Chapter 6

Do Changes in Brain Organization Reflect Shifts in Symbolic Functioning?

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This chapter focuses on a particular type of symbol, the infant's first words. During the first 2 years of life, infants undergo marked changes in their ability to understand and produce words. Yet little is known about the brain systems associated with the attainment of these language milestones. The broad goals of the research presented here are to examine: (1) how the experience of learning new words shapes the organization of language-relevant brain systems in very young children, and (2) how changes in the functional specialization of brain activity can provide information about apparent qualitative shifts in linguistic or symbolic processing.

In adults, different parts of the brain are highly specialized for processing different types of information. Even within the language domain, different aspects of information processing, such as semantics and syntax, activate different brain regions (Brown & Hagoort, 2000; Neville & Bavalier, 2002; Neville, Mills, & Lawson, 1992; Newman, Pancheva, Ozawa, Neville, & Ullman, 2001), and are differentially vulnerable to brain damage or other neurological abnormalities (Bates, Vicari, & Trauner, 1999; Eisele & Aram, 1993, 1994, 1995; Reilly, Bates, & Marchman, 1998). It is not known to what extent these specializations hold true for children. What *is* known is that the brains of infants and young children show a greater degree of plasticity than the adult brain. More specifically, infants and children under 5 years of age with injury to particular parts of the brain do not show the same levels of impairment as adults with the same type of injury (for a review see Bates & Roe, 2001). Brain imaging studies (electrophysiological studies, PET, and fMRI) also suggest that children show less specialization, as reflected by more diffuse brain activity, than adults on the same tasks (Durston, Thomas, Yang, Ulug, Zimmerman, & Casey, 2002; Passarotti, Paul, Bussiere, Buxton, Wong, & Stiles, 2003; Stiles et al., 2003; Tamm, Menon, & Reiss, 2002). Children also show a different organization, that is, patterns of brain activity in different regions, than adults (Moses, & Stiles, 2002; Stiles, Bates, Thal, Trauner, & Reilly, 2002). The greater degree of brain plasticity displayed by young children compared to adults has been taken as evidence in support of the hypothesis that language specializations develop as the child becomes older and more proficient with language. In contrast, earlier evidence from structural (Witelson & Pallie, 1973), electrophysiological (Molfese, Freeman, & Palermo, 1975; Molfese, Molfese, Gill, & Benshoff, 1977), and behavioral studies (Entus, 1977; Kinsbourne, 1975), and more recent neuroimaging studies (Dehaene-Lambertz & Baillet, 1998; Dehaene-Lambertz, Dehaene, Hertz-Pannier, 2002; Pena et al., 2003), suggest that there are left hemisphere asymmetries or biases for processing language stimuli present in very young infants and even at birth. In turn, these findings have been interpreted as support for an innate language acquisition device residing in the left hemisphere. Very few of the studies showing an early left hemisphere asymmetry to language have examined devel-opmental stability or changes in the organization of brain activity to these putative language stimuli. Rather, these asymmetries are often assumed to be immutable.

In this chapter we present data that challenge the idea that language, as a single module, is lateralized to the left hemisphere at birth and remains that way throughout development. The conclusion that early left hemisphere asymmetries for brain activity related to particular aspects of language processing reflect the existence of an innate, left hemisphere language acquisition device may be erroneous on several counts. First, language is not a single entity. Each aspect of linguistic processing, including the physical characteristics of the acoustic signal, phonology, prosody, semantics, syntax, and discourse might be differentially constrained in terms of plasticity and differently affected by experience. Second, studies using event-related brain potentials (ERPs) have shown that several different components (peaks or valleys in the waveform) may be elicited by the same type of language stimulus at different latencies, each reflecting a different aspect of language processing. ERPs are averaged epochs of brain activity time-locked to particular stimuli; this methodology is described in detail below. Each ERP component may be associated with different lateral asymmetries. For example, we reported that at 6 months of age the first positive component to auditory words, peaking at 100 ms (P100), was larger over the left than the right hemisphere for familiar words, whereas the first negative peak, peaking at approximately 250 ms (N200), was larger over the right than the left hemisphere (Neville & Mills, 1997, see also Thierry, Vihman, & Roberts, 2003, for similar evidence from slightly older infants). Neuroimaging methods such as optical topography or blocked fMRI studies are not as sensitive to temporal fluctuations as ERPs because they reflect averages of activity across longer epochs, making any asymmetries to language stimuli discovered using such techniques more difficult to interpret. Third, it is imperative to establish the functional significance of each observed asymmetry in order to determine what aspects of language processing may have a left hemisphere bias at birth. For example, within the domain of speech perception, ERPs to stimuli differing in voice onset time show right hemisphere asymmetries (Molfese & Molfese, 1988; Simos & Molfese, 1997), whereas ERPs reflecting discrimination of place of articulation show left hemisphere asymmetries (Dehane-Lambertz & Dehaene, 1994; Molfese, Burger-Judisch, & Hans, 1991). Additionally, even the presence of a particular left hemisphere asymmetry at birth and in adults does not necessarily mean that asymmetry is stable across childhood and adolescence. Lateral asymmetries present early in development can, and do, change with maturation and experience (Mills, 2003).

We review several of our infant ERP studies suggesting that the process of acquiring a vocabulary influences the organization of the infant brain and the development of some lateral asymmetries. We raise the hypothesis that in addition to the number of words a child has acquired, the rate of learning may also be an important factor in establishing lateral asymmetries. Additionally, we examine patterns of brain activity in children and adults from selected atypical populations who do not develop normal lateral asymmetries. It has been suggested that slow brain maturation and the failure to develop lateral asymmetries may underlie linguistic deficits in these atypical populations (Saugstad, 1998). In contrast, at the end of the chapter, we raise a very different hypothesis.

In this chapter, the term “experience” refers to a specific connotation of the word. It is often the case that the effects of experience are measured by comparing the effects of enriched vs. impoverished environments. However, because the environment is external to the learner, an enriched environment alone cannot induce changes in the brain. Modifications in neural activity can only occur as the result of interactions between the learner and the environment. Learning induced modifications in the brain emerge through the process of taking in new information, forming new associations and/or learning new skills. The term experience as it is used here is motivated by Greenough and colleagues’ work showing experience-dependent modifications in synaptic connections that occur through the process of learning (Greenough, Black, & Wallace, 2002). Specifically, learning a new skill triggers an increase in the number of synapses per neuron, whereas increased levels of physical activity per se do not (Kleim et al., 1998). In turn, these new synapses affect the functional organization of the brain in the regions in which they occur (Greenough, Black, Klintsova, Bates, & Weiler, 1999). Applying this work to child language acquisition, we are working from the assumption that when a child learns a word new synapses are formed, and these in turn shape the organization of the brain for language. Therefore, for the purposes of this chapter the word *experience* is used to refer to the experience of learning new words. We will use a child's absolute vocabulary size as an index of relative amounts of language experience, to investigate whether patterns of brain activity vary before and after the attainment of a language milestone.

By studying typically developing children, we can chart the developmental trajectories of cerebral specializations for specific aspects of language processing and link changes in language abilities with concomitant changes in the organization of language-relevant brain activity. By studying atypical populations, such as children who start talking late, we can begin to separate out the effects of increasing age and experience on the organization of brain activity and examine the effects of different rates of learning.

To study the development of brain organization, we employ the event-related potential, or ERP, technique. ERPs are safe, noninvasive, and the most practical brain imaging technique currently available for studying the development of cerebral specializations. ERPs have the added benefits that they do not require an overt response (the children are not asked to do anything, except sit still), and the same paradigm can be used to study development across several age groups.

Populations of neurons firing simultaneously generate electric fields that can be recorded from the scalp. Recordings of electrical activity are sampled every few milliseconds from electrodes placed at different locations on the scalp, and stored on a computer disk. ERPs are obtained by averaging the epochs of postsynaptic electrical activity time-locked to specific events (e.g., the 2 seconds of brain activity that immediately follow the presentation of a word). ERPs reflect changes in brain activity over time on a millisecond-by-millisecond basis. They are characterized by a series of positive and negative deflections in voltage called components. Typically, ERPs are illustrated by plotting changes in amplitude, measured in microvolts, along the Y axis, against changes in latency, measured in milliseconds, along the X axis. ERP components are most often named according to their polarity (P for positive, N for negative), and their peak latency. For example, a negative component that typically reaches its peak amplitude at 400 ms is called the N400, whereas a positive component reaching its peak amplitude at 300 ms is called the P300. The peak latency, amplitude, and distribution of these components reflect information about the timing, amount, and to some extent location of brain activity, respectively. Polarity of the ERP does not map onto excitatory or inhibitory activity. Rather, positive and negative voltages reflect opposite ends of a dipole, much like the positive and negative ends of a battery.

