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UNIVERSITY OF CALIFORNIA, SAN DIEGO

Acquiring a first language in adolescence:
Behavioral and neuroimaging studies in American Sign Language

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor
of Philosophy

in

Linguistics and Cognitive Science

by

Naja Ferjan Ramirez

Committee in charge:

      Professor Rachel Mayberry, Chair
      Professor Jeffrey Elman
      Professor Grant Goodall
      Professor Eric Halgren
      Professor Robert Kluender

2013

The dissertation of Naja Ferjan Ramirez is approved, and it is acceptable in quality and

form for publication on microfilm and electronically:

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Chair

University of California, San Diego

2013

DEDICATION:

For my husband, Alex, and my parents, Mojca and Borut.

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<center>****</center>

Chapter 2, in full, is a reprint of the material as it appears in Ferjan Ramirez, N., Lieberman, A., Mayberry, R.I. (2013) The initial stages of first-language acquisition begun in adolescence: When late looks early. *Journal of Child Language*, 40(2), 391-414. The dissertation author was the primary investigator and author of this paper. Permission to reprint was granted by *Cambridge University Press*.

Chapter 3, in full, is a reprint of the material as it appears in Leonard, M.K., Ferjan Ramirez, N., Torres, C., Travis, K.E., Hatrak, M., Mayberry, R.I., Halgren, E. (2012) Deaf signers process semantic but not visual information in left superior temporal cortex. *Journal of Neuroscience*, *32*(28), 9700-9705. The dissertation author was the co-principal investigator and co-author of this paper. Permission to reprint was granted by *Journal of Neuroscience*.

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Leonard, M.K., Ferjan Ramirez, N., Torres, C., Travis, K.E., Hatrak, M., Mayberry, R.I., Halgren, E.(2012). Deaf signers process semantic but not visual information in left superior temporal cortex. *Journal of Neuroscience*, *32*(28), 9700-9705.

Ferjan Ramirez, N., Lieberman, A., Mayberry, R.I.. (2013) The initial stages of first-language acquisition begun in adolescence: When late looks early. *Journal of Child Language*, 40(2), 391-414.

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Ferjan Ramirez, N., Leonard, M.K., Halgren, E., Mayberry, R.I. The neural correlates of childhood linguistic isolation. In S. Baiz, N. Goldman, R. Hawkes (Eds.) Proceedings of the 37th Boston University Conference on Language Development. Boston: Cascadilla Press.

ABSTRACT OF THE DISSERTATION

Acquiring a first language in adolescence:
Behavioral and neuroimaging studies in American Sign Language

by

Naja Ferjan Ramirez

Doctor of Philosophy in Linguistics and Cognitive Science

University of California, San Diego, 2013

Professor Rachel Mayberry, Chair

One of the most challenging questions in linguistics is why the ability to acquire language declines with age. The critical period hypothesis, which claims that language acquisition is driven by brain maturation, is widely accepted despite a lack of evidence to support it. Because most children experience language from birth, the relationship between brain growth and early language experience is poorly understood. This dissertation describes the language acquisition and the neural language processing in three deaf individuals (cases) who were cut off from nearly all language until adolescence; they could not hear spoken language and, due to anomalies in their upbringing, did not experience sign language until adolescence when they became immersed in American Sign Language (ASL). These developmental circumstances allow

us to investigate the effects of *first* language acquisition begun in adolescence, and test the critical period hypothesis from a unique perspective.

The first part of the dissertation focuses on the cases' language following one to two years of ASL use. Their language is remarkably similar to that of young children: their lexicons are biased towards nouns, and their utterances are short and simple. The second part of the dissertation explores the link between the age onset of language acquisition and the neural representation of sign meaning using anatomically constrained magnetoencephalography. Chapter 3 demonstrates that under ideal developmental circumstances, when language is available from birth, the neural processing of sign in deaf participants is highly similar to the processing of speech in hearing participants. However, in subsequent studies with the cases (Chapter 4), we observe atypical neural activation patterns, which diverge significantly from those associated with native sign or spoken language learning.

These results indicate that early language experience is crucial in establishing canonical neural language processing patterns. The atypical neural activation patterns we find in the cases may be associated with the slowed rate of language development we observe in follow-up language studies. Our findings provide some of the initial direct evidence in support the critical period hypothesis and have important theoretical and practical implications.

CHAPTER 1:

Introduction

Compared to adults, young children have a remarkable ability to rapidly and spontaneously acquire language. Given adults' superior cognitive skills, the question is why. The idea that language proficiency is related to age at which learning begins is known as the critical period for language (Penfield & Roberts 1959; Lenneberg 1967). The critical period hypothesis proposes that language acquisition is driven by early brain development, and, at later ages, is limited by a lack of neural plasticity. This hypothesis is decades old: in 1959, Penfield and Roberts argued that after the age of 9 years the human brain becomes "stiff and rigid" (Penfield & Roberts 1959; p. 236), and language acquisition is no longer possible. In 1967 Lenneberg claimed that language acquisition relies on the plasticity of both hemispheres. If language acquisition does not occur during childhood when the brain is still plastic, full mastery would never be attained (Lenneberg 1967). Critical period phenomena are well documented within the animal kingdom. For example, the learning of the species-typical song in songbirds is dependent on exposure to conspecific song during a critical temporal window (Marler 1970) and the development of binocular vision in cats is dependent on binocular visual input during a critical period in early life (Hubel & Wiesel 1977). Animal studies also indicate the existence of neural circuits whose architecture is modified by experience only at a specific time in development. These studies suggest that experience during a critical period modifies the architecture of neural circuits in fundamental ways, causing certain patterns of connectivity to become highly stable and energetically preferred (Knudsen 2004). Most language researchers believe that a similar relationship exists between early

1

brain development and language acquisition; however, the exact nature of this relationship is poorly understood.

Many studies have shown that language acquisition is guided by children's language experience. Infants can initially discriminate among all phonetic units used in languages of the world; this ability, which declines substantially by 12 months of age, is replaced by the improvement in discrimination of phonemic categories of a specific (ambient) language (Werker & Tees 1984). The sounds that infants produce are influenced by the language that they hear from as early as 6 months (Brown 1958). The first words, which emerge somewhere between 10 to 15 months of age, invariably refer to objects and people that the infants interact with (Nelson 1974; Bates, Marchman, Thal, Fenson, Dale et al. 1994). By 3 years of age, children produce full sentences. The emergence of grammar can be predicted from vocabulary size and composition, both of which are highly dependent on the amount and structure of language input (Huttenlocher, Haight, Bryk, Seltzer & Lyons 1991; Hart & Risley 1995). Moreover, syntactic complexity itself can be directly predicted from the amount and structure of language input that children receive (Huttenlocher, Vasilyeva, Cymerman, & Levine 2002).

With the advance of non-invasive neuroimaging and brain recording techniques, we have also been able to gain insight into the infant brain. These studies have shown important age- and proficiency-related differences in the neural architecture for language processing over development (Brown, Lugar, Coalson, Miezin, Petersen, & Schlaggar 2005; Ortiz-Mantilla, Choe, Flax, Grant, Benasich 2010; Deniz Can, Richards, Kuhl 2013; Travis, Curran, Torres, Leonard, Brown et al. 2013). While the neural processing of language shows adult-like characteristics from a young age (Travis, Leonard, Brown,

Hagler, Curran et al. 2011; Imada, Zhang, Cheour, Taulu, Ahonen et al. 2006; Dehaene-Lambertz, Dehaene, & Hertz-Pannier L. 2002), significant developmental changes have been observed. In particular the electrophysiological signatures of language comprehension become more and more adult-like as language processing develops (Mills, Coffey-Corina, & Neville 1993; 1997; Friedrich & Friederici 2005; 2010). Moreover, as more language is acquired, brain responses to language stimuli become increasingly more focal to the left hemisphere fronto-temporal areas (Kuhl & Rivera-Gaxiola 2008; Brown et al. 2005; Mayberry, Chen, Witcher, & Klein 2011).

Converging behavioral and neuroimaging evidence thus suggest that language acquisition and neural language processing are guided by early language experience. One hypothesis is that early language exposure and simultaneous brain maturation influence each other bi-directionally: early exposure to native language both enables and is enabled by a specific neural configuration for language processing (see Kuhl 2004). While many behavioral and neuroimaging studies with typically developing infants provide indirect evidence for this hypothesis, one crucial question remains to be answered: What happens in the absence of childhood language input? This question is essential for the advancement of the critical period theory for language, but is particularly difficult to study because the vast majority of children experience language from birth.

Congenital deafness often has the effect of delaying the onset of language acquisition, as most deaf children are born to hearing parents who do not use sign language. Deaf children frequently do not receive functional language input until they enter school, and in rare cases, not until adolescence. These developmental circumstances offer a unique opportunity to study the effects of critical period for *first* language (L1)

acquisition, and thus make a unique contribution on this topic. Previous research suggests that age of onset of L1 acquisition (L1 AoA) is negatively related with adult language processing skills, ultimate language proficiency, and the strength of neural activations in the classical left hemisphere language network (Mayberry 2010; Mayberry et al. 2011). The effects of L1 AoA are hypothesized to be especially prominent in those cases where no formal language has been available until late childhood or early teenage years; however, research in this area has been extremely limited in quantity and scope (Morford 2003; Morford & Hänel-Faulhaber 2011). In this dissertation, we study language development and neural processing in individuals who were almost completely linguistically deprived throughout childhood, have experienced little or no schooling, and have relatively little language experience at the time of studies. Because of the unique backgrounds of our participants, this dissertation could answer some of the most fundamental questions about the critical period: What is language acquisition like when it begins for the first time at an older age? How does the brain cope with a lack of childhood language stimulation? How is a late-acquired L1 represented in the brain? From a practical standpoint, a better understanding of how delayed language exposure affects the trajectory of language acquisition and the neural processing of language has the potential to improve the educational outcomes in the deaf population and other populations at risk for language delay.

The overarching hypothesis tested in this dissertation is based on previous behavioral and neuroimaging research with typically developing children, as well as on years of previous research on native and non-native acquisition and neural processing of sign language. We propose that language acquisition and neural representation are guided

by early language experience, regardless of modality through which language is received. As such, delayed exposure to language is hypothesized to have severe effects on the trajectory of language acquisition and on the neural representation of language. To test this hypothesis, we study three cases who were cut off from nearly all language until age 14 years; they did not have meaningful access to spoken language and, due to various circumstances in their upbringing, have not experienced any kind of sign language. We study the cases' language acquisition and neural processing following 1 to 3 years of full immersion in American Sign Language (ASL), begun at age ~14.

The dissertation is divided into two parts, based on the methodology used to study the cases. In the first part we use behavioral methods and ask what the process of language acquisition is like when it begins for the first time in adolescence (Chapter 2). We focus on the content and sequence of milestones in early lexical acquisition, a topic so far unexplored. We hypothesize that L1 lexical acquisition, when begun at a later age, is not characterized by the explosive and linear growth patterns that characterize child L1 acquisition. This may be the result of a lack of childhood experience in decoding the phonological patterns of native language, and failure to discover the recurrent sub-lexical structure. In typically developing children, the size and composition of the lexicon accurately predict subsequent morpho-syntactic development (Bates et al. 1994). We hypothesize that a slower and more protracted trajectory of lexical acquisition, if discovered, may be related to delays in morpho-syntactic development, which have already been documented in late L1 learners.

In the second part of the dissertation we explore the link between the timing of language acquisition and the neural representation of word (sign) meaning. Since the

spatio-temporal dynamics of sign processing is poorly understood, we first establish how signs are processed under ideal developmental circumstances, when sign language input is available from birth. In Chapter 3 we thus explore how the meaning of signs is represented in the brains of deaf native signers. We use anatomically constrained magnetoencephalography (aMEG), a technique novel to sign language research. Because of its millisecond temporal resolution and good spatial resolution, we believe that aMEG can overcome some of the limitations of previous neuroimaging studies on sign language (reviewed in section 2.2. of Introduction) and provide critical insights into the spatiotemporal dynamics of sign language from a novel perspective. Based on previous sign and spoken language research, we hypothesize that native sign language acquisition is associated with neural activation patterns similar to those associated with the processing of speech in hearing participants. In Chapter 4, we ask how the human brain represents word meaning when language is experienced for the first time in adolescence. We study the same deaf adolescents as in Chapter 2, and ask how they represent their newly acquired ASL signs in the brain. As reviewed above and discussed in more detail in subsequent sections of the Introduction, previous research with hearing infants and with deaf and hearing adults suggests that the neural representation of word meaning is dependent on language experience. We thus hypothesize that adolescent L1 acquisition is associated with neural activation patterns that diverge from those associated with native language learning.

The following literature review focuses on the current knowledge of critical period for language. In section 1, I review the spoken language literature on the critical period. Sections 2 and 3 focus on sign language; in section 2, I review the literature on

sign language acquisition and neural processing under ideal developmental circumstances, when language input is available from birth. In section 3, I focus on the effects of delayed sign language exposure.

1. Critical period effects in spoken language studies

Most spoken language research on the critical period is conducted with second language (L2) learners (section 1.1.). Other approaches include cases of social and linguistic isolation (section 1.2.), and case studies of deaf individuals who began to learn a spoken language at a late age (1.3.).

1.1.Second language acquisition and neural processing

Because the age at which people begin to acquire L2s varies widely in the population, the effects of L2 age of acquisition (AoA) have been studied extensively. This is an interesting and complex area of research, much of which is not directly relevant to the issues addressed in this dissertation. The scope of the discussion here is limited only to the topics that are relevant to the findings reported in Chapters 2, 3, and 4.

Psycholinguistic studies confirm the existence of a negative correlation between L2 AoA and grammatical outcome (for example, Johnson & Newport 1989; 1991). Late bilinguals with many years of L2 experience typically fail to acquire subtle aspects of grammar and phonology at the level reached by early bilinguals, even when the number of years of experience is controlled (Birdsong 1992; Johnson & Newport 1989; White & Genesee 1996; Flege, Yeni-Komshian, & Liu 1999).

While studies on L2 AoA generally agree that "earlier is better", some studies show the reverse pattern. For example, Snow and Hoefnagel-Hoehle (1978) studied L2 acquisition of Dutch by English speaking participants of different ages and showed that

older learners surpassed younger learners on many measures of L2 ability. Genesee (1987) found that native English speakers who receive late L2 immersion generally perform as well as or better than those who receive early immersion. Other studies have shown that older children or adolescents tend to learn the L2 faster than younger children, especially in the early stages of learning (Krashen, Long, & Scarcella 1979; McLaughlin 1984, 1985). This may be particularly true in the domain of lexical acquisition, which is known to continue throughout the lifespan; adults continue expanding their vocabularies throughout life, mostly through reading (Anglin 1993; Aitchinson 1994; Borovsky, Elman, & Kutas 2012).

Many neuroimaging and electrophysiological studies with L2 learners have been conducted to investigate the AoA effects on the neural representation of language. The central question in this literature is whether L1 and L2 activate overlapping or distinct brain areas, and the findings are somewhat inconsistent. In a widely cited fMRI study, Kim and colleagues (Kim, Relkin, Lee, & Hirsch 1997) found that participants who had acquired L2 in adulthood showed spatially distinct, but adjacent representations for the two languages. A study by Perani and colleagues (Perani, Abutalebi, Paulesu, Brambati, & Scifo, et al. 2003) showed that adults who acquired their second language early and had comparable levels of proficiency in L1 and L2 showed differences in brain activation that were affected by both AoA and levels of language exposure. In contrast to these findings, Chee and colleagues (Chee, Tan, & Thiel 1999), and Klein and colleagues (Klein, Milner, Zatorre, Mayer, & Evans 1995) failed to show any discernable differences between the representations of L1 and L2.

Electromagnetic studies indicate that responses to L2 typically exhibit slightly

delayed latencies compared to L1 (Moreno & Kutas 2005; Alvarez, Holcomb & Grainger 2003; Leonard et al. 2010; Leonard et al. 2011), or are more widely distributed and use additional brain substrate (Zhang, Kuhl, Imada, Kotani, & Tohkura 2005; Leonard et al. 2010; Leonard et al. 2011). Other electrophysiological studies observe that only a few months of L2 exposure can result in near native-like neural activation patterns. One such study with adult learners of French observed neural responses that distinguished real words from non-words after only 14 hours of instruction (McLaughlin, Osterhout, & Kim 2004). The neural evidence of semantic priming (as measured by the N400, see section 2.2.1. for review) was observed after only 63 hours of instruction, and increased in amplitude as more language input was received.

Taken together, neuroimaging and electrophysiological studies generally agree that the L2 is acquired and processed through the same neural mechanisms that support the L1, and that the neural differences for L2 may be observed in terms of more extended or slightly delayed activity of the brain system supporting L1 (Abutalebi 2008). Behavioral studies suggest that the magnitude of AoA effects on L2 learning is highly variable and dependent on a large number of factors such as frequency of L2 use (Flege & Liu 2001), motivation to achieve high proficiency in L2 (Moyer 1999), and relationship between L1 and L2 (Low, Grabe, & Nolan 1999; Birdsong & Molis 2001). Because of high variability of AoA effects on L2 learning, some researchers have begun to question the validity of the critical period theory for language in general. They claim that if CP was a real phenomenon, the relationship between AoA and L2 proficiency would be non-linear, which has been shown to be the case in one study (Johnson & Newport 1989), but has not been replicated. Other researchers emphasize that near native

proficiency in L2 is, in some cases, possible despite an older AoA (Birdsong & Molis, 2001).

In summary, the effects of AoA on L2 acquisition and neural processing are an interesting and fruitful area of research; however, since L2 acquisition entails L1 acquisition (which typically occurs in childhood), this line of research does not provide a direct test of the critical period hypothesis.

1.2. Social and environmental isolation

Another source of information on the critical period for language comes from children who experience social isolation during childhood due to physical and/or emotional neglect or abuse. Case studies by Koluchova (1972) and Fujinaga, Kasuga, Uchida, & Saiga (1990) suggest that victims of language deprivation who experienced language before the age of 7 years eventually overcome their delays to develop linguistic competence comparable to their peers. Victims of social isolation who have been rescued after puberty, on the other hand, are reported to follow a different course of linguistic development. One such case was Genie, who was physically isolated from the outside world until she was 13;7 (Curtiss 1976). Genie was reportedly able to learn some English through intense instruction; for example, she was able to use limited vocabulary to form basic sentences, but her grammatical structures were inconsistent and atypical even 8 years after her rescue (Curtiss 1976). A central claim concerning Genie's linguistic development was that her lexicon remained largely intact, but her syntax was severely affected. This generalization has been very influential despite the fact that Genie's vocabulary size and composition were never measured systematically.

Cases of severe social or environmental isolation have never been neuroimaged while undergoing a language task. Genie was tested on a dichotic listening paradigm that showed increased right hemisphere activations in response to verbal stimuli, but not to non-verbal stimuli (Fromkin, Krashen, Curtiss, Rigler & Rigler 1974). The authors suggest that the inadequate language stimulation during Genie's early life interfered with normal left hemisphere development and lateralization for language processing (Fromkin et al. 1974; p. 101). However, these results should be interpreted with caution due to the multiple complications associated with Genie's background, such as poor nutrition, emotional neglect, and/or abuse, which become confounding factors in research.

Some of these methodological issues are addressed in the Bucharest Early Intervention Project (BEIP; Zeanah, Nelson, Fox, Smyke, & Marshall 2003), which is a randomized controlled study of foster care as intervention for children abandoned at the time of birth and placed in an orphanage. Note that these children do not begin to acquire their first language at a late age; their language development is interesting because they spent their infancy in a poor social and physical environment. The main finding is that age of foster care placement reliably predicts language outcomes; placement by age 15-24 months results in expressive and receptive language test scores that do not differ from typical age peers at 30 and 42 months. By contrast, children placed in foster homes after 24 months of age have severe language delays (Windsor, Benigno, Wing, Carroll, & Koga 2011). These results point to the importance of early environmental and social input in language development, in agreement with studies with typically developing children (Werker & Tees 2005; Kuhl, Tsao, & Liu 2003). Unfortunately, no neuroimaging or electrophysiological studies on BEIP children have considered their brain responses to

language stimuli.

1.3.Deafness

Congenital deafness isolates infants from spoken language, and often has the effect of delaying language input. In the USA, less than 10% of deaf children are born to deaf parents and begin to acquire American Sign Language (ASL) at birth (Schein 1989). For the remaining 90% of deaf children, language acquisition begins at a range of ages after birth, which are determined by different educational, cultural, and familial factors.

Studies on late acquisition of spoken language in deaf individuals conclude that the learning patterns are abnormal (Curtiss 1988; Grimshaw, Adelstein, Bryden, & MacKinnon 1998). Grimshaw and colleagues studied the case of E.M., a deaf boy who grew up in rural Mexico and used homesign, a self-created idiosyncratic gestural system (Goldin-Meadow, 2003; see section 3.2. for further discussion), to communicate with his caregivers. At the age of 15, he was fitted with hearing aids and began to spend 6 months per year in Canada with his hearing relatives who communicated with him in Spanish. E.M. was able to read and spell isolated Spanish words, but he reportedly kept using gesture to communicate. Similar conclusions were drawn by Curtiss (1988), who reports a case of Chelsea, a deaf woman who had been fitted with hearing aids and experienced spoken English for the first time at the age of 32. Curtiss (1988) observed that Chelsea's acquisition of vocabulary was rapid, but her syntax learning was poor. Nine years after receiving the hearing aid, Chelsea reportedly had a vocabulary of 2000 words, but very poor syntactic skills. It is important to note, however, that a typically developing six-year old knows between 8000 and 14000 words (Cairns 1996). A vocabulary of 2000 words after 9 years of language immersion constitutes a major delay. The results of studies on

spoken language acquisition in deaf individuals should be interpreted with caution; spoken language input may not be accessible to deaf individuals at the level that would allow normal language learning. Sign languages, on the other hand, are fully accessible to deaf individuals.

Below I review the current literature on sign language acquisition and neural processing when language input is available from birth (Section 2). Section 3 reviews the negative effects of delayed exposure to sign language, which are well documented and exist across virtually all domains of linguistic structure.

2. Sign language

2.1. Acquisition

Sign languages are linguistically equivalent to spoken languages and are structured at the level of syntax, semantics, morphology, and phonology (Klima & Bellugi 1979). Given these structural regularities, it is perhaps unsurprising that the infant attentional bias to language is not speech specific, but applies to sign language as well (Krentz & Corina 2008). When begun at birth, the acquisition patterns for sign languages parallel those of spoken languages (Anderson & Reilly 2002; Mayberry & Squires 2006). Deaf infants who experience sign language from birth produce manual babbling at roughly the same age as hearing children produce vocal babbling (Pettito & Marentette 1991). The subsequent acquisition of phonology in sign language, like in spoken language, is a highly structured process that takes years to be completely mastered (Marentette & Mayberry 2000).

In deaf children who experience sign language from birth, lexical acquisition parallels that of spoken languages in hearing children. First signs, like first words, are

typically produced between 10 and 12 months of age and denote objects and people closely related to the child's experience (Mayberry & Squires 2006)[1]. In a longitudinal observational and diary study of 11 children learning ASL from birth, Bonvillian, Orlansky, & Novack (1983) found that the number of early signs increased steadily in a fashion comparable to early spoken word acquisition over the first 30 months of life. Like early-acquired words of spoken languages, early-acquired signs are overwhelmingly nouns as compared to predicates. These findings were later confirmed in a normative study using the MacArthur-Bates Communicative Developmental Inventory for ASL (Anderson & Reilly 2002), which identified a series of other parallels between the acquisition patterns of ASL and English. For example, two-word combinations in both ASL and English begin to appear only after the child can reliably produce 50-100 words. In both ASL and English, grammatical words are acquired after a critical mass of content words has been learned, and vocabulary size predicts utterance length in both languages (Bates et al. 1994; Anderson & Reilly 2002).

In conclusion, several studies have shown that native sign language acquisition is comparable to spoken language acquisition, at least in the early stages. Not many longitudinal studies have been conducted to consider the later stages of language development; for example, it is largely unknown how deaf children transition from single words to utterances. It is important to note, however, that native exposure to sign is fairly uncommon; the more typical developmental experience in the deaf population is sign

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[1] Like in spoken language, the exact content and sequence of lexical acquisition varies from sign language to sign language. In this dissertation we focus on ASL, as this is the

language acquisition at a later age, which has not been documented in great detail (but see section 3.1.).

2.2. Neural representation of sign language

Lesion studies indicate that sign language aphasia results from strokes to the left, but not the right hemisphere (Poizner, Klima & Bellugi 1987; Hickok, Bellugi & Klima 1996). As in spoken language, hemodynamic studies on sign language comprehension consistently show activations in the classic left hemisphere perisylvian areas and, to a lesser extent, in the homologous right hemisphere areas (Petitto, Zatorre, Gauna, Nikelski, & Dostie et al. 2000; MacSweeney, Capek, Campbell, & Woll 2008; Sakai, Tatsuno, Suzuki, Kimura, & Ichida 2005; Mayberry et al. 2011; MacSweeney, Campbell, Woll, Brammer, & Giampietro et al. 2006). This is particularly true for studies considering the neural representation of single lexical signs. MacSweeney et al (2006) used fMRI to show that lexical comprehension in BSL recruits a left-lateralized fronto-temporal network including the inferior and middle frontal gyri, extending into the precentral gyrus. Along similar lines, Corina and colleagues (Corina, Chiu, Knapp, Greenwald, & San Jose-Robertson et al. 2007) show that ASL lexical processing in native signers engages the left perisylvian network. Importantly, the same network was not activated when native signers watched non-linguistic gestures, suggesting that experience with sign language results in engagement of specialized neural systems that allow for rapid differentiation of linguistic and non-linguistic input (Corina et al. 2007).

