LANGUAGE AND COGNITIVE PROCESSES
0000, 00 (00), 1–19

Psychology Press
Taylor & Francis Group

Genetic predisposition and sensory experience in language development: Evidence from cochlear-implanted children

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Recent neurobiological studies have advanced the hypothesis that language development is not continuously plastic but is governed by biological constraints that may be modified by experience within a particular time window. This hypothesis is tested based on spontaneous speech data from deaf cochlear-implanted (CI) children with access to linguistic stimuli at different developmental times. Language samples of nine children who received a CI between 5 and 19 months are analysed for linguistic measures representing different stages of language development. These include canonical babbling ratios, vocabulary diversity, and functional elements such as determiners. The results show that language development is positively related to the age at which children get first access to linguistic input and that later access to language is associated with a slower-than-normal language-learning rate. As such, the positive effect of early experience on the functional organisation of the brain in language processes is confirmed by behavioural performance.

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This work was supported by grants from the Netherlands Organisation for Scientific Research (NWO VIDI grant # 276-75-004 to the first author) and from the Fund for Scientific Research Flanders (to all authors).

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http://www.psypress.com/lcp DOI: 10.1080/01690965.2010.520540

Keywords: Sensitive periods; Development of grammar; Hearing impaired; Cochlear implantation; Biological constraints; Environmental factors; Sensory input deprivation; Language production; Experience; Deaf.

INTRODUCTION

The impact of sensory deprivation on cognitive development

The question to which extent genotype-defined biological constraints and environmental input contribute to human cognition has been around for more than half a century. Recent advances in brain-imaging techniques allow for the study of the physiology of higher cognitive performance, mapping the sensory, and language systems of the human brain. Research in developmental cognitive neuroscience shows that these systems exhibit plasticity: the ability to modify pre-existing neural synaptic connections dedicated to particular cognitive systems, depending on the quantity or quality of the environmental stimuli (Neville & Bruer, 2001; Shouval & Perrone, 1995).

The effects of sensory deprivation on cortical development have been studied extensively for the visual and the auditory systems. During a specific time period in infancy, deprivation of environmental input leads to reduced cortical representations and to functional cognitive deficits associated with the relevant cortical regions. Outside this specific time period, sensory deprivation has little impact on the development of the visual and auditory cortex (Hubel & Wiesel, 1965; King & Moore, 1991; Ruben & Rapin, 1980). With respect to language acquisition, the effect of focal brain injuries and genetically based disorders (Reilly, Losh, Bellugi, & Wulfeck, 2004; Stiles, Reilly, Paul, & Moses, 2005), deprivation from linguistic input (Curtiss, 1977; Itard, 1801), timing constraints in native signing (Mayberry, 1993), and a limited number of studies on oral deaf populations (Geers, Nicholas, & Sedey, 2003; Ross & Bever, 2004; Svirsky, 2005; Waltzman & Cohen, 2005; Waltzman & Roland, 2005) all reveal important clues to the biological foundation of language. As for the development of language-related brain systems, neurobiological studies suggest similar limits on plasticity. Crucially, neural plasticity does not have a uniform time course across cortical areas. Differences in cortical development are reflected in the development of associated behavioural functions. In primary sensory cortical areas such as the auditory cortex (Heschl's gyrus), the production of synapses peaks earlier than in receptive (Wernicke's) and productive language (Broca's) areas. The respective functions of these areas mirror this order: auditory processing precedes language comprehension, which in turn precedes language production (Neville, Mills, & Lawson, 1992).

A sensitive window for native language development: Evidence from deaf populations

In previous studies, neuroanatomical and physiological arguments have been given in favour of distinct time courses in the development of different cognitive functions mediated by different cortical regions (Huttenlocher & Dabholkar, 1997). As for language, it has been hypothesised that the neural processes underlying this particular cognitive function are heterogeneous in their adaptations to maturation and experience and that different subprocesses are differentially sensitive to language experience (Weber-Fox & Neville, 2001). Neurobiological evidence supporting this hypothesis was found in congenitally deaf subjects who showed different event-related brain potentials (ERP) as compared to hearing subjects. More precisely, only processing of closed-class words elicited qualitatively different ERPs, whereas semantic processing did not. These findings suggest that different aspects of language are mediated by different neural systems with different developmental vulnerabilities (Neville et al., 1992).

The main aim of this study is to investigate whether there is behavioural evidence supporting these neurobiological findings in deaf individuals. We will do so by comparing the emergence of different components of language (phonology, lexicon, and morpho-syntax). In agreement with current linguistic theories, these components of language have distinct but interacting representations in the mind and brain (Smith & Tsimpli, 1995; Stromswold, 2001). The outcomes will be analysed in view of the onset and duration of language experience in the deaf subjects. By doing so, we intend to find out whether the relative importance of environmental and genetic factors in the development of language may vary for its different components and/or at different developmental stages. The logic is as follows: in a population, the variation in the onset of linguistic functions may be considered to result from genetic and environmental differences. If early vs. later access to linguistic input may be found to affect the onset of some linguistic functions but not of others, this would strongly suggest that there are particular language functions that are more prone to deprivation of language input while others are more determined by maturation, i.e., neurobiological development of the human being which does not interact with linguistic input.

We believe this behavioural evidence is ideally found in populations of children who have access to linguistic input at different moments of their early development. Whereas, a few studies report on the development of sign language in children isolated from linguistic input (Feldman, Goldin-Meadow, & Gleitman, 1978; Goldin-Meadow & Mylander, 1983), evidence based on oral language deficits of individuals deprived from linguistic input during childhood has not been entirely convincing. Such deficits mostly occur in combination with extreme neglect and/or abuse (Curtiss, 1977; Itard, 1801).

