of these differing techniques, Kooijman *et al.* (submitted) undertook a first study putting the two methodologies together.

Previous HPP data from Dutch-learning infants showed evidence of segmentation by nine-month-olds (Kuijpers *et al.* 1998; Houston, Jusczyk, Kuijpers, Coolen and Cutler 2000) but no trace of segmentation responses with 7.5-month-olds (Kuijpers *et al.* 1998). The ERP data which Kooijman *et al.* (2005; submitted) collected showed clear evidence of segmentation by ten-month-olds and likewise clear, but in some respects different, evidence of segmentation by seven-month-olds. However, it could be that the materials used in the ERP and HPP studies with seven-month-olds were dissimilar; some aspect of the materials used in the ERP study – for instance, the particular speaker's voice, the slow rate of speech (see Figure 1 for an example), the pitch contour of the child-directed speech – may have particularly encouraged word recognition by seven-month-olds. Note that the degree of mismatch between familiarization token and test token is known to affect the ease with which infants segment words from speech (Houston 2000; Singh, Morgan and White 2004). Kooijman *et al.* therefore undertook an HPP study directly parallel to their ERP experiment with seven-month-olds.

To achieve close comparability between the two data sets, they made certain modifications to the standard HPP paradigm. First, the two-stage familiarization-and-test procedure was replaced with a cycling testing design that more closely resembled the design of the ERP study. Instead of one familiarization phase and one test phase as in the version of HPP used by Jusczyk and Aslin, there were multiple consecutive phases of familiarization and test. Second, and again to make the HPP and ERP studies as similar as possible, the familiarization phase consisted of ten tokens of the same word, instead of the 30 seconds of speech used by Jusczyk and Aslin (1995). The test phase most closely resembled the original word segmentation

HPP studies. In each test phase, four trials of four sentences were presented, of which two trials contained sentences with the familiarized word, while two contained sentences with an unfamiliar word. From the speech stimuli used in the ERP study, ten blocks of familiarization and test were constructed for this HPP design; an example block is given in Table 2. The two test conditions (familiar, unfamiliar) were played to the infant equally often from the right and left speaker.

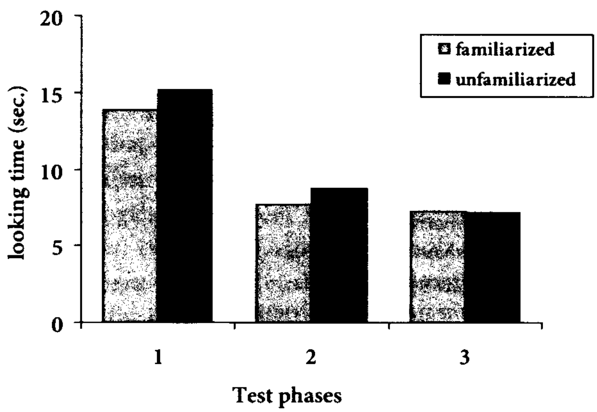

Figure 4. Mean looking times for seven-month-old infants in the first three Test phases in an adjusted HPP design to sentences containing familiarized and unfamiliarized words. The same materials were used in the ERP study.

Twenty-eight seven-month-old infants were tested in this study. As in the ERP study, familiarization and order of presentation of the blocks was counterbalanced across subjects. Figure 4 shows results of the first three blocks (one block consists of a familiarization and a test phase): there was no significant preference for one type of sentence over the other. This finding is fully in line with the results of Kuijpers *et al.*'s (1998) study with 7.5-month-olds using standard HPP. Dutch seven-month-olds do not show a behavioral indication of word segmentation, even though the ERP results suggest that their brain is capable of the cortical responsiveness which necessarily underlies such behavior.

Table 2. Example of an experimental trial in the adjusted HPP study of Kooijman *et al.* (forthcoming) with seven-month-olds

Familiarization: Ten repetitions of mosterd

Test:
Die oude mosterd smaakt echt niet meer goed.
That old mustard really doesn't taste so good any more.
Voor soep is de dikke mosterd ook te gebruiken.
The thick mustard can also be used for soup
De mosterd wordt verkocht bij elke slager.
The mustard is sold at every butcher's.
Bij de jonge mosterd past een goed stuk kaas.
A nice piece of cheese is good with with the young mustard

De oude pelgrim maakt een reis naar Lourdes.
The old pilgrim is travelling to Lourdes.
De pelgrim is niet blij met de openbaring.
The pilgrim is not happy about the revelation.
Met verbazing keek de dikke pelgrim naar het beeld.
The fat pilgrim looked at the statue in amazement.
Dankzij de jonge pelgrim kon de vrouw toch mee.
Thanks to the young pilgrim, the woman came along after all.