Lexical production in sign has also been shown to engage similar neural substrate as lexical production in spoken language. Using PET, Emmorey and colleagues conducted a naming task in ASL and observed activations in the left ventral infero-

temporal cortex, the left inferior frontal gyrus and in the left lateral occipital lobe Emmorey, Grabowski, McCullough, Damasio, Ponto et al. 2003); the same brain network was activated when hearing native speakers performed the task in English (Damasio, Grabowski, Tranel, Hichawa, & Damasio 1996). Importantly, the neural patterns associated with sign retrieval were unaffected by the iconic relationships between the meaning and phonological form of signs (Emmorey et al. 2003), a finding which has been confirmed in an fMRI study of German Sign Language using a lexical decision task (Klann et al. 2005). These results indicate that the neural processing of signs, regardless of their phonological form, is linguistic in nature.

Some have argued that sign language processing is more bilateral than spoken language processing (for example Newman, Bavelier, Corina, Jezzard, Neville 2002); however, other studies do not find these differences (Sakai et al. 2005; Emmorey et al. 2003). These inconsistencies tend to be associated with the hemodynamic studies that use longer sentence- or discourse-level stimuli. It has recently been reported that discourse level ASL stimuli, but not ASL sentences, elicit right hemisphere activations in native signers (Newman, Supalla, Hauser, Newport, & Bavelier 2010), in agreement with spoken language studies that show involvement of the right hemisphere for discourse-level processing (St George, Kutas, Martinez, & Sereno 2010). Recently, increased right hemisphere activations have also been linked to the retrieval of classifiers (Emmorey, McCullough, Mehta, Ponto, & Grabowski 2013). Importantly, the same study reports left fronto-temporal activations with no significant right hemisphere activity for retrieval of lexical ASL signs.

Taken together, studies generally agree that the left hemisphere fronto-temporal

areas play an important role in sign language processing. The role of the right hemisphere is less well understood. Some of the inconsistencies in findings may stem from different stimuli, tasks, or subject populations used among the studies. However, it is also the case that the hemodynamic response fails to capture the exact timing of neural responses, and may thus contribute to inconsistent findings due to its inability for identifying the brain regions involved in different processing stages. Unlike hemodynamic studies which rely on vascular changes that take place over seconds, a time-scale much longer than the speed of on-line language processing, electromagnetic techniques, such as electroencephalography (EEG) or magnetoencephalography (MEG) measure the transmission of the electromagnetic signal within the brain, which is effectively instantaneous. Due to their excellent temporal resolution, these techniques allow us to resolve specific stages of sign processing, presenting an important advantage over hemodynamic methods.

The current dissertation focuses on lexico-semantic encoding; i.e., we ask where and when signs are linked to their meaning. We focus on the neural processing of single words (signs) mainly because the cases that we study have just begun to acquire ASL, and thus have limited language skills (see Chapter 2). By focusing on the neural representation of single words we were able to design a study that the cases were able to perform with high accuracy and fast reaction times while in the MEG scanner.

Spatio-temporal dynamics of single word processing has not been studied extensively in sign, but is relatively well explored in the spoken and written modality. As explained in greater detail below (section 2.1.1.), these studies suggest that the neural networks for lexico-semantic processing are modality independent. What is currently

unknown, however, is whether auditory language stimulation is required to bring about the functionality of these networks (which can then subsequently be used for auditory and written language processing). AMEG studies with deaf participants processing sign language are thus important to advance our understanding of neural language processing in general, as they can tell us whether the neural underpinnings of language are dependent on auditory language experience. The section below provides a brief review of lexico-semantic processing in the spoken and written modality.

2.2.1. Lexico-semantic processing: The N400

Using event related potentials (ERPs), Kutas and Hillyard (1980) described a scalp-recorded negativity peaking at ~400 ms, which varies systematically with the processing of semantic information. The N400 was first observed in response to a semantically anomalous word at sentence endings, such as "sock" in "He spread the warm bread with butter and sock". The N400 is especially large in response to semantic violations, and it is attenuated depending on the ease of the word's integration into the cognitive context. Studies with single auditory and written words show that the N400 is attenuated to a given word by previous presentation of the same word (repetition priming) or a semantically related stimulus (semantic priming) (Kutas & Federmeier 2000).

Because of the inverse problem, the generators of the N400 are difficult to localize from scalp EEG alone. That is, for any distribution of EEG signals recorded on the scalp, there are infinitely many possible configurations of current sources and sinks within the brain that are consistent with the recording. Direct intracranial recordings suggest that the N400 is generated in the left anteroventral temporal, posterosuperior

temporal, and posteroventral prefrontal cortices (Halgren, Baudena, Heit, Clarke, & Marinkovic 1994a; Halgren, Baudena, Heit, Clarke, & Marinkovic 1994b; Smith, Stapleton & Halgren 1986; McCarthy, Nobre, Bentin, & Spencer 1995), in accordance with the hemodynamic literature, as well as clinical studies on aphasia (Goodglass 1993) and semantic dementia (Patterson, Nestor, & Rogers 2007).

The electrical currents that underlie the N400 also produce a magnetic field, which can be detected on the cortical surface with MEG, and has been termed the N400m (Dale, Liu, Fischl, & Buckner 2000; Halgren, Dhond, Christensen, VanPetten, & Marinkovic et al. 2002). The inverse problem in MEG is just as ill-posed as it is in EEG. However, the magnetic field is less distorted by the changes in conductivity between the brain, skull, and scalp than electric current. As a result, the MEG recorded outside of the head is very similar to what would be recorded on the exposed brain surface, making reconstruction far easier and more accurate (Hansen, Kringelbach, & Salmelin 2010). In addition, the MEG data can be analyzed by imposing constraints based on anatomical and physiological information derived from magnetic resonance imaging (MRI), thereby further disambiguating the inverse problem (Dale at al. 2000). The main cortical generators of MEG signals are in the gray matter and are oriented perpendicularly to the cortical sheet (Nunez 1981). Once we reconstruct the exact shape of each subjects' cortical surface (from MRI), the MEG solution space can be greatly reduced (Dale & Sereno 1993). This method is known as anatomically constrained magnetoencephalography (aMEG)[2]; and it affords excellent temporal resolution (on the order of milliseconds) and good spatial resolution (on the order of millimeters; see Dale

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[2] The same method is also known as dynamic statistical parametric mapping (dSPM).

et al. 2000).

Previous studies using aMEG have demonstrated that it is sensitive enough to detect fine differences in written and auditory language processing in healthy monolingual adults (Dale et al. 2000; Halgren et al. 2002; Marinkovic, Dhond, Dale, Glessner, Carr et al. 2003; Travis, Leonard, Chan, Torres, Sizemore et al. 2012), bilinguals (Leonard, Brown, Travis, Gharapetian, & Hagler et al. 2010; Leonard, Torres, Travis, Brown, & Hagler et al. 2011), and even 12-18 month old infants (Travis, Leonard, Brown, Hagler, & Curran et al. 2011). These studies have shown that early word processing is modality specific and occurs in the superior temporal region in response to spoken words at ~55 ms, and in the occipital cortex in response to written words at ~100 ms. For the spoken and written modality, neural activity then spreads along the respective ventral processing streams and converges on the anterior temporal and inferior prefrontal regions primarily on the left at about 400 ms, which is when lexico-semantic processing is thought to occur (Kutas & Federmeier 2000; Halgren et al. 1994 a,b; Marinkovic et al. 2003; Patterson et al. 2007). These patterns agree with studies on aphasia, studies using hemodynamic methods, and studies using intracranial recordings.

2.2.2. N400 in sign language

A few EEG studies have considered the temporal dynamics of meaning processing in sign language (Kutas, Neville, & Holcomb 1987; Neville, Coffey, Lawson Fischer, Emmorey et al. 1997; Capek, Grossi, Newman, McBurney, Corina et al. 2009, Grosvald, Gutierrez, Hafer, & Corina 2012; Gutierrez, Williams, Grosvald, & Corina 2012). Kutas and colleagues directly compared sentences in ASL, written, and auditory English, and proposed that lexico-semantic encoding as measured by the N400 is

equivalent across modalities. Consistent with spoken language studies, Capek et al. (2009) and Grosvald et al. (2012) show that in deaf native signers the N400 response to semantic anomalies in ASL sentences is bilaterally distributed and largest over posterior sites. These results are consistent with the idea that semantic processing within written, spoken, and sign languages, is not affected by the modality through which the linguistic signal is conveyed, or by the modality through which early language is experienced.

Other EEG studies point to potential differences between the processing of sign and spoken language. Neville et al (1997) report that while the ERP responses to written words in hearing native English speakers are left-lateralized by 150 ms post stimulus, the responses to ASL signs in deaf native signers do not display such asymmetries prior to 550 ms post stimulus. It is important to emphasize that these studies compare sign language to *written* language, which may be one of the cause of the observed discrepancies. Written language, unlike sign, is devoid of prosody, which is known to be processed largely by the right hemisphere. In addition, written language is not a primary form of language acquisition from birth.

Another potential difference between the N400 in spoken and sign language concerns its latency. Neville et al. (1997) and Capek et al. (2009) suggest that the N400 in sign is delayed compared to the N400 in response to auditory words. However, it should be noted that both studies consider the N400 effects in sentential contexts, which may be affected by the co-articulatory effects of the previous word or sign. It has previously been shown that co-articulatory effects do affect the perception of signs (see Morford & Carlson 2011); however, this is a poorly researched topic, and it is unknown whether the co-articulatory effects in signs are equivalent to those in speech. The

temporal dynamics of single sign processing without sentential context has not yet been studied.

In conclusion, electrophysiological studies, like hemodynamic studies, emphasize the parallels between the neural correlates of sign and spoken word processing. Hemodynamic studies point to the use of a similar neural substrate, regardless of modality. Electrophysiological studies indicate the sensitivity to semantic violations as indexed by the N400. Many questions remain to be answered, however. Due to the propagation and smearing of electrical signal through various media in the head, the differences in ERP components that have been observed in some, but not all ERP studies comparing sign and spoken language, are difficult to interpret. It is still unclear whether the recognition of word meaning in sign occurs through a process analogous to that in speech. The neural generators of the N400 in sign are unknown, and the spatio-temporal dynamics of lexico-semantic processing of signed words without sentential context has not yet been studied. Given a lack of research in this area, one of the goals of this dissertation is to characterize how (where and when) single signs are processed in the brains of those deaf individuals who have been using sign language as their main language of communication from birth (deaf native signers; Chapter 3). We then investigate whether and how sign processing is affected by a lack of childhood language experience (Chapter 4). In the following section, we review the currently available literature on the effects of delayed exposure to sign language.

3. Delayed exposure to sign language

Deafness often has the effect of delaying language input because sign language frequently is not immediately available to deaf children in their environment. Some deaf

children have virtually no exposure to sign throughout early childhood and do not acquire speech or lipreading due to restricted uptake of the spoken language input. Some extreme cases are cut off from nearly all language until adolescence (adolescent L1 learners); they do not have meaningful access to spoken language and, due to various circumstances in their upbringing, they have not been exposed to any kind of sign language. The current dissertation considers sign language acquisition and the neural representation of word meaning in three such individuals. Below I review the existing literature on sign language acquisition when begun at a late age (section 3.1.), and then turn to the psycholinguistic and neuroimaging studies with adult late L1 learners (sections 3.2. and 3.3.).

3.1. Sign language acquisition begun at a later age

Although most deaf children experience sign language at ages well past infancy, research on the patterns of sign language acquisition following delayed onset is sparse, and consists of a few case studies. A related line of research focuses on homesign, a gestural communication system that deaf children create in the context of spoken and signed language deprivation (Goldin-Meadow 2003; see also Morford & Hänel-Faulhaber 2011). Homesigners' gestures exhibit many properties of conventional language, such as the use of gestures in consistent manner, and regularity in the order of constituents (Goldin-Meadow 2003). However, homesign does not use complex syntactic structures found in conventional languages, nor is there evidence of phonological structure that is independent of morphological structure. In addition, homesigners' communicative experience is unconventional because it is primarily expressive from the start, as their parents generally do not adopt their full homesign system. Considering these important differences, it is perhaps unsurprising that homesign does not serve as L1

in terms of supporting future conventional language acquisition (Morford & Hänel-Faulhaber 2011).

In the United States homesigners typically begin to attend school and experience language (spoken or signed) by age 5 or younger. However, some rare cases do not receive any special services and do not experience any formal language until adolescence, mostly due to atypical family or social circumstances that include a lack of schooling at the typical age of 5. When such cases of deaf adolescent or adult homesigners are identified, attempts to teach them sign language are undertaken if resources are available.

Berk and Lillo-Martin (2006) studied two deaf children, Mei and Cal, who started acquiring ASL at age ~6 years. Due to unusual family and social circumstances, these two children reportedly did not develop an elaborate homesign system prior to ASL exposure. After about a year of ASL immersion, Mei and Cal had a mean length of utterance (MLU) of 2, comparable to that of 2-year-old native signing children. Like native signing children, they used nouns more frequently than verbs, and this ratio decreased as more language was acquired. One important finding was that Mei and Cal acquired ASL signs at a faster rate than deaf children who experienced ASL from birth, and that they, unlike infant learners, used mental verbs, such as "think" or "believe". The study concludes that older L1 learners exhibit the same language acquisition milestones as native learners (for example, an early noun bias and the emergence of a two-word stage), but display a greater variety of vocabulary items which include mental verbs and other vocabulary that is used to express more complex semantic relations (Berk & Lillo-Martin 2006). Interestingly, similar findings have previously been reported in

internationally adopted children who begin acquiring an L1 in their country of origin, but then become monolingual speakers of another language upon adoption to a new country (i.e. second first-language learners; Roberts, Pollock, Krakow, & Price 2005; Snedeker, Geren, & Shafto 2007, 2012). Together, these studies suggest that older language learners initially acquire language in a similar fashion as infants, but perhaps at faster rate. However, no longitudinal data is available, so it is unclear how they transition from single words to sentences.

Another case of late L1 acquisition was studied by Emmorey, Grant, and Ewan (1994). This case, named Anna, had an elaborate homesign system prior to ASL immersion at age 16. Anna began to rapidly replace her gestures with ASL signs, and after 9 months had a vocabulary of over 500 signs. Like infant learners, Anna exhibited a noun bias: 51% of her lexical items were nouns, 25% were verbs, and 16% were adjectives (Emmorey et al. 1994). Unfortunately, no longitudinal data on subsequent linguistic development is available.

Morford (2003) observed the linguistic development in Marcus and Maria, two homesigners who first began to acquire ASL at age 13. Like Anna, Marcus and Maria quickly replaced their gestures with ASL signs and were able to produce verb agreement and classifier constructions in a narrative elicitation task after only 3 years of ASL use (Morford 2003). However, their real-time comprehension of ASL utterances out of context was barely above chance after 7 years of ASL. Perhaps these communication deficits are related to the fact that, prior to the onset of formal language, Maria and Marcus, like other homesigners, did not have a native language model to learn from, but rather invented a communicative system of their own. As pointed out by Morford (2003),

homesigners innovate structure, but they do not automate the processing of structure (Morford 2003; Morford & Hänel-Faulhaber 2011). Their experience is thus very different from that of typically developing children, who begin their linguistic journey by observing and statistically analyzing the recurrent patterns of language, and whose language comprehension is ahead of production for several years.

In sum, studies on late and adolescent L1 learners of sign language suggest that these individuals retain the capacity of zeroing in on linguistic input when it becomes available, and quickly replace their idiosyncratic gestures with lexical items. However, severe comprehension deficits persist (Morford 2003). Our understanding of how exactly childhood language deprivation affects the trajectory of subsequent language acquisition is limited, mainly because the early stages of language acquisition in late learners (for example, the acquisition of vocabulary), remain unexplored. Furthermore, due to a lack of longitudinal studies with late L1 learners, it is unclear how they transition from single words to sentences. These questions are theoretically and practically important: theoretically, studying the patterns of late L1 acquisition allows us to consider the role of early input in language development. Practically, studying the developmental patterns in late L1 acquisition can illuminate the origin of the deleterious effects of childhood language deprivation on adult language processing, which have been well documented and are reviewed in the section below.

3.2. AoA effects on sign language processing: Psycholinguistic studies

Several studies have found a negative correlation between L1 AoA and ultimate proficiency in sign language (Mayberry & Fischer 1989; Newport 1990; Mayberry & Eichen 1991; Boudreault & Mayberry 2006). Mayberry and Fischer (1989) tested deaf

signers with varying AoA on a sentence-shadowing task. Native signers outperformed non-native signers on sentence comprehension as well as on the accuracy of shadowing. Interestingly, while native signers made lexical errors that were related to the target signs in meaning (such as producing the sign DOG instead of CAT) non-native signers primarily committed phonological errors (such as producing the sign SLEEP instead of AND; these two signs share phonological parameters) (Mayberry & Fischer 1989). These findings were replicated in the study by Mayberry and Eichen (1991), who tested 49 deaf participants with at least 20 years of ASL experience on a sentence-recall task. Performance declined as a function of AoA, and non-native learners produced phonological errors, while native learners produced semantic errors. These findings suggest that lexical processing in deaf native signers is automatic, which leads to good memory of semantic meaning of the sentence. Non-native signers, on the other hand, seem to pay attention to the phonological parameters of signs, which may lead to decreased ability to focus on meaning (Mayberry 1994). Two recent studies provide additional evidence to support this hypothesis: Morford & Carlson (2011) and Hall, Ferreira, & Mayberry (2012) show that late L1 learners differ significantly from deaf native learners in phonological recognition patterns for signs. Interestingly, both studies show that hearing L2 learners of ASL showed phonological recognition patterns that are more "native-like" than those of deaf late learners, suggesting that the observed phonological difficulties are caused by a lack of childhood language experience, not language acquisition at a later age. Together, these findings suggest that late L1 acquisition leads to more controlled, non-automatic and effortful phonological processing (Mayberry 1994), perhaps as a consequence of a lack of childhood exposure to

phonological patterns of native language.

Another area known to be severely affected by a lack of childhood language exposure is grammatical morphology. Using a task testing production and comprehension of complex morphology, Newport (1990) tested 3 groups of deaf adults: native learners who experienced ASL from birth, early learners who experienced ASL between ages of 4 and 6, and late learners who experienced ASL after the age of 12. Native learners outperformed the early learners, who outperformed the late learners; comprehension and production of grammatical morphology were directly predicted from AoA. These results agree with those reported by Mayberry and Eichen (1991) who found that native learners were far more likely than childhood and adolescent learners to produce grammatical morphology on a sentence recall task. AoA also affects the ultimate outcome of syntactic knowledge. Boudreault & Mayberry (2006) used a timed grammatical judgment task to test 30 deaf signers who first experienced ASL between ages 0 and 13 years. As AoA increased the accuracy of grammatical judgment decreased.

Taken together, the effects of L1 AoA have been shown across different levels of linguistic structure, and are strongest in those cases where no formal language has been available until late childhood, or even early teenage years (Boudreault & Mayberry 2006). Importantly, these effects are qualitatively distinct from those associated with L2 acquisition; while near-native L2 acquisition is, in some cases, possible despite older AoA, this is not the case for late L1 acquisition. In a sentence recall task, Mayberry (1993) tested two groups of subjects: L1 ASL learners who were born deaf and learned ASL at ages 0 to late childhood, and L2 ASL learners who were born normally hearing and learned English as their L1, and then learned ASL as L2 in late childhood because

they became deaf. L2 ASL learners significantly outperformed the L1 learners who acquired ASL at exactly the same age, indicating that AoA has more extensive effects on L1 than L2 outcome (Mayberry 1993). This finding has later been replicated on a grammatical judgment test in written English. Hearing L2 learners of English (L1 speakers of various languages, such as German, Urdu, and French) were compared to deaf learners of English who either experienced ASL from birth (native L1 ASL learners), or did not experience any language in infancy. The L2 learners outperformed the late L1 learners, independent of hearing status (Mayberry & Lock 2003; Mayberry, Lock & Kazmi 2002). These findings show that L1 AoA affects the ability to learn language, not just L1, but also subsequent L2s. These findings have recently been replicated in British Sign Language (Cormier, Schembri, Vinson, Orfanidou 2012).

3.3. AoA effects on sign language processing: Neuroimaging studies

The results of the above-described psycholinguistic studies have recently been linked to atypical brain activation patterns in response to language stimuli in late L1 learners. Mayberry et al. (2011) considered the neural underpinnings of ASL in 23 lifelong deaf signers who first experienced ASL at ages ranging from birth to 14 years. On a grammatical judgment task and on a phonemic hand-judgment task, early ASL exposure correlated with greater positive hemodynamic activity in the classical language areas (including the left inferior frontal gyrus, left insula, left dorsolateral prefrontal cortex, and left superior temporal sulcus), and greater negative activity in the perceptual areas of the left lingual and middle occipital gyrus. As age of L1 exposure increased, this pattern was reversed, suggesting that linguistic representations may rely to a greater extent on posterior brain areas when language is acquired late.

A recent study using Voxel-Based Morphometry shows that a lack of childhood language affects not only the functional, but also the anatomical organization of the brain (Penicaud, Klein, Zatorre, Chen, Witcher, Hyde, & Mayberry 2013). This study tested the same groups of participants as Mayberry et al. 2011, and showed that delayed L1 acquisition results in changes in tissue concentration in the occipital cortex, close to the brain areas that were recruited during language processing in late L1 learners. More specifically, gray matter concentration in V1/V2 and V3a/V7 was negatively correlated with AoA, and there was a trend towards a positive correlation between AoA and white matter concentration in V3a/V7 area. This suggests an important link between the brain function and structure in the occipital cortex for deaf signers; however, it is currently unclear whether the structural changes drive the functional changes or vice versa.

Taken together, behavioral and neuroimaging studies show that delayed exposure to sign language has severe and life-long consequences on language processing. Many questions remain to be answered, however. In this dissertation, we explore two main issues: First, how is language acquired when acquisition begins for the first time in adolescence? In Chapter 2 we focus on the early stages of adolescents' L1 lexical acquisition by measuring their lexical comprehension and production with the MacArthur-Bates Communicative Developmental Inventory for ASL and analyzing their spontaneous language production. Second, we explore the relationship between the timing of language experience and the neural representation of meaning with aMEG. We first study the spatiotemporal dynamics of lexico-semantic processing in deaf adolescents who acquired ASL from birth (Chapter 3), and then turn to two adolescent L1 learners of ASL (Chapter 4).

In conclusion, studying the patterns of language acquisition and neural processing of meaning following delayed exposure to language input seems to be a fruitful research area that can provide important theoretical advances in the area of critical period for language, and practical advances for deaf education and education of other populations at risk for language delay. In the following sections I present one behavioral and two neuroimaging studies with the goal of advancing our understandings of the critical period for language.

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CHAPTER 2:

The Initial Stages of First-Language Acquisition Begun in Adolescence:

When Late Looks Early

Abstract

What is language acquisition like when it begins for the first time in adolescence? This study investigates the initial language acquisition of three deaf adolescents who have, due to anomalies in their upbringing, begun to acquire American Sign Language (ASL) as their first language (L1) at age 14 years. We study their language after 12 to 24 months of acquisition using the ASL-CDI coupled with detailed analyses of spontaneous language production. Despite diverse backgrounds, adolescent L1 learners exhibit highly regular lexical acquisition, which is remarkably similar to child L1 learning. Further, adolescent L1 learners produce simple utterances; utterance length can be predicted from vocabulary size and composition, much like in typically developing children. Our results suggest that the initial stages of L1 acquisition are common to all L1 learning, irrespective of age, and we discuss why this may be so.

Introduction

Children typically acquire their native language naturally and spontaneously at a very young age. The emergence of early grammar can be predicted from children's vocabulary size and composition (Bates, Marchman, Thal, Fenson, Dale, Reznick, Reilly, & Hartung, 1994; Bates, Bretherton, Snyder, 1998; Bates & Goodman,1997). One central

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question in language research is understanding what causes the changes in early language acquisition. Some researchers argue that the qualitative and quantitative shifts in word learning simply reflect the changing character of the child's cognitive maturity (for example, Gentner, 1982), while others argue that the trajectory of early language acquisition is driven by the child's growing familiarity with the language (Gillette, Gleitman, Gleitman, & Lederer, 1999; Snedeker & Gleitman, 2004). These hypotheses are difficult to adjudicate because language acquisition in virtually all hearing children begins from birth and occurs simultaneously with cognitive development and brain maturation. The acquisition of sign languages, in contrast, is frequently delayed until older ages. In the USA, over 90% of deaf children are born to hearing parents who do not use sign language (Schein, 1989). As a result, deaf children are often exposed to sign language as a first language at a range of ages well beyond infancy (Mayberry, 2007). In rare cases, some deaf individuals are isolated from all linguistic input until adolescence when they start receiving special services and begin to learn sign language through immersion (Morford, 2003). Case studies of language acquisition in such extreme late first-language (L1) learners provide a unique opportunity to investigate first-language learning. The current study investigates three cases of young teens, who are in the early stages of acquiring American Sign Language (ASL) as a first language, to determine what first-language acquisition in adolescence looks like.

Although the exact sequence and content of early language development varies somewhat from language to language, some universal principles seem to be followed, such as the existence of a noun bias, and the relationship between vocabulary size and grammatical complexity. These characteristics of early language learning have been

documented in normally developing children cross-linguistically, as well as in atypical populations, such as early talkers, children with Williams and Down Syndrome, and children with focal brain injury (Bates & Goodman, 1997). Furthermore, these principles have been shown to be independent of the modality through which the language is conveyed, spoken or signed.