However, populations of children lacking these drawbacks are available. Today, infants who are born profoundly deaf can access spoken language by means of a cochlear implant (CI), an electronic device that partially replaces the cochlear function via electrical stimulation of the auditory nerve. Implantation in very young children (< 24 months) can be performed safely, providing early access to auditory stimuli (Waltzman & Cohen, 2005).

Previous studies based on populations of oral deaf children with a CI show that the optimal time window for the development of language begins to close at age 2: children receiving CIs in the third and fourth year of life show important general language delays compared to children implanted before that age (Geers et al., 2003; Svirsky, 2005; Waltzman & Cohen, 2005). Based on these findings, an in-depth analysis of spontaneous language data from children who received their CIs before age 2 will provide important new insights into the possible role of a sensitive window on the development of different language subsystems. Here, we examine the effect of access to linguistic input on the development of different language processes in a population of deaf children who received their CIs between 5 and 19 months. As language processes are known to develop in a fixed, interdependent sequence (Locke, 1997), we expect to find different sensitive windows for each of them. This hypothesis is tested by four measures of language development, each covering a particular phase of development of linguistic capacities: the 20% canonical babbling ratio (CBR or number of canonical syllables/total number of syllables, representing the onset of the babbling spurt), the early productive vocabulary (first 30 words, representing the early lexical stage), the first use of determiners (definite and indefinite articles, signalling early morpho-syntactic development), and the Type/Token ratio (TTR; total number of different words/total number of words, a measure for lexical diversity, and hence also for advanced lexical development).

METHOD

Participants

The study group consists of nine congenitally deaf children who received a CI before the age of 2 (median age at implantation 10 months, range 5 months 5 days—19 months 13 days), of which spontaneous spoken language samples were taken monthly until the age of 4. All children were implanted between November 2000 and June 2002 and were followed up in the same clinic (Eargroup, Antwerp, Belgium). They met the following criteria: (1) they were raised orally by hearing parents, living in families with Dutch (Flemish variant) as a primary language; (2) their hearing loss was congenital, detected during neonatal screening; (3) all children received bilateral classical hearing aids within the first few months after detection;

(4) they had an unaided Pure Tone Average (PTA) hearing loss (PTA at 500, 1000, and 2000 Hz) of more than 90 dBHL in the better ear; (5) no significant progress with hearing aids was attested; (6) all children received a Nucleus 24 implant; (7) the aided thresholds improved to 30–55 PTA dBHL at 1 year post-implantation; and (8) none of the children had other disabilities apart from their hearing loss. Written informed consent was obtained from all parents to participate in the study. The study group participants' characteristics are given in Table 1.

All children were videotaped once a month by means of a Panasonic NV-GS3 digital video camera with zoom microphone function in their homes or schools during a 60–80 minutes play session with a parent, family member, relative, or caregiver from 1 month before until 30 months after implantation and yearly from the age of 4 onwards. From each recording, a sample of 20 minutes was transcribed by an experienced researcher according to the CHAT format of the Child Language Data Exchange System (CHILDES; MacWhinney, 2000), and double-checked by a second researcher for errors and omissions. The transcripts include all nonvegetative vocalisations, babbling, spoken words, and occasional signing from the child and the adult(s) with whom he/she is communicating.

Design

A prospective longitudinal research design was opted for, serving two primary purposes: to describe patterns of change in language development and to

TABLE 1
Overview of the study group participant's data

ID	*PTA unaided (dBHL)*	*Age HA (y;mm.dd)*	*PTA aided (dBHL)*	*Age CI (y;mm.dd)*	*Age CI fitting (y;mm.dd)*	*PTA CI (dBHL)*
RX	117	0;04.00	107	0;05.05	0;06.04	43
AN	120	0;01.04	120	0;06.21	0;07.20	30
MI	120	0;01.21	107	0;08.23	0;09.20	43
YA	103	0;05.08	63	0;08.21	0;09.21	32
EM	115	0;01.18	113	0;10.00	0;11.20	33
RB	91↓117	0;03.06	45↓115	1;01.07	1;02.04	43
AM	120	0;09.03	120	1;01.15	1;02.27	47
JO	113	0;10.00	117	1;06.05	1;07.09	42
TE	112	0;02.00	58	1;07.14	1;09.04	52
Median	115	0;04.00	107	0;10.00	0;11.20	42
Range	91–120	0;02–0;10	45–120	0;05–1;07	0;06–1;09	30–52

Note: PTA, Pure Tone Average, tested binaurally in free-field condition: in case of no response at 120 dBHL (i.e., maximum output of the audiometer), this was coded as 120dBHL; HA, Conventional Hearing Aids; ↓, progressive hearing loss.

measure these changes with reference to two continua by which the subjects under investigation are determined. These two continua are measured internally to the subjects under study and involve: (1) the subjects' chronological age and (2) their hearing age, i.e., the amount of time they have had access to spoken language when reaching a particular linguistic milestone. Thanks to the exceptionally intense assessments, the obtained sample size is relatively high and allows a detailed investigation of language development over time. By measuring age longitudinally, the observed differences can be interpreted as developmental differences within a cohort over time.

The study group was matched to two control groups of hearing children for which data have been collected in a similar way, i.e., in a longitudinal design with spontaneous speech data collected monthly over a longer period of time. Study group and control groups were equalised as much as possible in their overall distributions on a number of relevant variables, such as ambient language, native language of the parents, and the stage of language development covered by the spontaneous data sample.