There are many different methods for recording ERPs. We use the electrocap, which has electrodes sewn into it and sits securely and comfortably on the child's head. A small amount of conductive gel is placed through each of the holes in the cap to conduct the electrical activity generated by the brain to the electrodes. The child is entertained with an abundance of toys and someone devoted to playing with the child, while the experimenter fixes the cap. This process takes about 10 minutes.

In each of the studies described here, we recorded brain activity from 16 electrodes, placed over anterior and posterior regions of the left and right hemispheres and central regions (Figure 6.1), and referenced to linked mastoids. Of particular importance to the studies presented here were those electrodes placed over frontal, anterior temporal, temporal, parietal, and occipital regions of both the left and right hemispheres. These sites were designed to cover areas roughly over the perisylvian fissure, known to be associated with different aspects of language processing in adults. Additionally we recorded the electro-occulogram (EOG) over and under the eyes to reject trials contaminated with blinks and vertical eye movements.

This chapter focuses on children in the 13- to 20-month-old age range. Typically, this period encompasses the time during which children start saying

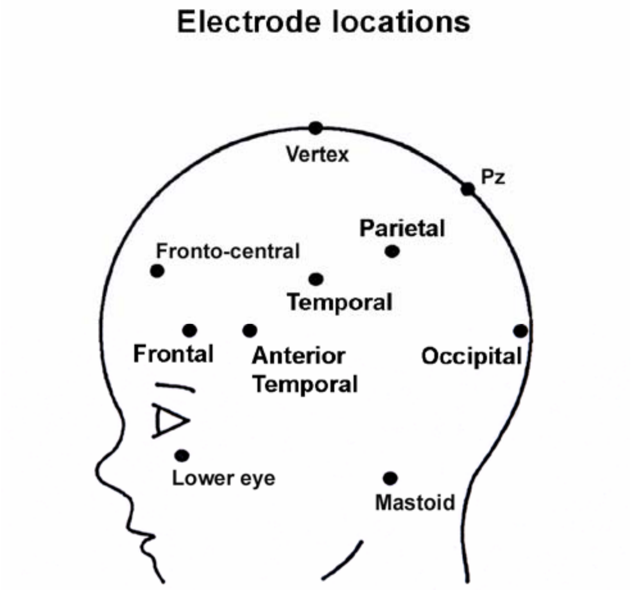

FIG. 6.1. Placement of electrodes for infant studies: view from left hemisphere.

their first words through the time in which they show a rapid increase in vocabulary size. This phenomenon has been called the naming explosion or vocabulary spurt and has been widely documented across groups of children, independent of their rate of vocabulary development. For example, Thal and colleagues (Thal, Bates, Goodman, & Jahn-Samilo, 1997), examined changes in vocabulary development across time for three groups of children, typically developing, early talkers, and late talkers. For all three groups, when they were learning their first few words the addition of new words was a slow process. At some point between a vocabulary of 50 to 100 words the slope of the curve changed, and children added new words to their vocabulary much more rapidly. Such rapid changes in vocabulary development have led several researchers to postulate a reorganization in cognitive processes that underlies the marked acceleration in vocabulary, such as changes in representational capacity for symbolic functioning (McCune, 1995; McCune-Nicolich, 1981; Nazzi & Bertoncini, 2003; Werner & Kaplan, 1963), the insight that objects do or should have names (Baldwin & Markman, 1989; Dore, 1974; McShane, 1979), changes in categorization (Gopnik & Meltzoff, 1987), word segmentation (Plunkett, 1993), and comprehension of social pragmatics (Baldwin & Moses, 2001; Tomasello, 2001).

If children show changes in the organization of language-relevant brain activity before and after the vocabulary spurt, this pattern would be consistent with a reorganizational hypothesis. The purpose of the first set of studies with typically developing children was to examine whether changes in age and vocabulary size were linked with concomitant changes in the timing and distribution of brain activity indexing word meanings in children between 13 and 20 months of age. We addressed this question using two different paradigms. In the first study we examined brain activity indexing semantic processing using a picture/word match/mismatch ERP paradigm. In the second set of studies we examined ERPs from typically developing children as they passively listened to a series of single words whose meanings they did or did not know.

ERP STUDIES OF TYPICALLY DEVELOPING CHILDREN

In addition to changes in the rate of word learning, there are differences in the way infants use the words they have before and after the vocabulary spurt. The child’s first words are often bound to a particular context and become more flexible and/or referential with increasing vocabulary size (Bates, Benigni, Bretherton, Camaioni, & Volterra, 1979). Vihman and McCune (1994) argued that these early context-bound words are qualitatively different than later words in their referential and symbolic status. That is, early context-bound words may reflect “simple associations’ between sound and object pairings, whereas later words reflect symbolic processing (see also, Nazzi & Bertoncini, 2003 for a similar view). An ERP paradigm frequently used with adults to examine the effects of context and word meaning involves setting up a context and then presenting a subsequent stimulus that is either congruent with the semantic context or is incongruent with the context in some way. The ERP associated with this paradigm is a negative potential peaking at approximately 400 ms that is larger in amplitude to the incongruent stimulus (Kutas & Hillyard, 1980; Neville, 1985; Schmitt, Muente, & Kutas, 2000). For example, the semantic context might be set up by showing a picture of a common object (e.g., a cup), and the subject tested by presenting an auditory word that either matches the picture (e.g., *"cup"*) or does not match the picture (e.g., *"shoe"*). In school-age children and adults tested on a similar paradigm, a larger N400 is elicited to the word when it does not match the preceding picture (Coch, Maron, Wolf, & Holcomb, 2002). The difference in N400 amplitude to the incongruent vs. congruent stimulus is called the N400 effect.

It is not known whether infants learning their first words use neural systems similar to those used by older children and adults to process word meaning. Showing that an N400 response is evident in infants learning their first words would suggest similar neural systems for processing meaning in infants and adults. However, the emergence of the N400 may be linked to shifts in the representational status of early words occurring during the vocabulary spurt. If this were the case, we would expect 20-month-old, post-vocabulary spurt children, to show an N400 semantic priming effect, whereas 13-month-old, pre-vocabulary spurt children would not. In contrast, if the same learning mechanism were involved during the acquisition of the child's first words before the vocabulary spurt, we would predict that both 13- and 20-month-old children would show an N400 effect.

Picture/Word Match–Mismatch Paradigm: Development of the N400

The language testing procedure was the same across all studies presented in this chapter unless mentioned otherwise. Children were brought into the lab for behavioral testing one week prior to collecting the ERPs. Parents were asked to fill out the MacArthur Communicative Development Inventory (CDI; Fenson, Dale, Reznick, Bates, Thal, & Pethick, 1994). The CDI is a parent report inventory that has been normed on more than 1,000 children and provides an estimate of the size of a child's vocabulary as well as a percentile score relative to other children of the same age. To determine which words would be presented as "known" words, parents were also asked to rate a set of words on a scale of 1 to 4 for how sure they were that the children understood the words. A separate rating scale was also used for production. A score of 1 indicated that the parents were sure the child did not understand (or produce) the word. A rating of 4 meant that the child understood (or said) the word in a variety of different contexts with a variety of different exemplars. The known words presented during testing were selected from the set of words rated as 4s. If the child had started talking, the words used were rated as 4s for both comprehension and production. Whenever possible, words that had ratings of 4 for both comprehension and production were used. For children who were not yet producing many words, words that had ratings of 4 for comprehension only were used. Additionally, the child was tested on comprehension of the known words using a picture-pointing task, in which he or she was asked to point to the appropriate picture in a book.

