Brain Development and Language Learning: Implications for Nonbiologically Based Language-Learning Disorders

Développement du cerveau et apprentissage de la langue : Incidences sur les troubles d'apprentissage d'origine non biologique

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Abstract

The objective of this manuscript is to describe our current understanding of relations between brain and behaviour in the very early stages of language development. We begin by describing the pertinent language and language-relevant behaviours, focusing on important developments in the first year of life, major language milestones that occur between one and three years of age, and individual differences that must be accounted for in explanations of language learning. This is followed by a short tutorial on basic neuroscience terminology and brain structure. We then discuss prenatal and postnatal events that are important for language development. Finally we discuss the interactions between neural events and learning, and the implications of these interactions for early language development. A strongly bi-directional model in which the process of development is seen as an interaction of biological maturation with experience from almost the moment of conception is proposed. The importance of experience to brain development and learning from the earliest points in life has powerful implications for the conceptualization of early language development and how to respond to early language delay.

Abrégé

Ce document a pour objectif de décrire l'état des connaissances sur le lien entre le cerveau et le comportement dans les tout premiers stades du développement linguistique. Nous décrivons d'abord les comportements linguistiques pertinents en mettant l'accent sur les jalons importants au cours de la première année de vie, puis entre l'âge de un à trois ans, et enfin sur les différences individuelles dont il faut tenir compte pour expliquer l'apprentissage linguistique. Nous enchaînons avec un bref rappel de la terminologie neuroscientifique et de la structure du cerveau. Nous discutons ensuite des événements prénataux et postnataux importants pour le développement linguistique. Enfin, nous abordons les interactions entre les événements neuronaux et l'apprentissage, ainsi que l'incidence de ces interactions sur le développement linguistique lors de la petite enfance. Nous proposons ici un modèle fortement bidirectionnel dans lequel le processus de développement est conçu comme une interaction entre la maturation biologique et l'expérience, pratiquement dès la conception. L'importance de l'expérience pour le développement cérébral et l'apprentissage linguistique dès le début de la vie a de grandes ramifications pour la conceptualisation du développement linguistique et pour la façon de réagir aux retards de l'apprentissage linguistique lors de la petite enfance.

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This special issue addresses prevention of nonbiologically based language-learning difficulties. Within that context, the goal of this manuscript is to describe our current understanding of relations between brain and behaviour in the very early stages of language development. In the important volume *Principles of Neuroscience* (Kandel, Schwartz, & Jessell, 2000), Kandel notes that a number of sweeping advances have occurred in biology over the past two decades. These include the ability to sequence genes and infer amino acid sequences from the proteins that they encode, and the development of a conceptual framework of the functions of cells that applies to all areas of cell biology. He argues that unification of the study of behaviour and neural science is the final necessary step for achieving a coherent scientific approach to understanding behaviour. This paper represents a step in that direction within the domain of language development. Our immediate challenge is to try to understand how brain function is reflected in the complex behaviours that comprise language. A logical way to approach the challenge is to study the co-development of brain and language during the early stages of language acquisition. In one of the first attempts to do that, Lenneberg (1967) proposed specific correlations between language acquisition and the development of motor skills in children from birth to four years of age. He argued, for example, that because first words consistently appear at about the time that children begin to walk, and because the language environment of children varies widely, language acquisition is more likely to be explained by some general maturational changes in the human brain than by learning. In fact, he claimed that language milestones are interlocked with other milestones, such as stance, gait, and motor coordination that were thought to be clearly attributable to physical maturation. Later studies (Bates, Benigni, Bretherton, Camaioni, & Volterra, 1979) in which researchers looked for the proposed correlations in longitudinal samples of children, found no significant connections between language and motor milestones. Yet, given the fact that the human nervous system continues to develop for some time after birth, it is still appealing to look for neural correlates, and possibly even causes, of the remarkable changes that typify language development in the earliest stages. In a more recent attempt, Bates, Thal, and Janowsky (1992) proposed two likely candidates: the achievement of adult-like patterns of connectivity and brain metabolism around eight to 10 months of age, and a marked increase in synaptic density and brain metabolism that was estimated to take place between 16 and 30 months of age. The former appeared to be associated with dramatic changes in infant cognitive and communicative abilities that occur around 8 to 10 months, including speech perception and production, memory and categorization skills, imitation, joint reference and intentional communication, and word comprehension. The latter appeared to be associated with the dramatic, nonlinear increases in vocabulary and grammar that occur between 16 and 30 months of age. However, in the time since that review, new developments in neuroscience have led to a better understanding of brain development during the first few years and that, in turn, requires a reconsideration of the closely linked brain-behaviour relations that were proposed. In a revised and updated version of the Bates et al. chapter (Bates, Thal, Finlay, & Clancy, in press) a more interactive and bi-directional model is proposed, one in which the process of development is seen as an interaction of biological maturation with experience from almost the moment of conception. Thus, we reject the conventional view of maturation as a biological timeline that unfolds independently of experience. The information provided in that chapter will be reviewed here, with a specific view to what it may mean for understanding and, therefore, having the information necessary for prevention of language learning disorders. The reader is referred to the original manuscript for a discussion that has greater detail and depth and to a related interactionist perspective that has also been proposed by Chapman (2000).

We will begin our discussion with the language and language-relevant behaviours that we need to explain. These will be discussed in the next three sections. The first focuses on language and language-related behaviours across the first year of life. This is followed by a description of the major language milestones that are achieved between one and three years of age. The third section spells out individual differences in the language acquisition process that must be accounted for in any explanation of language learning. Once the language-relevant behaviours have been identified, we will shift to a discussion of neural development. This will be discussed in four sections. First we provide a short and narrowly focused tutorial to familiarize or re-familiarize readers with basic terminology and brain structure. In the second section the prenatal events that are essential for language will be discussed. The third section focuses on the important post-natal events. Finally, in the last section we discuss the interaction between neural events and language learning. We will end the paper with some conclusions regarding the implications of these interactions for prevention of nonbiologically based language-learning difficulties.

What are the Language and Language-Relevant Behaviours?

A number of complex abilities, interacting across different modalities, must be in place for children to learn to use language. First, they must be able to recognize the linguistically relevant units of their native language and to figure out how to produce them. They must also be able to recognize and categorize objects and events, and to understand that those objects and events can be referred to with words. In order to learn a specific language, children must also have the ability to reproduce what they hear (i.e., to use imitation and memory). In addition to these specific skills, children must be highly motivated to communicate with other members of their community. Over the first year of life human infants develop an impressive number of these language-related skills. Towards the end of the first year clear signs of language development begin to appear. During the second and third years of life observable and measurable gains in language abilities are made. By the time typically developing children are three years old they are already skilled language users. Within another year they will have virtually all of the skills that adults have; all that remains is for them to polish and extend those skills. Clearly these first years are critical to normal language learning. Complicating the task for those who wish to determine if a child is developing typically, however, is that the single most characteristic quality of development during this period is variability (see Bates, Dale, & Thal, 1995; Fenson, Dale, Reznick, Bates, Thal, & Pethick, 1994 for a discussion of variability and individual differences in this period of language development). In addition, individual children are likely to demonstrate multiple bursts and plateaus that may look like qualitative changes in language learning. These create significant challenges to those trying to find meaningful relations between brain development and language acquisition. Any brain-behaviour explanations of language development will need to take into account both variability and the more regular sequences of events through which normal children pass in the process of learning language.

At two points across the first three years of life a dramatic qualitative change in language abilities occurs. The first of these occurs around 9 to 10 months of age when children appear to have figured out how to map sound onto meaning for communicative purposes. The developments that lead to and include this shift will be described in the next section that is focused on prelinguistic skills and nonlinguistic prerequisites to language use that occur across the first year of life. The second occurs between 16 and 30 months of age when dramatic increases are seen in vocabulary and grammar. These will be described in a subsequent section in milestones of language development.

Prelanguage and Prerequisites to Language Across the First Year

The skills attained during this period of development provide strong evidence for the power and speed of learning in human infants. Only recently, through the work of people like Kuhl (1993), Jusczyk (1997) and others, have we come to appreciate how much infants know. One reason for this dramatic change in our thinking about what infants know is the development of new research techniques that allow us to estimate their knowledge in a number of areas. These include the techniques of high-amplitude sucking (that makes use of the fact that infants suck more strongly when exposed to a novel or particularly interesting stimulus), habituation and dishabituation (based on the recognition that infants will attend to or re-focus on an object or sound when they perceive a change in the auditory or visual stimulus), operant generalization (specifically training an infant to turn his or her head to sounds from one speech category versus another), cross modal looking preference (capitalizing on the propensity of infants and toddlers to look at objects and actions that match the word or phrase said when they understand the utterance) and listening preference (using infants' inclination to look toward an auditory stimulus with novel qualities over one that is familiar). Reviews of research that have employed these techniques may be found in Aslin, Jusczyk, and Pisoni (1998), Eimas, Miller, and Jusczyk (1987), Haith and Benson, 1998, Kellman and Banks, (1998), and Kuhl (1986). Studies that used these methods have made it apparent that children learn a great deal during their first year of life. Five specific areas are of particular interest to understanding the development of language: speech perception, speech production, conceptual content of communicative acts, social uses of language, and coding capacity (including memory and imitation). Table 1 provides an overview of the developments in each of these categories over the first year of life.