For the assessment of pre-lexical development, the control group involved seven hearing children who were followed longitudinally from 6 months of age onwards up to the age at which they produced at least 50-word types as assessed by the Dutch adaptation of the Mac Arthur CDI (Zink & Lejaegere, 2002). The age of 6 months for the first recording session was chosen because this is the age at which babbling normally takes off. Regardless of their language environments normally developing infants start babbling when they are between 6 and 10 months of age (Holmgren, Lindblom, Aurelius, Jalling, & Zetterström, 1986; Koopmans-van Beinum & van der Stelt, 1986; Oller & Eiler, 1988). The children were selected based on the following criteria: (1) they had normal hearing (i.e., a PTA of < 25 dBHL in both ears), confirmed by the ALGO® test in the first few weeks of life; (2) they had Dutch-speaking normally hearing parents (and siblings); and (3) they did not show any patent health or developmental problems.

For the assessment of lexical and morpho-syntactic development, the control group is composed of 10 Dutch-speaking children for whom transcriptions of longitudinal data spontaneous speech data are available through the CHILDES database (Bol, 1995; Schaerlaekens, 1973; van Kampen, 1994). An overview of the control group participants' data is given in Table 2.

Measures of language development

For both groups, the obtained language samples are analysed for four measures of linguistic development: CBR, vocabulary diversity, and the emergence of particular morphemes assessing, respectively, the children's pre-lexical, lexical, and morpho-syntactic development.

TABLE 2
Overview of the hearing control groups participant's data

ID	*Age at first observation session*	*Age at last observation session*	*Number of observations*
Control group 1: Pre-lexical measure			
LK	0;06.05	1;08.29	16
RO	0;07.29	1;09.26	12
SA	0;06.05	0;10.29	6
WI	0;05.30	1;10.02	17
MA	0;06.02	1;09.07	16
BR	0;05.30	1;09.02	16
TO	0;07.28	1;06.00	11
Control group 2: Morpho-syntactic and lexical measures			
LA	1;09.18	5;10.09	72
SA	1;06.16	6;00.00	50
DA	1;07.23	3;03.30	13
JO	1;08.29	2;08.19	11
GI	1;08.29	2;08.19	11
MA	1;10.18	3;01.07	13
DI	1;10.18	3;01.07	13
AB	1;10.30	2;06.11	14
JO	1;06.16	3;04.17	28
TO	1;07.05	3;01.02	27

Pre-lexical development

The assessment of pre-lexical development is based on an orthographic transcription of the adult's utterances and of an orthographic and phonemic transcription of the lexical items uttered by the children (Schauwers, 2006). For the children's pre-lexical utterances, a special coding system was adopted: each vocalisation was coded in terms of phonation (uninterrupted/interrupted) and articulation (no articulation, one articulation, or 2+ articulations) according to the model proposed by Koopmans-van Beinum and van der Stelt (1986). A total of 11,921 utterances of the CI children were analysed, and 14,918 babbled utterances of the hearing controls. In agreement with standard practices in the field, 10% of the total relevant material was retranscribed and recoded independently, yielding an intersubjective agreement of 91.9% and a κ score of .75 (Landis & Kroch, 1977).

On the basis of these data, the CBR (or number of canonical syllables/total number syllables) was computed. Babbling was defined as the presence of multiple articulatory movements in one breath unit, combined with continuous or interrupted phonation (Koopmans-van Beinum & van der Stelt, 1986). Canonical babbles were distinguished from words by criteria based on both phonetic and contextual parameters following Vihman and McCune (1994) who propose a formal system for evaluating phonetic match in combination with a set of child-derived functional categories reflecting use in context. The CBR (Oller & Eiler, 1988) was used as a measure to quantify the onset of babbled utterances: the onset of babbling is taken to occur when the proportion of babbled utterances on the total number of analysed utterances exceeds 0.2. The operational definition includes the occurrence of a consonant–vowel or vowel–consonant syllable. For the computation of the CBR, 50 vocalisations were randomly selected from each session. The age at which a ratio of 0.2 or higher was reached, was considered to be the onset of the canonical babbling stage, and was also related to the children's age at implantation.

Lexical development

Two measures are taken to assess the children's lexical development, the first derived from the spontaneous language samples and the second from parental reports. Lexical diversity is quantified by means of a Type/Token Ratio (TTR). TTR is defined by the total number of different words divided by the total number of words in a sample, a computation performed automatically on transcripts by the CLAN software of CHILDES. The age at which the children first reached a TTR of 0.5 has been related to the children's age at implantation. In the literature, TTR 0.5 has been shown to be a relevant measure for language development in preschoolers. In a study using data coming from 480 children, Miller (1981) has found that the TTR is fairly constant at 0.5. Moreover, TTR 0.5 has also been shown to be a valid diagnostic of language problems (McEvoy & Dodd, 1992; Stickler, 1987). However, one of the well-known disadvantages of TTR is its extreme sensitivity to sample size: because function words tend to recur at a high rate, TTR will generally decrease with increasing sample size. To overcome this problem, TTR was computed in this study based on a randomly selected standard sample size of 50 utterances.[1] For the study group, the age at which the children reached a TTR of 0.5 was related to their age at implantation.

[1] An additional alternative method for measuring vocabularity diversity was used to exclude any remaining effects of sample size. This alternative method is based on a mathematical model of the curvilinear relationship between the size of a language sample and the range of vocabulary it contains. It has been implemented in a software program, *vocd* (Mc Kee, Malvera, & Richards, 2000) by which the value of a single parameter D is obtained. This value representing the best fit of the theoretical curve to the empirical curve is derived through a series of TTRs by randomly sampling words and has been shown to be a highly reliable measure of vocabulary diversity.

The second measure, dealing with the children's productive vocabulary, has been obtained through parent reports using the Dutch version of the MacArthur Communicative Development Inventory (Zink & Lejaegere, 2002), a standardised parent reporting system used to assess monolingual children's lexical growth. Parents have been asked to indicate the words produced by their child from an inventory of 680 different words arranged in a number of semantic fields. The word lists have been presented to the parents at 3, 6, 12, 18, 24, 30, and 48 months. Based on these parental reports, the age at which the children first reached a productive vocabulary of 30 words has been calculated and related to the age at implantation.