Like other sign languages, ASL is linguistically equivalent to spoken languages and obeys linguistic rules at the level of phonology, morphology, syntax and semantics (Klima & Bellugi, 1979; Sandler & Lillo-Martin, 2006). It is thus not surprising that when begun at birth, the acquisition patterns for ASL parallel those of spoken languages with respect to the timing and content of linguistic milestones (Anderson & Reilly, 2002; Mayberry & Squires, 2006; Newport & Meier, 1985; Reilly, 2006). In a study of 5 infants, Petitto and Marentette (1991) found that deaf infants who are exposed to sign language from birth produce manual babbling at 6 to 12 months, which corresponds to the age of onset of vocal babbling in hearing infants. First signs, like first words, are typically produced around the age of 10 months and denote objects and people closely related to the child's experience (Mayberry and Squires, 2006). In a longitudinal, combined observational and diary study of 11 children exposed to ASL from birth, Bonvillian, Orlansky, & Novack (1983) found the number of early signed words acquired increased steadily in a fashion comparable to early spoken word acquisition over the first 30 months of life. They found that early acquired signs are overwhelmingly nouns as compared to predicates. In a normative study using the MacArthur-Bates Communicative Developmental Inventory for ASL on a sample of 69 deaf children of deaf parents, Anderson & Reilly (2002) identified a series of parallels between the acquisition patterns

of ASL and English. Although the two languages are distinct, with ASL having significantly more inflectional morphology than English (Sandler & Lillo-Martin, 2006), two-word combinations in both ASL and English begin to appear only after the child can reliably produce 50-100 words. In both ASL and English, grammatical words are acquired after a critical mass of content words has been learned (Anderson & Reilly, 2002; Bates & Goodman, 1997). Although the proportion of predicates in early ASL vocabularies tends to be higher than in English, which may be attributed to its use of pro-drop and highly inflected verbs, children acquiring ASL or English exhibit a clear noun bias which begins to disappear as more predicates enter the lexicon. Further, vocabulary size predicts utterance length in both languages. This indicates that lexical and syntactic development are intertwined regardless of language modality (Bates et al, 1994; Anderson & Reilly, 2002).

A small percentage (less than 10%) of American deaf children are born to deaf parents and thus acquire sign language from birth (Schein, 1989). For the remaining 90% of deaf children who are born to hearing parents, sign language exposure and acquisition begins at a range of older ages determined by several educational, cultural and familial factors, but not biological ones. For example a school that uses sign language may not be accessible to the family, or the child may not have been enrolled in school at all until an older age. As is the case for hearing children's acquisition of spoken language (Huttenlocher, Vasilyeva, Cymerman & Levine, 2002), the quantity of sign language input deaf children receive in childhood affects their acquisition rate (Lederberg & Everhart, 1998; Spencer, 1993).

In rare cases, deaf individuals are linguistically isolated until adolescence; they cannot hear spoken language and, due to social and other factors, they have not been exposed to any kind of sign language. Unlike most deaf children, these individuals have experienced limited schooling and received very little or no language input of any kind (spoken, written, or signed) throughout childhood. After they are 'identified', they begin receiving special services and, if resources are available, may become fully immersed in sign language. Such deaf cases are unique because they have been linguistically isolated until adolescence, at which point they become immersed in sign language for the first time. We ask how these adolescent L1 learners begin to acquire language. Do they begin where young hearing children begin, or do they bypass some stages in acquiring their language due to the fact that they are cognitively more mature when first encountering language? If language acquisition in older learners shows a similar pattern as what we see in young children, we can conclude that at least some of the principles driving the language acquisition process are age independent. The answer to this question is important because it furthers our understanding of the mechanisms underlying language acquisition in general. Previous research has explored the question of language acquisition in older learners using four different approaches, which we discuss below.

The first approach involves experimental studies on language processing in life-long users of sign language. These studies consider various aspects of language processing in adults whose first language acquisition began at a variety of ages past infancy, but who have been using sign language for at least 20 years. Results consistently indicate a negative correlation between the age onset of sign language acquisition and ultimate proficiency (Mayberry & Eichen, 1991; Newport 1990). For example, Mayberry

and Eichen (1991) used a sentence recall task with 49 deaf life-long signers who began ASL acquisition at a variety of ages, and found that age at onset of acquisition (AoA) had significant effects on performance at all levels of linguistic structure. Importantly, AoA effects on L1 are unlike those documented to exist in second language (L2) learning (Birdsong, 1992; Flege, Yeni-Komshian, & Liu, 1999). Mayberry & Lock (2003) found in a study with 54 participants of varying language backgrounds, that learning an L2 at an older age can result in native-like proficiency, but acquiring an L1 at an older age results in attenuated proficiency and linguistic deficits across all languages subsequently acquired, regardless of modality. It is important to note that these studies, while crucial in demonstrating the severity of the effects of delayed language acquisition, do not directly address the question of *how* a first language is acquired at an older age.

The second approach to studying whether later language acquisition is similar to early acquisition is to investigate cases of international adoption (Pollock, Price, & Fulmer 2003; Roberts, Pollock, Krakow, & Price, 2005; Snedeker, Geren, & Shafto, 2007). Internationally adopted children typically begin acquiring a first language in their country of origin, but then become monolingual speakers of another language upon adoption to a new country. In a study of two toddlers adopted from China, Pollock et al (2003) found that age at adoption was negatively related to the rate of phonological acquisition, vocabulary acquisition, and syntactic development during the first two years following adoption. However, Roberts et al (2005) studied 55 children adopted from China and found that the majority soon catch up with their monolingual peers, scoring within the normal range on standardized language tests by preschool age. Because the age of onset of language acquisition in internationally adopted children varies, Snedeker et al

(2007) conducted a study with 27 children adopted from China and asked whether older adoptees follow the same general pattern of language acquisition as infants who begin to acquire a single language from birth. Interestingly, Chinese adoptees who began to acquire spoken English at a later age (between ages 2;7 and 5;1) followed the same early language acquisition path, with respect to sequence and content, as did monolingual toddlers acquiring English from birth. Based on these results, Snedeker and colleagues (2007) concluded that early word acquisition must, at least in part, be driven by an age-independent process. Note, however, that internationally adopted children have already begun to acquire a language from birth, although they switched acquisition to another language following adoption. International adoption has thus been characterized as 'second first-language acquisition' (Roberts et al, 2005), and its outcomes might differ significantly from those arising from very late exposure to linguistic input of any kind.

The third way of studying language acquisition begun at older ages is to consider cases of social isolation and/or abuse. Case studies by Koluchova (1972) and Fujinaga, Kasuga, Uchida, & Saiga (1990) suggest that victims of language deprivation who were exposed to linguistic input before the age of 7 years eventually overcome their delays to develop a linguistic competence comparable to their peers. Victims of social isolation who have been rescued after puberty, on the other hand, are reported to follow a different course of linguistic development. The case study known as Genie, who was physically isolated from the outside world until she was 13;7, was reportedly able to use limited vocabulary to form basic sentences, but her grammatical structures were inconsistent and atypical even 8 years after her rescue (Curtiss, 1976).

The fourth source of information on language acquisition begun at a later age is provided by case studies of deaf individuals who were born to hearing parents and were linguistically isolated because of their deafness. Due to a variety of factors, these children were not exposed to language input until adolescence or adulthood, when attempts to teach them a spoken or a signed language were undertaken. Case studies of two deaf adolescents acquiring a spoken language have found that they produce variable word order and almost no inflectional morphology (Curtiss, 1988; Grimshaw, Adelstein, Bryden, & MacKinnon, 1998). From these data, researchers have argued that adolescents' lexical development is advanced compared to their syntactic development (Curtiss, 1988; Grimshaw et al, 1998). It should be noted, however, that the research focus of these studies was on the development of syntactic skills and that the lexicon of these adolescent learners was not investigated. Further, these results should be interpreted with caution because spoken language input may not have been accessible to these deaf learners at a level that would allow normal language acquisition.

Morford (2003) observed the linguistic development of Maria and Marcus, two deaf adolescents who immigrated to North America with their families at ages 13;7 and 12;1 respectively. In their countries of origin Maria did not attend school and Marcus attended a hearing school for a short period of time. Like some other deaf children who acquired little functional language in early childhood, Maria and Marcus developed and used homesign. Homesign consists of combinations of points and idiosyncratic gestures generated by the child to communicate with family members (Goldin-Meadow, 2003). Morford studied the two adolescents longitudinally on a narrative retell task using the story *Frog, Where are You?* (Mayer, 1969) and observed significant gains in their

grammatical ability over time: their mean utterance length increased from an average of 3.3 signs after two months of ASL exposure to 8.3 signs after 31 months of exposure. Both adolescents had replaced most of their gestures with ASL signs and showed a significant increase in nonverbal IQ scores (Morford, 2003). However, comprehension tests after 7 years of ASL exposure showed persistent comprehension problems, with performance levels being only slightly above chance. Maria's and Marcus' lexicons were not studied in detail, and it is unknown what kinds of words they acquired in their first years of exposure to ASL, or whether their vocabulary size was related to the length and complexity of their utterances.

Emmorey, Grant, & Ewan (1994) studied the linguistic abilities of another home-signer who was first exposed to ASL at age 16 years. At the end of the study, after 9 months of exposure, this individual communicated predominantly through the use of ASL signs. Her vocabulary at that point was estimated to consist of over 500 signs, which is comparable to a 3-year-old, typically developing deaf child (Anderson & Reilly, 2002).

In sum, our understanding of how later exposure to language affects language acquisition in its beginning stages is primarily limited to adoption studies, as studies of other late-learning populations have focused on different aspects of language learning. To date, case studies of linguistic isolation have not systematically investigated *how* older individuals begin to acquire their first language. Studies of language acquisition in deaf late learners are theoretically important because they provide a unique opportunity to study what language acquisition looks like when it is not confounded by the factors of cognitive immaturity or child abuse. Additionally, understanding beginning language

acquisition in late learners can illuminate the origin of the deleterious effects of late L1 acquisition on adult language processing (Mayberry, 2007; Morford, 2003).

The current study is the first known one to systematically investigate early first language acquisition begun in adolescence. We ask how adolescent first-language learners compare to typically developing deaf children of deaf parents in terms of their vocabulary size and composition, and what kinds of sentences they produce in spontaneous conversation. First, we ask if their initial ASL vocabulary is child-like or atypical compared to normative data for deaf children acquiring ASL from birth. Second, we ask if adolescent L1 learners can take advantage of their cognitive maturity and begin producing complex multi-word utterances more quickly than do young children with comparable vocabulary sizes.

Methods

Cases

Three deaf adolescent first-language learners were studied. These adolescents had, at age ~14 years, just begun to acquire ASL, their first language. They were given pseudonyms Shawna, Cody, and Carlos to maintain confidentiality. At the time of testing, the three adolescents resided together at a group home for deaf students with two other deaf adolescents who were not included in the study. The group home was staffed and managed by deaf and hearing professionals, all highly proficient ASL signers, who worked with the adolescents every day exclusively in ASL. The adolescents thus became fully immersed in ASL upon placement in the group home. Background information (Table 1) was collected in form of a questionnaire filled out by a social worker who knew them well after having worked with them for several hours daily from their initial arrival.

Background information. The information regarding the cases' schooling and communicative strategies in childhood is sparse. Upon placement in the group home when they began receiving special services in sign language, they knew few if any ASL signs. They had no knowledge of any spoken language, and were illiterate. Due to a number of different circumstances, each had received little or no schooling prior to placement in the group home. Shawna's guardians were hearing and did not use any sign language, and she was reportedly kept at home until age ~12 years. Prior to first receiving special services at age 14;7, she had attended school for a total of 16 months, during which time she was placed in a number of deaf and hearing schools. Before receiving special services in ASL, she relied on behavior and very limited use of gesture to communicate. Cody lived with his legal guardian who was hearing and did not use any sign language. He first began to attend school at the age of 5 years, but the type of educational program is unknown. It is also unknown how he communicated with his guardian or his teachers. Upon receiving special services at age 14;8, Cody knew only a few basic ASL signs, and relied primarily on pointing and some use of gesture to communicate. Carlos was born in another country and lived there until the age of 11 years with his parents and family who were hearing. In his home country he was enrolled in a deaf school but soon stopped attending because the school was of poor quality according to parental report. At age 11 years, he immigrated with his family to the United States, and was placed into a classroom for mentally retarded children where the use of sign language was very limited. Upon receiving special services at age 13;8 he knew only a few ASL signs, and relied on some use of pointing and gestures to communicate.

It is unknown whether Shawna, Cody, or Carlos had ever developed a home-sign system to communicate with their caregivers. However, the professionals (deaf and hearing signers) who have worked with them since their initial arrival at the group home, believed that this is unlikely because the cases were not observed to use home-sign to communicate with deaf peers or adults. Unlike some home-signers discussed in the literature (for example, Morford, 2003; Emmorey et al, 1994), these cases were not raised in typical nuclear families, and may not have had stable interlocutors for extended periods of time prior to placement in the group home and receipt of special schooling. They can thus be described as linguistic isolates who became fully immersed in ASL in adolescence. At the time of the study, the three cases had been receiving consistent ASL input both in and out of school for a period of 1 to 2 years (see).

Table 1: Background characteristics of the cases.

Case	CA[a]	AoA[b]	Mos ASL[c]	Hearing Loss	Prior language knowledge
Shawna	15;7	14;7	12	Profound	No ASL signs, no English, illiterate
Cody	16;2	14;8	18	Moderate-Severe	Some ASL signs, no English, illiterate
Carlos	15;8	13;8	24	Profound	Some ASL signs, no English, illiterate

[a] Chronological age.

[b] Age of onset of ASL acquisition, equivalent to placement to group home.

[c] Number of months of immersion in ASL.

Cognitive testing. A few weeks prior to the initial testing session the participants were administered the Test of Nonverbal Intelligence, Third Edition (TONI-3), and two of them were also given the Wechsler Nonverbal Scale of Ability (NVW). Their scores on the TONI-3 were 67 (Shawna), 91 (Cody) and 85 (Carlos). The TONI-3 is typically used with children and adults between ages 6 and 90, and the average score in this population is 100 (SD=15). A raw score is assigned which is converted into an age-adjusted scaled score. Cody and Carlos were also tested on the NVW. Like the TONI-3, the NVW also uses age-adjusted scaled scores, and the mean score for hearing and deaf individuals between ages 4 and 21 is 100 (SD=15). Cody and Carlos scored 85 and 74 respectively. Cody scored within one standard deviation from the mean on both tests, and Carlos scored within one standard deviation from the mean on the TONI-3 and below one standard deviation from the mean on the NVW. Shawna was only tested on the TONI-3 and was well below one standard deviation from the mean. These results, however, should be interpreted with caution because of the participants' atypical life and schooling experience. As discussed by Mayberry (2002), the non-verbal IQ scores of late L1 learners who have suffered from educational deprivation tend to be low, but generally show significant increases over time as more education and linguistic input is received (see also Morford, 2003).

Language Sampling Procedures

Language skills were investigated using the MacArthur-Bates Communicative Developmental Inventory for ASL (CDI; Anderson & Reilly, 2002), as well as by conducting an analysis of spontaneous language samples collected during group

conversation at dinner time. The research protocol was approved by the Human Research Protections Program at UCSD.

The MacArthur-Bates Communicative Developmental Inventory (CDI) for ASL. The ASL-CDI (Anderson & Reilly, 2002) is an adaptation of the CDI, a parent report measure of vocabulary that has been shown to be a reliable resource in estimating the size and composition of early vocabularies in a number of different languages (Fenson, Dale, Reznick, Bates, Thal, & Pethick, 1994). The ASL-CDI has been standardized for use with deaf children between 8 and 36 months of age. The purpose of using the CDI was to compare the vocabulary size and composition of the three cases to deaf children who have been acquiring ASL for a comparable period of time (i.e. 1-2 years), but who began ASL acquisition from birth. The CDI checklists were completed by the social worker who had been working with the adolescents for several hours a day since their initial placement in the group home. Because the social worker had been teaching them ASL signs and conversing with them daily, she was highly familiar with their ASL skills.

For purposes of comparison with young children who have been exposed to ASL for a period of 1 to 2 years, we closely followed the procedures of Anderson & Reilly (2002). We counted the total number of signs that each adolescent produced in each semantic category, and then determined the number and proportion of nouns, predicates, closed class items, and other signs. As stated by Anderson & Reilly (2002), nouns include the following CDI categories: Animal Names, Clothing, Furniture and Rooms, People, Food and Drinks, Places to Go, Outside Items, Small Household Items, Toys, and Vehicles. The total number of nouns on the CDI is 277, which is 52% of the list. The category of predicates includes Action Signs, Helping Verbs, and Descriptive Signs. The

total number of predicates is 163, which is 30.5% of the list. The category of Closed Class includes Connectors, Prepositions, Pronouns, Quantitative Signs, and Question Signs. The total number of items in this category was 53 (10% of the checklist). The category Other consists of Games and Routines, and Signs about Time, which together consist of 42 items (7.5% of the list).

It should be noted that the classification of ASL signs into syntactic categories is not always straightforward; in particular, certain verbs and nouns may look very similar to each other. For example, the signs for SIT[3] and CHAIR share the same location, handshape, and path of movement; they only differ in that the movement for CHAIR is a nominal inflection consisting of a repeated movement on the verb stem SIT. When adapting the English CDI for ASL, these noun/verb pairs were modified to include only the verb form, which was always included in the Action Sign category. This decision was based on pilot data where parents consistently endorsed the verb form when presented with both options (Anderson & Reilly, 2002). Although there are other ways to address the issue of categorizing nouns and verbs, for purposes of comparison we followed the procedures outlined by Anderson and Reilly.

Although the CDI checklist is intended for use with young children and thus limited in the number and type of lexical items that it measures, its reliability has been confirmed in studies of children who are older than the age range of the CDI norming population (Thal, O'Hanlon, Clemmons, & Frailin, 1999), in studies of children with delays in language development (Heilman, Weismer, Evans, & Hollar, 2005; Thal &

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[3] Signs that appear in text follow standard notation conventions and are represented by upper-case English glosses.

Bates, 1988) and in studies of some atypical populations, such as preterm children and early talkers (Dale, Bates, Reznick, & Morisset, 1989). However, the current study is evidently the first to use the CDI with adolescent L1 learners. It was thus important to cross-validate the vocabulary results by also analyzing the cases' vocabulary during spontaneous signing.

Spontaneous language samples. Spontaneous language samples were collected by videotaping the three adolescents as they conversed freely at meal-time with each other and with several deaf peers and deaf adults they knew well. The entire session was approximately 50 minutes long and included the language samples of all three adolescents talking about a variety of different topics (food, school, everyday life) with several different interlocutors. Each adolescent produced a minimum of 100 utterances. If the sample was longer than 100 utterances, the first 100 utterances were used for analysis. The original videotapes were transferred to a computer and then imported into the annotation system ELAN (Crasborn, Sloetjes, Auer, & Wittenburg, 2006). All video segments were viewed and transcribed by a highly skilled ASL signer and double-checked by a deaf native signer who had many years of research experience.

Transcription and coding. All sign and non-sign communicative units that could be segmented were glossed into English. Utterance boundaries were determined by considering temporal and prosodic cues, including breaks, pauses, or lowering of the hands. In rare instances where the adolescents used streams of signing without any obvious temporal breaks, utterance boundaries were determined using structural and semantic cues such that each utterance contained one propositional unit corresponding to one semantically coherent idea.

ASL lexical signs. ASL lexical signs were categorized into the same syntactic categories as those used on the CDI: noun, predicate, closed class signs, and other signs. For the ASL noun-verb pairs that look alike (for example SIT and CHAIR), we followed the classifications as outlined by Anderson & Reilly (2002), which allowed us to compare the results from spontaneous language samples to those from the CDI. The noun category included common and proper nouns. Predicates included verbs and modifiers (adverbs and adjectives). Closed class items included pronouns, connectors, prepositions, question words, quantifiers, and signs indicating tense. Greetings (bye), comments (thank-you, ok), and numbers were classified as Other signs.

To obtain an estimate of the adolescents' minimum productive vocabulary, we calculated their total number of different ASL signs across both language analyses (CDI and spontaneous language samples). We also determined the number of signs produced in spontaneous samples that overlapped with the signs on the CDI, as well as the number of signs that were produced in the spontaneous samples and were part of the CDI, but were reported as unknown by the social worker who filled out the CDI questionnaires.

Classifiers and fingerspelling. In addition to ASL lexical signs, the adolescents' spontaneous samples contained some instances of fingerspelling and classifiers, neither of which are part of the CDI questionnaire, as they are typically acquired relatively late by young children (Anderson & Reilly, 2002; Schick, 1990). Fingerspelling and classifiers are important in conversations among ASL signers, but differ from the core lexicon in important ways. Fingerspelling is the use of manual alphabet to spell a word in English, for example to introduce proper names for individuals or places (Emmorey, 2002). Classifiers in ASL are used to encode spatial relations and to show movement

along a path (Schick, 1990). Unlike other lexical signs, classifiers are multi-morphemic units, and their use in discourse obeys different phonotactic constraints than those governing the core ASL lexicon (Supalla, 1982). For the purposes of this study, classifiers included units that had one of the ASL classifier handshapes combined with a classifier movement morpheme (Schick, 1990).

Non-sign units. Given their backgrounds, we expected that the three adolescents might use gesture (in addition to ASL) to communicate. Communicative units that did not pattern according to ASL phonology and were not divisible into separate meaningful parts were called Gestured Descriptions. They were considered as one unit when they occurred within an utterance and were used as a lexical item or as a whole proposition when expressed alone. These included enactments (pantomimes which involved a whole-body enactment of a situation), function descriptions (gestural description of how an object is used), shape outlines, and pragmatic gestures (waving goodbye, nodding head etc.). Self-body actions (for example, scratching a body part) were not included in this category.

Instances of pointing were divided into linguistic and non-linguistic points. Note that points in ASL can be used as pronouns to refer to people or objects, in which case they have a linguistic status; however, pointing gestures can also be used in an effort to describe the environment (Petitto, 1987). To separate linguistic and non-linguistic points, we adopted the definitions of deictic gestures and deictic signs developed by Pizzuto (1990). Points were classified as linguistic and were counted in the Closed Class category if they occurred together with other ASL signs. If they occurred in isolation, together

with other non-ASL units, or together with other points, they were regarded as non-linguistic points.

Utterance length and complexity. Analyses at the utterance level included a calculation of mean length of utterance (MLU) and an analysis of utterance types for each adolescent. MLU is one of the most robust indices of young children's language acquisition (Brown, 1973). Because the adolescents' morphological productions were limited, making it difficult to determine which grammatical morphemes were being used productively, MLU was measured in words (signs) rather than morphemes, which is also sensitive to syntactic development and widely used (Hurtado, Marchman & Fernald, 2008; Huttenlocher, Vasilyeva, Cymerman & Levine, 2002). All sign and non-sign units in each utterance were considered in the MLU computation, including inflected and uninflected signs, classifiers, gestured descriptions, linguistic and non-linguistic points, and fingerspelled words. Excluded from the computation were within-utterance back-to-back repetitions of lexical signs. Utterances were also classified by type and were either declarative, wh-questions, or yes/no questions. As another estimate of the adolescents' utterance complexity, we counted the number of lexical items used to indicate coordination, subordination, conditionals, and all instances of inflected verbs produced in the sample. These lexical items are typically acquired relatively late by young children in English and ASL (Mayberry & Squires, 2006; Reilly, McIntire, & Bellugi, 1991; Vasilyeva, Waterfall, & Huttenlocher, 2008), and can thus be regarded as markers of relatively complex sentence structure.

Results

The results are presented in two sections. The findings pertaining to lexical acquisition are presented first, followed by the results from the analyses of utterance complexity.

Vocabulary Acquisition

Figure 1 shows the adolescents' vocabulary size as measured by the CDI plotted with the normative data for young deaf children. Shawna used 250 signs on the CDI checklist, which is 47% of the list total. Cody and Carlos, on the other hand, used 419 and 401 CDI signs respectively, which is 78% and 75% of the list total. Importantly, the adolescents' CDI vocabulary sizes were larger than those of young deaf children with comparable lengths of exposure to ASL (Figure 1). This is particularly true for Shawna and Cody, and less so for Carlos, suggesting that adolescent L1 learners may have an advantage over children by learning vocabulary more quickly at the first stages of word learning.
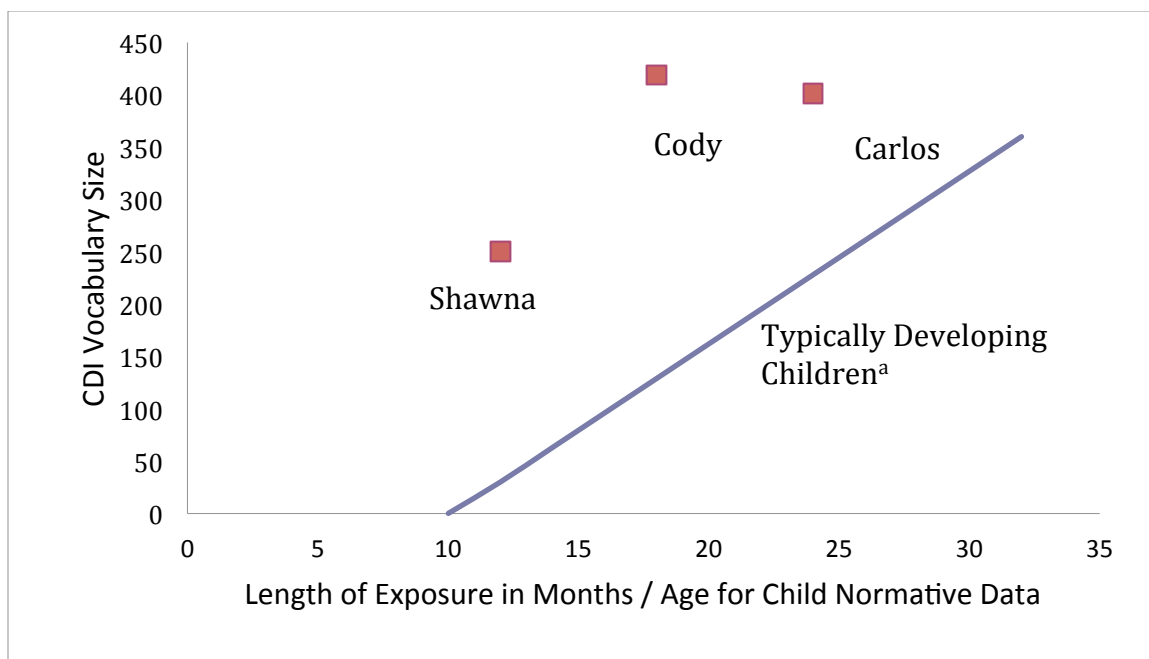
Figure 1: Vocabulary size measured by the ASL-CDI (normative data for typically developing children from Anderson & Reilly, 2002).