Speech perception. During the first months of life, infants are capable of perceiving essentially all of the phonemic contrasts that appear in naturally occurring languages. In fact, there is evidence to suggest that infants develop a preference for their native language during their last few weeks of gestation (DeCasper & Fifer, 1980; Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993; Mehler, Jusczyk, Lambertz, Halsted, Bertoncini, & Amiel-Tison, 1988). This incredible ability to detect the important contrasts that signal differences in meaning in spoken languages is not species

Table 1
Prelanguage and prerequisites to language across the first year.

Age In Months	Sound		Meaning	Intentionality	Coding Capacity
	Perception	*Production*	*Conceptual Content*	*Social and Non-social*	*Imitation and Memory*
0 1 2	All phonemic contrasts can be heard	Vegetative sounds	Object detection	Non-intentional signals (smiles, cries, etc.)	"Pseudo-imitation"
3 4	Cross-modal (vocal/mouth gesture) matching	Cooing, babbling without consonants		Passive anticipation of actions by others	Anticipates position of object in a moving display
5 6	Native language-specific vowel prototypes		Changes in complexity of pattern detection and pattern anticipation	Joint attention to objects; objects and people are familiar; goals achieved with familiar means	Ability to retrieve a hidden object at zero delay, if obstacle can be easily removed
7 8		Canonical or reduplicative babble with consonants			
9 10	Loss of sensitivity to non-native phoneme contrasts begins	Word-like sounds	Object categorization	First signs of tool use; novel means to familiar ends; humans as tools to objects; objects as tools to human interaction	True imitation Ability to retrieve a hidden object after delay of up to 15 seconds

Adapted from Bates et al. (in press)

specific (Kuhl, 1986), so it is clearly not an innate language-specific ability. However, combined with other skills that are present in early infancy, it provides a mechanism for infants to learn the critical sound-meaning connections of their native language. One of those abilities is the association of sound and lip shape. In a study by Kuhl and Meltzoff (1988), two- to three-month-old infants saw faces on two screens that had a speaker placed between them. One of the faces made the oral gesture that accompanies the sound /u/ (as in food) and the other made the oral gesture for /i/ (as in feet). The side at which each facial gesture was presented was changed randomly across trials. During a trial the faces were displayed and one of the two sounds (/u/ or /i/) was played from the speaker. Infants looked significantly longer at the face on which the oral gesture matched the speech sound, indicating that they recognized the oral configuration for the sounds.

Another highly relevant skill is the ability of children as young as eight months of age to detect the statistical regularities of language and use them to recognize patterns of sounds that are word-like. Saffran, Aslin, and Newport (1996) played strings of meaningless syllables that were spoken in a monotone for two minutes in a room in which eight-month-old infants were playing with toys. The stimuli were constructed of syllables like /ri *ba di co* ra bi lo *ba di co* bi ra/. As the example is designed to demonstrate, some syllables (/ba di co/) were always presented together and, thus demonstrated word-like regularity while others were randomly mixed into the word-like combinations. Following this the infants were tested in a preferential listening paradigm and they were exposed to either the same stimuli that they had heard for two minutes while playing, or to another set of stimuli composed of exactly the same syllables, but in which the syllables were now arranged in a different order and the regularities in the original stimulus were no longer present. The children turned toward the speaker in which the previously unheard strings were played reliably more than to the other speaker, indicating that they recognized the difference between the two sets of syllable strings. Since the only difference between the two sets of stimuli was the word-like combinations of syllables, this study demonstrated that infants have the ability to detect that kind of statistical regularity in an ongoing stream of speech. This is a remarkable phenomenon, indicating that infants have the capacity to learn to identify word boundaries from strings of speech even without specifically attending to the speech event.

Taken together, these results might suggest that infants have a special language acquisition device that determines what kinds of cross-modal stimuli and speech-stream regularities they attend and respond to. That, of course, may be the case and it is not possible to rule out such a hypothesis at the present time. On the other hand, the same kinds of pattern recognition abilities have now been demonstrated with auditory tones and with visual stimuli that have no speech content (Haith & Benson, 1988; Kellman & Banks, 1998). This suggests that the skill is one of statistical induction of regularities in the sensory input that is applied across all domains, functioning to help children understand the world in which they are living. This kind of ability, combined with strong social drives that will be discussed in a future section, may provide the means and motivation for infants to *learn* the mapping between mouth movements and speech sounds very early in life.

Yet another recently discovered phenomenon is that the ability to hear the phonemic contrasts used by all of the world's natural languages begins to be lost in infancy. Kuhl and colleagues have demonstrated that infants prefer to listen to the vowels of their own language by six months of age (Kuhl, 1993; Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992). This preference actually becomes a loss of sensitivity at later ages. It is as though infants lose interest in the irrelevant information and selectively listen to what will help them learn their language. Werker and colleagues have demonstrated that infants begin to exhibit selective loss or inhibition of non-native consonants when they are 10- to 12-months of age (Lalonde & Werker, 1990; Werker & Tees, 1984). This is an especially interesting finding since it occurs at a time at which a number of other significant language-relevant changes are seen, including comprehension of words and phrases (Bates, Bretherton, & Snyder, 1988), recognition of native-language-specific intonation contours (Hirsh-Pasek, Kemler Nelson, Jusczyk, Cassidy, Druss, & Kennedy, 1987), and production of native language sounds in babble (Boysson-Bardies, Sagart, & Durand, 1984). The fact that so many significant changes occur at the same time contributes to the impression that there is a major qualitative shift that is critically related to changes in brain maturation.

Speech production. Although development of perceptual skills leads to the onset of the comprehension of words (which is usually measurable by 10 months of age in most typically developing children), few children are capable of producing recognizable words until a few months later. There are a number of well-recognized milestones that lead to word production, and they are summarized in the third column of Table 1 (see Locke, 1983; Menn, 1985 for detailed reviews).

In the period in which speech perception is characterized by the ability to hear all the phonemic contrasts possible in natural languages (approximately the first three months), production can be characterized as reflexive sounds that are tied to the infant's internal states (e.g., comfort, distress). These "vegetative sounds" have no relation to language other than to serve the communicative function of signalling various states, some of which may need parental attention. Very shortly, however, the infant's sounds begin to change and become more systematic. Reproduction of vowel sounds (cooing) begins around three months of age, and the infant appears to enjoy playing with the sounds he or she hears herself produce. Babbling that contains consonants appears to be more directly related to speech, and generally begins when infants are between six and eight months of age. Research suggests that during the period in which children babble but do not yet produce words the sound of the babble becomes gradually more and more like the language of the community in which the infant lives (Boysson-Bardies et al., 1984). By 10 months of age the infant also begins to produce word-like combinations of sounds (that is, patterns of sounds that follow the phonological rules of the native language) and to use them in consistent ways (e.g., /numnum/ as part of a feeding routine, /boom/ said in the context of a game of knocking down blocks). Although the child does not yet produce recognizable words, the word-like sounds in combination with the inhibition of perception of non-native sounds and the first indications that he or she is beginning to understand some words has the child poised for using words to communicate thoughts and needs. Taking that step requires the child to have ideas that are organized into categories or concepts that the sounds of the language can be used to represent. We turn to development in that domain next.

Recognition and categorization of objects and events. We have learned an enormous amount concerning infants' knowledge about objects and how they are categorized in the past decade and a half. We now know, for example, that infants under six months of age are capable of fine-grained discriminations of object boundaries and of three-dimensional space (for thorough reviews see Bertenthal & Clifton, 1998; Gibson & Spelke, 1983; Haith, 1990; Osofsky, 1987). This capability is, at least to some extent, available for object classification across sensory modalities. For example, Meltzoff and Borton (1979) showed that very young infants who are shown two pictures simultaneously, one of a nonsense form with a smooth surface and one with a nubbly-textured surface, look at the nubbly-textured form if there is a nubbly-textured pacifier in their mouth and at the smooth form if there is a smooth pacifier in their mouth. They clearly recognize the differences between the two pacifiers across the tactile and visual modalities. Similarly, the work by Kuhl and Meltzoff (1988) in which children looked at a picture of rounded lips when they heard an /u/ and at a picture with flattened and laterally widened lips when they heard /i/ is an example of classification across the visual and auditory modalities. These perceptual abilities provide the child with information that allows him or her to take the next step (which, not surprisingly, occurs at about nine months of age). By that time infants can clearly anticipate changes in a moving display (Haith, 1990), synthesize a complete pattern out of local details (Bertenthal, Campos, & Haith, 1980; Bertenthal, Proffitt, Spetner, & Thomas, 1985; Spitz, Stiles, & Siegel, 1989), and recognize objects as members of a category (Cohen & Younger, 1983; Reznick & Kagan, 1983). It is fair to say that by 10 months of age object categories are present with adequate constancy and flexibility to serve as the basis for using words referentially.

Intentionality and joint reference. These are social factors that are fundamental to the development of language. We are a highly social species and the use of language is one of our most social qualities. In order to learn language a child must be strongly driven to communicate with other members of the species. They must also come to understand that language is a tool for reaching some of their most important social goals. As Bates and her colleagues pointed out many years ago (Bates et al., 1979) language is a symbol system in which the symbols are used as tools to get others to do things.

The human newborn comes with a limited set of social skills, but it includes the necessary ones: responsiveness to touch, ability to differentiate the human voice from other auditory stimuli, and ability to differentiate the human face from other visual stimuli. These are modified over the first 10 months in a manner that prepares the child for language learning by establishing the ability to share reference and developing an understanding of the function and power of the language tool. Through face-to-face interaction with caretakers that begins shortly after birth and vocal games in which the caretaker and child alternate making sounds in a "conversational" manner, infants establish patterns of interaction with adults that lead them to begin following adults' line of visual regard at around five months of age (Butterworth, 1990; Butterworth & Jarrett, 1991). This "joint attention" or "joint reference" to the same object or event establishes the minimally necessary conditions for learning what the names for things are. Interestingly, this is a skill at which human infants are significantly better than other primates, even chimpanzees and apes (Tomasello & Call, 1997).