Morpho-syntactic development

Finally, early morpho-syntactic development has been ascertained by looking at the first occurrence in the children's speech of determiners, and more specifically, definite and indefinite articles (*de*, *een*, the Dutch counterparts of, respectively, English "the" and "a").

The choice for article production as a hallmark of early morpho-syntactic development was motivated by a large number of longitudinal studies showing that articles are amongst the first grammatical morphemes to appear in the earliest forms of children's grammatical speech (see e.g., Brown, 1973, where articles are the 7th out of 14 early morphemes to emerge). At the same time, these early free morphemes appear to be extremely vulnerable in language development. Children with Specific Language Impairment (SLI) omit articles significantly more often than almost any other functional category or free morpheme, including even total absence of determiners in the speech of children affected by either expressive/receptive or expressive-only SLI (Bottari, Cipriani, Chilosi, & Pfanner, 1998). This may be due to the fact that articles are perceptually low salient elements that carry formal features, i.e., features that mainly induce morpho-syntactic operations but do not substantially contribute to meaning. Such features have been claimed to be extremely sensitive to critical period effects (Smith & Tsimpli, 1995). Building on these insights, substantial delays in the omission of articles are taken to be an important indicator for potential atypical language development.

To exclude nonrepresentative occasional single occurrences, articles were taken to have emerged only when present in at least three consecutive monthly transcripts. Definite and indefinite articles were defined as unbound morphemes functioning as a determiner in front of a noun or another nominal element. As such, their identification was based on distributional regularities characteristic of the target adult language: to be analysed as determiners, they had to be present in the noun phrase, i.e., they appeared in a pre-adjective or pre-noun position, they did not stand alone as the sole content of an utterance, and were never sequenced (see also Valian, 1986).

In addition, following Peters (2001), syllables that did not match adult target articles either based on phonological or on distributional grounds were considered to be phonological or (proto-)morphological filler syllables and therefore not taken into account as being possible articles. Therefore, potential determiners were taken into consideration only when containing *schwa* and, respectively, a dental consonant (*te* [tə]/*de* [də]) or a nasal consonant (*een* [ən]) and occurring in a prenominal context, i.e., in front of an adjective and/or a noun.

Statistics

Conventional five-parameter statistics are used for the descriptive statistics (Woods, Fletcher, & Hughes, 1986). Group results are displayed in box-and-whisker plots. Correlations results on age at implantation and hearing age are displayed in scatter plots with a linear regression and a 97.5 percentile cut-off point based on the hearing controls groups. Because of the group sizes (between 7 and 10 subjects), results will be presented by median scores and statistically analysed with nonparametric tests, i.e., a Mann–Whitney U test (MWU) and the Spearman's ρ nonparametric test for correlations.

RESULTS

Our analysis focused on the above-described linguistic measures comparing the CI group with the hearing control groups. With respect to CBRs, we found that two out of nine CI children had already reached the level of 20% CBR before implantation. For the remaining children, the analysis of the data shows that their babble spurt occurs at a significantly later age than in the hearing control group (control group: median 9 months, range 8–13 months; CI group: median 15.84 months, range 11–22 months, MWU $z = -3.013$, $p = .003$).

Analysing the data for determiner morphology, we observe a significantly later first emergence for the CI group (median age 28 month, range 21.5–39 months) compared to the hearing control group (median 23 months, range 21–26 months, MWU $z = -2.044$, $p = .041$).

One of the measures for lexical development, the TTR of 0.5, is reached at a median age of 24 months (range $21 - 34.5$ months) in the control group, which is significantly earlier than in the CI group (median age 31 months, range 21–45 months, MWU $z = -2.122$, $p = .034$).[2] For the CI group, spontaneous speech data from eight out of nine children were taken into

[2] The outcomes of the alternative lexical diversity measure *D* were clearly in line with those based on TTR. At 24 months for instance, CI children have a median *D* value of 9.847 (range 3.05–60.71), whereas hearing children have a median of 35.48 (range 20.94–50.22). The difference between both populations is statistically significant (MWU $p = .004$).

consideration, due to the drop-out of one of the children before reaching the relevant measure (Figure 1).

Strikingly, the observed differences in outcomes between the CI group and the hearing control group relate to the age at which the children have been implanted. Highly significant strong positive correlations were found between the age at implantation and the age at which each of the linguistic measures were reached. Very high coefficients of determination were obtained for the children's age at implantation, explaining between 72 and 84% of the observed variance in outcomes for the linguistic parameters under investigation (Spearman's ρ for 20% CBR: $R^2 = .833$, $p = .003$; for 30-word lexicon: $R^2 = .844$, $p = .007$; for determiner emergence: $R^2 = .722$, $p = .021$; for TTR 0.5: $R^2 = .787$, $p = .017$).