Next we analyzed the composition of the adolescents' vocabulary. Their vocabularies showed a preponderance of nouns (between 51% and 54% of total CDI vocabulary), followed by predicates (between 32% and 33% of total CDI vocabulary), and relatively few closed class signs (between 5% and 8% of total CDI vocabulary). A direct comparison between the vocabulary composition of the adolescents and that of young deaf children is shown in Figure 2. The average vocabulary of a two year-old deaf child acquiring ASL from birth exhibits a strong noun bias (51% of total vocabulary). Nouns are followed by predicates (34%), words classified as 'other' (8%) with closed class words representing only 7% of the total CDI vocabulary. As shown in Figure 2, the three adolescents exhibited remarkably similar composition patterns to one another and in comparison to typical deaf two-year olds. This composition trend is also a characteristic

of the CDI list itself, so it is possible that these results arose at least partially as a consequence of the checklist structure.
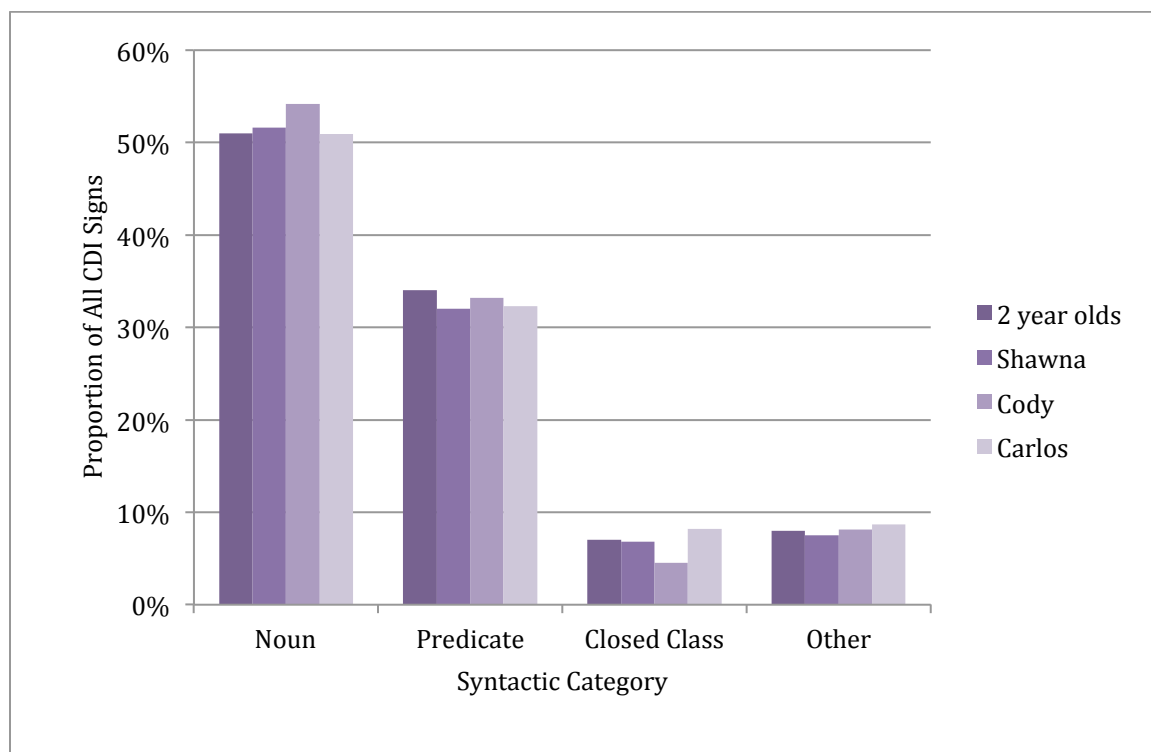
Figure 2: Vocabulary composition measured by the ASL-CDI of the cases and typically developing two-year old deaf children (normative data for two-year olds from Anderson & Reilly, 2002).

Spontaneous Language Samples

The CDI is limited in size and range of vocabulary that it tests so it was important to cross-validate our results using a different method. To explore the adolescents' linguistic abilities beyond the scope of the CDI we analyzed their spontaneous signing.

Proportion of ASL. Our first aim was to determine what proportion of the adolescents' communicative units were ASL signs, and what proportion were non-ASL (gestural) units. Counted as ASL units were nouns, predicates, grammatical signs,

greetings, comments (OK, thank you), numbers, ASL classifiers and all instances of fingerspelling. Gestured descriptions and non-linguistic points were counted as non-ASL units. Shawna's sample consisted of a total of 306 unit tokens, and Cody and Carlos had 308 and 324 unit tokens respectively.

The proportions of ASL signs in the samples were 87% (Shawna), 89% (Cody), and 95% (Carlos). Non-sign units (gestured description and points) thus represented between 13% and 5% of all tokens. Thus after 1 to 2 years of language exposure, the adolescents predominantly used ASL to communicate.

ASL sign types. Next we considered the adolescents' use of ASL lexical signs as a function of syntactic category. Table 2A shows the words that were produced in the language samples that were also part of the CDI checklist; Table 2B shows the words that were produced in the language sample that were not part of the CDI. Shawna used 113 different ASL signs in her spontaneous sample, of which 70 (62%) were also part of the CDI, yielding an estimated vocabulary size of 292 signs. Cody's and Carlos' samples consisted of 112 and 126 different ASL signs respectively, of which only 46% and 42% overlapped with those on the CDI. Their total vocabulary sizes were thus estimated at 477 and 471 signs respectively. It is noteworthy that almost all of the signs that were produced in the sample and noted to be part of the CDI checklist were, in fact, correctly reported as 'known signs' by the social worker. More specifically, the social worker 'missed' (i.e. reported as unknown) only 4 predicates (2 verbs for Shawna, 1 adjective for Cody and 1 verb for Carlos). This indicates that the social worker's CDI report of the adolescents' ASL vocabulary was highly reliable.

Another observation arising from this analysis is that the number and proportion of ASL signs in each syntactic category is remarkably consistent across the three adolescents, especially when considering the signs that are also part of the CDI checklist (Table 2A). One of the few notable differences among the adolescents is that Cody and Carlos produced a higher proportion of signs classified as 'other' and a lower proportion of nouns than Shawna (Table 2B). This can most likely be attributed to their extensive use of numbers in spontaneous conversation, which Shawna did not use at all; nor did she use an alternative to indicate number. It is also important to note that all three adolescents used a relatively low proportion of closed class signs, especially when considering those words that are not part of the CDI questionnaire (Table 2B). Combining all closed class words in the case samples (Table 2A and B), we find that they represent approximately 10% of the participants' lexicon. All three adolescents used a higher proportion of predicates than nouns (Table 2A, B), which does not accord with the findings from the CDI analysis and will be further addressed in the discussion.

Table 2: Proportion (number) of ASL types by syntactic category in spontaneous language samples: A) words produced in the sample that overlapped with those on the CDI checklist; B) words produced in the sample that are not part of the CDI checklist.

A)

Case	Syntactic Category			
	Noun [a]	Predicate [b]	Closed Class [c]	Other [d]
Shawna	.34 (24)	.43 (30)	.13 (9)	.10 (7)
Cody	.32 (17)	.48 (25)	.14 (7)	.06 (3)
Carlos	.30 (16)	.46 (24)	.17 (9)	.07 (4)

B)

Case	Syntactic Category			
	Noun [a]	Predicate [b]	Closed Class [c]	Other [d]
Shawna	.40 (17)	.49 (21)	.04 (2)	.07 (3)
Cody	.20 (12)	.42 (25)	.06 (4)	.32 (19)
Carlos	.30 (22)	.41 (30)	.04 (3)	.25 (18)

[a] Nouns include common and proper nouns.

[b] Predicates include verbs, adverbs, and adjectives.

[c] Closed class items include pronouns, connectors, prepositions, question words, quantifiers, and signs indicating tense.

[d] Other signs include greetings, numbers, and comments.

Non-CDI vocabulary. Analysis of the non-CDI signs used by the adolescents revealed that they were mostly signs that are semantically irrelevant for toddlers, but are highly relevant for adolescents, such as EMAIL, INTERNET, and MATH, as well as an

extensive use of numbers by Cody and Carlos. These results show that adolescents do indeed use some vocabulary outside the CDI checklist.

Classifiers and fingerspelling. The adolescents occasionally used ASL classifiers and fingerspelling, which are important features of (adult) ASL use (Emmorey, 2002), but are not part of the CDI checklist. In the 100 utterance sample, each of the adolescents produced a total of 10 different classifiers, and fingerspelled two different English words. All instances of fingerspelling were extremely slow and laborious, despite the fact that the target words were predominantly short proper or common names (such as JIM or BUS). In order to maintain consistency between the syntactic categories on the CDI and those on the spontaneous language samples, we did not include classifiers and fingerspelling in the final word classification computation. However, additional analyses indicated that the total proportion of classifier tokens in the language samples was between 4% and 5%, while fingerspelled words represented less than 1% of the samples.

Utterance Length and Complexity

The final analysis was of the adolescents' language at the utterance level. Computation of Mean Length of Utterance (MLU) revealed that their utterances were relatively short. Shawna's MLU was 2.4, Cody's was 2.7, and Carlos' was 2.8. Note that these averages were obtained by considering all sign and non-sign units in each utterance (including inflected and uninflected signs, classifiers, gestured descriptions, linguistic and non-linguistic points, and fingerspelled words). If non-signs (gestured descriptions and non-linguistic points) are excluded from the analysis, the MLU results are 2.3 for Shawna, 2.5 for Cody, and 2.8 for Carlos. Table 3 shows the proportion of 1 unit, 2 unit, and 3 or more unit utterances used by each of the adolescents. More than half of

Shawna's spontaneous ASL productions consisted of 1 and 2 unit utterances, while slightly over half of Cody and Carlos's utterances were longer than 2 units. Together these results indicate that these adolescent L1 learners used relatively short utterances.

Table 3: Proportion of 1, 2, and 3 or more unit utterances in spontaneous language samples.

Case	Utterance length in units		
	1	2	3+ [a]
Shawna	.28	.28	.44
Cody	.25	.23	.52
Carlos	.18	.26	.56

[a] 3 or more unit utterances

Examples of the adolescents' utterance are given below as English glosses (cases' names are given in square brackets at utterance ends).

Two-unit utterances:

    (1) FOOD BRING. [Shawna]

    (2) BROTHER SMOKE. [Cody]

    (3) NAME J_I_M(fs)[a]. [Carlos]

    [a] fs = fingerspelling

Three-unit utterances:

    (1) CAT WATER LICK(desc)[b]. [Cody]

    (2) SCHOOL FOOD LIKE. [Shawna]

    (3) MY DOG GONE. [Cody]

    [b] desc = gestured description

Four-unit utterances:

(1) YES THERE(ling-point)[c] MY ROOM. [Cody]

(2) NEXT PAY MONEY COACH. [Carlos]

(3) WE EAT VEGETABLES CHICKEN. [Shawna]

[c] ling-point = linguistic point, counted in the closed class category.

Analysis of the adolescents' utterance types reveals that they used predominantly declarative utterances (between 92% and 97% of all utterances). Yes/no questions and wh-questions were used only rarely, accounting for 2-5% and 0-3% of all utterances respectively. When language is acquired from birth, declarative utterances are typically acquired before yes-no questions, which are acquired before wh-questions in English and ASL (Anderson & Reilly, 2002; Lillo-Martin, 2000; Mayberry & Squires, 2006; Vasilyeva et al, 2008). The adolescents thus exhibited the same acquisition pattern for sentence type as young children. After one to two years of ASL input, they rarely used syntactic question forms.

The results at the utterance level indicate that adolescent L1 learners, despite their age, used neither long nor complex sentences in spontaneous conversations. This result parallels the results for their acquisition of closed class ASL signs. Lexical items indicating subordination or conditionals were never used (nor were non-manual use of these grammatical markers ever observed). The use of coordination was limited to a few instances of the signs AND and BUT that were frequently used by Cody, albeit incorrectly. In addition, as one would expect of a young child with comparable vocabulary size and utterance length, the majority of the verbs that the three adolescents used were bare forms, that is, uninflected. Shawna and Cody produced a total of two

inflected verbs, and Carlos produced four inflected verbs. These results indicate that the adolescents' utterances, like their lexicons, were child-like in their composition.

Discussion

The main objective of the current study was to describe the initial stages of language acquisition begun in adolescence; specifically, we asked whether adolescent first-language acquisition is similar to child language acquisition. In order to do this, we systematically analyzed the language skills of three deaf adolescents with one to two years of experience with ASL as their first language. In the first part of the study we used the ASL-CDI (Anderson & Reilly, 2002) to gain insights into their vocabulary acquisition. After 1 to 2 years of ASL exposure, they knew and used between 47% and 78% of the words on the CDI checklist. The most noteworthy finding was that the adolescents, despite the differences in their vocabulary size, exhibited highly consistent vocabulary compositions with a preponderance of concrete vocabulary items, and few closed class words. Further, the adolescents, like young children, produced simple utterances that were generally 3 units or less in length. Newport & Meier (1985) state that deaf children acquiring ASL from birth produce two sign utterances by the middle of their second year. Petitto (1987) suggests that an MLU of 2.4 is comparable to deaf children between ages 1;3 and 1;6, and an MLU of 2.7 or 2.8 is comparable to deaf children between ages 1;8 and 2;0. These results suggest that early language acquisition in adolescence is a highly structured process with many characteristics resembling childhood language acquisition.

Another key finding of the current study was that the adolescents used a higher proportion of predicates than nouns in spontaneous signing. There are several potential

explanations for this finding. The use of the CDI is limiting since the items are predetermined and are based on what is expected from children. As shown in the study of spontaneous language, the adolescents used words that are not listed on the inventory but are relevant of their age. At the same time, the CDI represented most of the signs that the adolescents were observed to use during spontaneous conversation, suggesting that it is a useful guide for studying the lexicon of early-stage, late language learners. It has previously been shown that in some languages the proportion of nouns in relation to verbs is sensitive to the type of measure used (Tardif, 1996). For example, Tardif, Gelman, & Xu (1999) directly compared spontaneous language samples and CDIs for English- and Mandarin-speaking children and found that a verb advantage was present in spontaneous samples, but not in the CDI results. These discrepancies may arise as a result of limits on maternal memory, or due to the fact that mothers tend to remember words produced in certain contexts better than others (Tardif et al, 1999). It may also be the case, as argued by Caselli and colleagues (Caselli, Bates, Casadio, Fenson, Fenson, Sanderl, & Weir 1995), that verbs are oversampled when vocabularies are measured using spontaneous language samples because of their low type-token frequencies. The lower proportion of nouns in spontaneous conversations may be partly due to subject omission. In ASL, like in Mandarin and Italian, subject omission can and does occur in perfectly grammatical sentences (Sandler & Lillo-Martin, 2006), and we observed it frequently in our data. In sum, cross-linguistic studies on lexical acquisition in normally developing children suggest that the proportions of nouns in relation to verbs are highly dependent on the method used. It is likely that, in spontaneous samples of young deaf children acquiring ASL, words are used that are not listed on the inventory and possibly

the percentage of nouns to predicates would vary. A higher proportion of predicates in adolescents' spontaneous signing could indicate an advanced stage of language knowledge, perhaps suggesting that the three adolescents are shifting towards grammar more quickly than young children. However, the results from the adolescents' spontaneous language are consistent with the data from the CDI (total lexical types, number of closed class words, MLU, and sentence type), suggesting that this is not the case.

In addition to the commonalities between the three adolescents and children, we also observed some important differences between them. Most notably, the rate of vocabulary acquisition in adolescent L1 learners appears to be initially faster than in children, which was indicated by the fact that the their vocabulary sizes were consistently above those of young children with comparable amounts of ASL exposure. Interestingly, Snedeker et al (2007) report that internationally adopted preschoolers initially acquire words at a faster rate than toddlers acquiring English from birth. Our results suggest that older language learners have an advantage over young children in acquiring initial word-world pairings, even when they begin to do so without the benefit of a previously acquired language.

Another potential difference between the three cases and typically developing deaf children of deaf parents was the amount of classifier use. As much research on ASL vocabulary development comes from the administration of the ASL-CDI, which does not include classifiers, our understanding of ASL classifier acquisition and use under typical learning circumstances is fairly limited (Kuntze, 2011). However, we do know that deaf children of deaf parents, as well as deaf children of hearing parents, do produce

productive classifier forms between ages 2 and 3 (Schick, 2006; Slobin, Hoiting, Kuntze, Lindert, Weinberg, Pyers, Anthony, Biederman, & Thumann, 2003). Kuntze (2011) studied a group of 5 deaf children between ages 3;9 and 4;3 and observed that their use of classifiers tends to hover between 3% and 4% of lexical items, although it can be as high as 9.6% or as low as 1.6%. Our analyses showed that classifiers comprised between 4% and 5% of all vocabulary items in the adolescents' language samples. Since the adolescents have only been exposed to ASL for a period of 1 to 2 years, it may be the case that their proportion of classifier use is somewhat higher than in typically developing deaf children with a comparable length of ASL exposure. However, classifier use has been shown to be highly context dependent in typically developing deaf children and adults (Kuntze, 2011; Morford & MacFarlane, 2003), which makes it difficult to draw any firm conclusions about the comparability of the adolescents' classifier usage to that of young children.

Other differences between children and adolescents that emerged in our data may be more or less directly related to the adolescents' backgrounds and previous communicative experience. Although the adolescents occasionally used gesture to communicate, this was surprisingly limited. In fact, the proportion of ASL was remarkably high considering their relatively short amount of ASL exposure. Emmorey and colleagues (1994) report the case of Anna, another deaf adolescent L1 learner of ASL, who used ASL 80-90% of the time after only 9 months of exposure. Maria and Marcus, the two adolescent L1 learners studied by Morford (2003), were also reported to have replaced most of their gestures with signs after less than 3 years of exposure to ASL. The results of these studies in conjunction with our results indicate that adolescent

L1 learners retain the capacity of zeroing in on, and using, linguistic input remarkably quickly, suggesting that the ability to distinguish between linguistic and non-linguistic input is not lost after early childhood (see Krentz & Corina, 2008).

Another noteworthy characteristic of the adolescents' spontaneous signing is that they occasionally used language to discuss concepts that may be irrelevant for young children, such as computers or movie characters. They occasionally conversed about things that were not in their immediate environment, such as volcano eruptions in Hawaii that they learned about at school, or football games that they watched on TV. This ability to talk about non-immediate, and unexperienced, events shows that adolescent L1 learners are able to use their newly acquired ASL skills to represent concepts more typical of advanced and older language users, and is a skill also reported in homesigners who have not yet learned a full language (Morford & Goldin-Meadow, 2006).

Having acquired the initial set of base vocabulary items and beginning sentences, the question is whether the adolescent L1 learners we studied here will continue to develop ASL in a child-like manner and eventually develop linguistic competence close to that of native ASL signers. Given that previous studies have shown that significant delays in the onset of language acquisition leads to processing deficits across all domains of linguistic structure, this outcome is unlikely. We hypothesize that subsequent language learning stages that require inducing a system of complex relations are age-sensitive. That is, it may be that adolescent L1 learners are slower then children when it comes to further expanding their lexicon and grammatical system by means of learning its internal contingencies.

The implications of the current study are limited by the small sample size (3 participants), as well as by the differences among the cases, such as the differences in their backgrounds and length of exposure to ASL. In addition, the cases' non-verbal IQ scores were not equivalent, which could potentially affect their language learning ability. However, it is unclear whether their nonverbal IQ is driving their language learning, or whether their level of language ability and lack of schooling is driving their nonverbal IQ performance. Other late L1 learners who have suffered from educational deprivation have shown increases in their non-verbal IQ scores as they received more education and linguistic input (Morford, 2003), suggesting that the relationship between non-verbal IQ and language acquisition may be reciprocal in these circumstances. Despite these limitations, our results provide compelling evidence to suggest that first language acquired in adolescence is remarkably consistent and noticeably similar to child language acquisition as far as vocabulary size, vocabulary composition, and utterance length and complexity. The current study investigated productive language only. Future studies should consider whether similar conclusions can be drawn with regard to language comprehension. Subsequent longitudinal studies will also reveal how adolescent first-language acquisition develops over time; we suspect that delays will eventually be evident across all domains of linguistic structure.

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CHAPTER 3:

Signed words in the congenitally deaf evoke typical late lexico-semantic responses with

no early visual responses in left superior temporal cortex

Abstract

Congenitally deaf individuals receive little or no auditory input, and when raised
by deaf parents, they acquire sign as their native and primary language. We asked two
questions regarding how the deaf brain in humans adapts to sensory deprivation: (1) Is
meaning extracted and integrated from signs using the same classical left hemisphere
fronto-temporal network used for speech in hearing individuals, and (2) in deafness, is
superior temporal cortex encompassing primary and secondary auditory regions
reorganized to receive and process visual sensory information at short latencies? Using
magnetoencephalography (MEG) constrained by individual cortical anatomy obtained
with magnetic resonance imaging (MRI), we examined an early time window associated
with sensory processing and a late time window associated with lexico-semantic
integration. We found that sign in deaf individuals and speech in hearing individuals
activate a highly similar left fronto-temporal network (including superior temporal
regions surrounding auditory cortex) during lexico-semantic processing, but only speech
in hearing individuals activates auditory regions during sensory processing. Thus, neural
systems dedicated to processing high-level linguistic information are utilized for

processing language regardless of modality or hearing status, and we do not find evidence for re-wiring of afferent connections from visual systems to auditory cortex.

Introduction

Neuropsychological and neuroimaging studies generally show that, when acquired as a native language from birth in congenitally deaf individuals, sign language is processed in a primarily left fronto-temporal brain network, remarkably similar to the network used by hearing subjects to understand spoken words (Petitto et al., 2000; MacSweeney et al., 2008; Mayberry et al., 2011). Similarly, the N400, an event-related component correlated with lexico-semantic processing (Kutas and Federmeier, 2011), is similar when evoked by signs in deaf individuals and spoken or written words in hearing individuals (Kutas et al., 1987; Neville et al., 1997; Capek et al., 2009). Language deficits in deafness are more pronounced after lesions in the left hemisphere (Klima and Bellugi, 1979; Poizner et al., 1987; Hickok et al., 1996). Finally, direct cortical stimulation in left inferior frontal and posterior superior temporal regions in a deaf signer disrupted sign language production similar to speech disruptions in hearing individuals (Ojemann, 1983; Corina et al., 1999).

Left fronto-temporal language areas include the cortex surrounding primary auditory cortex (Price, 2010), which is functionally deafferented in congenitally deaf individuals. In animal models, it has been demonstrated that afferent connections from the retina can be induced to connect with the medial geniculate nucleus of the thalamus (Sur et al., 1988), resulting in maps of visual space within primary auditory cortex (Roe et al., 1990; Barnes and Finnerty, 2010). Likewise, in congenitally deaf humans, auditory

regions have been shown to exhibit hemodynamic and neurophysiological activation to low-level moving visual stimuli, particularly in the right hemisphere (Finney et al., 2001; Finney and Clementz, 2003) and even to sign language narratives more than in hearing controls (Lambertz et al., 2005). However, other studies have not found such responses (Hickok et al., 1997) or have found extensive inter-individual variability (Bavelier and Neville, 2002).

If auditory cortex is actually re-wired in deaf individuals to receive visual input directly, then the similar activation patterns evoked by signed words in deaf signers and spoken words in hearing individuals would be a natural consequence of neural plasticity: in both groups, low-level sensory processing in auditory cortex should projected to adjacent superior temporal areas, and thence to the broader left fronto-temporal language network for lexico-semantic processing. Alternatively, activity in the region surrounding auditory cortex to signed words in deaf individuals and to spoken words in hearing individuals may reflect higher level semantic encoding rather than sensory analysis. In this scenario, common activations in superior temporal cortex occur only after distinct modality-specific sensory processing for sign or speech. These alternatives can be dissociated based on the timing of the activity in superior temporal regions, information that is not available from hemodynamic measures, but can be obtained using magnetoencephalography (MEG). Here we show that this activity is semantic, not sensory. Only speech in hearing individuals activates auditory areas during early sensory processing. However, both speech in hearing individuals and sign in deaf native signers activate similar temporal and frontal regions in the classical language network during later semantic processing stages.

Materials and Methods

Participants

12 healthy right-handed congenitally deaf native signers (6 F, 17-36 years) with no history of neurological or psychological impairment were recruited for participation (Table 1). All had profound hearing loss from birth and acquired American Sign Language (ASL) as their native language from their deaf parents. In addition, 8 hearing controls from an analogous task with spoken English were included for comparison (5 F, 21-29 years).