The stimuli consisted of 33 words identified as those most frequently understood by 16-month-olds from the CDI norms, and 33 pictures of the objects that matched those words. If a child did not understand one or more of the words, the corresponding picture/word trial was coded separately as unknown and was not included in the analysis. A picture was displayed on a computer monitor for 1500 ms. At 500 ms after the onset of the picture the child heard a word that either matched the picture or did not match the picture. All of the pictures and words were used twice, once in the match condition and once in the mismatch condition. That is, the same physical stimuli were used in each condition, only the preceding context changed. If a child looked away and did not see the picture on a given trial, that trial was coded separately and not included in the analysis. The participants included fifteen 20-month-olds and fifteen 13-month-olds. Additionally, we tested 10 right-handed adults and thirteen 3-year-olds to investigate developmental trends on this paradigm. Approximately half of the children in each age group were girls.

The ERPs to the pictures and words over fronto-central (see Figure 6.1 for electrode location) regions for all age groups are shown in Figure 6.2 (Mills, Larson, Horton, Voss, Lewis, and Addy (2004). The solid lines represent ERPs when the picture and word match, the dashed lines represent ERPs when the picture and word do not match. The first 500 ms of the waveform are time-locked to the picture before presentation of the word. There should not be any amplitude differences between the waveforms in this period because the stimuli are identical in both conditions. The line at 500 ms marks the presentation of the word. Measurements were taken at 100 ms intervals from the onset of the word to establish reliable amplitude differences. For all age groups, words that did not match the preceding picture elicited larger negative amplitude ERPs starting from 200 ms after word onset to the end of the epoch. The timing of this difference is consistent with previous ERP studies of adults (Holcomb, 1988; Holcomb & Anderson, 1993; Rodriguez-Fornells, Schmitt, Kutas, & Muente, 2002; Schmitt, et al., 2000) and the effect is consistent with the N400 family of ERPs. Of particular importance is that both the 20- and 13-month-old groups showed an N400 mismatch effect to the incongruent word similar to the 3-year-old children and the adults. Remarkably, the timing of the onset and duration of this effect did not change with age.

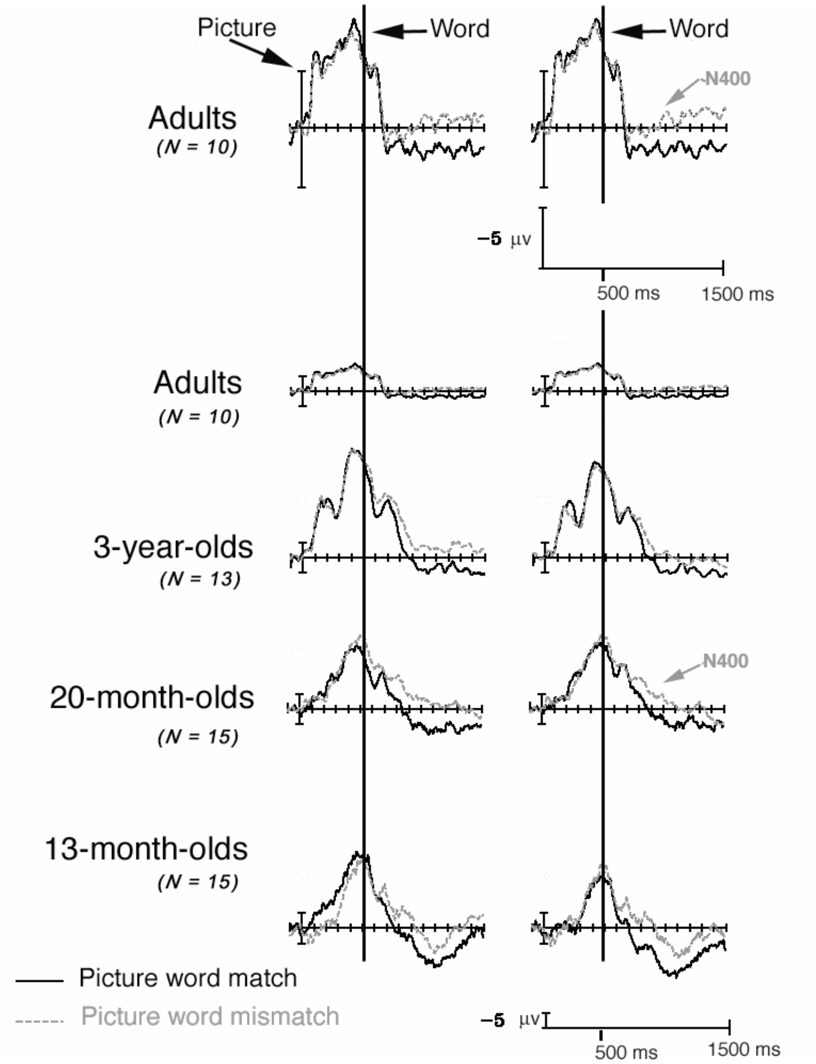

FIG. 6.2. ERPs to pictures and words in a match-mismatch paradigm for adults, 3-year-olds, 20-month-olds and 13-month olds.

These results suggest that the neural systems involved in processing word meaning are similar across development, from the child's first words through the vocabulary spurt and beyond. Moreover, the results do not provide neurobiological evidence of a qualitative shift in the representational status of early words between 13 and 20 months. The idea that a single learning mechanism may underlie apparent qualitative shifts in learning will be revisited later in the chapter when we describe a study on the relative effects of vocabulary size vs.

experience with individual words. However, there may be an alternative interpretation of these results. The lack of ERP evidence supporting a qualitative shift in these data, even if one actually exists, could be due to two factors. First, although most of the 13-month-olds did not produce the majority of these words, their parents rated them as being understood in multiple contexts, that is, in a flexible manner. It could be that comprehension of the words in a variety of different contexts with a variety of different exemplars is sufficient to signify symbolic status. That is, our 13-month-olds may have already been processing these words as referential symbols. Another possibility is that the mismatch detection mechanism indexed by the N400 is so robust and broadly distributed across the scalp (Curran, Tucker, Kutas, & Posner, 1993), the N400 response itself may mask more subtle indices of qualitative differences in word processing between groups. In the next set of studies we used a different paradigm to directly compare ERPs to words whose meanings children did or did not comprehend, in order to further explore such indices of word processing.

Studies of Single Word Processing: Known and Unknown Words

The language measures and ERP recording procedures were the same as described earlier. However, in this paradigm children listened to a series of words without a picture context. The stimuli were 10 words whose meanings the child understood (known words), 10 words whose meanings the child did not know (unknown words), and 10 backward words. The known words were selected based on the CDI, parental rating scale, and picture-pointing task. The unknown words were selected from a list of English words unlikely to be understood by children in this age range (e.g., pint, dent), and received a parental rating of 1 on the parental rating scale. To conserve space, data from the backward words are not presented here (see Mills, Coffey-Corina, & Neville, 1993, 1997). Words were presented serially in random order at the rate of one every 2 to 3 seconds over a high quality speaker located in front of the child. Because children in this age range are not particularly motivated to sit still for

TABLE 6.1
Vocabulary Scores for Typically Developing Children (13 to 17 Months and 20 Months) and Late Talkers (20 Months and 28 to 30 Months)

	Typically Developing Children		*Late Talkers*	
Group	*13 to 17 Months N=28*	*20 Months N=24*	*20 Months N=15*	*28 to 30 Months N=12*
Mean # Words (SE)	42 (6.6)	184 (6.4)	46 (1.36)	207 (12.29)
Range	1–148	33–531	12–77	8–437
Mean CDI Percentile	53rd	47th	15th	10th
Range	< 5th – 95th	10th – 95th	< 5th – 25th	< 5th – 25th

Note. Data for typically developing children is from Mills et al. 1993, 1997.

the sake of science, we presented the words through a puppet show. Mechanical toys on the front of the puppet theater were activated about every 10 to 15 words to reward the children for sitting still and paying attention.

Table 6.1 (left side) shows that the mean number of words produced by the 13- to 17-month-olds and 20-month-olds (Mills et al., 1997) fell below and above the 100-word mark thought to indicate the vocabulary spurt, respectively.

Unlike the match–mismatch paradigm described earlier, which is known to elicit an N400, the ERP components observed in this paradigm do not have direct correlates to adult ERP components. Therefore the functional significance of these components must be established through experimental manipulations. For the purpose of this study, we started with the working hypothesis that any ERP differences to known versus unknown words would index word meaning. Figure 6.3 illustrates ERP differences to known and unknown words at one electrode site. ERPs to the known words are shown in black solid lines. ERPs to the unknown words are illustrated in dashed lines. The vertical bar is time-locked to the onset of the word. Amplitude in microvolts is represented on the y axis with negative voltage plotted up. Latency in milliseconds is plotted on the x axis.