Moreover, setting the upper bound for each measure at the 97.5 percentile found in typically developing hearing controls (respectively, 13.51 months for CBR 20%, 21.25 months for 30-word lexicon, 25.70 months for determiner

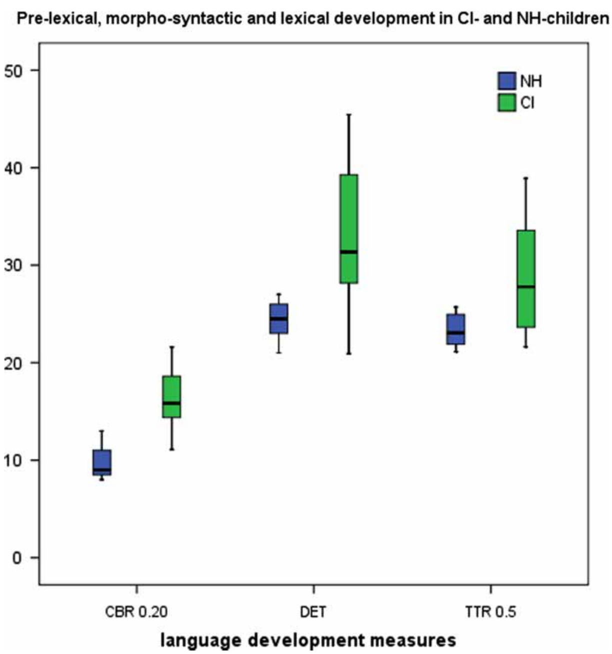

Figure 1. Between-group comparisons for pre-lexical, morpho-syntactic, and lexical development. NH represents the normal hearing and CI the cochlear-implanted group. On the horizontal axis, the results of the three linguistic measures under investigation for each study group. On the vertical axis, the age in months at which the children reach the relevant linguistic measure. Note: CBR 0.20, Canonical babbling ratio of 20%; DET, onset of the use of definite and indefinite articles; TTR 0.5, Type/Token ratio of 0.5, indicator for lexical diversity.

onset, and 32.88 months for TTR 0.5, see Figure 2), we found that only children who had access to linguistic input through CI by 12 months at the latest, had language capacities emerging within normal biological time limits.

A more fine-grained analysis of the observed delay interval reveals that the effect of timing of linguistic input on language development is not a unitary phenomenon, but varies for the different measures, ranging from 6.5 months for pre-lexical development (measured through CBR 20%) to 11 months for later lexical development (measured through TTR 0.5). These findings show that the timing of linguistic experience is sequentially related to the onset of the different stages in language development. Pre-lexical and

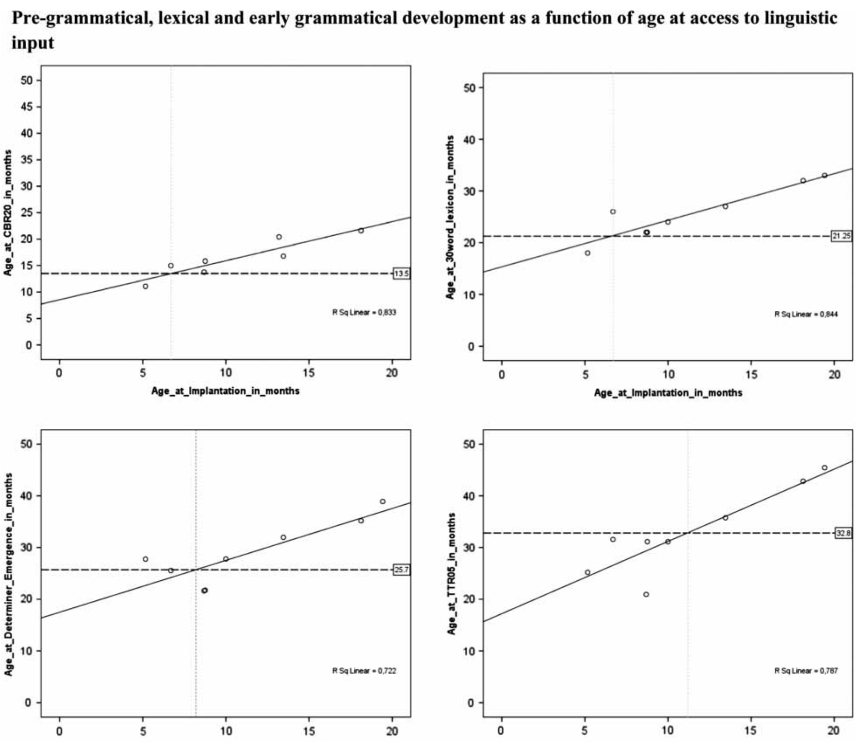

Figure 2. Pre-grammatical and early grammatical developments in terms of the onset of linguistic processes are set off as a function of the deaf children's access to linguistic input by means of cochlear implantation. There are strong correlation effects between the timing of environmental input and linguistic outcomes. For each measure, the horizontal dotted lines correspond to the 97.5th percentile found in typically developing hearing controls. The vertical lines, drawn from the crossing point between the P97.5 and the linear fit lines indicate the age at which children have to get access to language experience at the latest in order to show an oral language performance that is within normal range.

early lexical development, as measured by canonical babbling and 30-word production, is dependent on linguistic input by 6.5 months at the latest, whereas vocabulary growth and later emerging analytic and computational processes, measured here in terms of the emergence of determiners, allow a delay in environmental input of, respectively, 8.5 and 11 months (see Figure 2). As such, these results provide behavioural support for neurophysiological evidence that has been found in favour of temporal dimensions for sensitive periods for distinct subprocesses of language (Neville et al., 1992).

DISCUSSION

Studies of the development of the auditory system as measured by early auditory evoked responses have shown that the auditory system does not fully develop without stimulation. Nevertheless, the auditory system seems to retain its plasticity during the period of deafness: after introduction of stimulation by the CI in young deaf children, normal auditory development was observed (Ponton et al., 1996). If language development is subject to similar principles, the time limits for language development might also be extensible in the absence of linguistic input. Under this hypothesis, environmental input at any biological age would be a sufficient condition for normal language development. In the case of children with CIs, this implies that the outcomes on the relevant linguistic measures would be dependent only on the duration of linguistic experience (hearing age) regardless of the biological age at which deaf children are given first access to spoken language thanks to their CI (age at implantation). By contrast, the hypothesis that the development of language is largely determined by biological constraints predicts that there is an important effect of the chronological age of the child at the moment of first access to linguistic information on his/her linguistic performance.