Around eight or nine months of age human children begin to take an active role in joint reference activities rather than simply following the parent's line of regard. At this age they begin to use what Bates, Camaioni, and Volterra (1975) referred to as "proto-declaratives" (use of objects to obtain adult attention) and "proto-imperatives" (use of adults as a means of obtaining a desired object) by showing, giving, and pointing to objects. Proto-imperatives are often accompanied by looks that alternate between the desired object and the adult, and sounds that appear to serve the purpose of requesting. These protoforms, along with the ability to use one object to obtain another (a nonsocial form of tool use that also develops at this time) are strongly correlated with the soon-to-follow emergence of speech (Bates et al., 1979).

Coding capacity: imitation and memory. Although these may seem like capacities that fall into distinct domains, they are placed together because they both involve storage of coded information. Imitation, the ability to reproduce novel motor patterns, is clearly an important ability for transforming the auditory input of a spoken message into comparable output. Memory is required to retain, identify, and remember signals in the right context. These two abilities work together in language development, and both undergo significant changes in the first year of life.

Imitation. Neonates can produce a limited set of innate motor patterns like sticking out the tongue and opening the mouth in response to an adult model (Meltzoff & Moore, 1979). This is known as "pseudo-imitation" because the models that the child can imitate are restricted to patterns that are already in their own motor repertoire. This kind of imitation persists, increasing with the child's expanding motor skills until he or she is around nine months old, when "true imitation" begins (Piaget, 1954, 1962). This ability to reproduce novel vocal and gestural patterns is seen in the production of gestures like "bye-bye" and "pattycake", and the appearance of prosodic patterns and consonant-vowel sounds in babbling that begin to approximate those in the ambient language. At about the same time that children begin to use true imitation they also begin to be able to reproduce novel vocal and gestural patterns from memory ("deferred imitation") after delays of up to a month (Meltzoff, 1988), suggesting that there is interdependent growth of both abilities. Like joint referencing, imitation appears to be something at which human infants excel compared to other primates. There is very little evidence of systematic imitation of novel models in any other primate species (Tomasello & Call, 1997). Indeed, the combination of joint referencing and imitation skills are probably among the major factors that allow humans to learn the kinds of complex languages that are impossible for other primates to learn.

Memory. In order to use language adequately children will need recognition memory for understanding words and sentences, recall memory for putting their ideas into recognizable speech, and working memory for creating novel utterances. This is yet another area in which infancy researchers have learned a great deal in recent years (Haith & Benson, 1998; Harris, 1983; Mandler, 1983; Schneider & Bjorklund, 1998). As early as three months of age infants can learn to anticipate the position of an object in a moving display (Haith, Benson, Roberts, & Pennington, 1994). Increases in the ability to retrieve a hidden object after a short delay (Baillargeon & Graber, 1988; Piaget, 1954), and increases in the length of time the location of the object can be held in memory (Diamond, 1985) are seen between seven and 10 months of age. Meltzoff's (1998) demonstration of deferred imitation in nine-month-old children also shows the presence of some form of recall memory. Thus, it appears that by the time infants are nine or 10 months old (when they have the ability to categorize objects, understand how to use symbols as tools, are restricting recognition of phonemic contrasts to those of their native language, and are producing word-like strings of sounds) they have developed sufficient memory to hold in mind a sound or word while retrieving from memory an object category (i.e., they can now comprehend words). They may also be able to retrieve and produce a sound from memory when an exemplar of a class of objects or events (e.g., an animal like a dog) is present (i.e., they are ready or almost ready to produce words).

The achievements of children in the first 10 months of life described above appear to be at least partly a result of interaction with the environment. For example, babble would not drift to the sounds of the infant's linguistic community without input from that community, object categories would not develop without exposure to objects, and the kinds of social games (like bye-bye or pattycake) that support the communicative process are highly culturally specific. By 10 months of age the typically developing child has reached a critical level in all five areas: sound perception, sound production, categorizing objects, intentionality, and coding capacity. If the requisite threshold level is not reached in any one of these domains, language acquisition is not likely to proceed in a typical manner.

Language Milestones

In this section the major language events that occur in the first three years will be reviewed briefly. Sufficient detail will be provided to support claims about relations between language milestones and cognitive developments (how things come together) and variations and dissociations that occur under normal and abnormal conditions (how things come apart). However, Bates, Thal, and colleagues have previously reviewed these stages of early language development in a number of different places for a number of different purposes. Readers are referred to those sources if they are interested in the continuity of individual differences from infancy to childhood (Bates et al., 1995; Thal & Bates, 1989), relations between the development of language and gesture (Bates, Thal, Whitesell, Fenson, & Oakes, 1989; Iverson & Thal, 1997; Shore, Bates, Bretherton, Beeghly, & O'Connell, 1990; Thal & Bates, 1990; Thal & Tobias, 1992; 1994; Thal, Tobias, & Morrison, 1991), similarities between adult aphasia and dissociations observed in normal and abnormal language development (Bates & Thal, 1991; Reilly, Bates, & Marchman, 1998), and norms of language development from a clinical point of view (Thal & Bates, 1989; Thal & Katich, 1996; Thal et al., 1991).

Word comprehension. Around eight to 10 months of age, during the period when children begin to use word-like sounds, appropriate responses to specific, contextually supported sounds (for example to their own name, to "mommy" or "daddy", to "no no") are observed. This is the first systematic evidence of word comprehension. As noted in the previous section on prelinguistic development, a number of shifts also occur in nonlinguistic cognitive domains. As children begin to understand tool use and to recognize language as a useful tool, they begin to use gestures (like giving, pointing, and showing) to establish and maintain communicative interactions, and they begin to classify objects into conceptual categories. The correlations between language and other nonlinguistic cognitive accomplishments (that occur at many of the early milestones as will be seen below) are significant because they suggest that language development is paced by mechanisms outside of language itself, possibly mechanisms that are the result of changes in the maturing brain.

Comprehension grows rapidly after 10 months of age. For example, in a sample of more than 1,800 children from three different cities in the United States (Fenson et al., 1994), parents reported that their children understood an average of 67 words at 10 months of age, 86 words at 12 months, 156 words at 14 months, and 191 words at 16 months. Beyond 16 months of age most parents have difficulty keeping track of the words that their children understand because comprehension vocabulary has grown too large.

Word production. The pattern for early word production parallels that for comprehension, but comes a little later. That is, production of word-like sounds in situations of high contextual support (e.g., using a specific sound to request a particular object or activity, using an animal sound in a familiar game) begins between 11 and 13 months of age. These word-like sounds are considered to be early word forms by some because they are used consistently and for purposes of communicating some specific intent on the part of the child. They rapidly become what appear to be real words, although they are quite unstable, coming and going from the child's repertoire, until the child has developed a vocabulary of about 10 consistently produced words. During this time and over the next months until the child's vocabulary has reached approximately 50 to 75 words, children use single words almost entirely for the purpose of reference rather than predication. That is, they use them to label and/or to ask for objects and people and not to say things about those objects and people. After their vocabulary reaches 50 to 75 words children begin to use more verbs and adjectives, and other words that allow them to begin to say things about the objects and people in their world.

An important cognitive correlate of first words is the use of recognitory gestures (Bates et al., 1979; Escalona, 1973; Werner & Kaplan, 1963). These are gestures such as putting a hand to the ear to "represent" the object "telephone", patting a hand on one's head to indicate "hat", or putting a closed hand to the mouth and tilting the head back to indicate "cup", that are frequently seen in children who are just beginning to use words (see Bates et al., 1979; Escalona, 1973; Thal & Bates, 1988; Werner & Kaplan, 1963 for more detailed descriptions). Unlike the earlier gestures, recognitory gestures appear to be representational in nature. Thus, children have moved beyond the use of gestures largely for purposes of social engagement to using them for identifying objects and events in their environment (i.e., for labelling). Like early words recognitory gestures are used consistently and for purposes of communicating some specific intent. At this point in time the gestural and vocal modalities have equal potential for supporting the development of a complex linguistic system. Children who have hearing that is within the normal range move very quickly to the oral modality, dropping their use of recognitory gestures between 14 and 18 months of age as speech becomes the dominant mode for representational communication.

Vocabulary burst and word combinations. The 50- to 75-word point marks two important changes in the child's process of acquiring language. First, there is acceleration in the rate of learning new words that has been called the "vocabulary burst". Evidence can be seen in the large norming study mentioned earlier (Fenson et al., 1994) in which parents reported that their children produced an average of 10 words at 12 months of age, 64 words by 16 months, 312 words by 24 months, and 534 words by 30 months. Clearly the rate of word acquisition increases substantially after 16 months, with an increase of 248 words over the next eight months and of another 212 words over the next six months. As the rate of vocabulary growth increases, there is also a change in the proportion of words that serve a referential versus a predicative purpose, with increases in the proportion of predicative words. For example, verbs typically com-

Table 2
Nonlinguistic correlates of early language milestones.