ERP Components. The first positive component peaked at 100 ms (called the P100). Unlike subsequent components, this component probably does have an adult correlate, the P50, which is thought to index sensory processing. Its amplitude and latency did not differ for known and unknown words. The absence of P100 amplitude differences is important because it is therefore

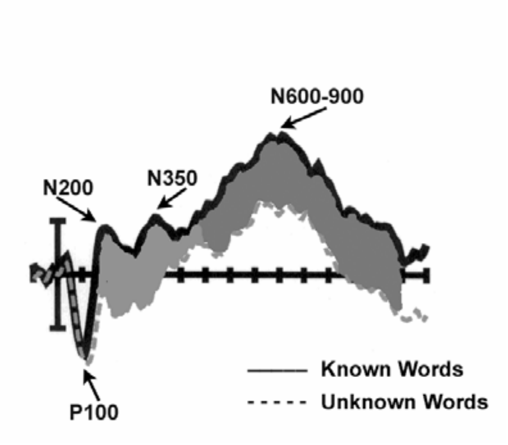

FIG. 6.3. ERP differences to words whose meanings are known (solid lines) versus unknown (dashed lines) at one electrode location. Shaded areas denote area measures that are reliably different for known versus unknown words. The N200, N350 and N600-900, but not the P100, are larger in amplitude to known than unknown words.

unlikely that later ERP amplitude differences are the result of acoustical differences in the words. The two components following the P100 were negative going and peaked at approximately 200 and 350 ms after word onset (called the N200 and N350, respectively). These negative components were larger in amplitude to known than unknown words (Figure 6.3). The statistically reliable differences in amplitude between the N200 and N350 are shaded in the figure. The third component, a slow negative wave between 600 and 900 ms, called the N600-900, was also larger to known than unknown words. The timing and distribution of this component is reminiscent of a component only found in infants, called the Nc (Courchesne, 1978; Karrer & Ackles, 1987; Nelson, 1994). It is thought to index attention and integration of the stimulus.

Age-Related Differences. ERPs to known and unknown words from the 13- to 17-month-olds are displayed from over frontal to occipital regions of the left and right hemispheres on the left side of Figure 6.4. The shaded area shows that the N200 and N350 amplitude differences to known and unknown words were broadly distributed and significant over anterior and posterior regions of both hemispheres. Additionally, the N600-900 was larger to known than unknown words over anterior regions of the right hemisphere.

We predicted that if the vocabulary spurt were associated with changes in brain organization we might expect to see a different pattern in the distribution of ERPs to known and unknown words in the 20-month-olds, since they have larger vocabulary sizes than the 13- to 17-month-olds. As predicted, there was a marked change in the distribution of brain activity to known and unknown words in the children with larger vocabularies (Figure 6.4, right side). At 20 months of age, ERP differences to known and unknown words were observed only over temporal and parietal regions of the left hemisphere. These differences were not observed over the frontal regions, over the occipital regions, nor at any location over the right hemisphere. Additionally, at 20 months the N600-900 did not differ in amplitude to the known and unknown words. Our hypothesis that the N600-900 is linked to attentional processing is consistent with this finding. If a child has a large vocabulary, and more experience with the individual words, processing the words for a shorter amount of time would facilitate processing of what comes next in the speech stream.

These data raised the working hypotheses that the N200 and N350 index word meaning, and that changes in the organization of brain activity observed here are linked to the remarkable changes in language development between 13 and 20 months, such as the vocabulary spurt. To examine to what extent these differences were due to vocabulary size independent of chronological age, we performed a median split for each age group based on vocabulary size. Both high-producer groups showed more focally distributed ERPs than did the low-producer groups at the same age. However, in this sample there were large differences in vocabulary size even between the 13- to 17-month-old high

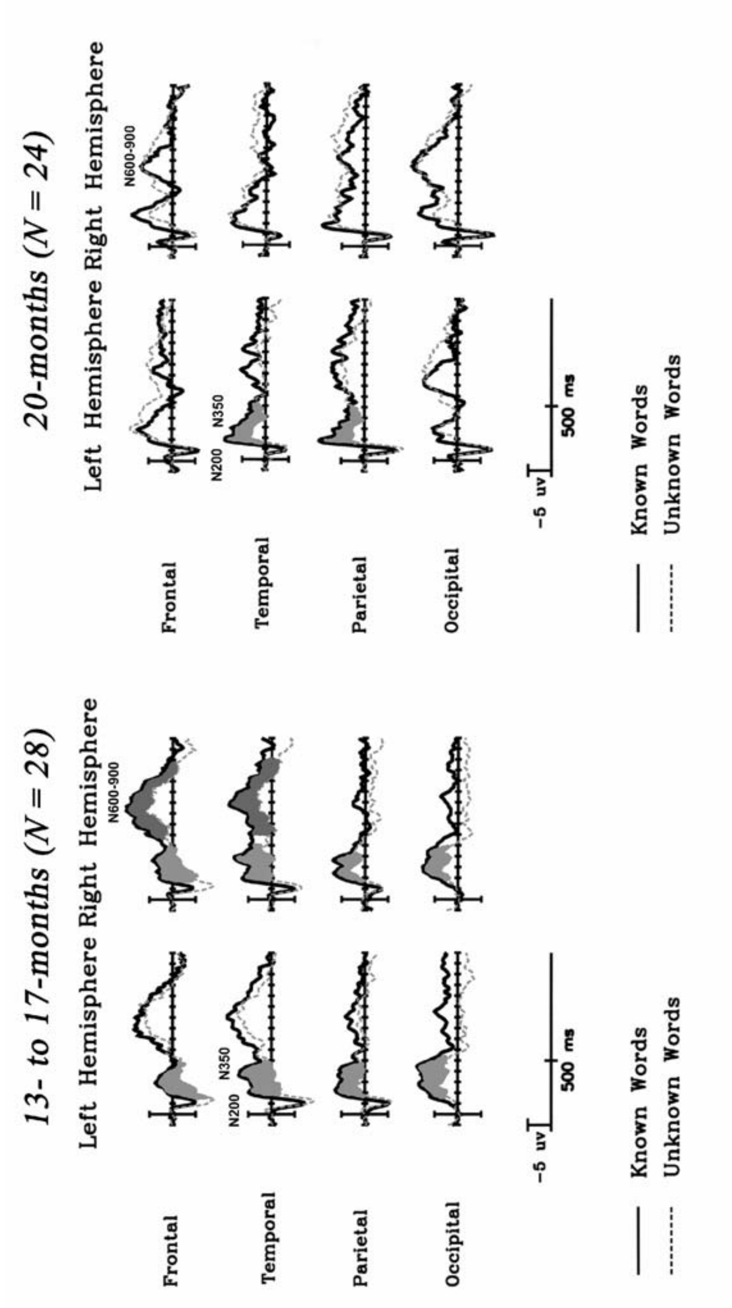

FIG. 6.4. ERPs to known (solid lines) versus unknown (dashed lines) words over frontal, temporal, parietal and occipital regions for both the left and right hemispheres for 13- to 17-month-olds (left side of figure), and 20-month-olds (right side of figure).

producers and the 20-month-old low producers. In order to further explore whether changes in the distribution of ERP differences to known and unknown words are linked to the number of words a child has in his or her vocabulary, we investigated whether similar shifts in distribution were evident in older "late talkers" before and after the vocabulary spurt.