Procedures

Each deaf participant viewed single signs that were either congruously or incongruously paired with a preceding picture (Figure 1). Stimuli were high frequency concrete nouns in ASL presented as short video clips (range = 340-700ms; mean 515.3 ms). Since no frequency norms exist for ASL, the stimuli were selected from ASL developmental inventories (Schick, 1997; Anderson and Reilly, 2002) and picture naming data (Bates et al., 2003; Ferjan Ramirez et al., in press). The signs were all concrete nouns representing highly imageable objects, and were reviewed by a panel of 6 deaf and hearing fluent signers to ensure they were accurately produced and highly familiar from an early age. Words that are typically fingerspelled or are compound signs were excluded. Each sign video began when all phonological parameters (handshape, location, movement, and orientation) were in place, and ended when the movement was completed. Each sign appeared in both the congruent and incongruent conditions, and if a

trial from one condition was rejected due to artifacts in the MEG signal, the corresponding trial from the other condition was also rejected to ensure that sensory processing across congruent and incongruent trials was identical. Subjects were instructed to press a button when the sign matched the preceding picture in meaning, and response hand was counterbalanced across 6 blocks of 102 trials each. The hearing participants performed the same task, except that instead of viewing pictures and signs, subjects saw photos and then heard single auditory English words through earphones and pressed a button to matches. The picture remained on the screen throughout the duration of the auditory word. Word duration ranged from 304 to 637ms, with a mean of 445ms. To analyze the response to pictures, we compared the deaf group to a different group of hearing participants who saw the same white-on-black line drawings in a separate, but similar task.
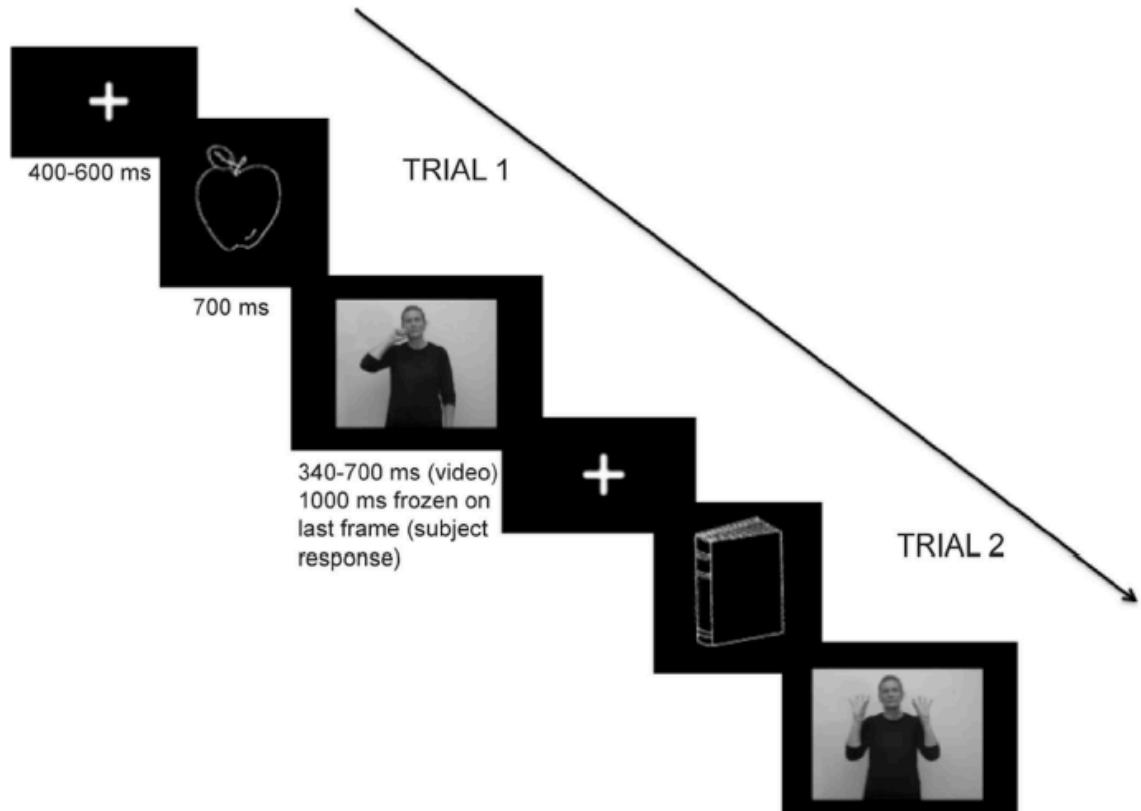
Figure 1: Schematic diagram of task design. Each picture and sign appeared in both the congruent and incongruent conditions. Trials were presented pseudo-randomly so that repetition of a given stimulus did not occur with fewer than 8 intervening trials. Incongruent pairs were not related semantically or phonologically in ASL.

Neuroimaging

While subjects performed the task, we recorded MEG from 204 planar gradiometer channels distributed over the scalp, at 1000Hz with minimal filtering (0.1-200Hz). Following the MEG session, each subject's structural MRI was acquired as a T1-weighted image. Sources were estimated by coregistering MEG and MRI data and using a linear minimum-norm approach, noise normalized to a pre-stimulus period, according to previously published procedures (Dale et al., 2000; Leonard et al., 2010; McDonald et

al., 2010). Random-effects statistical analysis on the dynamic statistical parametric maps (dSPMs) was performed using a cluster thresholding approach (Hagler et al., 2006; McDonald et al., 2010). Table 2 shows surface Talairach coordinates for peak vertices in the clusters. Two time windows were selected for analysis based on a grand average of the activity to signs and speech across both groups of participants. For the early (80-120ms) time window, a grand average of all signed or spoken words was displayed on an average brain, and for the later time window (300-350ms), a subtraction of congruous-incongruous words was displayed on the average brain. Regions with significant clusters (cluster threshold for signs 80-120ms = 208.58mm^2, 300-350ms = 212.32mm^2; cluster threshold for speech 80-120ms = 238.60mm^2, 300-350ms = 206.63mm^2) were selected for timecourse extraction (Figure 2C-D, *surround*).

Results

Behavioral Responses

Both groups of participants performed the task with high accuracy and fast reaction times (Table 1). Deaf participants were accurate on 94.3% of trials (SD = 3.93) and responded at 619.10ms on average (SD = 97.5ms). Hearing participants were accurate on 98.25% of trials (SD = 3.01) and responded at 561.23ms on average (SD = 94.28ms). The between-group RT difference was not significant (t-test; *p* > 0.1).

Table 1: Deaf and hearing participant information and task performance. Values in parentheses are standard deviations. [a] Years. [b] Age of Acquisition. [c] Percent correct. [d] Milliseconds

Group	Gender	Age (years)	Education (years)	Accuracy (%)	RT (ms)
Deaf	6F, 6M	30 (6.37)	15.92 (2.87)	94.3 (3.93)	619.10 (97.5)
Hearing	5F, 3M	27 (2.87)	19.00 (2.45)	98.25 (3.01)	561.23 (94.3)

Anatomically-constrained MEG – Early time window (80-120ms)

During early sensory processing (80-120ms), we examined the grand average of activity for all signed words in deaf participants and all spoken words in hearing participants. Responses to signs were significant in posterior occipital regions including the occipital pole (Figure 2A). Responses to spoken words were strongest in bilateral superior temporal cortex, including primary auditory areas on the superior temporal plane (Figure 2B). An auditory peak in superior temporal channels that did not differentiate between congruent and incongruent conditions was visible in individual hearing subjects, but was not present in deaf subjects (Figure 3). Thus, at early latencies neural responses are confined to modality-specific sensory regions and do not differentiate between semantically congruent and incongruent trials. Crucially, signs do not evoke activity in auditory cortex at ~100ms in deaf native signers.

To determine whether auditory cortex activity differs between deaf and hearing individuals in response to visual stimuli, we compared the response to the pictures with that from a separate group of hearing subjects who saw the same line drawings. While both groups showed significant cluster-thresholded activity in posterior occipital cortex at ~100ms (minor localization differences between groups may be due to differences in the

task design between the deaf group and this particular hearing group), neither group

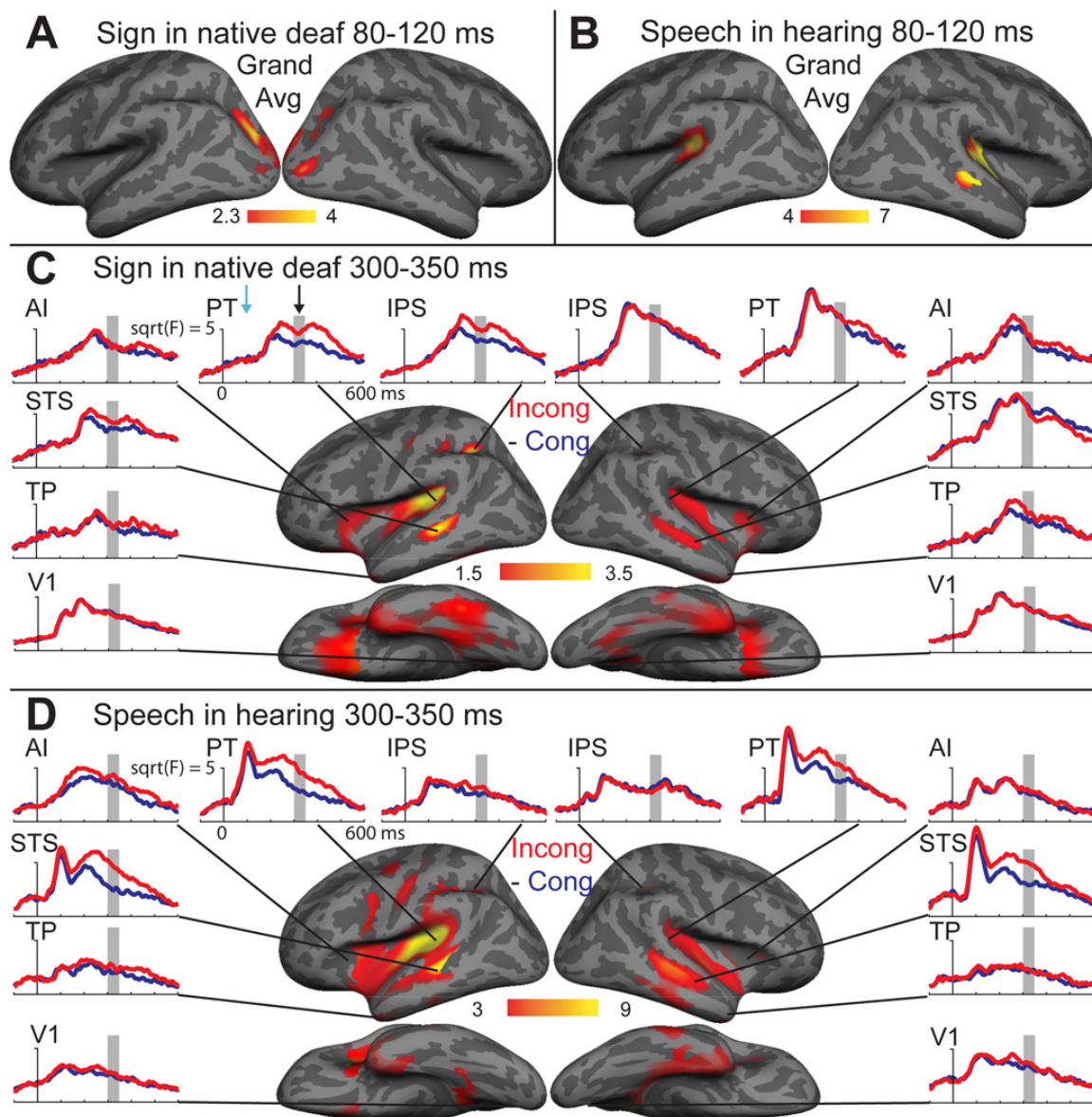showed activity in auditory areas (Figure 4).

Figure 2: Superior temporal areas surrounding auditory cortex are active for both sign and speech during lexico-semantic processing, but only for speech during sensory processing. **(A)** Grand average activity to signs at ~100ms in deaf subjects is localized to occipital cortex in calcarine and superior occipital sulci. **(B)** Grand average activity to speech at ~100ms in hearing subjects is localized to posterior temporal cortex. **(C)** *Center*: Grand average activity to incongruent-congruent signs at 300-350ms (black arrow) in deaf subjects. *Surround*: Regional timecourses for congruent and incongruent conditions in 5 bilateral regions of interest from -100 to 600 ms (light blue arrow at 100ms). **(D)** Same as (C) for speech in hearing subjects. Abbreviations: IPS, intraparietal sulcus; PT, planum temporale; AI, anterior insula; STS, superior temporal sulcus; TP, temporal pole; V1, primary visual. All mapped activity is cluster thresholded dSPM, significantly greater than pre-stimulus baseline at $p<0.05$, corrected.

Table 2: Talairach surface coordinates for selected ROIs shown in Figure 2.

ROI Name	Coordinates (x, y, z)	
	Left	Right
Anterior Insula (AI)	-31, 13, 6	31, 16, 10
Planum Temporale (PT)	-35, -31, 22	36, -30, 17
Superior Temporal Sulcus (STS)	-47, -35, 0	46, -20, -7
Temporal Pole (TP)	-25, -1, -24	35, 5, -30
Intraparietal Sulcus (IPS)	-33, -47, 34	37, -42, 34

Anatomically-constrained MEG – Late time window (300-350ms)

In contrast to early latencies, very high overlap was observed between the deaf and hearing groups during lexico-semantic processing. In both groups, the subtraction of congruent from incongruent trials revealed semantically-modulated activity in the classical left hemisphere fronto-temporal network around the *a priori* time window at 300-350ms. Although words in both sign (Figure 2C) and speech (Figure 2D) activated some modality specific areas (e.g., left intraparietal sulcus (IPS) for sign), most activity occurred within a shared network including the left planum temporale (PT), superior temporal sulcus (STS), and temporal pole (TP), and the homologous areas in the right hemisphere to a lesser extent. Representative single subject waveforms from individual sensors reveal similar onset in the timing and location of the congruent vs. incongruent difference in left superior temporal areas surrounding auditory cortex (Figure 3), as determined by a random effects resampling statistic (Maris and Oostenveld, 2007).
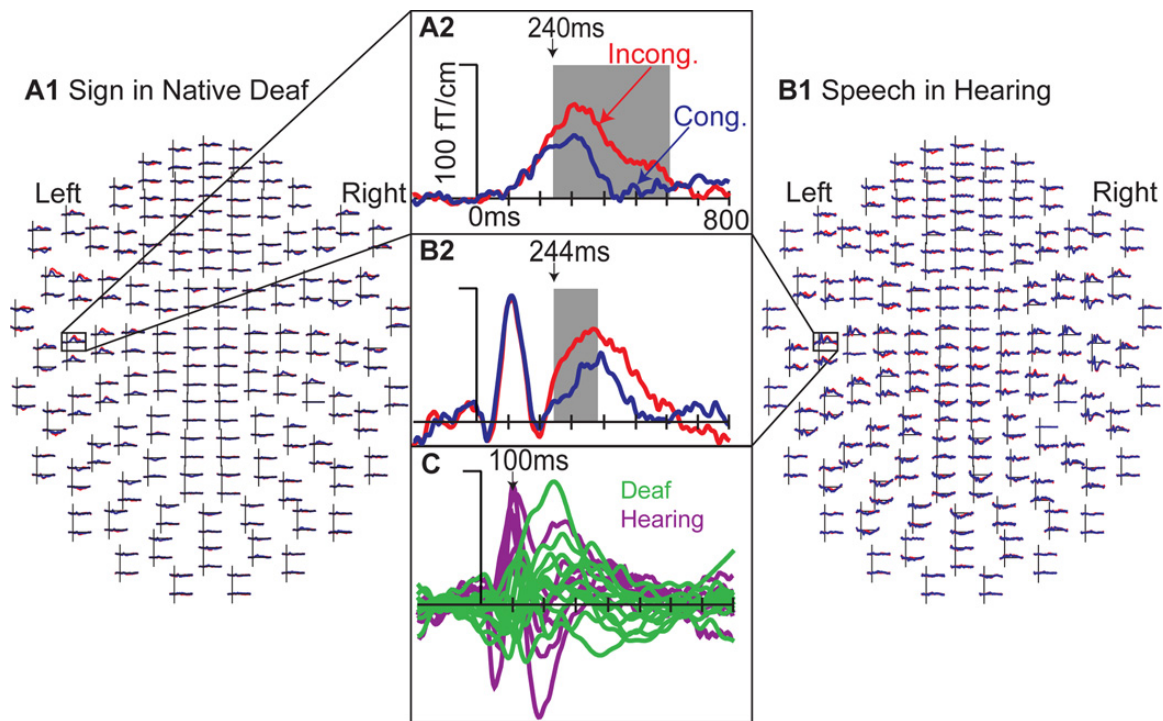
Figure 3: Individual MEG sensors demonstrate the dissociation between early and late activity in auditory regions. **(A1)** Head plot shows the location of a left superior temporal MEG channel showing significant incongruent>congruent activity in a deaf native signer. **(A2)** The left superior temporal MEG channel shows the congruent vs. incongruent difference for signs. **(B1)** Head plot from a hearing participant. **(B2)** The same channel shows a similar difference for speech in a single representative hearing participant. Both subjects begin to show a significant difference between conditions at ~240ms. **(C)** The same channel shows a sensory peak at ~100ms for hearing (purple), but not deaf (green) subjects. Gray regions indicate significance at $p < 0.01$.

Figure 4: Direct comparison of response to pictures between (**A**) deaf and (**B**) hearing subjects. Both groups show significant activity at ~100 ms in occipital visual areas, and neither shows activity in auditory cortex.
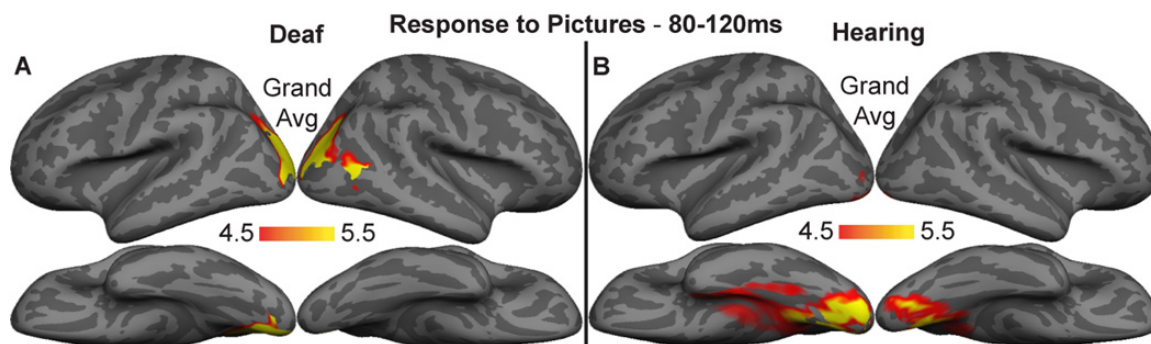
Discussion

Sign languages possess the sublexical, word-level, syntactic and semantic characteristics typical of spoken language (Emmorey, 2002; Sandler and Lillo-Martin, 2006). When a deaf child is reared by signing parents, the developmental trajectory of linguistic knowledge (including specific syntactic structures) follows that of spoken language in hearing children (Anderson and Reilly, 2002; Mayberry and Squires, 2006).

We examined two stages of signed and spoken word processing in deaf and hearing participants. While the early sensory processing stage (~100ms) is confined to modality-specific visual cortex for signs and auditory cortex for speech, both kinds of language activate an overlapping network of left hemisphere fronto-temporal regions (including areas surrounding auditory cortex) during lexico-semantic processing (~300ms). The similarity between sign and speech during the later time window confirms the hypothesis that areas including anteroventral temporal, superior temporal, superior planar, and inferior prefrontal cortex are specialized for processing word meaning, regardless of modality. In contrast, the early differences between modalities provide

evidence that visual afferents are not directed to auditory cortex for initial sensory processing to a greater extent in deafness. Rather, early sensory processing of signed words takes place in visual cortex.

The current study is among the first investigations of the spatiotemporal dynamics of sign processing. The timing of the activity in the present study reveals that speech in hearing and sign in deaf participants activates the classical left fronto-temporal language network between ~200-400ms, well beyond short-latency sensory processes. These areas have been shown to be involved in processing high-level semantic information for both auditory and written words in normal individuals with fMRI (Patterson et al., 2007; Binney et al., 2010; Price, 2010; Binder et al., 2011), MEG (Marinkovic et al., 2003; Leonard et al., 2011), and in direct intracranial recordings in patients with medically intractable epilepsy (Chan et al., 2011), although there is evidence for functional and modality-specific specialization within anterior temporal subregions (Visser and Lambon Ralph, 2011). These same areas are deficient or damaged in patients with semantic dementia (Binney et al., 2010; Lambon Ralph et al., 2010; Mion et al., 2010). Lexico-semantic activity in antero-ventral temporal and superior temporal areas is observed in both languages for bilinguals (Leonard et al., 2010; Leonard et al., 2011) and in 12-18 month old infants (Travis et al., 2011), further demonstrating their fundamental role in processing meaning. We found only relatively minor differences in active loci, including greater activity in IPS, possibly related to an inherently greater praxic and biological motion component to sign (Emmorey et al., 2002; Pobric et al., 2010). Activity in this network in congenitally deaf native signers processing a visuo-gestural language provides

additional support for the hypothesis that this processing reflects abstract, supramodal representations of word meaning regardless of the input modality.

Capitalizing on the high spatiotemporal resolution of MEG constrained by individual cortical anatomy obtained by MRI, we also examined whether activity observed in auditory regions in congenitally deaf individuals (Finney et al., 2001; Finney and Clementz, 2003; Lambertz et al., 2005) is caused by re-wiring of visual sensory information to cortex that has been underutilized due to sensory deprivation for the individual's entire life. While previous MEG results indicated that hemodynamic activation in these regions, particularly in the right hemisphere, reflected early processing, the time window that was examined extended to 400ms after stimulus onset, well beyond initial sensory processing for both visual and auditory stimuli (Finney and Clementz, 2003). Furthermore, other investigations with single deaf subjects have failed to find evidence for the hypothesized cross-modal plasticity in auditory areas (Hickok et al., 1997; Nishimura et al., 1999). The present study investigated a sensory-specific, short-latency time window and found that during the first pass of sensory processing, auditory cortex is not active in deaf participants, whether they are viewing signs or static pictures. Rather, these areas show semantically-modulated activity only well after first-pass sensory processing is thought to be completed. Lexico-semantic activity in the left antero-ventral temporal lobe between ~200-400ms has been shown with laminar multi-microelectrode recordings from different cortical layers to reflect recurrent associative or second-pass processing (Halgren et al., 2006). The latency of the responses in superior temporal cortex in deaf signers indicates that they receive the output of a long chain of

visual processing, instead of participating in the early encoding of sensory information (which is performed in primary and secondary visual areas).

Cortical plasticity is a hallmark of early development (Bates and Roe, 2001), and continues well into adulthood in the form of learning-induced cortical and synaptic changes (Buonomano and Merzenich, 1998). Experimental results with animals showing cross-modal plasticity in the context of sensory deprivation are intriguing and of great importance for understanding fundamental principles of neural organization (Sur et al., 1988; Roe et al., 1990; Sur, 2004; Barnes and Finnerty, 2010). While there is extensive and convincing evidence that auditory stimuli activate visual areas in blind individuals (Sadato et al., 1996; Cohen et al., 1997; Barnes and Finnerty, 2010), such clear evidence for a reorganization of auditory cortex in deafness is lacking in both human (Bavelier and Neville, 2002; Kral, 2007) and animal (Kral et al., 2003; Kral, 2007) studies. Factors such as the extent of hearing loss and age of onset of deafness may impact cortical reorganization and rewiring (Bavelier and Neville, 2002; Lambertz et al., 2005), and there may be functional distinctions between A1 and surrounding areas that do show plasticity, such as the anterior auditory field in cats (Lomber et al., 2010; Meredith et al., 2011; Meredith and Lomber, 2011). Additionally, some neurons in auditory regions may be involved in processing non-auditory information (particularly in multimodal contexts), however the present results suggest that in humans who are born profoundly deaf and are native signers, unimodal responses in primary sensory and semantic systems remain intact.

Thus, in deaf signers who acquired sign language from birth from their deaf parents, signs are processed in a brain network that is strikingly similar to that for spoken

words in hearing individuals. The timing of activity in the language network (including superior temporal regions surrounding auditory cortex) reveals that this is due to semantic encoding, rather than to a re-routing of visual-sensory input. This provides evidence that left fronto-temporal regions including the superior temporal plane surrounding auditory cortex are specialized for encoding word meaning regardless of input modality.

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CHAPTER 4:

Neural language processing in adolescent *first*-language learners

Abstract

The relation between the timing of language input and development of neural organization for language processing in adulthood has been difficult to tease apart because language is ubiquitous in the environment of nearly all infants. However, within the congenitally deaf population are individuals who do not experience language until after early childhood. Here we investigated the neural underpinnings of American Sign Language (ASL) in two adolescents who had no sustained language input until they were ~14 years old. Using anatomically-constrained magnetoencephalography (aMEG), we found that recently learned signed words mainly activated right superior parietal, anterior occipital, and dorsolateral prefrontal areas in these two individuals. This spatiotemporal activity pattern was significantly different from the left fronto-temporal pattern observed in young deaf adults who acquired ASL from birth, and from that of hearing young adults learning ASL as a second language for a similar length of time as the cases. These results provide direct evidence that the timing of language experience over human development affects the organization of neural language processing.

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Introduction

One of the most challenging questions in neurolinguistics is the role early language input plays in the development of the left hemisphere canonical network for language processing (Penfield and Roberts 1959). The left hemisphere shows adult-like activations from a very young age (Dehaene-Lambertz et al. 2002; Imada et al. 2006; Travis et al. 2011). However, the degree to which such neural activation patterns are contingent upon language experience is unknown because nearly all hearing children experience language at, or even before, birth (Moon and Fifer 2000). Congenital deafness often has the effect of delaying the onset of language acquisition, and many deaf children born to hearing parents do not receive functional language input until they receive special services or interact with other deaf individuals who use sign language. These circumstances thus offer a unique opportunity to investigate the effects of delayed onset of *first* language (L1) acquisition on the classic network for language processing. Here we ask how an extreme delay in L1 input affects the organization of linguistic processing in the brain which requires that we first consider how age of acquisition, AoA, affects L2 and sign language learning and neural processing.

The most common means of investigating the effects of delayed AoA on the neural processing of language is by studying second language (L2) acquisition. Most neuroimaging studies agree that the L2 is acquired and processed through neural mechanisms similar to those that support the L1, with differences observed in more extended activity of the brain system supporting L1 (for review see Abutalebi 2008). A number of studies also show that a less proficient and/or a late acquired L2 engages the right hemisphere to a greater extent than L1 (Dehaene et al. 1997; Perani et al. 1998;

Wartenburger et al. 2003; Leonard et al. 2010, 2011).