Age In Months	Language Milestone	Nonlinguistic Correlate
8 to 10	Word comprehension Intentional communication, vocal routines	Tool use, deictic gestures (pointing, showing), gestural routines (pattycake), causal understanding, shifts in categorization
11 to 13	Word production	Recognitory gestures in symbolic play
20 to 24	Vocabulary burst and word combinations Changes in vocabulary composition	Gestural combinations in symbolic play, shifts in categorization, changes in patterns of block building,
28 to 30	Onset of grammar	Active sequencing in spontaneous symbolic play

Adapted from Bates et al. (in press)

prise about 2% of the vocabulary of a child who has only 50 words. For a child with a vocabulary of 100 words the proportion of words that are verbs increases to around 12%. This suggests that a shift from reference (using single words) to predication (in which words are used in a relational manner) is under way. Further support is offered by the second change that is seen at the 50- to 75-word point; the child begins to use utterances that contain more than one word. This shift to word combinations is tightly tied to the vocabulary burst (more closely than it is to age) and the new use of verbs, adjectives, and other predicative terms. The early combinatorial forms used by children appear to code similar relational meanings, regardless of the language that the child is learning (see, for example, Braine, 1976). These include existence (e.g., “here car”, ‘bye-bye bunny”), desires (e.g., “want juice”, “no night-night”), basic event relations (e.g., “kitty fall”, “daddy byebye car”), and attribution (e.g., “wet”, “hot”), despite the fact that languages vary widely in the forms used to express these relational meanings.

In nonlinguistic domains we see active combining of gestures in symbolic play (Brownell, 1988; Fenson & Ramsay, 1981; McCune-Nicolich, 1981; McCune-Nicolich & Bruskin, 1982; O’Connell & Gerard, 1985; Shore, 1986; Shore, O’Connell & Bates, 1984). For example, a child might stir in a cup with a spoon and then put the spoon to a doll’s mouth, or feed the doll with the spoon and then stir in the cup. The awareness that things go together appears to be present, but the typical order in which they usually occur is not necessarily maintained.

Development of grammar. Around 28 months of age children begin to use the grammatical forms specific to their language. This will continue, growing rapidly until the majority of grammatical forms are mastered by the time a child is three or four years old. There is a general order of acquisition of grammatical morphemes that was outlined for English-speaking children by Roger Brown in his seminal book *A First Language, The Early Stages* (Brown, 1973). A large number of these forms are first seen some time within the period between 24 and 26 months, a rapid growth that seems to parallel the vocabulary burst that occurred earlier.

The length of utterances produced by children also increases at this time and with it comes greater knowledge of the syntactic regularities that are important for the language being learned. In a normative study of middle-class American children by Miller and Chapman (1979) and in Miller (1981), mean length of utterance (MLU) was observed to increase from approximately 1.2 words at 20 months to approximately 2.4 at 30 months and 3.2 at three years of age.

In the gestural domain there is evidence of a link between grammatical development at around 28-months of age and the ability to produce an arbitrary sequence of five gestures (Bauer, Hertsgaard, Dropik, & Daly, 1998). The correlation between grammar and gesture is not observed with shorter sequences, or if the sequence in which the gestures are modeled is either meaningful or causal. Thus, at this point in time, the correlations found appear to result from similar demands placed on memory by language and nonlinguistic systems.

Individual Differences in Language Development

Variability in rate. Although the regular sequence of development portrayed above is generally correct, the reality is that there is fairly wide variability in the timing of every one of these milestones for individual children, making rate of development a poor metric of language development in these early stages. In some cases even the nature of the development is somewhat different. For example, the range of ages at which parents may expect the onset of babble (6 to 10 months) is quite wide when considered in the context of all the changes that occur during the first year of life (see Table 1). In addition to the variation in rate, however, what children do once they start to babble can be quite different. Some children will attempt many sounds from the very beginning, while others may produce only a small set of phonemes for a number of months.

The variability is even greater once language development proper is under way. Table 3 provides examples of the mean, standard deviation, and range for number of words understood, number of words produced, and the mean of the three longest utterances (M3L) that parents reported their children produced for selected ages from the norming study of the MacArthur Communicative Development Inventory (CDI; Fenson et al., 1994). The variability is clear, with very large standard deviations and wide ranges of variability for all three measures. As vocabulary increases, so does variability, until it peaks around 24 months of age. Since these data are based on parent report, one might argue that the variability is the result of many parents over- or under-estimating what their child knows (Feldman, Dollaghan, Campbell, Kurs-Lasky, Janosky, & Paradise, 2000). However, laboratory validations of the CDI for both word comprehension (Bates & Goodman, 1997; Jahn-Samilo, Goodman, Bates, Appelbaum, & Sweet, 1999; Reznick, 1988, Ring & Fenson, in press) and vocabulary production (Dale, 1991; Dale, Bates, Reznick, & Morrisett, 1989; Thal, O’Hanlon, Clemmons, & Fralin, 1999) suggest that the means and standard deviations represent actual behaviour (see Fensonet al., 2000, for a discussion of this issue).

Similar levels of variability are seen in measures of early grammar. Chapman and Miller (in Miller, 1981) provided norms for MLU in comparison to Brown's developmental stages (Brown, 1973). The relevant stages for our purposes here are Early Stage I (single words to first combinations, MLU 1.05-1.50), Late Stage I (first morphological inflections, MLU 1.5-2.0), Stage II (beginning of productive control over grammar, MLU 2.0-2.5), Stage III (grammatical development well under way, MLU 2.5-3.0), and Stage IV (beginning of complex sentences, MLU 3.0-3.5). The norms are presented as average ranges for each stage: Early Stage 1, 19.1-23 months; Late Stage 1, 23.8-26.9; Stage II, 27.7-30.8 months; Stage III, 31.6-34.8; Stage IV, 35.6-38.7 months. This, in itself, indicates significant variability, but it is actually even wider. In a detailed study of 27 normally developing middle class children at 28 months of age, Bates et al. (1988) reported MLUs across the whole range described by Brown. Further evidence of variability comes from a larger study of 241 normal 3-year-old children; Dollaghan et al. (1999) reported that MLUs ranged from approximately 1.9 to 4.0.

The "upper limit" measure (M3L) used by Fenson et al. (1993, 1994) is highly correlated with MLU (.77 and .74, p <. 01, for 20- and 24-month-old children, respectively). Like the vocabulary measures and MLU, M3L variability is quite high and increases as the measure itself increases. Taken together, these data provide evidence of significant variability in the development of both grammar and vocabulary in this early period.

Variability is also present in the vocabulary burst and in the timing of word combinations. Although many children experience a vocabulary burst, others develop at a much more steady and even rate (Goldfield & Reznick, 1990; Goodman et al., 1999; Goodman & Bauman, 1995), suggesting that this is not a universal pattern. Similarly, although word combinations have been described as appearing when a child has between 50 and 75 words, at an age of 20 to 24 months, Bates et al. (1988) reported novel word combinations as early as 14 months. There is also variability in the relation between vocabulary size and word combinations. In the CDI norming study, 20% of the children were reported to produce some word combinations when they had fewer than 50 words in their vocabulary and 15% produced no word combinations at all despite vocabularies of 100-300 words. Other reports have described exceptional children with vocabularies of 600 words or more that were not yet combining words (Thal, Bates, Zappia, & Oroz, 1996). This variability in typically developing children suggests that clinicians must use caution in identifying children as either impaired or gifted when they are in these very early stages of language development.

Variability in style. A large literature now documents variations in learning style that affect early language behaviour. It is generally agreed that these styles reflect the differential performance of two fairly general learning mechanisms that operate across many cognitive domains. One of these mechanisms, described as analytic, is responsible for breaking down sensory input into smaller segments. The other, described as holistic, oper-

Table 3
Variability in early language development.

	Vocabulary Comprehension			**Vocabulary Production**			**Mean of the Three Longest Utterances (M3L)**		
Age In Months	*Mean*	*SD*	*Range*	*Mean*	*SD*	*Range*	*Mean*	*SD*	*Range*
10	67	60.19	2-280	5	7.63	0-53	NA		
12	86	49.23	7-242	10	11.20	0-52	NA		
14	156	77.95	11-343	29	33.36	0-193	NA		
16	191	87.58	40-396	64	70.27	0-347	1.48	.88	1-4.7
20	NA			192	136.20	3-544	2.78	1.59	1-7.7
24	NA			312	173.67	7-668	4.69	2.66	1-12.3
30	NA			534	116.65	208-675	8.18	3.45	3-19

ates to allow memory and reproduction of large segments of sensory input before those segments have been completely analyzed or understood. In the realm of language, these styles have been described across the whole range of early development (Bates et al., 1988; Bloom, Lightbown, & Hood, 1975; Dore, 1974; Horgan, 1979, 1981; Nelson, 1973; Peters, 1977, 1983; Thal et al., 1996). In "analytic" (also called referential style) babies, short and consistent consonant-vowel segments predominate in their babble whereas "holistic" (also called expressive style) babies produce long streams of sentence-like intonation in which occasional consonants are embedded. Similarly, the first words of "analytic" babies tend to be object names and those of "holistic" babies tend to be more heterogeneous and formulaic, containing "words" like "wannit." At the level of word combining, "analytic" children are often described as using content words only, excluding function words and inflections (telegraphic speech) while "holistic" children are likely to use inflections, pronouns, and other function words in frozen expressions or formulaic utterances from the start.