In order to verify these predictions, we measure the age at which the children first reach the four linguistic measures in terms of the amount of time they have been exposed to language (hearing age) and set the outcomes as a function of the age at which they first got access to linguistic input. Strikingly, no significant correlations were found between the duration of exposure to input and the different language measures under investigation (Spearman's ρ for CBR 20%: $R^2 = .384$, $p = .215$; for 30-word lexicon: $R^2 = .061$, $p = .56$; for determiner emergence: $R^2 = .001$, $p = .823$; and for TTR 0.5: $R^2 = .231$, $p = .183$).

Importantly, in the course of language development, the direction of the correlation turns from a negative one (at the pre-lexical stage, measured through CBR) into a positive one (at the advanced lexical and grammatical stage, measured through TTR), see Figure 3, Panels A and B. These findings

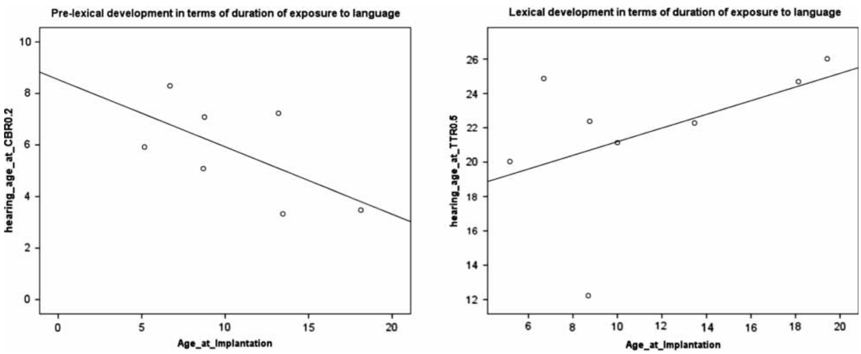

Figure 3. The outcomes for the two linguistic measures representing, respectively, the pre-lexical and the advanced lexical stage have been recalculated here in terms of duration of the children's exposure to language. Differences in the effect of input at different stages of language development are illustrated by the change from a negative to a positive direction of the correlation from the earlier to the later stage of language development. This graph illustrates that a child implanted at approximatively 18 months needs about 2.5 months less hearing experience for the onset of the babbling spurt as compared to a child implanted at 5 months. However, to achieve the same level of lexical development, s/he will need about 5 months more input than the child implanted at 5 months.

not only suggest that native language acquisition results from a delicate interplay between the innate blueprint and sensory input, but also that the possibility to fully develop oral language after a particular period without linguistic experience may vary over time and for the different linguistic processes investigated. In particular, pre-lexical language processes such as babbling seem to be less affected by the duration of deprivation than later developing language processes, which seem to be more tightly constrained by the biological timing of exposure. As such, the language outcomes measured in terms of duration of exposure to input are in line with the recently advanced hypothesis that specific innate neural mechanisms increase in importance from early childhood to adolescence (Spinath, Price, Dale, & Plomin, 2004).

Additional evidence in favour of the increasing effect of timing constraints can be found in measures of language growth, as defined in terms of a language quotient (the ratio of language age/chronological age) over a particular amount of time (Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000). If both early and later developing language processes are only influenced by the duration of linguistic input, regardless of biological timing, the language quotient is expected to remain steady over time. By contrast, an increase in the importance of biological timing is reflected in a decreased language quotient, creating a gap between the children's chronological age and language age. For the population under investigation, the language quotients are measured over the time interval between the first and last measure, and results are set as a function of the children's chronological age of access to linguistic stimuli. A correlation analysis of the growth in language quotient by age at access to input shows that children with early language experience have a faster language-learning rate (i.e., ≥ 1). Moreover, this learning rate is proportionally inverse to the children's age at implantation, suggesting again that the effect of biological timing constraints increases with the increasing complexity of the developing linguistic system (see Figure 4).

CONCLUSIONS

Bearing in mind that previous studies have advanced that the sensitive window for language development is likely to close somewhere between 6 and 12 years of age (Lenneberg, 1967; Ruben, 1997), the observed delay interval for the children's first access to linguistic stimuli occurs surprisingly early. Recent investigations have shown that deaf infants receiving a CI below 24 months develop language skills faster than those implanted after that age.

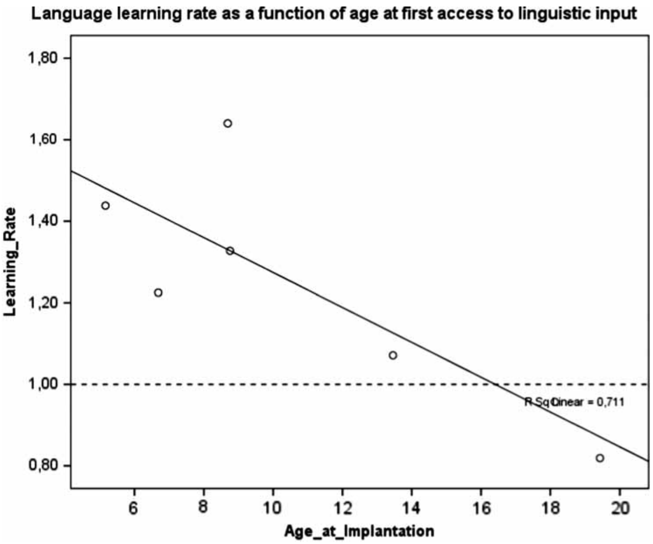

Figure 4. Language growth in terms of biological timing constraints. Language-learning rates (language age/chronological age for the time-interval between the pre-lexical and the advanced lexical measures) are set as a function of age at access to linguistic input. Correlation effects of the growth in language quotient by age at access to input shows that children with early language experience are faster learners. Here, the cut-off point for an average language growth rate ($=1.0$) is found for first access to oral language at 16 months approximatively.