Studies using event-related potentials (ERP) indicate that responses to L2 typically exhibit slightly delayed latencies compared to L1 (Alvarez et al. 2003; Moreno and Kutas 2005). Two recent magnetoencephalography (MEG) studies on Spanish-English bilinguals replicate these findings indicating that the representations of L1 and L2 are largely overlapping in the left-hemisphere frontal regions but that L2 additionally recruits bilateral posterior and right hemisphere frontal areas (Leonard et al. 2010, 2011). Many behavioral studies with L2 learners confirm the existence of a negative correlation between L2 age of acquisition (AoA) and language outcome at various levels of linguistic structure (Birdsong 1992; White and Genesee 1996; Flege et al. 1999). While it is generally agreed that earlier acquisition of L2 is "better", there is disagreement as to the exact nature of AoA effects on L2 learning. The disagreement arises from the fact that the magnitude of the AoA effects is variable and near-native L2 acquisition is sometimes possible despite late AoA (Birdsong and Molis 2001).

Near-normal language proficiency does not occur when L1 acquisition is delayed, as demonstrated by a number of studies of deaf signers with varying L1 AoA. Sign languages are linguistically equivalent to spoken languages (Klima and Bellugi 1979; Sandler and Lillo-Martin 2006) and, similar to spoken language, early onset of sign language results in native proficiency and the capability to subsequently acquire L2s (Mayberry et al. 2002). Delays in sign language acquisition, on the other hand, have been associated with low levels of language proficiency. Specifically, as acquisition begins at older ages, language processing becomes dissociated from meaning and more tied to the perceptual form of words; syntactic abilities decrease, and sentence and narrative

comprehension decline (Mayberry and Fischer 1989; Newport 1990; Mayberry and Eichen 1991; Boudreault and Mayberry 2006). These effects are greatest in those cases where no functional language has been available until late childhood or even early teenage years (Boudreault and Mayberry 2006). While few, if any, such individuals have been followed longitudinally, psycholinguistic studies with adult deaf life-long signers with late childhood to adolescent AoA show that language processing deficits are severe and long-term (for discussion see Mayberry 2010).

In rare cases, some deaf individuals do not have access to meaningful spoken language because they are deaf and, due to various circumstances in their upbringing combined with social and educational factors, have not been exposed to any kind of sign language. Deaf individuals who are not in significant contact with a signed or spoken language typically use gesture prior to their exposure to language (Morford 2003). Such individuals have been termed homesigners because they typically develop an idiosyncratic gesture system (called homesign) to communicate with their caregivers and/or families (Goldin-Meadow 2003). In the United States, homesigners typically begin receiving special services at a very young age, and enter school and experience language (spoken or signed) by age 5 or younger. This may not be the case in other parts of the world where the use of homesign without any formal language may extend into adolescence or adulthood, for example in the case of homesigners in some Latin American countries where special services may be sparse or non-existent (Senghas and Coppola 2001; Coppola and Newport 2005). Rare cases of homesigners in the United States also do not receive any formal language instruction until adolescence, mostly due

to unusual family or social circumstances that include a lack of schooling at the typical age of 5 years.

We studied two such deaf adolescents named Shawna and Carlos (pseudonyms) who had not been in contact with any formal language (spoken or signed) in childhood and had just begun to acquire ASL at age ~14 years, 2 to 3 years prior to participating in the study. Shawna and Carlos were thus unlike the previously described North American homesigners (Goldin-Meadow 2003) in that they were not immersed in a language environment until they were teenagers and, importantly, received very little schooling, and no special services or intervention until age ~14 years. Their backgrounds thus resemble those of first-generation homesigners in some Latin American countries (Senghas and Coppola 2001; Coppola and Newport 2005).

Shawna's and Carlos' backgrounds have been described elsewhere (Ferjan Ramirez et al. 2013). Briefly, they had begun to acquire ASL, their L1, through full immersion at age ~14 years when they were placed in a group home for deaf children where they resided together at the time of our study. The group home was managed by deaf and hearing professionals, all highly proficient ASL signers, who worked with the adolescents every day and exclusively through ASL. Despite their clear lack of linguistic stimulation and schooling in childhood, however, both had an otherwise healthy upbringing, unlike previously described cases of social isolation and/or abuse (Koluchova 1972; Curtiss 1976). Shawna lived with hearing guardians who did not use any sign language, and was reportedly kept at home and not sent to school until age 12 years. Prior to first receiving special services at age 14;7, she had attended school for a total of 16 months, during which she was switched among a number of deaf and hearing schools.

She reportedly relied on behavior and limited use of gesture to communicate. Carlos was born in a Latin American country and lived there until the age of 11 with his large biological family all of whom were hearing. In his home country he enrolled in a deaf school at a young age, but stopped attending after a few months because the school was of poor quality according to parental report. At age 11 years he immigrated to the United States with a relative and was placed in a classroom for mentally retarded children where the use of sign language was limited. Upon receiving special services at age 13;8 he knew only a few ASL signs, and relied on some use of gestures and whole body pantomime to communicate.

Beyond the description given here, whether Shawna or Carlos developed sophistication with homesign gestures is unknown. However, the professionals (deaf and hearing signers) who have worked with them since their initial arrival at the group home, believed that this is unlikely because the cases were not observed to use homesign to communicate with deaf peers or adults (Ferjan Ramirez et al. 2013). It is also interesting to note that after 1 to 2 years of ASL immersion, Shawna and Carlos used very little gesture and almost exclusively used ASL to communicate. Thus, their homesign gestures, if they were used prior to group home placement, were no longer used soon after a formal language became available. It is important to understand that even those cases reported to have developed complex homesign systems prior to exposure to conventional languages show marked deficits in later language development (Morford 2003), suggesting that homesign does not serve as an L1 in terms of supporting future conventional language acquisition (Morford and Hänel-Faulhaber 2011). The professionals at the group home also reported that Shawna and Carlos had no knowledge of any conventional spoken

language, were illiterate, and unable to lip-read upon placement in the group home. The limited schooling they received thus seems to have had little effect on their language development.

About 1 year prior to participating in the current study, Shawna and Carlos were administered the Test of Nonverbal Intelligence, Third Edition (TONI-3). The TONI-3 is typically used with children and adults between ages 6 and 90. Their age-adjusted scaled score was 1 to 1.5 standard deviations below the mean. These results, however, should be interpreted with caution because of the participants' atypical life and lack of school experience. As discussed by Mayberry (2002), the non-verbal IQ scores of late L1 learners who have suffered from educational deprivation tend to be low when they first become immersed in a conventional language. As documented by Morford (2003), however, IQ scores show significant increases over time as more education and linguistic input is received.

In preparation for the present neuroimaging study, we estimated the size and composition of Shawna's and Carlos' vocabularies using the MacArthur-Bates Communicative Developmental Inventory (CDI) for ASL (Anderson and Reilly 2002), which we cross-validated by further analyzing their spontaneous ASL production. (We have previously reported the results of our analyses of Shawna's and Carlos' language after 1 to 2 years of ASL immersion in Ferjan Ramirez et al. 2013). Shawna knew 47% of the signs on the ASL-CDI list, and Carlos knew 75% of the list total. In addition, their vocabularies included several signs that are not part of the ASL-CDI list. Their ASL vocabulary composition was similar to that of child L1 learners, with a preponderance of nouns, followed by predicates, and relatively few grammatical words (Bates et al. 1994;

Anderson and Reilly 2002). Further, Shawna and Carlos, like young deaf and hearing children who acquire language from birth, produced short utterances (Newport and Meier 1985; Bates et al. 1998). Shawna's mean length of utterance in sign units was 2.4, and Carlos' mean length of utterance was 2.8. Their utterances were predominantly declarative and simple, and included examples such as SCHOOL FOOD LIKE, or LETTER BRING[4]. They did not use conjunction, subordination, conditionals, or wh-questions. As in child L1 (Bates and Goodman 1997), their syntactic development was consistent with their vocabulary size and composition. These analyses suggested that the language acquisition of Shawna and Carlos, although begun extraordinarily late in development, was highly structured and shared basic characteristics of young child language learners.

With these ASL acquisition findings in mind, the present study asks how Shawna and Carlos neurally represent their newly acquired ASL words. Given that their language acquisition looks child-like, one hypothesis is that their neural language representation will look child-like as well. Recent neuroimaging studies suggest that infant language learners activate the canonical left-hemisphere fronto-temporal network when presented with language stimuli. The occurrence of adult-like activations has been reported in French- (Dehaene-Lambertz et al. 2002), English- (Travis et al. 2011), and Finnish-learning infants (Imada et al. 2006) between the ages of 3 and 18 months. These results suggest that the language network is functional for language processing from an early

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[4] Examples are given as English glosses because ASL has no written form. For more examples see Ferjan Ramirez et al 2013.

age. We asked whether these canonical patterns of neural activation would also appear in the cases whose initial language immersion occurred in adolescence rather than infancy.

Deaf babies who experience sign language from birth have not yet been studied with neuroimaging methods. However, given the parallels between sign and spoken languages (Klima and Bellugi 1979; Sandler and Lillo-Martin 2006) there is no reason to assume that the infant neural representation of sign language would diverge from that of spoken language. Evidence from aphasia (Hickok et al. 1996), cortical stimulation (Corina et al. 1999) and neuroimaging (Petitto et al. 2000; Sakai et al. 2005; MacSweeney et al. 2006; MacSweeney et al. 2008a; Mayberry et al. 2011; Leonard and Ferjan Ramirez et al. 2012) suggests that when acquired from birth by deaf native signers, the neural patterns associated with sign language processing look much like those associated with spoken language processing. Interestingly, Newman and colleagues suggest that this may not be the case for *hearing* native signers (Newman et al. 2002). In agreement with spoken language studies on L2 acquisition, the canonical language areas are also the main sites of neural activity in deaf individuals who acquire British Sign Language at a later age, following acquisition of a spoken/written language (as indicated by their reading scores; MacSweeney et al. 2008b). These findings confirm that the canonical language network is supramodal in nature (Marinkovic et al. 2003), further demonstrating its robustness for linguistic processing. The question considered here is whether the predisposition of this network to process language is independent of the timing of linguistic experience over development; if this is the case, then Shawna's and Carlos' neural activations in response to ASL signs should look like those of infants and adults with early L1 onset.

Alternatively, Shawna and Carlos may exhibit neural activation patterns that diverge from the canonical one. This would suggest that early language experience is required to bring about the functionality of the left-hemisphere language network, i.e., that there is a critical period when language input must occur for this network to become functional. Such findings would explain why delayed L1 acquisition has severe and long-term negative effects on language acquisition and processing (Mayberry and Fischer 1989; Newport, 1990; Mayberry and Eichen 1991; Boudreault and Mayberry 2006). One fMRI study with deaf non-native signers suggests that delayed exposure to L1 significantly alters the adult neural representation of language (Mayberry et al. 2011). Specifically, Mayberry and colleagues scanned 23 lifelong deaf signers who were first immersed in ASL at ages ranging from birth to 14 years. On an ASL grammaticality judgment task and on a phonemic hand judgment task, early language exposure correlated with greater positive hemodynamic activity in the classical language areas (such as the left inferior frontal gyrus, left insula, left dorsolateral prefrontal cortex, and left superior temporal sulcus), and greater negative (below baseline) activity in the perceptual areas of the left lingual and middle occipital gyrus. As age of L1 exposure increased, this pattern reversed, suggesting that linguistic representations may rely to a greater extent on posterior brain areas, and to a lesser extent on the classical language areas, when the L1 is acquired late. These neuroimaging results accord with previous psycholinguistic findings and show that delays in L1 AoA significantly affect language processing, even after 20 years of language use. What is currently unknown is how the human brain processes a language that it has just begun to acquire for the *first* time in adolescence. Such individuals have never before been neuroimaged.

Materials and Methods

Participants:

Cases:

Two cases were studied whose language input was delayed until adolescence. The cases' backgrounds are described in the Introduction. The present neuroimaging results for the cases are compared to those of two carefully selected control groups: 12 young deaf adults who acquired sign language from birth (native signers), and 11 young hearing adults who studied ASL in college (L2 signers). The two control groups studied here, unlike the cases, had ideal language acquisition circumstances from birth. The native group serves to establish a baseline of how ASL is processed in the deaf brain when acquired from birth. The L2 group serves as a control in establishing how ASL is processed in the hearing brain when acquisition begins later in life, and full proficiency has not yet been achieved. Like the cases, the L2 learners began to acquire ASL in adolescence or young adulthood, have only used it for a limited period of time, and were not highly proficient at the time of study. Importantly, and unlike the cases, the L2 control participants experienced language (English) from birth and the L1 control participants were proficient L2 learners of English. The results from the control groups have been reported in detail elsewhere (Leonard and Ferjan Ramirez et al. 2012, Leonard and Ferjan Ramirez et al., under review), and are only reported here insofar as they are relevant and necessary to the interpretation of the two cases.

Deaf native signers:

Twelve healthy right-handed congenitally deaf native signers (6 F, 17-36 years) with no history of neurological or psychological impairment were recruited for

participation. All had profound hearing loss from birth and acquired ASL from their deaf parents.

Hearing L2 ASL learners:

Eleven hearing native English speakers also participated (10 F; 19-33 years). All were healthy adults with normal hearing and no history of neurological or psychological impairment. All participants had four to five academic quarters (40 to 50 weeks) of college-level ASL instruction, and used ASL on a regular basis at the time of the study. Participants completed a self-assessment questionnaire to rate their ASL proficiency on a scale from 1-10, where 1 meant "not at all" and 10 meant "perfectly". For ASL comprehension, the average score was 7.1 ± 1.2; ASL production was 6.5 ± 1.9.

While the participants in the control groups were older then the cases, this should not have a significant effect on our results because our dependent measure, the N400 semantic congruity effect, has been shown to be particularly stable in the age range tested here (Holcomb et al. 1992; Kutas and Iragui 1998). The N400 effect undergoes a change in amplitude between ages 5 and 15 years (Holcomb et al. 1992), and then again with normal aging (Kutas and Iragui 1998). However, in the age range of our participants (16 to 33 years), the N400 changes are very small to non-existent.

Stimuli and Task:

We developed a stimulus set of ASL words that Shawna and Carlos knew well (Ferjan Ramirez et al. 2013) along with a task they were able to perform with high accuracy in the scanner. The cases and all control participants performed a semantic decision task that took advantage of decades of research on an event-related neural response between 200-600 ms after the onset of meaningful stimuli, known as the N400

(Kutas and Hillyard 1980, Kutas and Federmeier 2000; 2011) or N400m in MEG (Halgren et al. 2002). While we recorded MEG, participants saw a line-drawing of an object for 700 ms, followed by a sign (mean length: 515.3 ms; length range: 340-700 ms;) that either matched (congruent; for example "cat-cat") or mismatched (incongruent; for example, "cat-ball") the picture in meaning. (Fig. 1). To measure accuracy and maintain attention, participants pressed a button when the word matched the picture; response hand was counterbalanced across blocks within participants. Responding only to congruent trials makes the task easy to perform, which was important for successful testing of the cases who lack experience in performing complex cognitive tasks. Responding only to congruent trials could theoretically lead to important differences in neural responses to congruent and incongruent conditions; however, previous studies in our laboratory (Travis et al. 2011; Travis et al. 2012), as well as additional analyses conducted in the present study (see supplemental materials, Fig. S2), indicate that the neural response to button press does not affect the N400 semantic congruity effect. The number of stimuli was high, allowing us to obtain statistically significant results for individual participants. To ensure that the cases were able to perform the task with high accuracy, we worked with them extensively prior to scanning to ensure that they understood the task instructions and were comfortable with the scanners.

All signs were highly imageable concrete nouns selected from ASL developmental inventories (Schick 1997; Anderson and Reilly 2002) and picture naming data (Bates et al. 2003; Ferjan Ramirez et al. 2013). Stimulus signs were reviewed by a panel of 6 deaf and hearing fluent signers to ensure accurate production and familiarity. Fingerspelling or compound nouns were excluded. Each sign video was edited to begin

when all phonological parameters (handshape, location, movement, orientation) were in place, and ended when the movement was completed. Each sign appeared in both the congruent and incongruent conditions, and if a trial from one condition was rejected due to artifacts in the MEG signal, the corresponding trial from the other condition was also eliminated to ensure that sensory processing across congruent and incongruent trials included in the averages was identical. Native signers saw 6 blocks of 102 trials each, and L2 signers saw 3 blocks of 102 trials each because they were also scanned on the same task in the auditory and written English modality (3 blocks for each; See Leonard and Ferjan Ramirez et al., under review). Our previous work with MEG sensor data and aMEG analyses suggests that 300 trials (150 in each condition) are sufficient to capture clean and reliable single subject responses. Shawna saw 5 blocks of 102 trials because she was not familiar with the rest of the words (Ferjan Ramirez et al. 2013). Carlos saw 5 blocks of 102 trials due to equipment malfunction during one of the blocks. Prior to testing, Carlos and Shawna participated in a separate acclimation session during which they were familiarized with the MEG and MRI scanners and practiced the task. Before scanning began, all participants performed a practice run in the scanner. The practice run implemented a separate set of stimuli that was not part of the experimental stimuli. All controls and both cases understood the task quickly. No participant required repetitions of the practice block in the MEG.
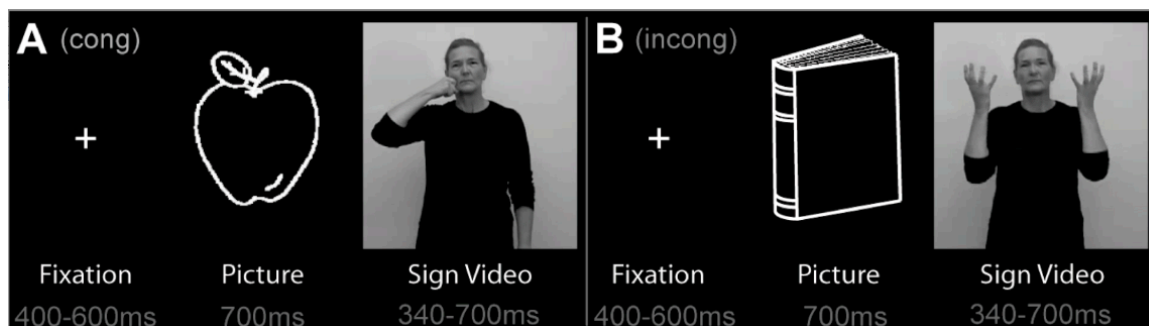
Figure 1: Schematic diagram of task design. Each picture and sign appeared in both the congruent **(A)** and incongruent **(B)** conditions. Averages of congruent versus incongruent trials thereby compared responses to exactly the same stimuli.

Procedure:

Using the above-described experimental paradigm with spoken words in hearing subjects, we previously found a typical N400m evoked as the difference in the magnitude of the neural response to congruent versus incongruent trials (Travis et al. 2011). In the present study, we estimated the cortical generators of this semantic effect using anatomically constrained magnetoencephalography (aMEG) a non-invasive neurophysiological technique that combines MEG and high resolution structural MRI (Dale et al. 2000). MEG was recorded in a magnetically shielded room (IMEDCO-AG, Switzerland) with the head in a Neuromag Vectorview helmet-shaped dewar containing 102 magnetometers and 204 planar gradiometers (Elekta AB, Helsinki, Finland). Data were collected at a continuous sampling rate of 1000 Hz with minimal filtering (0.1 to 200 Hz). The positions of four non-magnetic coils affixed to the subjects' heads were digitized along with the main fiduciary points such as the nose, nasion, and preauricular points for subsequent coregistration with high-resolution MRI images. Structural MRI

was acquired on the same day after MEG, and participants were allowed to sleep or rest in the MRI scanner.

aMEG has previously been used successfully with 12-18 month old infants (Travis et al. 2011) and it was likewise suitable for use with these cases whose language was beginning to develop. Importantly, and unlike hemodynamic techniques, aMEG allows us to focus on the spatial *and temporal* aspects of word processing and to estimate the spatiotemporal distribution of specific neural stages of single word (sign) comprehension. Using aMEG, we have previously shown that, when learned from birth, sign languages are processed in a left fronto-temporal brain network (Leonard and Ferjan Ramirez et al. 2012), similar to the network used by hearing subjects to understand speech, concordant with other neuroimaging studies (Petitto et al. 2000; Sakai et al. 2005; MacSweeney et al. 2006; MacSweeney et al. 2008a; Mayberry et al. 2011).

Anatomically-constrained MEG (aMEG) Analysis:

The data were analyzed using a multimodal imaging approach that constrains the MEG activity to the cortical surface as determined by high-resolution structural MRI (Dale et al. 2000). This noise-normalized linear inverse technique has been used extensively across a variety of paradigms, particularly language tasks that benefit from a distributed source analysis (Marinkovic et al. 2003; Leonard et al. 2010), and has been validated by direct intracranial recordings (Halgren et al. 1994; McDonald et al. 2010).

The cortical surface was obtained with a T1-weighted structural MRI, and was reconstructed using FreeSurfer (http://surfer.nmr.mgh.harvard.edu/). A boundary element method forward solution was derived from the inner skull boundary (Oostendorp and Van Oosterom 1992), and the cortical surface was downsampled to ~2500 dipole locations per

hemisphere (Dale et al. 1999; Fischl et al. 1999). The orientation-unconstrained MEG activity of each dipole was estimated every 4ms, and the noise sensitivity at each location was estimated from the average pre-stimulus baseline from -190 to -20ms. aMEG was performed on the waveforms produced by subtracting congruent from incongruent trials.

The data were inspected for bad channels (channels with excessive noise, no signal, or unexplained artifacts), which were excluded from further analyses. Additionally, trials with large (>3000 fT/cm for gradiometers) transients were rejected. Blink artifacts were removed using independent components analysis (Delorme and Makeig 2004) by pairing each MEG channel with the electrooculogram (EOG) channel, and rejecting the independent component that contained the blink. For the cases, fewer than 9% of trials were rejected due either to artifacts or cross-condition balancing. For native signers fewer than 3% of trials were rejected; for L2 signers fewer than 2% were rejected.

Individual subject aMEG movies were constructed from the averaged data in the trial epoch for each condition using only data from the gradiometers; these data were combined across subjects by taking the mean activity at each vertex on the cortical surface and plotting it on an average Freesurfer fs average brain (version 450) at each latency. Vertices were matched across participants by morphing the reconstructed cortical surfaces into a common sphere, optimally matching gyral-sulcal patterns and minimizing shear (Sereno and Dale 1996; Fischl et al. 1999). All statistical comparisons were made on region of interest (ROI) timecourses, which were selected based on information from the average incongruent-congruent subtraction across all subjects.

Results

Behavioral results:

Both the native and L2 signer control groups performed the task with high accuracy and fast reaction times (94%, 619 ms, and 89%, 719 ms respectively, from the onset of the signed stimulus; see Table 1). Shawna and Carlos performed within one standard deviation of the L2 group (84%, 811 ms, and 85%, 733 ms respectively). The neural results were unchanged when only correctly answered trials were included in the MEG analyses.

Table 1: Participant background information and task performance: mean (SD).

Participant(s)	Gender	Age	Age of Language Onset	Age of ASL Acquisition	Accuracy %	RT ms
Native signers	6M, 6F	30 (6.4)	Birth	Birth	.94 (.04)	619.1 (97.5)
L2 learners	1M, 10F	22;5 (3.8)	Birth	20 (3.9)	.89 (.05)	719.5 (92.7)
Shawna	F	16;9	14;7	14;7	.84	811.4
Carlos	M	16;10	13;8	13;8	.85	733.1

Anatomically-constrained MEG (aMEG) results:

We examined aMEG responses to ASL signs at the group level (two control groups) and at individual levels (two cases and two representative control participants) from 300-350 ms post-sign onset, a time-window during which lexico-semantic encoding is known to occur in spoken and sign languages (Kutas and Hillyard 1980; Marinkovic et al. 2003; Kutas and Federmeier 2000, 2011; Leonard and Ferjan Ramirez et al. 2012). The N400 is a broad stimulus-related brain activity in the 200-600 ms post-stimulus time window (Kutas and Federmeier 2000, 2011). In our previous studies on lexico-semantic processing using spoken, written, and sign language stimuli, we have observed that the

onset of this effect is around ~220 ms post stimulus, and the peak activity occurs slightly before 400ms post stimulus. The 300-350 ms post-stimulus time window was selected because we have previously observed that the semantic effect in picture-priming paradigms with spoken and signed stimuli is the strongest at this time (see Travis et al. 2012; Leonard and Ferjan Ramirez et al. 2012). Similar results were obtained using a broader time window (see supplementary materials, Fig. S1).

Given their sparse language exposure throughout childhood, we hypothesized that Shawna's and Carlos' neural activation patterns would diverge significantly from both control groups. Specifically, we expected that ASL processing in Shawna and Carlos would occur in more posterior and right hemisphere areas based on previous neuroimaging studies on late L1 acquisitions of sign language (Mayberry et al. 2011) and on L2 acquisition of spoken languages (Abutalebi, 2008; Leonard et al. 2010, 2011). We further expected that neural activations in the classical left hemisphere language network would be weaker in both cases compared to both control groups based on previous research (Mayberry et al. 2011).

To directly compare the strength of semantically-modulated neural activity in Shawna and Carlos with that of the control groups, we first considered the neural activation patterns in 9 bilateral regions of interests (ROIs). ROIs were selected by considering the aMEG movies of grand-average activity across the whole brain of all 25 subjects (all 12 native signers, all 11 L2 signers, and the two cases). These movies are a measure of signal to noise ratio (SNR), being the F-ratio of explained variance over unexplained variance. The strongest clusters of neural activity across all the subjects and

conditions were selected for statistical comparisons, thereby producing empirically derived ROIs that were independent of our predictions.

Table 2 presents normalized aMEG values for the subtraction of incongruent-congruent trials for both control groups and for Carlos and Shawna. We defined as "significantly different" those ROIs in which Shawna's or Carlos' aMEG values were more than 2.5 standard deviations away from the mean value of each control group. We applied a strict significance threshold (a z score of 2.5 corresponds to a p-value of 0.0124) because we conducted comparisons in multiple ROIs. As shown in Table 1, both the cases exhibited greater activity than the control groups in several right hemisphere ROIs. Specifically, Carlos showed greater activity than native signers in right lateral occipitotemporal (LOT) and posterior superior temporal sulcus (pSTS), and greater activity than the L2 signers in the right intraparietal sulcus (IPS). Similarly, Shawna showed greater activity than the natives in right inferior frontal gyrus (IFG), IPS, and pSTS, and greater activity than the L2 signers in the right IPS.