Die oude mosterd smaakt echt niet meer goed.
That old mustard really doesn't taste so good any more.
Voor soep is de dikke mosterd ook te gebruiken.
The thick mustard can also be used for soup
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Dankzij de jonge pelgrim kon de vrouw toch mee.
Thanks to the young pilgrim, the woman came along after all.

7 What does it mean when behavior and brain activity fail to line up?

As we pointed out above, difficulties do arise in interpreting ERP data. So how do we interpret ERP data and behavioral data which do not line up? Kooijman *et al.*'s

(2005) report of an ERP response to familiarized words in 10-month-olds fits well with the HPP literature; studies with both English- and Dutch-learning infants have demonstrated that infants begin segmenting words from speech before this age. However, Kooijman *et al.*'s (submitted) evidence from ERPs that seven-month-olds too can segment words from speech contrasts starkly with their own finding of no HPP effect in the same age group, and with other earlier findings. In fact, no HPP study with infants learning any language has found evidence that infants as young as seven months can segment words from fluent natural speech (though see Bortfeld, Morgan, Golinkoff and Rathbun 2005, for an exceptional situation with English-learning six-month-olds). English-learning infants have been shown to segment speech by 7.5 months of age (Jusczyk and Aslin 1995), but the HPP studies have suggested that Dutch infants are slightly delayed compared to English-learning infants in their ability to segment words from speech (this has been attributed to phonological differences in word boundary salience in English vs. Dutch; Kuijpers *et al.* 1998). Kooijman *et al.*'s result with seven-month-olds now reveals that the absence of an effect in HPP does not imply the absence of any relevant processing in the infant brain.

As also discussed above, the ERP and HPP are very different measures. Thus, it is easy to construct different explanations for the observed patterns of results that they yield. Such explanations can involve different levels of processing, in the same way as, for instance, explanations at different levels have been proposed for the fact that mastery of linguistic abilities often appears earlier in perception than in production: that perception is a more sensitive behavioral test than production, that the behavioral response required in perception tasks is less cognitively demanding than the responses required in production studies, or that there is a difference in the levels of knowledge tapped by the tasks. The mismatch between the HPP and ERP findings we have described allows a similar range of accounts.

First, it is possible that the ERP measure is simply more sensitive than the HPP measure. Thus the difference between ERP and HPP data could be analogous to differences between two behavioral paradigms requiring different types of response. There are differences in task sensitivity even between different perceptual measures, often depending on how engaging the task is or how metabolically expensive the response is (Gout *et al.* 2004; McMurray and Aslin 2004). Second, the difference between ERP and HPP data could be due to different levels of processing being tapped. Third, the discrepancy could be due to theoretically uninteresting differences between experiments, such as differences in speech stimuli or in test phase length. More studies collecting parallel ERP and HPP data with the same speech stimuli, as Kooijman *et al.* did, will help clarify these issues.

A fourth possibility, however, and the one which we favor in the interpretation of Kooijman *et al.*'s results, is that the brain response observed in seven-month-olds is a precursor of an overt behavior which is to come. Certainly overt behaviors cannot appear overnight without some drastic changes first taking place in the mind of an infant. The suggestion that the ERP component found in the seven-month-olds is a precursor of overt behavior is comparable to the interpretation which McLaughlin, Osterhout, and Kim (2004) offered of their findings with adults learning a second language; modulation of the N400 appeared after only 14 hours (on average) of classroom instruction, but the same participants still performed at chance level on a word discrimination task, thus showing no behavioral evidence of increased knowledge of the second language. Cortical responsiveness to a difference in stimuli is one essential prerequisite for a differential behavioral response to the same stimuli, but it need not be the only precondition on which the behavior depends.