STUDIES OF LATE TALKERS

In this study we examined ERP differences to known and unknown words before and after the vocabulary spurt in somewhat older children who got a late start in talking, that is, 20- and 28- to 30-month-old late talkers (Mills, Thal, Llamas, & Prat, 2005). We hypothesized that if experience with learning language, as reflected by vocabulary size, shaped the organization of language-relevant brain activity, then the ERPs from 20-month-old late talkers (pre-spurt children) would show bilaterally distributed ERP differences to known versus unknown words, much like their language-equivalent 13- to 17-month-old counterparts. Similarly, left-lateralized ERP differences to known versus unknown words would be observed in 30-month-old late talkers (post-spurt children), as with the 20-month-old typically developing children. The participants included fifteen 20-month-olds and twelve 28- to 30-month-olds who scored at or below the 25th percentile (most scored below the 15th percentile) for productive vocabulary size on the MacArthur CDI (Table 6.1, right side). The procedure was the same as in the previous study (Mills et al., 1997). ERPs to known and unknown words are shown in Figure 6.5 for the two groups of late talkers. As predicted, the 20-month-old late talkers showed broadly distributed differences in the N200 and N350 to known versus unknown words over anterior and posterior regions of the left and right hemispheres (Figure 6.5, left side). In contrast, the 28- to 30-month-old late talkers, like the typically developing 20-month-olds, showed N200 and N350 differences only over temporal and parietal regions of the left hemisphere (Figure 6.5, right side). Moreover, the 20-month-old late talkers showed ERP differences to known and unknown words at the later N600-900 time window. In contrast, the 28- to 30-month-old late talkers, like the typically developing 20-month-olds, did not show this pattern. In summary, the two groups of late talkers showed patterns of brain activity similar to those of typically developing children at a younger age who were their language equivalents. These findings are consistent with the hypothesis that developmental changes in the organization of language-relevant brain activity are linked to vocabulary size, rather than chronological age per se.

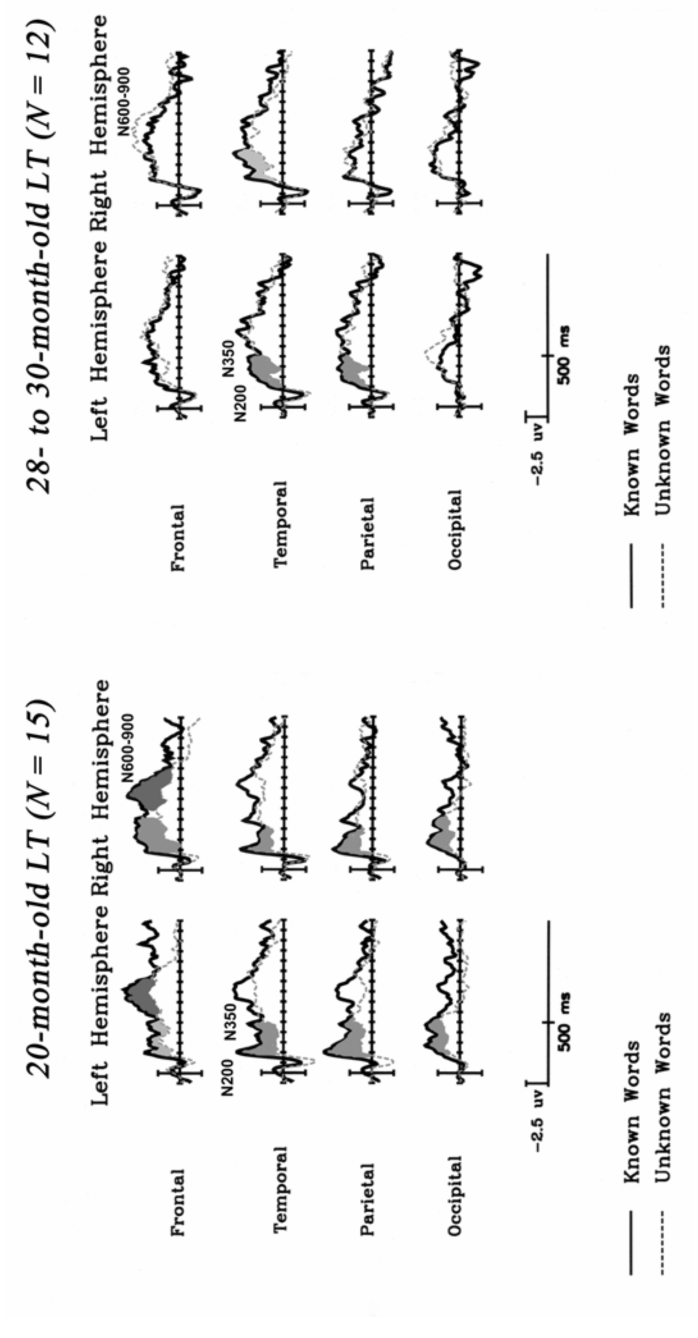

FIG 6.5. ERPs to known (solid lines) and unknown (dashed lines) words for the 20-month-olds (left side of figure) and 28- to 30-month-old (right side of figure) late talkers.

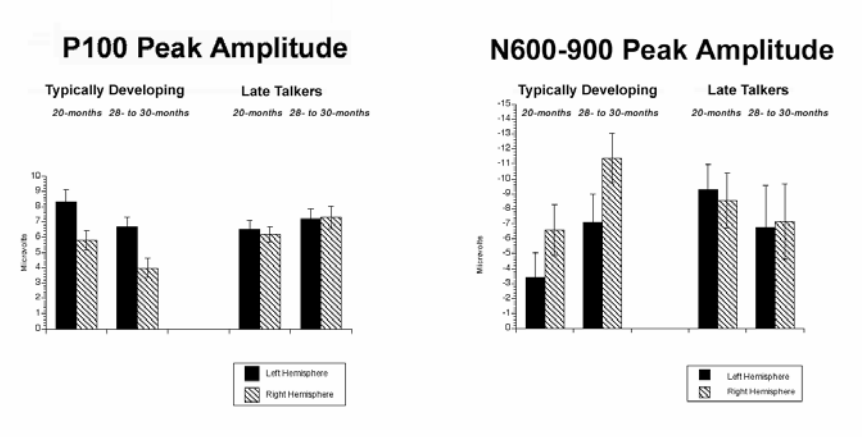

FIG. 6.6. Peak amplitudes for the P100 (left side of figure) and N600-900 (right side of figure) for typically developing infants and late talkers.

There were some important differences in the lateral distribution of ERPs between the late talkers and typically developing children. Although the patterns of brain activity linked to word comprehension showed a typical developmental pattern, ERP asymmetries linked to sensory processing (i.e., the P100) and to attention and integration (i.e., the N600-900) were associated with percentile ranking rather than absolute vocabulary size. In typically developing children 13 to 30 months of age who score above the 50th percentile on both comprehension and productive vocabulary size, the P100 is larger over the left than the right hemisphere (Figure 6.6, left side), and the N600-900 is larger over the right than the left frontal regions (Figure 6.6, right side). That is, children who are above average in vocabulary size for their age show asymmetries for the ERP components associated with sensory and attentional processes. One possible explanation is that children born with a predisposition to process speech sounds in these specialized systems are at an advantage for language development. An alternative process, and the one we adopt as our working hypothesis, is that the rate at which learning occurs may be important in the development of some of these lateral asymmetries. During slow effortful learning it may be more efficacious to use more brain tissue. After a certain level of competency is achieved and learning is more rapid, specialized brain systems may be more efficient. Late talkers show asymmetries to ERP differences to known versus unknown words after the vocabulary spurt. This particular asymmetry may be linked to an absolute vocabulary size, or the amount of experience with individual words. The lack of asymmetries in the P100 and N600-900 may reflect ongoing difficulties in sensory and attentional processes.

Another possible explanation for the lack of P100 and N600-900 asymmetries in the late talkers is that these children have slower developing brains. ERP peak latencies and amplitudes tend to decrease with increasing age at this point in development (Courchesne, 1978; Holcomb, Coffey, & Neville, 1992; Nelson & Monk, 2001). If the late talkers had delayed brain development they should show delayed peak latencies and mean amplitudes similar to those of younger children. However, overall their ERP peak latencies and mean amplitudes are similar to those of age-matched controls. Thus it is unlikely that these findings can be attributed solely to slower brain maturation.

Fortunately, there is a naturally occurring phenomenon that allows us to address the issue of brain maturation vs. rate of learning in typically developing children: by examining brain activity in children who are learning two languages at the same time. Infants learning two languages at the same time usually have a larger vocabulary (i.e., a faster learning rate) in one language than the other language due to differences in language-learning contexts and amounts of input in each language (Marchman & Martínez-Sussman, 2002; Patterson, 2000; Pearson, Fernández, Lewedeg, & Oller, 1997; Romaine, 1996). If the distribution of brain activity observed to known and unknown words differed for the same child's two languages, the differences in brain activity could not be attributed simply to different rates of brain maturation. This naturally occurring experiment is happening in the same developing brain! In the next section we examine patterns of brain activity to known and unknown words in 20-month-old infants learning Spanish and English simultaneously. It was our hypothesis that the patterns of brain activity to known versus unknown words would be more focally distributed in the language that had a larger vocabulary size.