Table 2: ROI analyses. Normalized aMEG values for the subtraction of incongruent-congruent trials.

A) Control Groups

ROI	Native mean (sd)		L2 mean (sd)	
	LH	RH	LH	RH
AI	0.39 (0.14)	0.40 (0.18)	0.33 (0.12)	0.36 (0.13)
IFG	0.29 (0.12)	0.30 (0.12)	0.26 (0.12)	0.28 (0.14)
IPS	0.37 (0.10)	0.32 (0.13)	0.36 (0.13)	0.28 (0.08)
IT	0.43 (0.12)	0.35 (0.11)	0.36 (0.13)	0.34 (0.18)
LOT	0.29 (0.12)	0.29 (0.10)	0.30 (0.16)	0.32 (0.15)
PT	0.54 (0.14)	0.45 (0.17)	0.45 (0.16)	0.43 (0.18)
STS	0.43 (0.08)	0.41 (0.18)	0.32 (0.09)	0.36 (0.16)
TP	0.45 (0.16)	0.46 (0.15)	0.34 (0.14)	0.38 (0.16)
pSTS	0.33 (0.09)	0.27 (0.07)	0.34 (0.16)	0.32 (0.15)

B) Cases

ROI	Carlos		Shawna	
	LH	RH	LH	RH
AI	0.27	0.43	0.38	0.43
IFG	0.26	0.31	0.34	0.60[+]
IPS	0.31	0.54[♦]	0.41	0.66[+♦]
IT	0.50	0.43	0.41	0.27
LOT	0.43	0.57[+]	0.17	0.29
PT	0.33	0.57	0.52	0.33
STS	0.26	0.40	0.47	0.23
TP	0.42	0.51	0.27	0.20
pSTS	0.26	0.47[+]	0.35	0.54[+]

[+] = 2.5 standard deviations from native mean

[♦] = 2.5 standard deviations from L2 mean

These results partly confirmed our hypotheses. As expected, Shawna and Carlos exhibited stronger activity than the controls in a number of right hemisphere ROIs. Also in agreement with our hypotheses is the fact that two of the significant ROIs were located in posterior parts of the brain (pSTS and LOT). The finding that both Shawna and Carlos

exhibited stronger activity than the native signers in the right IPS, and that Shawna's right IPS activity was also stronger than that of the L2 group, was unexpected. The hypothesis that Shawna and Carlos would exhibit weaker activity than the control groups in the classical left hemisphere language regions (for example IFG or STS) was not confirmed.

The next step of our analysis was to look at the activation patterns across the entire brain, including the areas outside the ROIs. Because the ROIs were derived based on the grand average of all participants (the cases and both control groups), it is possible that some brain areas that were strongly activated in Shawna and Carlos were not selected as ROIs. An analysis of activations across the entire brain surface allowed us to focus on Shawna's and Carlos' individual neural activations patterns. We first qualitatively compared the aMEGs associated with the incongruent vs congruent contrast of the cases to those of the control groups and two individual control participants. We then examined whether differences between congruent and incongruent condition were due to larger signals in one or the other direction by examining the MEG sensor level data directly. Planar gradiometers were examined, which, unlike other MEG sensors, are most sensitive to the immediately underlying cortex.

The aMEG maps in Figure 2 represent the strength of the congruent-incongruent activity across the whole brain for Carlos (panel A) and Shawna (panel B), 2 representative control participants (panel C: 17yo native signer; panel D: 19yo L2 signer), and both control groups (panel E, native signers; panel F, L2 signers). The two control participants (panels C and D) were selected for analyses at the individual level based on being closest in age to Carlos and Shawna. Recall that the aMEG maps are

essentially a measure of SNR. The areas shown in yellow and red represent those brain regions where the SNR is larger than the baseline. The maps are normalized within each control group or each individual, allowing for a qualitative comparison of overall congruent-incongruent activity patterns.

We previously showed that, consistent with other neuroimaging studies of sign language, in the native signers signs elicited activity in a left-lateralized fronto-temporal network including the temporal pole (TP), planum temporale (PT), STS, and to a lesser extent in the homologous right hemisphere areas (Fig. 2E data from Leonard and Ferjan Ramirez et al. 2012). Consistent with previous studies on L2 acquisition (Abutalebi 2008), this canonical language network was also activated in L2 signers (Fig. 2F, data from Leonard and Ferjan Ramirez et al. (under review)).

The same left-lateralized fronto-temporal activations are observed when we look at the aMEG maps of the two individual control participants (panels C and D). Note that the normalized aMEG values of the two control participants were also compared to the average aMEG values of their respective groups in each of the 18 ROIs, and no significant differences were found (i.e., there were no ROIs where the individual control subjects were more than 2.5 standard deviations away from the respective group mean). Together these results corroborate previous research showing that the left fronto-temporal areas process word meaning independently of modality (spoken, written, or signed) (Marinkovic et al. 2003) and hearing status (Leonard and Ferjan Ramirez et al. 2012). Importantly, in the participants who acquired language from birth (native and L2 signers), we were able to observe these canonical activations at the individual and group level.

Consistent with the fact that they were developing language and were able to understand the stimuli signs (Ferjan Ramirez et al. 2013), Carlos and Shawna exhibited the semantic modulation effect -- the N400 effect. MEG channels with significant semantic effects for the two cases and the two representative control participants are highlighted in red and blue in Figure 2, panel G (Carlos), H (Shawna), I (native signer) and J (L2 signer). Using a random-effects resampling procedure (Maris and Oostenveld 2007), we determined in which MEG channels the incongruent>congruent and the congruent>incongruent effects were significant (at $p < 0.01$). Channels with significant congruent>incongruent activity are shown in red, and channels with significant incongruent>congruent activity are shown in blue.
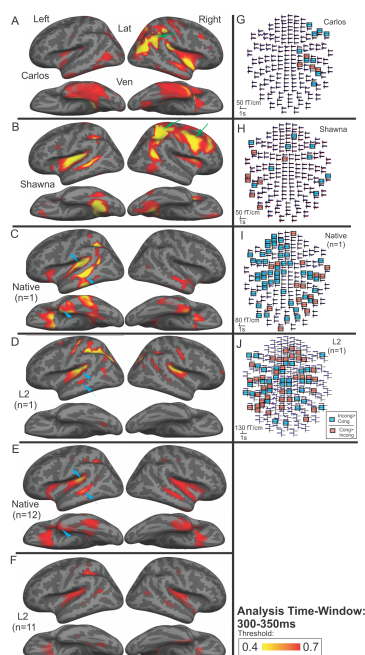
Figure 2: A-F: Contrasting semantic activation patterns to signs in cases who first experienced language at ~14 yo, compared to a native and L2 signers. During semantic processing (300-350ms), **(A)** Carlos and **(B)** Shawna show the strongest effect in right occipito-parietal cortex (blue arrows). Shawna also shows left superior temporal and right frontal activity. **(C)** A representative native signer (17yo female, accuracy: 97%, RT: 573 ms) and **(D)** a representative L2 signer (19 yo fem ale, accuracy: 94%, RT: 584.8 ms.) show semantic effects in left fronto-temporal language areas, as does the native signer group **(E)**. The L2 group **(F)** also shows similar patterns of activity, but with overall smaller subtraction effects. Maps are normalized to strongest activity for each participant or group.

G-J: Individual MEG sensor data. The cases lack a strong incongruent>congruent effect in left fronto-temporal regions. Blue channels: significant incongruent>congruent activity between 300-350ms, red channels: significant congruent>incongruent effects at the same time. **(E)** Carlos has the strongest incongruent>congruent effects in right hemisphere channels (blue channels); **(F)** Shawna also shows the most incongruent>congruent effects in right occipito-temporo-parietal channels (blue channels). In the cases, the semantic effect in left (Shawna) and right (Carlos) temporal cortex seen in panels A & B is mostly due to congruent>incongruent activity (red channels, panels G and H). **(I)** A native signer shows strong incongruent>congruent effects in left fronto-temporal channels (blue channels). **(H)** An L2 signer also shows predominantly left-lateralized semantic effects (blue channels). Statistical significance was determined by a random-effects resampling procedure (Maris and Oostenveld 2007) and reflects time periods where incongruent and congruent conditions diverge at $p < 0.01$. The two control participants are the same individuals as those whose aMEGs are displayed in panels C and D.

By simultaneously inspecting the MEG sensor data (Fig.2, panels G & H) and the aMEGs (Fig. 2, panels A & B), it is clear that the localization patterns of semantically modulated activity in Shawna and Carlos were quite different from those observed in the control participants. While both cases exhibited semantic effects in parts of the classical left-hemisphere language network and the homologous areas in the right hemisphere (for example left PT/STS for Shawna, right PT/STS for Carlos), examination of the MEG sensor data revealed that this was predominantly due to congruent>incongruent activity (channels highlighted in red). That is, although the aMEG data suggests that the cases' left hemisphere activations were in similar locations to those of the control participants, the nature of these activations was quite different because the majority of the left hemisphere effects shown in the cases were in the opposite direction to those shown in the control participants (Fig. 2, panels G, H, I, J). In Shawna and Carlos, the signature of word comprehension (incongruent>congruent responses, channels highlighted in blue) primarily localized to right superior parietal, anterior occipital, and dorsolateral prefrontal areas that were not activated in the controls.

For the final step of our analyses, we mapped the z-score of the aMEG for each case compared to each of the control groups. Since the aMEG is calculated from the difference in activity evoked between congruent and incongruent signs, and is always positive, large z-scores reflect areas where the magnitude of the responses may be unusual in the cases; their polarity (congruent larger vs incongruent larger) is uncertain but can be inferred from the sensor data noted above. Figure 3 shows that Carlos' neural activity for sign-word meaning was greater than that of native signers (panel A) and that of the L2 learners (panel C) predominantly in the right parieto-occipital cortex. Native

signers exhibited greater activity than Carlos in the left PT and STS. Shawna's neural activity for sign-word meaning was greater than that of the native (panel B) and L2 signers (panel D) in the right parietal and frontal cortex and in the left PT. Both control groups exhibited stronger activity than Shawna in portions of the right and left temporal lobe.
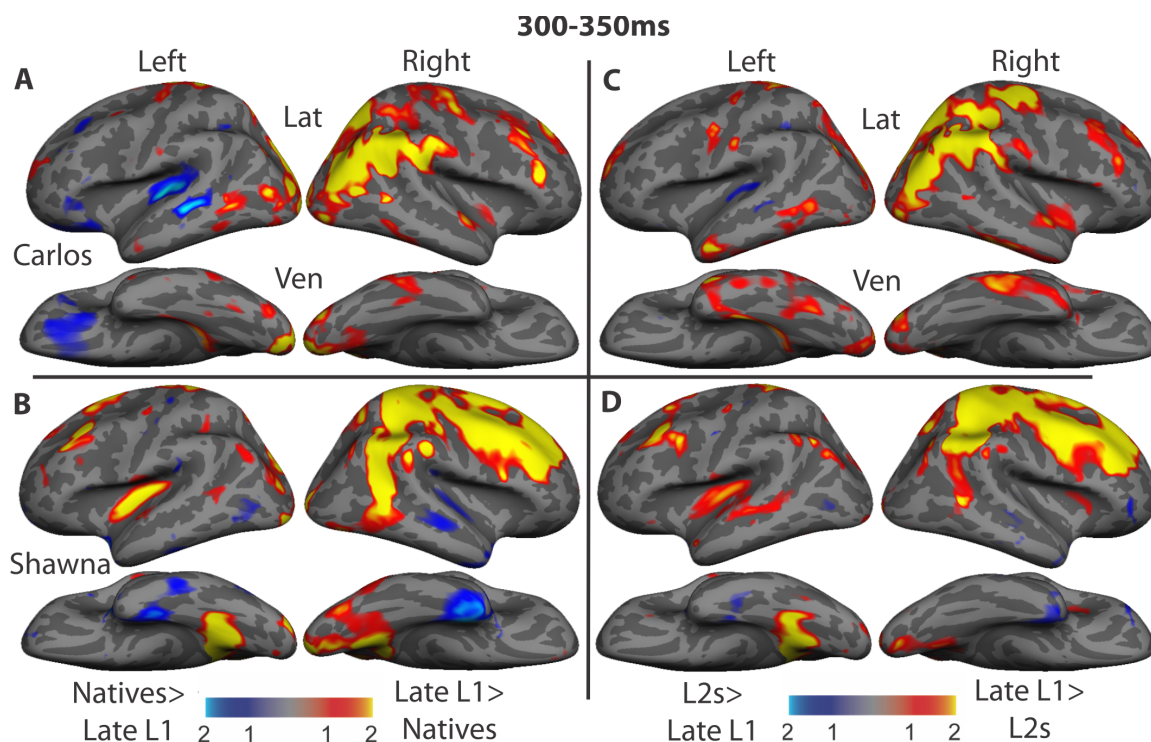

Figure 3: Z-score maps showing brain areas where semantic modulation is greater in the two cases compared to the control groups (yellow and red) and areas where semantic modulation is greater in the control groups compared to the two cases (blue) **(A)** Carlos vs native signers **(B)** Shawna vs native signers **(C)** Carlos vs L2 signers **(D)** Shawna vs L2 signers. The cases exhibit stronger activity than the control participants predominantly in the right hemisphere parietal cortex, with additional areas in the right occipital cortex (Carlos) and right frontal cortex (Shawna).

Discussion

The present study is the first to consider the neural underpinnings of language in adolescents learning a *first* language after a childhood of sparse language input and, as

such, provides novel insights into the nature of a critical period for language. Previous research suggests that childhood environmental, social, and linguistic deprivation severely limits subsequent language development (Koluchova 1972; Curtiss 1976; Windsor et al. 2011). The cases studied here provide unique insights into the role of language experience in the organization of neural processing because they were linguistically, but not physically or emotionally deprived.

The cases are roughly analogous to uneducated homesigners from other parts of the world previously described in the literature (Senghas and Coppola 2001; Morford 2003; Coppola and Newport 2005). Prior case studies with such individuals show that when sign language input becomes available, they quickly replace their idiosyncratic gestures with signs (Emmorey et al. 1994; Morford 2003). This was confirmed in our prior analyses of the language development of Shawna and Carlos; after 1 to 2 years of language acquisition, they had a limited, noun-biased ASL vocabulary, and were able to produce short, simple utterances, much like young children who acquire language from birth (Ferjan Ramirez et al. 2013). The question we asked here was how (where and when) the cases process their newly acquired words in the brain. In order to answer the question we also compared their neural processing to two control groups, one deaf group who acquired ASL from birth and one hearing group who acquired English from birth who had been learning ASL for the same amount of time as the cases.

Consistent with previous research (Hickok et al. 1996; Petitto et al. 2000; Sakai et al. 2005; Abutalebi 2008; MacSweeney et al. 2008a; Mayberry et al. 2011; Leonard and Ferjan Ramirez et al. 2012), the present aMEG results for the native and L2 signers show that when either a spoken or sign languages is acquired from birth, word meaning is

processed primarily in the classical left-hemisphere fronto-temporal language network. This network is well established to be the main site of neural generators of the N400 response across modalities (Halgren et al. 1994; Marinkovic et al. 2003), and is involved in processing word meaning in L2 learners (Leonard et al. 2010; 2011) as well as in infants (Dehaene-Lambertz et al. 2002; Imada et al. 2006; Travis et al. 2011).

By contrast, the results for the cases indicate that a paucity of language experience throughout childhood significantly disrupts the organization of this canonical language network. The cases were able to learn and process word meaning despite their atypical childhood experience, as demonstrated by both their accurate behavioral performance and their strongly modulated neural processing of words due to semantic priming. However, the cortical localization of this activity and its polarity diverged significantly from the pattern of the deaf and hearing controls (native and L2 signers). Both cases showed the classical incongruent>congruent responses (i.e., semantic priming decreasing the neural response) in some brain areas, but these responses localized mainly to the right hemisphere superior parietal, anterior occipital, and dorsolateral prefrontal cortices, areas that were not activated when the control participants processed signs, deaf or hearing, native or L2 learners. These striking results demonstrate that the timing of functional language experience during human development has marked affects on the organization of the neural network underlying word comprehension.

Areas outside the classical left hemisphere language network have previously been linked to the processing of later-acquired or less proficient languages. Relatively strong right hemisphere activations have previously been reported in less proficient L2 learners and in L2 learners who began their L2 learning at a late age (Dehaene et al.

1997; Perani et al. 1998). In addition, two MEG studies reported greater right hemisphere activations in ex-illiterates compared to control subjects when reading words (Castro-Caldas et al. 2009) or listening to words (Nunes et al. 2009). This series of findings indicates greater right hemisphere involvement when a language skill is learned after childhood. Modulations within non-classical brain regions have also been previously reported during language tasks performed by hearing adult populations (Travis et al. 2011). From low level phonetic processing (Kuhl 2010) to syntax (Mayberry et al. 2011), there is a general pattern of broader, more extensive neural activity at early stages of linguistic and biological development. Anterior occipital regions have previously been described as markers of underdeveloped language in normally developing populations (Mayberry et al. 2011). For example, when performing language tasks, toddlers show greater hemodynamic activation in occipital areas when compared to older children (Redcay et al. 2008), and children show greater hemodynamic activation in occipital regions than adults (Brown et al. 2005).

Previous findings from a range of language learning situations thus predict that a highly delayed onset of language acquisition and lower proficiency would result in more activity in right frontal and occipito-temporal areas. This was apparent to some extent for the two cases. However, unlike the cases studied here, normally developing infants and children, L2 learners, and ex-illiterates all show activation in the classical neural language network reflecting the common timing of their initial language experience, namely early life. Previous studies do not illuminate how the developing brain copes with a paucity of language experience over childhood in the absence of emotional and physical deprivation. Our results show that the patterns of neural organization for language arising

from this unique developmental situation are unlike those associated with language learning in infants (Dehaene-Lambertz et al. 2002; Imada et al. 2006; Travis et al. 2011), children (Brown et al. 2005; Redcay et al. 2008), L2 learners (Leonard et al. 2010, 2011), or ex-illiterates (Castro-Caldas et al. 2009; Nunes et al. 2009).

Shawna and Carlos showed responses in posterior visual areas similar to deaf signers whose L1 acquisition begins in late childhood (Mayberry et al. 2011). The previously studied late L1 learners had a mean length of ASL experience of 19 years, in contrast to the present cases who had only two to three years of ASL experience. The cases uniquely showed increased activity in right occipito-parietal and frontal regions, which could either be due to the fact that they were comparatively more linguistically deprived throughout childhood than the previously studied late L1 learners, or that they had comparatively less language experience at the time of neuroimaging. Longitudinal studies are required to adjudicate these alternative possibilities.

The distinctive superior parietal activity we observed in both cases suggest that the adolescent brain meets the challenge of learning language for the first time in a different fashion from either that of infant L1 or older L2 learners. It is generally accepted that planning, generating, and analyzing skilled manual movements engages the parietal cortex (Buccino et al. 2001). We might thus hypothesize that the activation patterns observed in Shawna and Carlos arise from a childhood of watching the gestures hearing people commonly produce. However, hemodynamic studies of native speakers show that semantic aspects of co-speech gestures are processed in brain areas typically associated with spoken language comprehension, including the left inferior frontal gyrus

(Skipper et al. 2007; Willems et al. 2007) and superior temporal sulcus (Holle et al. 2008), and not in right superior parietal cortex.

The superior parietal areas that were activated when Shawna and Carlos identified the meanings of ASL signs are part of the so-called dorsal stream. A well-established neural framework indicates that human action recognition begins in the visual cortex and then continues through either the dorsal or the ventral stream depending upon how meaningful the action is (Goodale and Milner 1992). Meaningful actions, such as opening a bottle or drawing a line, are processed primarily by the ventral stream (for review see Decety and Grezes 1999), consistent with the theory that the ventral stream accesses the semantic knowledge associated with visual patterns. By contrast, meaningless actions primarily engage the dorsal pathway, which is theorized to be involved in the analysis of the visual attributes of unfamiliar movements and the generation of visual-to-motor transformations. Consistent with the dual steam model, hearing adults have been found to primarily engage the dorsal stream when watching ASL signs, which were meaningless visual actions for them (Decety et al. 1997; Grezes et al. 1998). The dual stream model has also been applied to language processing. Listening to meaningful spoken language primarily engages the ventral stream, but the dorsal stream is recruited when articulatory re-mapping is used to aid language performance (Hickok and Poeppel, 2004).

The strong parietal activations for sign processing that we observe in both cases suggest that their lexical processing involves articulatory re-mapping and visual-to-motor transformations of signs in order to access sign meaning. Crucially, however, neither the deaf native nor the hearing L2 control groups showed such dorsal parietal activations. Previous research has found that late L1 learners have unique phonological recognition

patterns for signs in comparison to deaf and hearing adults who had infant language exposure (Morford and Carlson 2011; Hall et al. 2012), and that these effects extend to sentence processing (Mayberry et al. 2002; Mayberry et al. 2011). The present results suggest when the adolescent brain acquires language for the first time it uses different strategies than those employed by either the infant language learner or older L2 learner.

Infants are exquisitely sensitive to the dynamic patterns of the ambient language in the environment and learn the basic phonetic structure of words, consonant and (Werker and Tees 1984) vowel (Kuhl et al. 1992) features, before the end of the first year of life. Note that this early passive learning precedes the ability to produce words. This early tuning to the phonetic structure of words may both enable and be enabled by the neural architecture and connections of the ventral pathway and classic language system for language processing (see Kuhl 2004). The cases studied here, and late L1 learners we previously studied, experienced sustained dynamic language patterns only well after infancy when their expressive-motor and receptive-perceptual systems had already been developed without the synchronizing constraints of word structure where phonetic form and meaning are inextricably linked. Under such learning conditions, an alternative strategy, such as visuo-motor transformations and remapping of visual-motor forms may be necessary to recognize word meaning, a mechanism suggested by the activation of the dorsal stream in the cases.

In addition to learning phonetic structure of words for the first time, the cases must also map their prior world knowledge onto the specific semantic structure and categories of their new L1, learning that native and L2 learners accomplished in early childhood. Although the cases, especially Shawna, did show some neural responses in

the classical language network, they were qualitatively different from those of the native signers in that they were increased rather than decreased by semantic priming. Such responses were also observed in the age-matched L2 control signer (Figure 2, panel H). In the cases, the congruent>incongruent responses were mainly in the anteroventral temporal lobe (AVTL), which in typically developing individuals contains neurons that respond to the semantic categories of words across modalities (Chan et al. 2011) and are hypothesized to function as "semantic hubs" (Patterson et al. 2007). We might predict that as time passes and the cases create a stronger semantic network with the requisite phonetic representations, the more typical incongruent>congruent modulation may appear in their AVTL. In the same vein, the congruent>incongruent modulation may be a signature of new language learning because they have also been reported in 12 month-olds, but not in 14 or 19 month olds undergoing a picture priming ERP study (Friedrich and Friederici 2004, 2005). Interestingly, similar neural responses have been observed in response to non-words (Holcomb and Neville 1990) and to "grooming" gestures inserted in ASL sentences (Grosvald et al. 2012.). Both non-words and grooming gestures lack phonetic structure (and lexical meaning).

Finally, we observed that Carlos' and Shawna's neural activation patterns were not identical to one another. For example, Shawna showed the semantic modulation effect in the right frontal cortex, which was absent in Carlos. These differences should not be surprising given their backgrounds. Language in the ambient environment constrains learning: infants induce the phonetic and semantic structure of words within a similar developmental timeframe across languages and cultures (Ambridge and Lieven 2011). Without external language to guide the developing brain, the result may be more

neural variation. Future studies are necessary to discover the extent of variation in neural activation patterns when the adolescent brain first begins to learn language and whether it reduces as more language is acquired.

Our results provide initial direct evidence that the timing of language experience during human development significantly disrupts the organization of neural language processing in later life. The cases reported here exhibited neural activity in brain areas that have previously been associated with learning language at a late age, in addition to unique activation patterns heretofore unobserved. Longitudinal studies are necessary to determine whether the neural patterns we find here will become more focal in left anteroventral and superior temporal cortex as more language is learned, or whether they will remain right-lateralized with the strongest activity in areas not typically associated with lexico-semantic processing.

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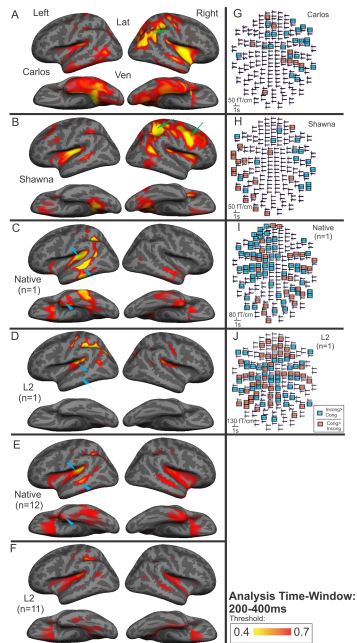
Supplemental Figures

Figure S1: A-F: Contrasting semantic activation patterns to signs in cases who first experienced language at ~14yo, compared to a native and L2 signers in the 200-400 ms time-window. Like in the 300-350 ms time window (Figure 2), **(A)** Carlos and **(B)** Shawna show the strongest effect in right occipito-parietal cortex (green arrows). The two representative control participants **(panel C – native signer; panel D L2 signer)** show semantic effects in left fronto-temporal language areas. Similar activation patterns are observed at the group level **(panel E – native signers; panel F – L2 signers)**.