Both of these mechanisms are necessary for learning language, and most children apply both from the earliest stages. However there have always been subsets of children who appear to favour one type of learning over the other for periods of time. The actual source of these differences is unresolved: hypotheses that support environmental factors such as maternal linguistic style, temperament of the child (e.g., impulsive versus reflective methods of solving problems), and differences in the rate at which the different neural mechanisms responsible for language start to mature (to be discussed further below). None of these is mutually exclusive; perhaps all of them interact to encourage a balance between the two mechanisms or there is preferential reliance on one over the other. Recent reports of language development in children with focal brain injury (Bates et al., 1997; Thal et al., 1991), to be discussed below, suggest that these styles may be affected by different roles played by processes specific to the left and right hemispheres of the brain in early language learning.

The individual differences literature focuses on ways that things hold together in typically developing children. Yet any attempt to fully explain the relations between brain and language development must also account for dissociations that are found in both typically developing children and some atypical populations. We turn to that next, with specific focus on late-talking toddlers and children with pre- or perinatal brain injury in addition to those who are following the typical course of development.

Dissociations in Early Language Development

Children with no identifiable brain lesions. The most conspicuous dissociation when children are between one and two years old (and even somewhat older in a group of children who have been called "late talkers") is that seen between word comprehension and word production. Children almost always comprehend many more words than they produce and, as noted in the section on language milestones, measurable comprehension of words starts well before children produce recognizable words. Comprehension appears to indicate an upper limit on the number of words a child can produce, but it does not fix a lower limit. Examples from the MacArthur Communicative Development norming sample (Fenson et al., 1994) provide good illustrations. Children with fewer than 50 words in their receptive vocabularies rarely produced more than 10 words, and those who understood fewer than 100 words usually had production vocabularies between 0 and 50 words. It was only after a reported comprehension vocabulary of 150 words or more that large expressive vocabularies were also seen. However, the fact that children had large (for their age) comprehension vocabularies did not mean that they had comparably large production vocabularies. Until comprehension vocabularies were 200 words or more, there were always some children in the sample who produced few to no words. Thus, comprehension vocabulary does not predict production vocabulary in the earliest stages, and substantial gaps between comprehension and production are not uncommon, even in typically developing toddlers.

The dissociation between comprehension and production may be particularly marked in children who appear to be language delayed when they are between 18 and 28 months of age (Thal, 1999; Thal & Bates, 1989; Thal et al., 1991). In those studies, some of the children were in the normal range for language comprehension but in the lowest 10 percent for their age in language production (low producers), making them comparable to late talkers studied by other researchers (Paul, 1991, 1996; Rescorla & Schwartz, 1990; Rescorla, 1993; Whitehurst & Fischel, 1994). Other children in that group were equally delayed in comprehension and production (low comprehenders). Thal (1999) reported that the low producers were well within the normal range for grammar and vocabulary at a follow-up one year later. This too is compatible with results from more long-term studies by Paul (1991), Rescorla (1993), and Whitehurst & Fischel (1994). Low comprehenders, on the other hand, remained significantly delayed. In a later study using the CDI, Thal (1999) identified low producers and low comprehenders when they were 16-months of age, using the same lowest tenth percent as the definition. The differential growth of low comprehenders and low producers was replicated in that study. Low producers (with normal comprehension) scored well within the normal range by 28 months of age, while low comprehenders continued to score around the 10th percentile.

These findings initially led Thal to propose that an atypically large dissociation between comprehension and production is associated with positive long-term outcome. However, findings reported by Olswang and Bain (1996) led to a modification of that hypothesis. The children studied by Olswang and Bain all had delays in both comprehension and production. In those children, greater gaps between comprehension and production were associated with slower progress in language therapy. It appears then that large dissociations between comprehension and production mean more positive outcome if comprehension is in the normal range and more negative outcome if comprehension is also delayed.

Children with Focal Brain Injury. The work described in this section focuses on children who sustained a localized insult to the brain in utero or within the first six months of life. It might seem inappropriate to discuss such children in a volume on prevention of nonbiologically based language-learning difficulties, but to leave them out would be an unfortunate mistake. Understanding the course of language development for these children will provide important clues regarding the neural basis of some of the dissociations that were discussed above. In addition, since the extant literature indicates that these children are not significantly delayed in language by school age, they provide information about the range of neural plasticity for early language development.

The studies described here followed children prospectively, some through fiveor six years of age. All of them have shown moderate to severe delays in all of the language milestones described in Tables 1 and 2. These include late onset of babbling and preverbal behaviour (Marchman, Miller, & Bates, 1991), and delays in lexical and grammatical development between one and fiveyears of age (Bates et al., 1997; Reilly, Bates, & Marchman, 1998; Thal et al., 1991; Vicari et al., 1999). For the purposes of the discussion here, however, the most important thing is that more dissociations than would be expected by chance were found in this period of development. Interesting correlations between these dissociations and specific lesion sites provide evidence that brain specialization for language in the early stages of development is very different from the conventionally held views. The findings from these studies have been unexpected and quite surprising given what we know about brain and language in adults with focal brain injury, and they have caused us to rethink issues of brain specialization for language.

Comprehension vs. Production. The original hypotheses about language development in these children were based on knowledge of English-speaking adults with similar lesions (Thal, Marchman, et al., 1991; Bates et al., 1997). That is, we proposed that children with left frontal lobe damage would develop normal comprehension but have significant delays in production (a developmental version of Broca's aphasia) and children with left temporal lobe damage would have significant delays in language comprehension (a developmental version of Wernicke's aphasia). Results indicated that both hypotheses were completely wrong. Lesions to the left temporal lobe were not implicated in comprehension deficits. Delayed comprehension was, instead, more common in children with *right hemisphere* damage. Although this pattern is completely different from the adult pattern, it is compatible with subsequent electrophysiological studies of normally developing children (Mills, Coffey, & Neville, 1993; Mills Coffey-Corina, & Neville, 1997). In those studies the brain responded differently to familiar versus unfamiliar words, and the different responses occurred bilaterally (but somewhat larger on the right) prior to about 18 months of age. At a slightly later age, and strongly correlated with the "vocabulary burst", the response changed so that a larger difference between known and unknown words was now observed in the left hemisphere, primarily in the frontal and temporal regions. Bates et al. (1997) proposed that the right hemisphere plays a larger role in the first stages of word comprehension because that hemisphere appears to be particularly important for integration of information across multiple sources (Stiles, Bates, Thal, Trauner, & Reilly, 1998). For older infants, children, and adults who know a fair amount about their language, this sort of multimodal integration may not be necessary to understand a familiar word. For infants who are just starting to figure out what the speech stream is all about, on the other hand, right hemisphere resources may play a particularly important role.

Stylistic Differences. Using the norms from Fenson et al. (1993), Thal et al. (1991) found a significantly higher incidence of holistic style children than would be expected by chance in a random sample of normal children across the whole group of children with focal brain injury (regardless of site of lesion). As noted earlier, holistic style children are those who use inflections, pronouns, and other function words from the earliest stages of language development, but they are used in rote or formulaic utterances. There were also several children in that study who used an extreme analytic style, however. These children used content words (mostly nouns and verbs) almost exclusively, producing utterances that lacked the more grammatical function words and grammatical morphemes. Unlike the holistic children, their utterances appeared to be analyzed rather than rote or formulaic. In earlier work, Bates et al. (1988) suggested that these styles might reflect differential reliance on left versus right hemisphere processes for language use (the interhemispheric hypothesis). This hypothesis is based on claims that the left hemisphere is specialized for fine-grained analytic procedures, and the right hemisphere is specialized for holistic or configurational processes (see Bradshaw & Nettleson, 1981, for example). If this hypothesis were correct, then the holistic children in the Thal et al. study should be those with left hemisphere damage, and those with extreme analytic styles should have right hemisphere damage. The actual data were just the reverse of what was expected. Thal et al. reported a significantly higher incidence of holistic style children who had right hemisphere damage, and proportionally more analytic style children with left hemisphere damage. Similarly, in a later study with a larger sample of children with focal brain injury who were between 19 and 30 months of age, Bates et al. (1997) reported that the holistic language style was significantly more common in children with right hemisphere damage. Thus, the right hemisphere account of holistic processing in children receives no support from prospective studies of children with carefully identified focal brain injury.

Is there some potential explanation for this unexpected finding? We believe that there is, although it is one that has not been explored in the literature on individual differences in normally developing children. The motivation for this hypothesis comes from research on visual-spatial pattern analysis by Stiles and others (see Stiles et al., 1998, for a review) in which we learned that children and adults with left hemisphere damage have deficits in the extraction of local detail and that those with right hemisphere damage demonstrate difficulty with overall configuration. For example, if asked to reproduce a letter H in which each of the lines that form the H is constructed of small Xs, people with left hemisphere damage will draw a fairly typical H (without any Xs). People with right hemisphere damage, on the other hand, will draw a lot of small Xs, but not in a configuration that creates a letter H. In the interhemispheric hypothesis discussed above, it is assumed that formulaic speech is a product of holistic, overall configurational analysis in which the finer details are not perceived. But this cannot be correct if children with intact left hemispheres (in which the temporal lobe is specialized for extraction of detail) and damaged right hemispheres (specialized for configurational analysis) have holistic language styles. Bates et al. (1997) and Stiles and Thal (1993) propose instead that holistic style children use a relatively high proportion of function words and pronouns in their early word combinations because they have extracted a higher-than-normal proportion of detail from the linguistic input that they have heard. These words are produced in rote fashion because they have not yet been integrated into the larger semantic-grammatic structure that motivates the use of pronouns and other function words in the adult language.