8 Simultaneous measures: Future goals

The use of ERP and HPP measures in parallel is, as we have seen, clearly possible, and it can prove highly informative; the asymmetry in the appearance of ERP and HPP reflections of lexical segmentation sheds light not only on how infants learn to segment speech but also on how behavioral responses should be explained. In other areas of processing, simultaneous measures have been collected that allow alternative views of the same individual's speech processing at the same time. Thus Berger, Tzur and Posner (2006) have successfully demonstrated infant sensitivity to arithmetic errors in ERP in combination with looking-time methods. In our view, simultaneous ERP and behavioral reflections of infant word segmentation should be equally feasible

Obviously there are practical difficulties: dependent measures such as headturns cause artifacts in the EEG signal (Luck 2005), so standard HPP would be incompatible with EEG measures. Abrupt eye movements can also disrupt the EEG signal, so that it would similarly be difficult to run an eye-tracking study at the same time as recording ERPs. Given these issues, it is clear that combinations of behavioral and brain measures need to be very creative. Thus even if simultaneous HPP and ERP measures seem to be ruled out, partially simultaneous measures involving a modified familiarization phase should be perfectly possible. HPP studies have succeeded in familiarizing infants to fluent passages through passive listening to speech accompanied by a visual stimulus on a TV screen, with infants moved to a HPP booth after familiarization for the behavioral test of segmentation (Hollich, Newman and Jusczyk 2005). These experiments kept children's attention to the speech signal by showing a video of a woman speaking, but attention could also be held by a colorful image on a small screen, as Kooijman *et al.* (2005) used in their ERP study. With this procedure, ERPs could be measured while children passively listened to passages. Following exposure, the ERP cap could be removed and infants could be moved to the headturn booth for behavioral testing.

This design assumes that the ERP measurement will pick up evidence of segmentation of a word without exposure to that word in isolation. This seems justified, given that, as we noted above, HPP works well with fluent speech in both familiarization and test (Seidl and Johnson, forthcoming). This suggests that passive exposure to words in passages will result in evidence of segmentation. However, ERP requires multiple measurements for evidence of segmentation, because ERP signals are quite noisy. Thus, if ERP measurements were made during the familiarization phase, this phase might need to be lengthened, or the stimuli adjusted such that sentences contained multiple target words. Given the limited attention span of young children, it is possible that by the end of a lengthy familiarization phase infants might be too fatigued to successfully complete a further test phase. This potential problem can, however, be overcome. Infants familiarized with a word one day will easily recognize the word the next day (Houston and Jusczyk 2003). In fact, there is evidence that children continue to recognize words for at least two weeks after familiarization (Jusczyk and Hohne 1997). These considerations thus motivate the hope that partially simultaneous measures of word segmentation could be obtained by slightly modifying the classic HPP design, and collecting ERP measurements during the familiarization phase of the experiment.

Fully simultaneous measurements would require that a dependent measure other than headturns be used in the test phase. One possible candidate behavioral measure requiring no headturns might be a modified version of the Visual Fixation Procedure, in which infants' looking time to a single visual display is measured as a function of different auditory inputs. Although the paradigm has chiefly been used to test discrimination, it is not unrealistic to imagine that it could be adapted to study word segmentation. As in the ERP study of Kooijman *et al.* (2005), a single visual stimulus is fixated, so that no eye movements between multiple stimuli will cause interference with EEG measurement. With this procedure, infants could be familiarized to isolated words using the passive exposure method described above. They could then be presented with passages containing familiar and unfamiliar words, and their fixation time to the screen would serve as the dependent measure to gauge word recognition. The prediction would be that infants would fixate the screen longer for familiar than for unfamiliar words. At the same time, ERP data could be collected and ERP signals to the familiar and unfamiliar words could be compared.

Candidates therefore seem to exist for the next generation of methodologies; in particular, we predict that comparison of simultaneously measured behavioral and ERP response will constitute a powerful tool for a better understanding of both behavioral and brain responses to familiar words. Longitudinal studies, i.e., testing infants three or four times between the ages of six and ten months, could also provide an informative window into the development of word segmentation abilities. We see a bright future for the continuing attempts to capture the elusive reflections of infant word recognition.

Notes

Preparation of this chapter, and the research reported here, were supported by the NWO-SPINOZA project "Native and Non-native Listening" awarded to the third author. We thank Dennis Pasveer for making Figure 1, and Holger Mitterer for helpful comments on the text.

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