STUDIES OF BILINGUAL 20-MONTH-OLDS LEARNING SPANISH AND ENGLISH

In this study, we examined patterns of brain activity to known and unknown words in both Spanish and English, in twenty-nine 20- to 22-month-olds learning Spanish and English simultaneously, that is, from birth or shortly thereafter (Conboy, 2002; Conboy & Mills, 2005). Parental ratings were used to assess each child's comprehension and production of words in each language. For our purposes, the language with the larger expressive vocabulary size was called the "dominant" language, and the language with fewer words was called the "nondominant" language. In this sample the mean number of words was 115 for the dominant language and 44 for the nondominant language, and approximately equal numbers of children were English- and Spanish-dominant. We also examined the hypothesis that the organization of brain activity for both languages would be linked to overall vocabulary size rather than differ for each language. To test that hypothesis we examined total conceptual vocabulary (TCV) size, which is a measure of the number of lexicalized concepts across languages. TCV is calculated by summing the total number of words in both languages and then subtracting out the number of times a pair of conceptually equivalent words occurred across the two languages (e.g., "*cat*" and "*gato*" are two different words for the same concept and would thus be counted only once in the TCV score). The children were divided into two groups, high and low producers, based on their TCV scores. The high producers had a mean TCV of 211 words, and the low producers had a mean TCV of 82 words. The procedure was similar to the single-word paradigm mentioned earlier for previous studies except that the child heard half of both the known and unknown words in English and half in Spanish.

The ERPs to known and unknown words for the children's dominant and nondominant languages are shown in Figure 6.7. For the nondominant language across the entire group of 29 children, ERP differences to known and unknown words were broadly distributed over the left and right hemispheres, resembling the pattern observed for the 13- to 17-month-old monolingual children (Figure 6.7, left side). However, ERP differences were apparent later in the waveform, 600 to 900 ms, than for the monolingual children. For the dominant language of the same group of children, ERP differences to known vs. unknown words were more focally distributed as we predicted, but these differences were larger over right frontal regions within the same time window (Figure 6.7, right side). In this study the stimuli switched back and forth randomly between Spanish and English. The right hemisphere has been implicated in integration across domains (Goldberg & Costa, 1981). It is possible that switching back and forth between languages elicited more right hemisphere activation than the monolingual version of the same paradigm. Switching between languages has also been shown to elicit more frontal activation in an fMRI study (Hernandez, Dapretto, Mazziotta, & Brookheimer, 2001; Hernandez, Martinez, & Kohnert, 2000) and an ERP study (Jackson, Swainson, Cunnington, & Jackson, 2001) of bilingual adults.

Total conceptual vocabulary was also related to the distribution of brain activity to known and unknown words. For the high producers, the ERP differences to known and unknown words occurred earlier, at 200-400 ms, which was consistent with the latency observed in the monolingual children at the same age. The pattern of more focally distributed differences to known and unknown words for the dominant versus nondominant language was found for both the high and low producers. Recall that typically developing monolingual children who had a relatively large vocabulary size for their age showed a left greater than right asymmetry for the P100 linked to sensory processing. In contrast, the monolingual late talkers showed a symmetrical P100. For the bilingual high producers, the P100 amplitude was greater over the left than the right hemisphere for the dominant language, but symmetrical for the nondominant language. For the bilingual low producers, the P100 was symmetrical for both languages. These findings provide strong evidence that experience with learning language, rather than chronological age or the rate of brain development, is linked to the presence of these asymmetries.

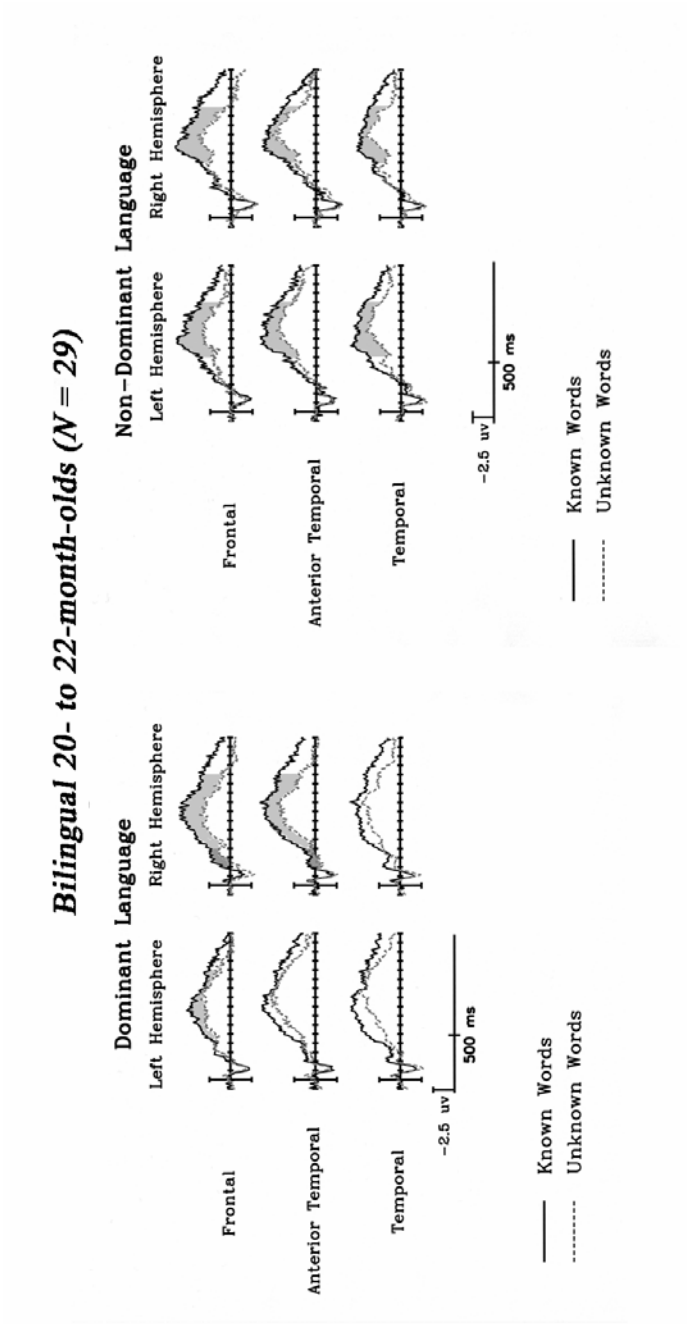

FIG 6.7. ERPs to known (solid lines) and unknown (dashed lines) words for 20- to 22-month-old bilingual toddlers. ERPs are shown for the dominant (left) and non-dominant (right) language over frontal, temporal, parietal, and occipital regions of the left and right hemispheres.

In all of our studies described to this point, we hypothesized that the observed changes in the organization of brain activity to known vs. unknown words were linked to the dramatic changes in language abilities at this age, such as the vocabulary spurt. Moreover, we hypothesized that differences in hemispheric specialization may result from a qualitative shift in the way children process words before and after the vocabulary spurt. However, one could also argue that bilingual children have more experience with the individual words in their dominant vs. nondominant language. Similarly, older children may have more experience with specific words than younger children. That is, the observed differences in the distributions of brain activity across groups in the previous studies may be due to differences in how well known the individual "known" words were for each child at the time of testing (i.e., the strength of the word/object associations). In the next study, we investigated changes in brain activity brought about by the learning of new words.

Vocabulary Size or Experience With Individual Words?

Recent connectionist models of early word learning claim to account for apparent qualitative changes in language development, such as the vocabulary spurt, without positing any underlying qualitative changes in the mechanisms of word learning (Plunkett, 1993). For example, Plunkett, Sinha, Møller, and Strandsby (1992) found that with increasing experience with "image/label" associations, their network showed a nonlinear rapid increase in productive performance, similar to the vocabulary spurt observed in child language development. Moreover, the network also showed a change from making only specific image/label associations to the ability to extend the labels to novel exemplars (distorted prototypes) of the images. This is similar to the phenomenon of moving from context-bound to context-flexible uses of words. That is, apparent qualitative shifts in the network's performance emerged through the process of a single progressive learning mechanism without any changes in the network architecture.