Unlike the interhemispheric hypothesis, the local detail hypothesis suggests that the holistic style of language learning is not likely to occur with damage to the left temporal lobe, a claim that is compatible with the existing data. In addition, it could explain the other expressive language problems seen in infants with left posterior brain damage. For example, the studies reported that children with left temporal lobe damage are more likely to have delayed language production than delayed comprehension. Because the adult literature has been used as the model, it is generally assumed that comprehension is based on sensory processing (at which the left temporal lobe is very skilled) and production depends on motor abilities (primarily the job of the frontal lobe). However, in the earliest stages of language development children must figure out how to produce meaningful sounds for the very first time. That requires them to analyze the sensory input from speech in enough detail to permit the construction of a motor analogue. Thus, it may be that the delays in production seen in children with left temporal lobe damage are the result of limitations on the kind of sensory analysis needed to make precise sensory-to-motor maps rather than to motor problems. A higher incidence of holistic style in children with right hemisphere damage was also reported, suggesting that this pattern may occur when the right hemisphere cannot carry out the modulating and integrative functions important to early language learning. These ideas have major implications for hypotheses about prevention of nonbiologically based language-learning difficulties. In particular, they suggest that professionals constructing programs and stimuli for early language stimulation need to consider the importance of sensory analysis to early language learning and whether the recommendations they make to parents should take that into account. We will discuss this further once we have completed the next section, which is focused on human brain development and its relation to language development.

Relevant Neural Development

It is probably appropriate to begin this discussion with a very brief review of the structure of the nervous system. The focus here will be narrow, providing only the gross skeleton on which to hang the content of the discussion to follow. To allow us to remain focused on the issues that are relevant to this special issue, only structures that are essential to understanding the arguments put forward in this manuscript will be described.

The brain is organized into six main parts, the spinal cord (which controls limb and trunk movement), the medulla oblongata (which controls digestion, breathing and heart rate), the pons and cerebellum (involved with movement), the midbrain (involved in sensory/motor functions such as saccadic eye movement), the diencephalon, and the cerebral hemispheres. The diencephalon contains the thalamus and the hypothalamus; the cerebral hemispheres contain the cerebral cortex, the underlying white matter, basal ganglia, hippocampus, and amygdala. Our discussion will focus primarily on the thalamus and the isocortex (or the neocortex), the folded sheet of cerebral cortex that is prominent on surface views of the brain. Language processing takes place in the isocortex, based on sensory and motor input relayed there via the thalamus. Thus, both the thalamus and the isocortex are essential for language learning and use.

The brain is made up of two basic types of cells, neurons (or nerve cells) and glial cells. Glial cells support nerve cells in many ways; some form white fatty sheets, called myelin sheaths, which serve to insulate some extensions from nerve cells. This insulation serves to increase the efficiency with which information is transmitted. Glial cells clearly play an important role in brain-behaviour relations, but it is usually considered a secondary one. The complex behaviours of humans likely originate with the neurons and the connections formed between them. Although these basic units of human behaviour are fairly simple, complex behaviour occurs because vast numbers of neurons work together in a unified manner (Kandel, 2000). In order to understand the neural correlates of early language development, it is important to understand the course of development of neurons and their connections.

A typical neuron consists of a cell body and two kinds of processes that extend from the cell body - one axon and (usually) several dendrites. Dendrites branch out around the neuron and serve as the main device for receiving input from other nerve cells. The axon is the main conducting unit of the neuron, transporting information from the cell by means of chemoelectrical signals. Small currents of positively or negatively charged chemical ions cause a signal, called an action potential, to travel down an axon. Axons may be very long (up to one meter in length); the insulating myelin insures that the action potential continues throughout its entire length. Information is then transmitted between cells at interfaces of the axon from one cell with the dendrites, axon and/or cell body of another neuron. This region, where an axon of one neuron almost meets a process or cell body of another neuron, is called a synapse.

Synaptic transmission occurs when the action potential traveling down the axon of one neuron reaches a synapse and causes information, in the form of chemicals stored in the signalling cell (neurotransmitters), to be released across the synapse onto receiving units (receptors) of another neuron. This chemical signal may have an immediate direct effect on the receiving cell or may prompt an indirect biochemical cascade of 'post-synaptic' reactions, triggering what is sometimes called a 'second messenger' system.

On some occasions in the adult brain, but more often during development, the synapse junction between two cells is so tight (about three nanometers wide) that transmitting and receiving cells are joined via very small channels. These almost contiguous connections, called 'gap junctions' or 'electrical' synapses, can transfer excitatory reactions between cells. Here ion currents can pass quickly and directly from the one cell to the other, in either direction, without the action of neurotransmitters or receptors. However, the 'larger' (yet still only 20 nanometers), more conventional, unidirectional chemical synapse may utilize a variety of over 50 excitatory or inhibitory neurotransmitters and neuromodulators, and thus is more flexible than the electrical synapse.

The process through which cells are formed is called neurogenesis, and the formation of interconnections between neurons is called synaptogenesis. Neurogenesis and synaptogenesis are considered to be additive events because new structures or functions are being added to the nervous system. As will become apparent later, subtractive (also called regressive) events in which cells die, synapses are eliminated, and axons are retracted are equally important in the development of skilled human behaviours.

With that basic information in hand, it is appropriate to proceed with an examination of the main events in human brain development that precede and parallel the process of learning language. Following Bates et al. (in press) prenatal and postnatal neural events that are important for language learning will be described. This will be followed by a discussion of interactions of neural patterns and events with language learning, and what they may imply for early prevention of language disorders.

Prenatal Events

During the prenatal period the human organism changes from a single cell into a living entity capable of learning complex behaviours such as communicating through an intricate linguistic symbol system. Thus, prenatal events build the foundation that prepares the brain for language learning. As Bates et al. (in press) point out, no experimental studies that directly relate language development to brain maturation exist, and only a few have attempted to relate disorders of brain development and behaviour to the fundamental cellular processes that occur during this period. This is because access to the human brain is profoundly limited since direct studies require invasive techniques. Therefore, estimates of the time at which specific maturational events occur in the human brain must be based on comparative, correlational, and statistical approaches. The support for correlation and inference is very strong thanks to an abundant literature in brain development in other mammals developed over the past decades. Using this literature, neuroscientists recently have shown that the schedule of human brain development can be mapped onto that of other mammals with remarkable accuracy (Clancy, Darlington, & Finlay, 2000; Darlington, Dunlop, & Finlay, 1999; Finlay & Darlington, 1995). Because the order and relative timing of early neural events is notably consistent across all mammalian species, Finlay and Darlington (1995) were able to generate a comparative statistical model which relates development across several mammalian species. This model was recently adapted to predict dates of specific neural events in the developing human brain (Clancy et al., 2000). The statements about the timing of events in human brain development that follow are drawn from this comparative mammalian modeling unless a different source is indicated.

First Trimester

The three months following conception are characterized by the development of neurons and glial cells, differentiation of those cells into different subtypes, and their migration from their birthplace to their ultimate destinations in the cerebral cortex. It is remarkable that virtually every neuron that exists at birth and that will form the "work force" of the adult human brain is generated in the first trimester (before many women are aware that they are pregnant). Some exceptions do exist. Cells that will live in some superficial layers of the isocortex or in the external granular layer of the cerebellum develop later in uterine life. Also, recent research has shown that a small number of cells are generated throughout life in the dentate gyrus of the hippocampus (an area implicated in memory) and the olfactory bulb (Bayer, 1982, 1983; Kornack & Rakic, 1999; Kuhn, Dickinson-Anson, & Gage, 1996; Luskin, 1998). However, it is unlikely that these cells have much influence on early language learning. Thus, the basic workforce for language learning is in place by the end of the first trimester. Although some neurons extend processes locally almost immediately following neurogenesis, the vast system of interconnections through which different areas of the brain communicate with each other begins next.

Second Trimester

Among the events that occur during the second trimester, two have special importance for the development of higher cognitive functions: the establishment of connections between neurons across different regions of the brain and the beginning of activity-dependent self-organization.

Cross-Regional Connections. Development of patterns of neuronal connectivity in humans in the second trimester has been confirmed by experimental studies that measured molecular markers of the proliferating growth of axons and dendrites (Honig, Herrmann, & Shatz, 1996). This is another additive event in the development of the nervous system, and it occurs across different levels of the brain as well as intracortically at this time (Innocenti, 1991, 1995). The development of connections between the isocortex and the thalamus is of particular importance for the development of language (and other related skills). As was briefly mentioned above, almost all sensory input to the isocortex is routed through the subcortical structure called the thalamus (the major exception is olfactory input). This input is topographically organized to represent the "external" source. For example, input from the auditory sensory organs is packaged together and routed through one path while input from the visual sense organs is packaged into another pathway. The pattern of connections developed during the second trimester of pregnancy matches the final adult pattern of sensory input (Miller, Chou, & Finlay, 1993; Molnar, Adams, & Blakemore, 1998; O'Leary, Schlaggar, & Tuttle, 1994). Thus, the different types of information that will be processed by each of the major regions in the mature brain are determined by the thalamocortical connections that are established during this prenatal period.