However, no further benefit of access to linguistic input before the second year of life has been found so far (Svirsky & Holt, 2005), although predictions have been made in this direction (Nicholas & Geers, 2006; Valencia, Rimell, Friedman, Oblander, & Helmbrecht, 2008). Our findings show that for all assessed linguistic measures, i.e., CBRs, vocabulary diversity, and determiner emergence, children who have access to auditory input during the first 16 months of life are more likely to develop age appropriately and that these same children are able to acquire language at an accelerated rate, possibly catching up with their normally hearing mates at later stages of language development. These findings confirm evidence from the literature that oral language development is crucially dependent on access to linguistic input during the first year of life (Yoshinago-Itano, Sedey, Coulter, & Mehl, 1998).

Our study further also supports neuroanatomical and physiological research showing that the development of the cortical regions associated with different aspects of language processing is not continuously plastic, but subject to genotypical constraints. Different subsystems of language are sensitive to sensory input at distinct developmental times. As such, different sensitive periods can be distinguished, varying in the extent to which they allow their biological basis to be shaped by linguistic experience. Variability is also found in the timing of the onset of the sensitive periods related to the different subsystems. The later language processes emerge, the later their sensitive period will start closing.

Finally, it should be observed that the presence of language input within the pivotal neuromaturational time window for morpho-syntactic acquisition is a necessary, but not a sufficient condition to achieve normal levels of syntactic proficiency. Our data show that normal capacities for later developing language subsystems crucially depend on early developing linguistic processes such as babbling. Children who are deprived from linguistic input during the first year of life are more likely to show atypical babbling behaviour, and consequently, also atypical syntactic behaviour during the second and third years of life. This suggests that the cut-off point for normal development of later developing cognitive functions may lie years before its observed effects.

Manuscript received 1 December 2008
Revised manuscript received 25 July 2010
First published online month/year

REFERENCES

Bol, G. W. (1995). Implicational scaling in child language acquisition: The order of production of Dutch verb constructions. In M. Verrips & F. Wijnen (Eds.), *Papers from the Dutch-German colloquium on language acquisition* (pp. 1–13). [Amsterdam Series in Child Language Development, 3]. Amsterdam: Institute for General Linguistics.

Bottari, P., Cipriani, P., Chilosi, A. M., & Pfanner, L. (1998). The determiner system in a group of Italian SLI children. *Language Acquisition*, *7*(2–4), 285–315.

Brown, R. (1973). *A first language: The early stages.* London: George Allen & Unwin.

Curtiss, S. (Ed.). (1977). *Genie: Psycholinguistic study of a modern-day "wild child"*. London: Academic Press.

Feldman, H., Goldin-Meadow, S., & Gleitman, L. (1978). Beyond Herodotus: The creation of language by linguistically deprived deaf children. In A. Lock (Ed.), *Action, symbol, and gesture: The emergence of language* (pp. 351–414). New York: Academic Press.

Geers, A., Nicholas, J., & Sedey, A. (2003). Language skills of children with early cochlear implantation. *Ear and Hearing*, *24*, 46S–58S.

Goldin-Meadow, S., & Mylander, C. (1983). Gestural communication in deaf children: Noneffect of parental input on language development. *Science*, *221*, 372–374.

Holmgren, K., Lindblom, B., Aurelius, G., Jalling, B., & Zetterström, R. (1986). On the phonetics of infant vocalization. In B. Lindblom & R. Zetterström (Eds.), *Precursors of early speech* (pp. 51–63). New York: Stockton Press.

Hubel, D. H., & Wiesel, T. N. (1965). Binocular interaction in striate cortex of kittens reared with artificial squint. *Journal of Neurophysiology*, *28*(6), 1041–1059.

Huttenlocher, P. R., & Dabholkar, A. S. (1997). Regional differences in synaptogenesis in human cerebral cortex. *The Journal of Comparative Neurology*, *387*, 167–178.

Itard, J. M. G. (1801). *De l'education d'un homme sauvage ou des premiers developpements physiques et moraux du jeune sauvage de l'Aveyron* [On the education of a savage man or the first physical and moral developments of the young savage boy of Aveyron]. Paris: Goujon.

King, A. J., & Moore, D. R. (1991). Plasticity of auditory maps in the brain. *Trends in Neuroscience*, *14*, 31–37.

Koopmans-van Beinum, F. J., & van der Stelt, J. M. (1986). Early stages in the development of speech movements. In B. Lindblom & R. Zetterström (Eds.), *Precursors of early speech* (pp. 37–50). New York: Stockton.

Landis, J. R., & Koch, G. G. (1977). The measurements of observer agreement for categorical data. *Biometrics, 33*, 159–174.

Lenneberg, E. (1967). *Biological foundations of language.* New York: John Wiley.

Locke, J. L. (1997). A theory of neurolinguistic development. *Brain and Language*, *58*, 265–326.

MacWhinney, B. (2000). *The CHILDES project: Tools for analyzing talk. Volume 1: Transcription format and programs. Volume 2: The database* (3rd ed.). Mahwah, NJ: Lawrence Erlbaum.

Mayberry, R. (1993). First language acquisition after childhood differs from second language acquisition. *Journal of Speech and Hearing Research*, *36*, 1258–1270.

Mc Kee, G., Malvera, D., & Richards, B. (2000). Measuring vocabulary diversity using dedicated software. *Literary and Linguistic Computing*, *15*(3), 323–337.