Changes in the lateral organization of brain activity to known versus unknown words, observed in our earlier studies, might be linked either to the attainment of a specific language milestone such as the vocabulary spurt, or to the strength of the word to meaning mappings for the individual words as described in the connectionist model by Plunkett and colleagues. To distinguish the two hypotheses we will call the former the "vocabulary spurt" hypothesis. The vocabulary spurt hypothesis predicts that the left greater than right ERP effect should be observed when a child's vocabulary reaches approximately 100 words. In our previous studies (Mills et al., 1993, 1997), we hypothesized that the observed shift in the lateral distribution of ERP differences to known vs. known words might be related to a shift in the way infants process words before and after the vocabulary spurt, such as from simple associations to symbolic processing. This interpretation of the vocabulary spurt hypothesis is consistent with a dual processes learning mechanism reflecting a qualitative reorganization in underlying cognitive processes before and after the vocabulary spurt (see below for an alternate explanation). The second possibility we will call the "word experience" hypothesis. The word experience hypothesis posits that the shift in the lateral distribution of the ERP effect is linked to the strength of the word/ object association. Specifically, 20-month-olds may have had 7 months more experience with the known words than did the 13-month-olds who probably learned a significant proportion of the words more recently, and this may have influenced the distribution of ERP effects for those words. Thus, the word experience hypothesis is consistent with the single mechanism process demonstrated by the connectionist model. To test these contrasting hypotheses we examined ERPs to newly learned words in 20-month-olds with small and large vocabularies (Mills, Plunkett, Prat, & Schaffer, in press). If the distribution of brain activity were linked to the amounts of experience with individual words rather than vocabulary size, then we would expect a bilateral distribution in ERP differences to newly learned words versus not-trained words, as displayed by the 13- to 17-month-old infants in the Mills et al. (1997) study to known vs. unknown words. In contrast, if the lateral distribution of these effects were determined by the vocabulary spurt, or a productive vocabulary of over 100 words, then we would expect the distribution of the effect to vary with vocabulary size, that is, a bilateral distribution for the low producers and ERP effects limited to the left hemisphere for the high producers.

Twenty-two 20-month-olds participated in the study. ERPs were collected to novel (*gaf, sarl, wug, bard*) and familiar (e.g., *cat, dog, ball, nose*) words during three conditions: before training, during training, and after training. The novel words were either trained (paired with an object) or not-trained (repeated the same number of times the child heard the trained word but not paired with an object). For all twenty-two 20-month-olds, in the before training condition, ERPs to the novel words to-be-trained and the novel words that were not-to-be-trained were identical. After the training condition, the ERPs (N200-500) to the newly learned novel words were larger in amplitude than to the not-trained novel words over anterior and posterior regions of both the left and right hemispheres (Figure 6.8, left side-whole group). Thus, pairing an object with the word increased the neural activity to the novel-trained words between 200-500 ms after word onset.

Of particular interest was whether the distribution of the N200-500 would be bilateral, like the 13- to 17-month-olds in the Mills et al. (1997) study, or limited to the left hemisphere, like the 20-month olds in that study. The results showed that the distribution of ERP differences to the newly learned versus not-trained words was consistent with the "word experience" hypothesis. That is, the ERP differences between novel-trained and novel-not-trained words (the ERP effects) were distributed bilaterally like those observed in the monolingual 13-

to 17-month-old children. However, when we examined the distribution of ERP effects according to vocabulary size, the 20-month-old high producers showed ERP effects that were significant over both the left and the right hemispheres, but larger over the left than the right hemisphere (Figure 6.8, right side). The results suggest an interaction between vocabulary size and experience with the individual words. A similar pattern showing effects of both vocabulary size and language experience was observed in the study of bilingual 20- to 22-month-olds. In that study, the organization of brain activity varied according to vocabulary size for the high and low producers and by experience with individual words in the dominant vs. nondominant language.

In the training study, the lateral distribution of the ERP effects for the high producer groups could be interpreted as reflecting a combined process that is somewhere between the "vocabulary spurt" and the "word experience" hypotheses. If we consider our original interpretation of the vocabulary spurt hypothesis as reflecting a qualitative reorganization in cognitive processes consistent with a dual mechanism model, this blend of hypotheses is difficult to interpret. However, the vocabulary spurt hypothesis does not necessitate invoking

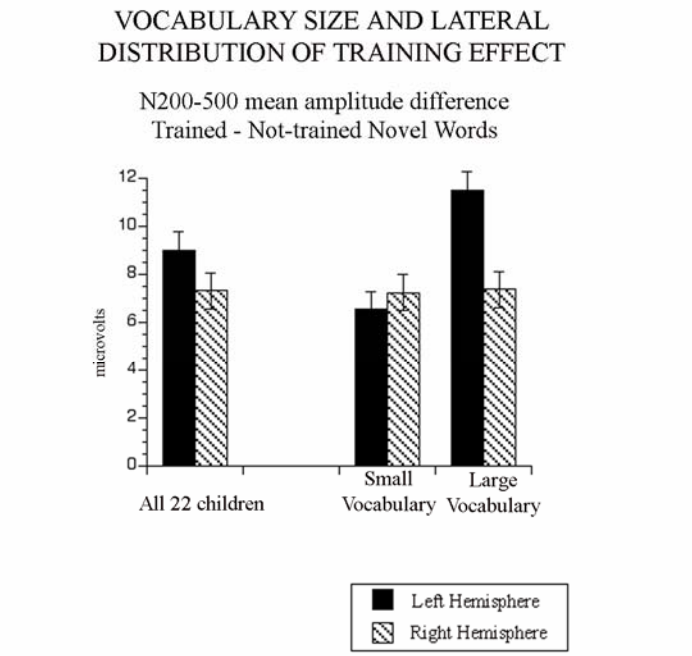

FIG. 6.8. ERP differences before versus after "training" between 200 and 500 ms over the left and right hemispheres. The difference was symmetrical for 20-month-olds with small vocabularies but larger over the left than the right hemisphere for children with large vocabularies.

a dual process model. Earlier, in our studies of late talkers, we raised the hypothesis that rate of learning may play an important role in the development of lateral asymmetries. As children attain new language milestones and their vocabularies increase, their general experience with making word/object associations also increases, making the task of learning new words easier and faster. A more parsimonious interpretation would argue that a single learning mechanism subserves the process of lateralization regardless of vocabulary size, but the process is faster in children with larger vocabularies. That is, brain activity mediating word learning shifts from a bilateral to a more focal distribution as the word/object association increases for both high and low producers. The high producers may have shown a left greater than right asymmetry because the process of lateralization occurred more rapidly in these children. In this sense, the high producers provide a snapshot of the emergence of a lateral asymmetry in progress. If so, we would expect to see similar lateral asymmetries emerge, but at a slower rate, in the low producers as they gain increasing experience with the individual words. The findings from the training study are consistent with a rate of learning hypothesis if we consider the high producers to be faster word learners. To test this hypothesis we would need to study both high and low producers longitudinally during the process of learning.

If we adopt the more parsimonious of the two interpretations of the vocabulary spurt hypothesis, the results from the training study are consistent with a continuous learning mechanism rather than a stage-like reorganization in neural activity linked to vocabulary size. In light of these results we propose the following working hypothesis. As the strength of a word/object association increases, the amount of brain activity it takes to discriminate the newly learned word from unfamiliar words decreases. That is, the brain activity needed to discriminate known from unknown words becomes more focally distributed as an emergent property of learning those specific words. In our training study, even the high producers did not show the same pattern of lateralization as shown by the 20-month-olds in either of the Mills et al. (1997) or Mills, Prat, Stager, Zangl, Neville, and Werker (2004) studies. It is likely that the novel-trained word/object associations were weaker than those of the “known” words in the previous studies. It would be interesting to examine whether the left temporo-parietal specializations (as shown by the 20-month olds in the previous studies) emerge in tandem with the child’s ability to generalize the newly learned words across different exemplars of novel objects (the criteria for referential, or symbolic, status set by Vihman & McCune, 1994). Although it may seem that we are once again positing a dual mechanism account, recall that Plunkett et al. (1992) showed that with increased experience, their single mechanism connectionist network was able to generalize across novel exemplars.