Activity-Dependent Self-Organization. The process of reorganizing the connections between neurons based on information received from the sense organs is one of the major mechanisms of learning, and much of this reorganization is regressive. By regressive reorganization we mean that existing connections are actually eliminated. A novel form of potential reorganization has been documented in the visual system of rats and ferrets before 'true' visual experience is possible, at a time corresponding to the second trimester of human development (reviewed in Wong, 1999) and it seems such a useful process that it is likely to be discovered in other systems as well. In the retina, neighbouring groups of cells become spontaneously active in a wavelike pattern of activity that sweeps across the retina, probably through a combination of gap junctions connecting the cells and transmitter-based synapses. These waves of activation are probably not synchronized between the two eyes and so are most likely a factor in early reorganization of the visual system rather than an experience-based reorganization. By this we mean that the waves may be a genetically preprogrammed event that demonstrates an innate patterning circuitry in the nervous system. It is even possible that the waves may turn out to be an early example of input helping to organize the structural architecture of the brain. In humans, one input source could be based in the motor activity that begins in the fetus late in the first trimester since the visual system is known to respond to nonvisual stimuli produced from movement (such as pressure) and temperature. It is also possible that the waves may occur based on interactions between genetic and environmental factors.

Neural patterning events, perhaps initially triggered by genetic factors but modified by experience (or even the other way around), likely occur in the brain itself. For example, initially cells in the visual thalamus and visual cortex receive input from both eyes, but this pattern cannot be maintained because the information is conflicting. The brain's solution is to eliminate input from one eye or the other from successive groups of cells. In the cortex, this will create alternating rows of cells called ocular columns that respond either to input from the right eye or the left eye, but not from both. This segregation may also begin as a genetically preprogrammed event, although development of the columnar pattern will require later visual input.

Third Trimester

In this last period of gestation two additional important phenomena become apparent. Descending (or 'top-down') pathways from the cortex to the sensory input (or 'bottom-up') systems are established now and, just prior to birth, a huge burst of development of synaptic connections in the isocortex and related structures begins. Before this intrauterine period is completed everything that is needed for the brain to learn is in place and, as the new literature on prenatal learning suggests, learning has probably already begun.

Development of Descending Pathways. The descending pathways that develop in this period (and that will continue to develop well after birth) create connections from the cells in the cortex to those that actually activate the neuromuscular system. This will allow the brain to control motor behaviour, and it will also provide a means for the brain to convey information to the input areas. As a result, there is now interdependent connectivity in which top-down and bottom-up connections can work together to help the organism learn how to live in the external environment, although the process by which this occurs is not completely clear. It has been suggested that the 'top-down' processing sequences are involved in the dynamic strategies that are tied to attention and learning (Cauller, 1995; see collection of essays in Koch & Davis, 1994). At the least, it is clear that the interconnections are important since many behavioral phenomena cannot be adequately explained by simple bottom-up processing. This would include behaviours that demonstrate that we are not simply "receiving units" for incoming data, but that we are actively engaged in receiving, focusing, and filtering our input via our numerous top-down connections. One example may be those optical illusion posters constructed out of thousands of dots. They look just like thousands of dots but, if stared at long enough, specific images may emerge and subsequently the emergent images are readily seen. A personal experience of one of the authors might serve as another example. At a social engagement in the United States a woman approached her and began to speak in what seemed to be nonsense words. In desperation she looked to her companion for help, and he said "This is Kai, remember, I told you that she had lived in Denmark for a year?" As soon as that information was provided everything that the woman had previously said was suddenly comprehensible to the author (who speaks and understands some Danish). These types of top-down/bottom-up associations are likely to have considerable behavioral significance during language learning.

Development of Synaptic Connections. During the last weeks in utero, the final stages of connectivity begin to take place in the form of the beginnings of a huge burst of synaptogenesis in the isocortex and its related structures. Although gap junctions already connect some neurons and glial cells, and some conventional neurotransmitter synapses developed as the axons from neurons met the target neurons in their destination structures, a great surge in synapse production begins now (Huttenlocher & Dabholkar, 1997; see also Antonini & Shatz, 1990; Bourgeois & Rakic, 1993). This synapse burst continues after birth, and will be discussed in detail in the section on postnatal events. However, the developments during this period are the final steps necessary for creating a brain that is fully connected and capable of learning. It is believed that one manner in which what we call "knowledge" can be strengthened or weakened by experience at the synapse, a phenomenon called Hebbian learning. In other words, synapses are formed or modified as a function of experience. Connections intensify or weaken as a result of activity: the greater the activity the stronger and/or more numerous the synapse and vice versa. Because one might think of this outcome of the interaction of the brain and the environment as the physical representation of knowledge, some cognitive scientists argue that synaptic connectivity is the primary means by which knowledge is represented in the brain (Elman, Bates, Johnson, Karmiloff-Smith, Parisi, & Plunkett, 1996). From this perspective, an increase in the number of synaptic connections at this time is highly significant, because it provides many more opportunities for this kind of learning than will be present later in life when experience has resulted in strengthening of some but elimination of other synaptic connections. In other words, birth is probably a time of optimal brain plasticity. All the components for learning are now in place, presumably functional, and likely already undergoing some fine-tuning. At birth the human infant is fully capable of learning and may, in fact, have already learned about some conditions of the speech environment that are useful for language learning (e.g., Mehler et al., 1988).

Postnatal Events

The immediate postnatal period is characterized by a continued burst in synaptogenesis and the accompanying overproduction of receptors for a great number of neurotransmitters. Neurotransmitters, as discussed above, are the chemicals released at the synaptic junction, which affect the receiving cell in a specific manner. A number of these chemicals are implicated in chronic disorders such as Alzheimer's disease, Parkinson's disease, and schizophrenia. The timing of the development of the connections between neurotransmitter-specific synapses and their receptors suggests that they are likely to have an important influence on learning, but our understanding of how they function is not yet sufficient to shed much light on the precise mechanism. However, the fact that the huge overproduction of synapses that occurs postnatally is accompanied by a similar overproduction of receptors supports the idea that the synapses that develop are functional. The next section will focus on the timetable of synaptogenesis from birth to adulthood, without detailing information about neurotransmitters and receptors that could be redundant and confusing.

Synaptogenesis and Synapse Elimination. The rapid propagation of synapses that began toward the end of the first trimester speeds up around birth, overproduces by a large percentage (potentially reaching over 150% of the adult level) in the first six months of life, and then declines to the adult level (Huttenlocher & Dabholkar, 1997; see also Zecevic & Rakic, 1991). Since this overproduction and pruning back occurs in the same time period as language development, it is a likely candidate in attempts to explain these events. In fact, in an earlier chapter on brain and language development, Bates, Thal, and Janowsky (1992) proposed specific relations between a number of early language development events and the subtractive events involved in pruning back synaptic connections to adult levels. In the period since that publication it has become apparent that our notion of overproduction followed by the subtractive events of axon retraction and synapse elimination were far too simplistic. Although the period of overproduction of synapses occurs primarily within the first postnatal months and the period of major subtraction or pruning occurs between two and five years of age (during a similar time period in monkeys, there is a loss of approximately 5000 synapses each second in the visual cortex alone [Bourgeois, 1997]), the two processes actually co-occur over most of early postnatal development, and continue (albeit at much lower levels) throughout life.

The timing of the rapid growth of synaptogenesis to just precede the onset of experience (that is, tied explicitly to birth) occurs in most other primates as well. Since it occurs across so many species, prior to major sensory input from the environment, experience cannot be responsible for the burst. It appears that the coordination of synapse hyper-production with mammalian birth is a product of evolution and, therefore, likely serves some adaptive purpose. What could that be, particularly for learning language?

The combination of overproduction of synapses with subsequent elimination of some as a result of experience with the environment provides two important advantages for learning: flexibility and ability to refine what has been learned. The increased flexibility of such a dynamic structure makes the kinds of structural changes necessary for evolutionary change more feasible (Innocenti, 1995), and might also account for the great variety of structure in the languages that have evolved. At the least, it provides a large supply of resources for a wide range of learning possibilities that may or may not follow birth. Refinement is particularly important for language learning, and may be a significant advantage of regressive events. By eliminating unused or less optimally placed connections, one may achieve greater accuracy and speed despite the complexity of a particular cognitive task. This possibility receives support from computer simulations designed to test the consequences of overproduction of connections followed by experience-based pruning (Elman et al., 1996). Input information is preserved more reliably in such networks than in simple feed-forward networks with stable numbers of connections in which "unused" connections are not removed, and networks that include regressive events allow quicker transformations of complex data than do those with nonadjustable connective mechanisms (Adelsberger-Mangan & Levy, 1993, 1994). Even though production and pruning drops off as children mature, both processes continue to co-occur throughout life, providing the possibility of adjusting and improving on the initial connections. In other words, although plasticity is greatest when children are younger, and drops off significantly after adolescence, the mechanisms necessary for fine tuning old knowledge and acquiring new knowledge are still present in the mature human nervous system. Some level of plasticity is present throughout life.

Interactions of Neural Events and Language Learning: Implications for the Prevention of Nonbiologically Based Language-Learning Difficulties.