G-J: Individual MEG sensor data in the 200-400 ms time-window. Like in the 300-350 ms time-window (Figure 2), the cases lack a strong incongruent>congruent effect in left fronto-temporal regions. Blue channels: significant incongruent>congruent activity between 200-400ms, red channels: significant congruent>incongruent effects at the same time. **(E)** Carlos has the strongest incongruent>congruent effects in right hemisphere channels (blue channels); **(F)** Shawna also shows the most incongruent>congruent effects in right occipito-temporo-parietal channels (blue channels). In the cases, the semantic effect in left temporal cortex seen in panels A & B is mostly due to congruent>incongruent activity (red channels, panels G and H). **(I)** A native signer shows strong incongruent>congruent effects in left fronto-temporal channels (blue channels). **(J)** An L2 signer also shows predominantly left-lateralized semantic effects (blue channels). For more details on statistical procedure and subjects see Figure 2.
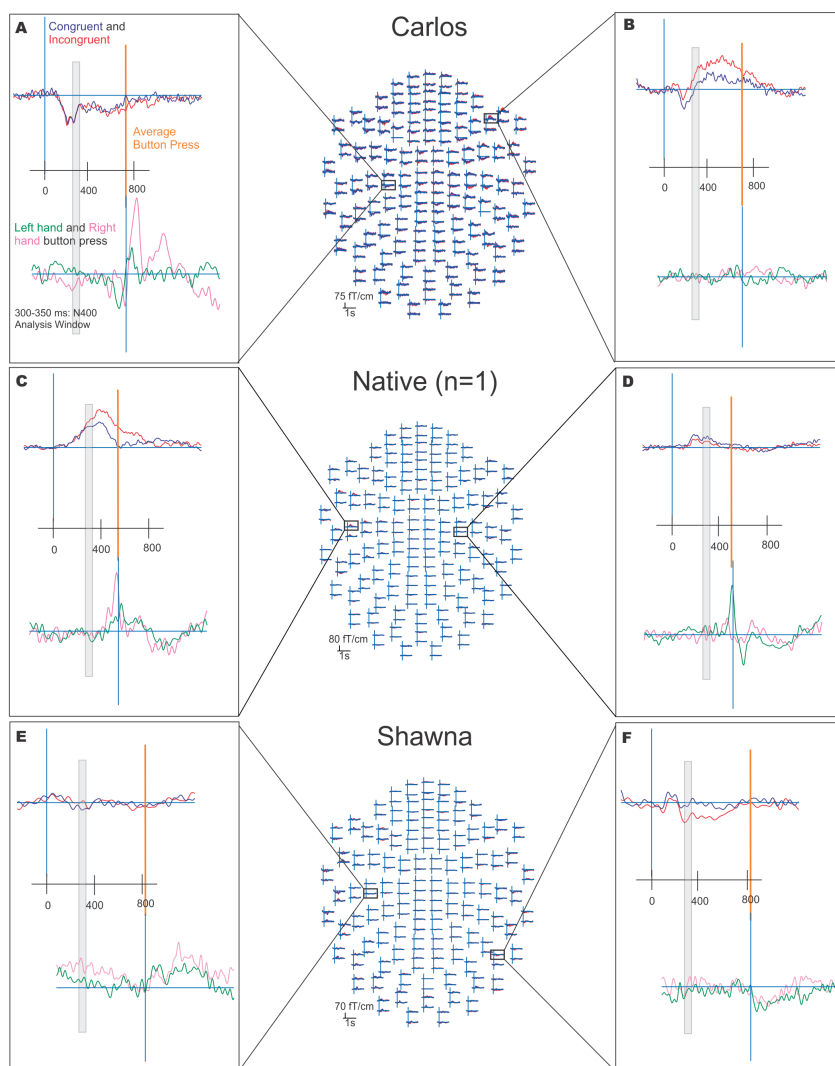
Figure S2: Neural responses to experimental task and motor control task. Selected channels are shown for Carlos and Shawna (panels A, B, E, & F) and a representative native signer (panels C & D). Panels B, C, and F show channels with large semantic congruity effects. The motor response to button press in these channels is either minimal (panels B and F), or occurs after the gray-shaded 300-350 ms time-window used in the N400 analyses (panel C). Conversely, panels A, D & E show channels with minimal semantic congruity effects but strong activity related to button press. Again, the MEG response to button press occurs well past the time window used in the N400 analyses. In the motor control task participants saw a grey dot on the screen and were asked to press a button when the dot changed its color to red. Each participant saw 120 trials, and responded 60 times with each hand. The motor control task was presented at the end of the MEG session, after the participants had completed the experimental blocks.

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Chapter 4, in full, is a reprint of the material currently under review at *Cerebral Cortex*, and may appear as Ferjan Ramirez, N., Leonard, M.K., Torres, C., Hatrak, M., Halgren, E., Mayberry, R.I. Neural language processing in adolescent *first*-language learners. The dissertation author was the primary investigator and author of this paper. Permission to reprint was granted by *Cerebral Cortex*.

CHAPTER 5:

General Discussion

The critical period hypothesis for language is decades old, but poorly understood. While most researchers agree that there must be some association between brain development and linguistic experience, this relationship has not been studied extensively, mostly due to a lack of human model where the onset of a first-language varies in the absence of other confounding factors. This dissertation used deafness and sign language as a test case to study both language acquisition and neural language processing in adolescent *first*-language learners. The results provide some initial evidence that the timing of language experience over human development affects the patterns of language acquisition and the neural organization for language processing.

It should be emphasized that the negative effects of delayed exposure to sign language have previously been described in a number of studies with deaf adults who have used sign language for a minimum of 20 years, but varied in their initial age of exposure to it (for review see Mayberry et al. 2010; see also section 3 of the Introduction). These studies have shown that increased L1 AoA is negatively related with adult language processing skills, ultimate language proficiency, and the strength of neural activations in the classical left hemisphere language network (Mayberry, Chen, Witcher, & Klein 2011). What is novel about the approach adopted in this dissertation is that the cases we studied were comparatively more linguistically deprived throughout childhood than the previously described L1 learners, received little or no schooling, and had comparatively less language experience at the time when the studies were conducted. By

studying the acquisition patterns and the neural processing of language in deaf adolescent L1 learners, this dissertation explored two specific issues: 1) What is the process of language acquisition like when it begins for the first time in adolescence? 2) How does the human brain represent language when it is acquired for the first time in adolescence? Before turning to a more general discussion and interpretation of our findings, I briefly review and discuss the results from each chapter.

Acquiring a first-language in adolescence

Cross-cultural and cross-linguistic studies have shown that when begun in infancy, language acquisition follows a precise developmental trajectory. In most languages, the earliest words in children's vocabularies are nouns and social words, followed by verbs and adjectives. Grammatical words such as prepositions, determiners and conjunctions, emerge only after a base vocabulary has been acquired. The first utterances tend to be short and simple, but then increase in length and complexity as more and more vocabulary is acquired. In Chapter 2, we asked whether this trajectory of early language acquisition milestones is age-dependent. Three cases who had no formal language in childhood were studied. We asked what language acquisition looks like when formal language input becomes available for the first time in adolescence. Can the cases capitalize on their cognitive maturity and sidestep the initial stages of language acquisition? Alternatively, do they begin where all young children begin, by acquiring an initial lexicon that looks child-like, and then proceed through the well-documented stages of L1 acquisition?

After 1 to 2 years of ASL input, the cases used almost exclusively ASL to communicate, suggesting that, once formal language became available, they were able to

zero-in on it and began to use it remarkably quickly, suggesting that the ability to distinguish between linguistic and non-linguistic input is not lost after early childhood (Krentz & Corina 2008). Indeed, the cases initially acquired signs at a faster rate than child L1 learners. Their ASL lexicons, like those of young children were biased towards nouns, and included relatively few grammatical words. As in child L1, the syntactic development of the adolescent L1 learners was predicted from vocabulary size and composition. These findings suggest that the acquisition of initial vocabulary and simple utterances is common to all L1 learning, regardless of age.

Having acquired the initial simple lexicon, the question is whether the cases continue to develop ASL in a child-like manner. Psycholinguistic studies suggest that delays in the onset of language acquisition lead to life-long language processing deficits across all domains of linguistic structure, suggesting that this outcome is unlikely. In addition, previous studies with deaf participants of similar linguistic backgrounds, as well as follow-up studies with Shawna, Cody, and Carlos suggest that the subsequent stages of lexical and syntactic acquisition are severely slowed (Hargraves 2002; Gates 2002; Garfinkel 2005; Ferjan Ramirez, Lieberman, & Mayberry, in preparation).

The procedures used in our language studies with the cases were based on two previous case studies with deaf adolescent L1 learners of ASL. These two cases, named Chris and Jenna, had similar linguistic backgrounds as our participants, and started acquiring ASL through full immersion in adolescence. Their language was studied after 3 years of ASL input; Chris also participated in a follow-up study after 6 years of ASL use. Results indicate that their vocabulary compositions were remarkably similar to those of Shawna, Cody, and Carlos, despite the fact that they had been using ASL for a longer

period of time. After 3 years of ASL use, their vocabularies were small and biased towards nouns, they used remarkably few closed class words, and their utterances were short (Hargraves 2002; Gates 2002). Longitudinal studies with Chris report similar findings even after 6 years of ASL use (Garfinkel 2005); his vocabulary did increase, but several orders of magnitude slower than in typically developing children with comparable amount of language experience. Similar findings are reported with regard to his utterance development; while his MLU of 2.3 after 3 years of exposure put him at a lower end of the expected range for his vocabulary size and language exposure, he was considerably behind after 6 years of exposure, when his MLU was 3.6. Thus, although adolescent L1 learners initially acquire signs faster than child L1 learners, they seem to reach a developmental plateau: their subsequent language acquisition seems to taper off and is not characterized by the explosive growth patterns characteristic of child L1 learners.

These findings are in agreement with the preliminary results of our follow-up language study with Shawna, Cody, and Carlos (Ferjan Ramirez, Lieberman, & Mayberry; in preparation). Using the same procedures as those reported in Chapter 2, the three cases were studied again after 2.5 to 3.5 years of ASL use. Their type-token ratios indicate that their vocabulary size did increase, but not substantially. They continue to use few closed class signs and remarkably few verb types, resulting in limited argument structure. Their utterances thus remain short and simple; their MLU, which was comparable to that of young children acquiring sign from birth in our initial study (Chapter 2) remains small and is now below that of typically developing children.

Together, these findings suggest that while the acquisition of initial vocabulary and simple utterances may be possible despite an older age, the later stages of language

acquisition are age-sensitive. The results of our follow-up studies suggest that a larger, more diverse lexicon and longer, more complex utterances develop from a previously acquired simple lexicon and shorter utterances, but only when acquisition begins at a young age. Before we discuss why this may be so, we review the findings of our neuroimaging studies.

Neural representation of lexical meaning in sign language

The overarching hypothesis of this dissertation is that delayed onset of language experience has severe effects on language acquisition and on the neural representation of word meaning. With the results of the behavioral studies in mind, the second part of the dissertation considered how the cases represent their newly acquired words in the brain. We explored the link between the timing of language acquisition and the neural representation of word (sign) meaning by using anatomically constrained magnetoencephalography (aMEG). Since the spatio-temporal dynamics of lexico-semantic processing in sign language are poorly understood, it was critical to first establish how signs are processed under ideal developmental circumstances, when language input is available from birth. Chapter 3 explored how signs are represented in the brains of deaf native signers. Two specific questions were addressed: (1) When sign language is acquired from birth, is word meaning processed through the same classical left hemisphere fronto-temporal network used for speech in hearing individuals? (2) Where in the brain are signs extracted from their visual form and put into a form that can access lexico-semantic representations? Are the primary and secondary auditory regions of deaf native signers reorganized to receive and process visual sensory information? To

answer these questions, a separate control group of hearing English speakers was tested on an analogous task presented in the auditory English modality.

Results show that the processing of meaning in response to sign and speech stimuli activate a shared left lateralized fronto-temporal network with similar timing. This result agrees with previous research using hemodynamic and lesion methods, and confirms the hypothesis that the processing of word meaning in the left anterior-temporal areas is modality independent. In stark contrast, the early sensory processing stages of sign and auditory word processing were radically different from each other; signs activated the visual areas in the occipital cortex, and speech activated the temporal lobe auditory areas. This finding is important, because it shows that during the first pass of sensory processing, auditory cortex of deaf participants watching signs is not activated.

Together, these data suggest that when sign language is acquired from birth in deaf individuals the neural processing of lexical meaning is virtually indistinguishable from the processing of auditory word meaning in hearing individuals. Moreover, deafness and early use of sign language do not result in re-wiring of afferent connections from visual to auditory cortex. Using aMEG's excellent temporal resolution was critical in teasing apart the early (first pass, sensory) stages, and the later (linguistic, lexico-semantic) stages of word processing; note that these stages are confounded in hemodynamic studies. Our findings are novel, and might have important implications for clinicians and educators working with the deaf population. In particular, our results show that native sign language experience does not result in a "destruction of auditory cortex by visual takeover" (Kral & Sharma 2012); this argument is frequently used to discourage sign language use in deaf children (see also Yoshida, Kanda, Miyamoto,

Fukuda, Takahashi 2008). Our findings instead suggest that native sign language experience, like native spoken language experience, establishes the functionality of the canonical neural network for lexico-semantic processing. This suggests that the neural systems for high-level language processing are independent of modality through which early language is received, and truly supra-modal.

With these results in mind, Chapter 4 asked how the neural representations of sign are affected by delayed exposure to sign language. As outlined in the introduction, the overarching hypothesis of this dissertation is that early language exposure is critical for establishing the canonical patterns of language acquisition and neural processing within the left hemisphere fronto-temporal network. Thus, we hypothesized that delayed L1 acquisition would be associated with neural activation patterns that diverge from those associated with native language learning. Our predictions were confirmed. In Shawna and Carlos, lexical processing of ASL signs mainly activated right superior parietal, anterior occipital, and dorsolateral prefrontal areas. This spatiotemporal activity pattern was significantly different from that observed in our deaf and hearing control participants who experienced language from birth.

Interpretation

Taken together, the findings reported in this dissertation support the critical period hypothesis, and suggest that language acquisition and neural language processing are guided by early language experience. In thinking about the possible mechanisms that drive these effects, it is important to consider how the experience of an adolescent first-language learner differs from that of typically developing infants. Several research studies have shown that infants actively attend to the phonological patterns of language

stimuli in their environment and use computational strategies to detect statistical patterns in the input (Werker & Tees 1984; Saffran, Aslin, & Newport 1996). Drastic improvements in sensitivity to detect the phonological patterns of native language, and a simultaneous loss of this ability for non-native languages, occur in the first year of life, i.e. before the first words are understood or produced (Werker & Tees 1984; Kuhl, Williams, Lacerda, Stevens, & Lindblom 1992). The cases studied here experienced sustained dynamic language patterns only well after infancy, when they learned to sign in the context of communication. We speculate that the ability to detect the sub-lexical structure of language may be age-dependent. When the typical learning conditions are not met, and form-meaning relationships are established without the discovery of recurrent phonological patterns of native language (Morford & Mayberry 2000), word meaning may have to be recognized through a mechanism that is less dependent on deconstructing the words into subparts, but instead relies on whole word analysis.

While this is currently only a working hypothesis that requires further testing, some evidence in our current data speaks in its favor. An important clue is provided by the cases' neural responses to words (signs), which localized mainly to the right superior parietal, anterior occipital, and dorsolateral prefrontal cortex, areas corresponding to the so-called dorsal stream. Interestingly, dorsal stream activations are reported in response to ASL signs in hearing sign-naïve participants, for whom the signs are meaningless gestures that do not lead to lexical access, and cannot be deconstructed into sublexical parts (Decety, Grezes, Perani, Jeannerod, Procyk et al. 1997; Grezes, Costes, Decety 1998). Dorsal stream activations, and superior parietal activations in particular, have recently also been linked to the processing of ASL location and motion classifiers, which

encode information non-categorically, in an analogue fashion (Emmorey, McCullough, Mehta, Ponto, Grabowski 2013). Importantly, the same study reports ventral stream activations in relation to retrieval of lexical signs and categorical classifier constructions, in agreement with other studies that indicate ventral stream involvement in the retrieval of semantic and conceptual knowledge (Hickok & Poeppel 2004; Patterson, Nestor, & Rogers 2007), and in phonological encoding (Indefrey & Levelt 2004). Together, these results suggest that meaning conveyed in the visuo-gestural modality can be accessed through either the ventral or the dorsal stream, depending on the internal structure of the communicative stimulus: communicative patterns that have sub-lexical structure are analyzed by the ventral stream, in a fashion analogous to lexical processing of auditory speech. Analogue structures, on the other hand, may require the involvement of the dorsal stream, which has been associated with articulatory re-mapping and transformations of the visual-spatial representations into a body centered reference frame (Glover 2004; Corbetta, Shulman, Miezin, & Petersen 1995).

The engagement of the superior parietal areas by the cases suggest that their processing of sign meaning may involve articulatory re-mapping and visual-to-motor transformations, despite the fact that they are watching lexical signs that are categorically structured and obey the phonological rules of ASL. It is possible that this alternative strategy is used due to a lack of sensitivity to detect the phonological (sub-lexical) structure of signs; several studies with late L1 learners suggest that their phonological processing is non-automatic, and represents a "bottleneck" in accessing lexical meaning (Mayberry & Fischer 1989). When tested on phonological priming paradigms late learners are inhibited by phonological primes, while native signers exhibit facilitation

effects (Mayberry & Witcher 2006). Other studies confirm that late learners have unique phonological recognition patterns for signs in comparison to deaf and hearing adults who had infant language exposure (Morford & Carlson 2011; Hall, Ferreira, & Mayberry 2012). Importantly, the unique phonological recognition patterns are not characteristic of hearing L2 learners, who instead tend to pattern with native signers (Morford & Carlson 2011; Hall et al. 2012). Having language exposure from birth thus facilitates native-like acquisition of a second phonological system, even in a different modality (Hall et al. 2012). Non-native signers, on the other hand, have no L1 phonological representations to rely on; if the ability to detect the sub-lexical structure is age-sensitive, the cases' acquisition and processing of words may have to rely on an alternative mechanism that is less dependent on breaking signs down into sub-lexical parts.

It may be that analyzing lexical signs as non-categorical, analogue structures is a strategy that initially allowed the cases to acquire vocabulary at a fast rate. After all, once they became immersed in language, they did not spend a year observing the phonotactic forms and babbling with their hands, but rather began to use ASL for referential communication right away. However, skipping the initial observational stage in which the recurrent contrasts of language are learned may be one of the causes behind the slowing in lexical and syntactic acquisition that we have observed in our follow-up studies. Recent studies with hearing infants show that their ability to detect native language phonetic contrasts as measured by a head-turn conditioning task at 7.5 months predicts their CDI scores at 14, 18, 24, and 30 months, and their MLU at 30 months of age. Furthermore, infants and toddlers with larger vocabularies show stronger negative mismatch negativity (MMN) effects to native contrasts (Kuhl, Conboy, Padden, Nelson,

Pruitt 2005; Kuhl, Conboy, Coffey-Corina, Padden, Rivera-Gaxiola et al. 2008), and show neural responses that are more focal to the left hemisphere fronto-temporal areas (Mills, Coffey-Corina, Neville 1993; 1997). Early tuning to the phonological (sub-lexical) patterns of native language thus may enable word learning, as well as lead to physical changes in the neural architecture for word processing.

It may be that the ability to zoom in on the internal structure of words is not entirely lost with age; it is possible that the process of detecting the sub-lexical structure is just so severely protracted that native-like levels are not reached even after years of language use (Mayberry & Fischer 1989). Previous studies support this hypothesis: late L1 learners with many years of sign language experience pay attention to the phonological properties of signs; in fact, it has been suggested that their *increased* attention to phonological form may lead to decreases in their ability to focus on meaning (Mayberry 1994). It may be that Shawna and Carlos initially began to acquire words as wholes, but will eventually begin to break them down into sub-lexical parts. If this hypothesis is correct, we may expect that they will continue to acquire language, but perhaps at a slower rate. As previously discussed, such a learning trajectory has previously been observed in one other adolescent L1 learner of ASL (Garfinkel 2005).

Likewise, we may expect to see some change in Shawna's and Carlos' neural representation of lexico-semantic encoding, which we measured with the N400. In agreement with the rest of developmental neuroimaging and electrophysiological literature, the N400 has been related to language development. A recent ERP study using a picture-priming paradigm reports no N400 in 12 month-olds whose productive vocabularies are under 4 words; however, the N400 is present in those 12 month-olds

whose productive vocabularies exceed 4 words (Friedrich & Friederici 2005; 2010). In 19 month olds, the N400 looks adult-like in terms of scalp distribution, but is slightly delayed in latency (Friedrich & Friederici 2004). A recent aMEG study with a group of 12 to 18 month olds confirms these findings and shows that the N400 in this age group localizes to left fronto-temporal cortices (Travis, Leonard, Brown, Hagler, Curran et al. 2011). These findings thus suggest that when language input is available from birth, the N400 becomes adult-like and focal to the left fronto-temporal areas relatively early in development.

Interestingly, the cases, especially Shawna, did show some semantic priming effects in the left fronto-temporal network; however, these effects were in the opposite direction from those observed in native signers (i.e. congruent>incongruent instead of incongruent>congruent). Such effects have previously been reported in hearing 12 month-olds, but not in 19 month olds, who show a canonical N400 pattern (Friedrich & Friederici 2005). In infants, the congruent > incongruent effects are hypothesized to change polarity as the mechanisms of semantic priming mature. Thus, the reversed polarity of the semantic response may simply be part of normal language learning. This hypothesis is further supported by the fact that some of our L2 control participants exhibited the congruent > incongruent effects as well; on the other hand, such responses were not observed in highly proficient Spanish-English bilinguals (Leonard, Brown, Travis, Gharapetian, Hagler et al. 2010). One possibility is that as Shawna and Carlos receive more language input, their semantic priming responses in the left fronto-temporal areas will change polarity and become canonical, in a manner analogous to children. Such outcome would be expected especially if their ability to detect the sub-lexical

structure of words is not entirely lost; this would lead to a continuation in language learning, although at a slower rate. It should also be noted that Shawna and Carlos, unlike infant or L2 learners, must map their *prior* world knowledge on the newly acquired semantic categories of L1. Infants acquire language simultaneously with cognitive development, and L2 learners can use their existing L1 as a scaffold in this process. One might speculate that carving up the semantic space on existing cognitive structure may add additional cognitive load and thus contribute to the cases' difficulties in analyzing the physical properties of the linguistic stimulus and figuring out its phonological structure. Longitudinal studies will show whether Shawna's and Carlos' neural responses in the left fronto-temporal areas change as they receive more language input.

Taken together, the behavioral and neural studies presented in this dissertation suggest that early language input is crucial in establishing the canonical language acquisition and neural processing patterns. These findings refine our understanding of the critical period by providing crucial behavioral and neuroimaging data on cases who were severely linguistically deprived until adolescence.

Conclusions and future directions

A critical period constitutes a limited time window in development during which an organism is particularly responsive to specific environmental inputs. In the animal kingdom, critical periods tend to characterize behaviors that are crucial for the survival of the species; for example, in the case of filial imprinting in geese, young animals learn to follow the first moving stimulus (usually their mother) 13-16 hours after hatching (Lorenz 1937). If this time-window is missed, the geese fail to imprint their mother and never learn how to find food and avoid predators. Critical period behaviors in animals

have been associated with modifications in the neural architecture. In particular, environmental stimulation has been shown to modify neural circuits such that they become particularly responsive to the relevant stimuli, and simultaneously non-responsive to the kinds of stimuli that are not experienced (Knudsen 2004). The findings reported in this dissertation provide some initial evidence that a similar relationship may apply to human language; we suggest that early language experience affects the configuration of the neural language processing system, which then affects subsequent language learning.

Our results also provide some initial clues as to what exactly is "critical" about the critical period for language. In infants, lexical and conceptual knowledge develop simultaneously, following the initial "observational" stage in which infants become "tuned" to the recurrent sub-lexical structure of native language. Under such developmental circumstances, word learning is initially slow, but then takes off at a fast rate, reflecting familiarity with the recurrent structure of language. Morpho-syntactic structure "grows out" of the lexicon in a highly predictable fashion, only after specific lexical milestones have been reached (Bates, Marchman, Thal, Fenson, Dale et al. 1994). In other words, language is acquired from the inside out. Such learning patterns may enable and be enabled by the canonical left-dominant neural language processing.

If sustained dynamic language input is experienced for the first time in adolescence, and form-meaning relationships are established without the discovery of recurrent phonological patterns, an altered pattern of subsequent language learning and neural processing may be expected. Specifically, if words are acquired as analogue wholes, learning may initially occur at a faster rate, but then taper off as a result of a

failure to recognize and reuse the recurrent sub-lexical structure. This is exactly the pattern that we observe in the cases. The cases' sensitivity to the phonological structure of language may not be forever lost. It may simply be severely slowed, perhaps because they acquired language in the context of communication from the start, and had to simultaneously map new lexical categories on existing cognitive structure.

The cases' neural underpinnings of word meaning may reflect their use of alternative word-learning strategies; instead of accessing lexical meaning through the ventral stream which relies on phonological encoding, articulatory re-mapping and visuo-motor transformations have to be used, likely because lexical items are treated as analogue, rather than categorical structures. If the cases begin to better understand the sub-lexical structure of signs with more input, we may expect to see that their neural responses to words will become more canonical.

With these hypotheses in mind, the obvious question is how fast and how far the cases' language development can progress. Will they ever transition to multi-word or multi-clause utterances? Will their neural patterns in response to language stimuli become more and more canonical and focal to the left fronto-temporal areas as more language is received? Some of the answers to these questions will be provided by follow-up behavioral and neural studies with the three cases. A detailed analysis of their utterances and verb types is currently underway. We have also conducted a follow-up aMEG study with Shawna and Carlos using the same protocol, and we are currently analyzing these data. Future research with other deaf participants of similar linguistic backgrounds will consider the neural underpinnings of language beyond a single word level. The findings reported in this dissertation provide the initial insights into the critical

period for language, and will hopefully lead to important theoretical and practical advances of the field.

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