McEvoy, S., & Dodd, B. (1992). The communication abilities of 2- to 4-year-old twins. *European Journal of Disorders of Communication*, *27*(1), 73–87.

Miller, J. F. (1981). *Assessing language production in children: Experimental procedures.* Baltimore, MD: University Park Press.

Neville, H., & Bruer, J. T. (2001). Language processing. How experience affects brain organization. In D. B. Bailey, J. T. Bruer, & F. J. Symons (Eds.), *Critical thinking about critical periods* (pp. 151–172). Baltimore, MD/London: P. Brookes.

Neville, H., Mills, D., & Lawson, D. (1992). Fractionating language: Different neural subsystems with different sensitive periods. *Cerebral Cortex*, *2*, 244–258.

Nicholas, J. G., & Geers, A. E. (2006). Effects of early auditory experience on the spoken language of deaf children at 3 years of age. *Ear and Hearing*, *27*(3), 286–298.

Oller, D. K., & Eiler, R. E. (1988). The role of audition in infant babbling. *Child Development*, *59*, 441–449.

Peters, A. (2001). Filler syllables: What is their status in emerging grammar. *Journal of Child Language*, *28*(1), 229–242.
Ponton, C. W., Don, M., Eggermont, J. J., Warning, M. D., Kwong, B., & Masuda, A. (1996). Auditory system plasticity in children after long periods of complete deafness. *Neuroreport*, *8*, 61–65.
Reilly, J., Losh, M., Bellugi, U., & Wulfeck, B. (2004). Frog, where are you? Narratives in children with SLI, early focal brain injury and Williams syndrome. *Brain and Language*, *88*(2), 229–247.
Ross, D. S., & Bever, T. G. (2004). The time course for language acquisition in biologically distinct populations: Evidence from deaf individuals. *Brain and Language*, *89*, 115–121.
Ruben, R. J., & Rapin, I. (1980). Plasticity of the developing auditory system. *Annals of Otology Rhinology and Laryngology*, *89*, 303–311.
Ruben, R. J. A. (1997). Time frame of critical/sensitive periods of language development. *Acta Otolaryngology*, *117*, 202–205.
Schaerlaekens, A. M. (1973). *The two-word sentence in child language*. The Hague: Mouton.
Schauwers, K. (2006). *Early speech and language development in deaf children with a cochlear implant: A longitudinal investigation* (PhD, University of Antwerp, Antwerp).
Shouval, H. Z., & Perrone, M. P. (1995). Post-Hebbian learning rules. In M. A. Arbib (Ed.), *The handbook of brain theory and neural networks* (pp. 645–748). Cambridge, MA: MIT Press.
Smith, N., & Tsimpli, I. M. (1995). *The mind of a savant: Language learning and modularity*. Oxford: Blackwell.
Spinath, F. M., Price, T. S., Dale, P. S., & Plomin, R. (2004). The genetic and environmental origins of language disability and ability. *Child Development*, *75*(2), 445–454.
Stickler, K. (1987). *Guide to analysis of language transcripts*. Eau Claire, WI: Thinking.
Stiles, J., Reilly, J., Paul, B., & Moses, P. (2005). Cognitive development following early brain injury: Evidence for neural adaptation. *Trends in Cognitive Sciences*, *9*(3), 136–143.
Stromswold, K. (2001). The heritability of language: A review and meta-analysis of twin, adoption and linkage studies. *Language*, *77*(4), 647–723.
Svirsky, M. (2005, May 16). *Language learning declines after second year of life*. Retrieved from news@nature.com
Svirsky, M., & Holt, R. (2005). Language acquisition after cochlear implantation of congenitally deaf children: Effect of age at implantation. *Journal of the Acoustic Society of America, 117*(4), 2375.
Svirsky, M., Robbins, A. M., Kirk, K. I., Pisoni, D. B., & Miyamoto, R. T. (2000). Language development in profoundly deaf children with cochlear implants. *Psychological Science*, *11*(2), 153–158.
Valencia, D. M., Rimell, F. L., Friedman, B. J., Oblander, M. R., & Helmbrecht, J. (2008). Cochlear implantation in infants less than 12 months of age. *International Journal of Pediatric Otorhinolaryngology*, *72*, 767–773.
Valian, V. (1986). Syntactic categories in the speech of young children. *Developmental Psychology*, *22*(4), 562–579.
van Kampen, N. J. (1994). *The learnability of the left-branch condition*. In R. Bok-Bennema & C. Cremers (Eds.), *Linguistics in The Netherlands* (pp. 83–94). Amsterdam, The Netherlands: John Benjamins..
Vihman, M. M., & McCune, L. (1994). When is a word a word? *Journal of Child Language*, *21*(3), 517–542.
Waltzman, S., & Cohen, N. (2005). Cochlear implantation in children younger than 2 years old. *American Journal of Otology*, *19*, 158–162.
Waltzman, S. B., & Roland, J. T. (2005). Cochlear implantation in children younger than 12 months. *Pediatrics*, *116*(4), 487–493.

Weber-Fox, C., & Neville, H. (2001). Sensitive periods differentiate processing of open- and closed-class words. An ERP study of bilinguals. *Journal of Speech, Language, and Hearing Research*, *44*, 1338–1353.

Woods, A., Fletcher, P., & Hughes, A. (1986). *Statistics in language studies*. Cambridge, UK: Cambridge University Press.

Yoshinago-Itano, C., Sedey, A., Coulter, D., & Mehl, A. (1998). Language of early- and later-identified children with hearing loss. *Pediatrics*, *102*, 1161–1171.

Zink, I., & Lejaegere, M. (2002). *N-CDIs. Lijsten voor communicatieve ontwikkeling* [(Dutch) MacArthur CDI's for communicative development]. Leuven, Belgium: Acco.