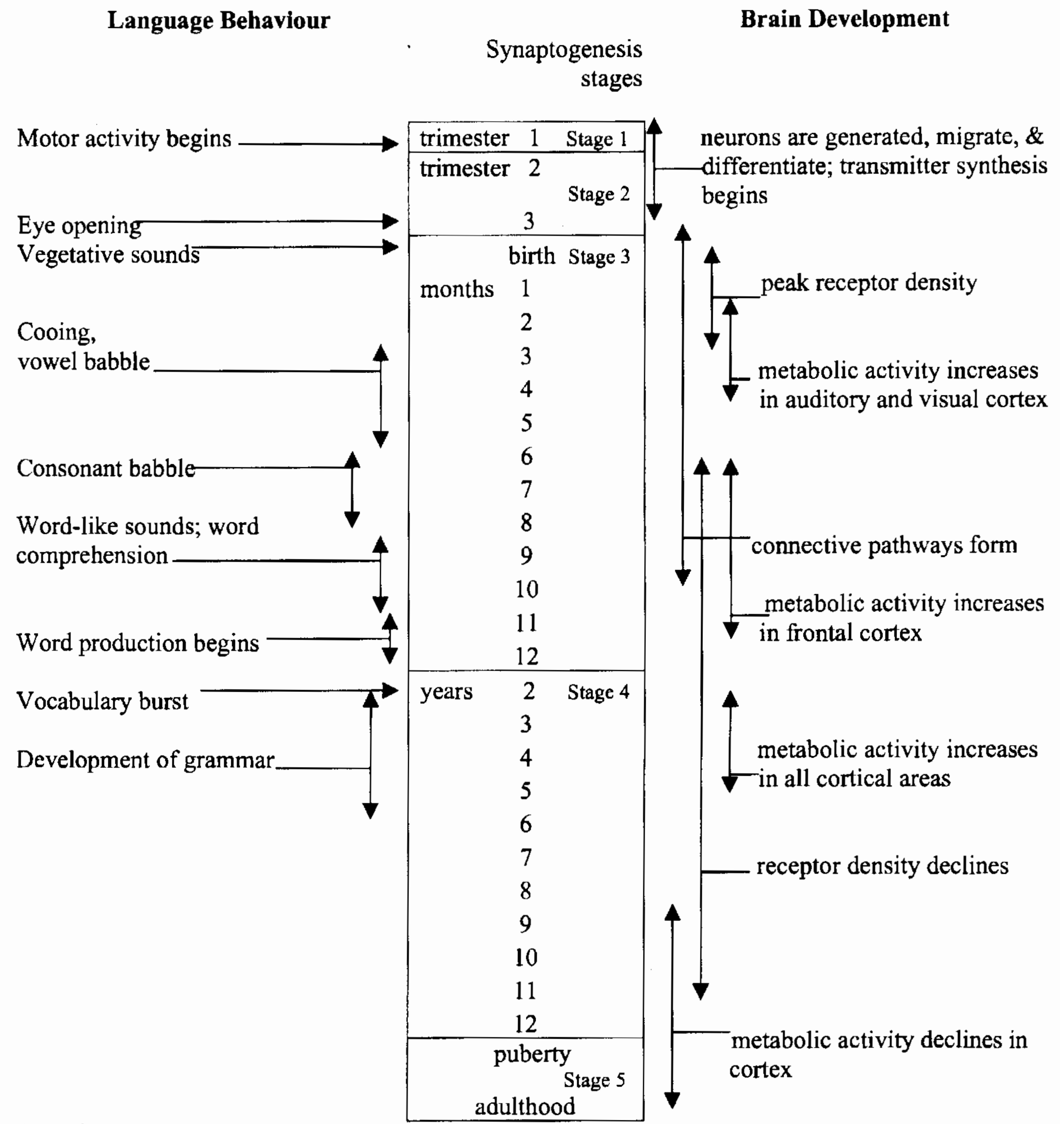
Figure 1 provides a more realistic view of the relation between brain development and language behaviour than the time-locked views that have been presented previously. Two points provide useful conclusions about the bidirectional influence of brain development, language learning, and prevention of early language learning disorders: the capacity for learning is fully present at birth and learning changes the structure of the brain. These facts support some clear recommendations for prevention of language learning disorders.

The capacity for learning is present by the time of birth. There is now a large and varied literature that demonstrates what the neural development implies. Examples include research that demonstrates some learning in utero (Mehler et al., 1988), the presence of rich perceptual skills in the first weeks of life (Bertenthal & Clifton, 1998; Kellman & Banks, 1998), and a capacity for rapid learning of arbitrary statistical patterns (including language-specific phonetic details) in the first months of life (Saffran et al., 1996). The current state of understanding of the nervous system shows us that the brain of the newborn infant is fully capable of processing distributed patterns within and across modalities. Visual-motor mapping, auditory-motor mapping, etc., begin at the latest, when the child is born. There also is no evidence to support the hypothesis that any region of the brain is inactive and awaiting a specific maturational signal or set of signals before being triggered. There are, of course, going to be reorganizations that look like qualitative changes in brain structure may have occurred (the vocabulary spurt and word combining, for example) but they are more likely to be the result of the way the brain has been used (i.e., a result of learning) than the sudden appearance of a new system. This leads us to the next insight.

Learning changes brain structure. The recent literature on the rich abilities of infants has made us aware that we have underestimated the power and speed of learning that is present in young children, and forced a reconsideration of the extent to which children's behaviour is influenced by learning rather than innate biases about the nature of the physical and social world (Elman & Bates, 1997; Seidenberg, 1997; Thelen & Smith, 1994, 1998). There is now considerable evidence that learning itself changes the structure of the brain in infants and adults. For example, experience determines the course of synapse elimination. It also produces increases in synapse numbers. Greenough and colleagues have provided some excellent examples of these experience-driven changes in brain structure. In a series of studies rats were either raised in complex environments rather than traditional sterile cages or they were involved in learning complex tasks. In both cases significantly greater increases in the density of dendrites and the ratio of synapses per neuron were observed in the "educated" or "enriched" rats than in controls (Black, Isaacs, Anderson, Alcantara, & Greenough, 1990; Greenough, Hwang, & Gorman, 1985; Turner & Greenough, 1985). In addition to the higher rate of synaptogenesis that was induced by the enriched environments, there were increases in populations of supporting cells, mitochondria volume (Sirevaag & Greenough, 1987), and vasculature branching (Sirevaag, Black, Shafron, & Greenough, 1988). The latter two phenomena are considered to reflect increased metabolism (or brain activity). Although there is no direct evidence of such changes in the human brain, analysis of adult human brains after death that show a correlation between high levels of education and a greater number of dendritic branches (Jacobs, Schall, & Scheibel, 1993) suggest that similar changes accompany learning in humans. Thus, if we ever do find clear neuroanatomical or neurophysiological correlates of language milestones, it may well be the case that the neurological changes have been induced by the language learning rather than vice versa, and the correlates of language delay may reflect the effect of the limitation in language ability on the brain. This has profound implications for early prevention and intervention for nonbiologically based language-learning disorders.

Implications for the prevention of language-learning difficulties. Given our current state of knowledge about the abilities of human infants and the development of the human brain, it is more than fair to conclude that input matters. The image of a sculptor creating a figure out of stone has been used in the past as a metaphor for the relation between learning and the important regressive events in brain development that are related to learning. If we replace the stone with clay, the metaphor still seems apt and, perhaps even more encouraging. Learning does shape the brain by removing nonessential connections so that skills can be refined and polished. However, if the shape isn't quite right, additional input can create new connections that will further refine the model. There are many reasons why children who have no known damage to their neural mechanism may develop language slowly. Among factors that have been implicated in highly respected research are low levels of conversational language (Hart & Risley, 1995, 1999), prolonged, repetitive bouts of otitis media (Friel-Patti & Finitzo, 1990;

Figure 1
Neural Events and Language Development.



Adapted from Bates et al., in press.

Stages of Synaptogenesis

stage 1	synapses in preplate
stage 2	synapses in cortical plate
stage 3	global surge of synapse development
stage 4	stabilized high level of synapses
stage 5	steady decrease of synapses

Bourgeois, 1997

Shriberg, Friel-Patti, Flipsen, & Brown, 2000), and a combination of otitis media and low responsiveness of the care-giving environment (Roberts, et al., 1998). There is also a large body of research that documents the effects of the amount and type of linguistic input from adults on language development in typically developing and language delayed populations (see Conti-Ramsden, 1990; Gallaway & Richards, 1994; Girolometto, Weitzman, Wiigs, & Pearce, 1999; Hoff-Ginsberg, 1986; Kaiser & Hemmeter, 1996; or Yoder & Warren, 1998 for some examples). Taken together with our current understanding of brain function, there is ample evidence that an environment that provides high levels of appropriate input is the best tool for prevention of language delay in many children, and that increased and focused input for children with nonbiologically based delays will help to change the rate at which the children are learning.

This is not to imply that prevention is a simple matter of talking more to children (although the results described by Hart and Risley, 1999, suggest that it may be a major factor). Nor is it to imply that it is appropriate to use very nonfocused general play situations such as those that were labelled "language stimulation" in the past. There are a host of other considerations, such as conceptual level, memory, interest in interacting with others through imitation and/or to obtain things that the child needs or wants. Some of these require input that is not necessarily verbal in nature. Providing more enriched environments should, given what we know about learning and the brain, create significant changes in all these areas, so long as the enrichments are carefully designed to meet a given child's linguistic, cognitive, and social levels. We already have evidence of the effects of enriching environments and teaching parents about the specific things that create enrichment for their children in the positive results of Project Headstart on children living in the United States. Additional evidence comes from research that has shown larger increases in vocabulary in children whose parents used symbolic (or recognitory) gestures in combination with words during the early period of word learning as compared to children whose parents talked to them just as much, but used no gestures (Acredolo & Goodwyn, 1988, 1990; Goodwyn, Acredolo, & Brown, in press). This is a good example of enrichment that is specific to the level at which the child is currently focusing their learning, that is, representation of objects and events through some symbol system. Cross modal input appears to provide significant additional learning in this case. The enrichment possibilities are numerous and likely to be limited only by restrained imaginations in people responsible for creating them, whether they are professionals assigned to specific children or to policy makers whose responsibility it is to create funding and programs to prevent health care problems.

Author Notes

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