SUMMARY AND DISCUSSION

Electrophysiological recordings of auditory words from infants, children, and adults show a protracted course of development in the organization of language-relevant brain activity. For example, there are marked changes in the morphology of the ERP components from infancy and throughout childhood. Some ERP components present in infants, such as the Nc, are not observed at all in older children and adults. Other ERP components, such as the P100 in infants, have analogous components in adults. To the extent that ERP components are correlated in infants and adults, some general conclusions can be drawn. In general, from 6 months to adulthood, ERP component latencies and amplitudes tend to decrease with increasing age. Changes in overall component latencies and amplitudes may reflect general changes in neural development, such as myelination, that affect how quickly neurons can transfer information from one brain region to another. Not all developmental ERP studies report the same trends; the amplitudes and latencies of components and ERP effects between conditions depend on the specific experimental conditions. For example, we observed reduced latencies in the N200, N350, and N600-900 from 13- to 20-months in our studies of single word comprehension, but did not find age-related differences in the onset of the N400 effect in the picture/word study. There are also changes in the anterior/posterior and lateral distributions of ERP asymmetries. For example, the first positive component to auditory speech is larger over the left than the right at 20 months and is larger over the right than the left by 9 years of age. In contrast, the first negative component is larger over the right than the left and larger from posterior than anterior regions at 13 months, but is largest over temporal regions of the left hemisphere by 9 to 13 years of age (Mills, 2003; Neville & Bavalier, 2002). Thus, there is little evidence to suggest that "language" as a single entity elicits left hemisphere asymmetries that are immutable throughout development. On the contrary, the distributions of a variety of different ERP components change with increasing age and sophistication with language.

In reminder, the goals of this research were to examine how the experience of learning new words shapes the organization of language-relevant brain systems in very young children, and in turn, how changes in the functional specialization of brain activity can provide information about apparent qualitative shifts in linguistic or symbolic processing. With respect to early vocabulary development, we reviewed a series of studies that examined changes in the distribution of brain activity linked to word meaning around the developmental period of the vocabulary spurt in 13- to 20-month-old typically developing children, 28- to 30-month-old late talkers, 20- to 22-month-old bilingual toddlers, and typically developing 20-month-olds learning novel words. Across these studies the following points can be made:

1. Increased experience with words is linked to increased cerebral specializations (as indexed by more focally distributed ERPs).

Evidence for this statement comes from studies showing changes in the distribution of ERP differences to known vs. unknown words at different ages and vocabulary sizes. At 13 to 17 months of age ERP differences to known and unknown words are broadly distributed over anterior and posterior regions of both the left and right hemispheres. By 20 months these differences are limited to temporal and parietal regions of the left hemisphere (Mills et al., 1997; for a replication using different stimuli see Mills, Prat, et al., 2004). A similar change in the distribution of ERP differences, from bilateral to left temporo-parietal, was observed in 28- to 30-month-old late talkers, who were matched with typically developing younger children (13-20 months) for vocabulary size. Our study of 20- to 22-month-old bilingual children further supported the hypothesis that the distribution of brain activity to known vs. unknown words is related to vocabulary size and not rates of brain maturation.

2. "Language" does not move to the left hemisphere at 20 months of age.

Although the observed changes in the distribution of ERP differences to known and unknown words, from bilateral to left lateralized, has been observed reliably across several studies reported here and elsewhere, it is important to note that these changes (a) reflect differences between two word types, (b) reflect a group phenomenon, and (c) do not reflect the mature pattern of brain activity to auditory words. First, the bilateral to left lateralized changes are observed in amplitude *differences* between known and unknown words. They do not reflect changes in the distributions of the N200 and N35O to known words. The N200 and N350 are larger over the right than the left at 13 months and younger (we have tested infants as young as 3 months, unpublished data). At 20 months the N200 and N350 to known words is bilateral. The mature left greater than right asymmetry for the first negative component is not evident until quite late in development, that is, 9 to 13 years of age (Neville et al., 1992). Second, not all children at 20 months show these differences only over temporo-parietal regions of the left hemisphere. In fact, most 20-month-olds also show differences over additional sites, especially left and right frontal regions, and right temporal regions. Also, the studies reported here use a cross-sectional design. We are currently conducting longitudinal studies to examine whether a similar pattern of changes will hold for the same group of children. Third, the lateral distribution of the N200 and N350 to known words matures quite late in development. This is also true for the lateral distribution of the N200 and N350 to unknown words. Thus the distribution of ERP *differences* to known and unknown words also changes. Although reliable, the left lateralized N200 and N350 differences to known versus unknown words appears to be limited to children in the 20 to 30 month age range. The pattern changes again around age 3 (unpublished data).

3. Apparent qualitative shifts in the organization of brain activity emerge as a result of increasing proficiency and can be explained by continuous development.

The hypothesis that a qualitative reorganization in cognitive processes may underlie the observed shift in the lateral distribution of ERP differences to known and unknown words has been revised from the original position offered by Mills et al. (1993). Here, we propose a general trend from a broad to more focal pattern of activity during the course of leaning that might not be specific to language learning. Slow and effortful processing, which is a hallmark of early word learning, leads to a broad distribution of brain activity. When an association or skill is well learned and more automatic, the pattern of brain activity elicited by that cognitive process becomes more focally distributed. The level of proficiency of the learner at a given time interacts with this process. For example, although the mechanism, from broad to more focal patterns of activity, may be the same in an adult and an infant, it will occur much faster in a skilled adult than unskilled infant learner. That is, these asymmetries emerge through the process of learning language.

The first study presented in the chapter examined semantic processing in a picture/word context. In contrast to the studies discussed later in the chapter, the ERPs to a violation of semantic context did not show marked changes in the distribution of brain activity with increasing age. Even 13-month-old children showed an N400 like response when the word did not match the picture, suggesting that the neural systems mediating semantic processing were the same in infants and adults even when the infant had a very limited vocabulary. This raises the question as to what mechanisms might account for the marked changes we see in language development in children in this age range. Some preliminary data from our lab (Mills, Larson, et al., 2004) suggests that working memory may be an important factor in explaining changes in language skills between 13 and 20 months. In this study, if the word was presented before the picture, 20-month-olds, but not 13-month-olds, showed an N400-like response when the picture did not match the preceding word. The difference in the two paradigms is that in the former there was no working memory component, the picture was still visible when the infant heard the word. In the latter, the infant had to keep the word in memory and then compare that representation with the subsequent picture. In this sense, apparent discontinuous changes in development such as the vocabulary burst may emerge out of incremental and continuous changes in capacity such as working memory and experience with individual words (see Bates & Dick, 2002; Elman, Bates, Johnson, Karmiloff-Smith, Parisi, & Plunkett, 1996, for a similar idea).

4. The rate of learning may be important in the development of some lateral asymmetries.

Typically developing children who acquire new words at a faster rate displayed some lateral asymmetries, not observed when children learned new words at a slower rate. This pattern was observed across our studies of known and unknown words in monolingual 13- to 20-month-olds, bilingual 20- to 22-month-olds, and typically developing 20-month-olds learning new words. That is, children who scored above the 50th percentile on the MacArthur CDI relative to children their own age showed asymmetries not observed in children who scored below the 50th percentile, nor in late talkers. These findings raise the hypothesis that slow and effortful language learning, rather than slow brain maturation, may be an underlying factor associated with the absence of lateral asymmetries in some atypical populations such as Williams Syndrome, autism, and children with language impairments.

CONCLUSIONS

Developmental changes in ERPs to known and unknown words during early vocabulary acquisition suggest that cerebral specializations for language occur along a protracted course of development. These studies do not support a strong nativist position that left hemisphere asymmetries observed to some linguistic stimuli at birth are immutable and that cerebral asymmetries do not develop. Instead, these studies are consistent with the position that the organization of language-relevant brain activity is dynamic and shaped through the process of learning language. Our studies further suggest that in early language development, changes in cerebral specialization occur both as a function of increasing experience with individual words and increasing proficiency with language. Additionally, the rate at which children learn new words may be linked to the development of certain asymmetries.

In response to what changes in brain organization can tell us about changes in symbolic processing, the results from the studies presented here suggest that marked shifts in the lateral organization of brain activity linked to the attainment of a particular language milestone do not necessarily reflect discontinuity in the underlying cognitive mechanisms. In contrast, these findings suggest that continuous developmental changes such as experience with individual words, increased experience with word learning in general as indexed by vocabulary size, and increases in working memory capacity interact to allow the brain to process information in a more efficient manner. Apparent discontinuities in language development and the patterns of brain activity linked to the attainment of specific language milestones emerge through the process of continuous development.

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