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Effects of impoverished early language on American Sign Language development: Longitudinal, processing, and anatomical outcomes

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Effects of impoverished early language on American Sign Language development: Longitudinal, processing, and anatomical outcomes

A dissertation submitted in partial satisfaction of the
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in

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by

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2020

The dissertation of Qi Cheng is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

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Chapter 4, in full, has been submitted and may appear as a publication in Cheng, Q., Mayberry, R. I. When event knowledge overrides word order in sentence comprehension: Learning a first language after childhood. The dissertation author was the primary investigator and author of this paper.

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ABSTRACT OF THE DISSERTATION

Effects of impoverished early language on American Sign Language development: Longitudinal, processing, and anatomical outcomes

by

Qi Cheng

Doctor of Philosophy in Linguistics and Cognitive Science

University of California San Diego, 2020

Professor Rachel I. Mayberry, Chair

Deaf individuals are more likely to experience impoverished language during early life. Delayed sign language onset often leads to later language deficits, especially at the morpho-syntactical level. As early experience plays a crucial role in postnatal brain development, the developmental and processing difficulties may reflect altered brain development due to lacking sufficient early language. Examining the behavioral and neural outcomes in this population increases our understanding of the mechanisms of first language development.

In this dissertation, I focused on one basic syntactic cue – basic word order in simple transitive sentences. Pinning down the developmental, processing, and anatomical characteristics

of native and late signers of ASL with respect to simple transitive structures is key to our understanding of the morpho-syntactic difficulties shown by this population. Simple transitive clauses represent the earliest of hierarchical structures, a hallmark of human language capacity. The current dissertation thus sheds light on the role of early language on the emergence of this core linguistic structure.

I examined the early syntactic development of American Sign Language among deaf individuals with an extremely late sign language onset, combining observations from three perspectives: longitudinal development, sentence processing strategies, and brain language pathways. Chapter 3 presents a longitudinal study of 4 deaf late signers on their word order development. The results suggest a similar developmental trajectory regardless of first language onset, but the process is prolonged for late signers, and only limited to the early stages. Chapter 4 uses a sentence-picture verification experiment to examine whether deaf late signers robustly rely on word order to comprehend simple Subject-Verb-Object sentences. The results show that, unlike native signers and second language signers who consistently rely on word order, deaf late signers prefer event plausibility over word order. Chapter 5 presents a study on the connectivity patterns of major language pathways in the brain using diffusion tensor imaging, and finds less robust connectivity in left arcuate fasciculus, a pathway crucial for syntactic processing. Together, these findings suggest profound effects of impoverished early language on early syntactic and brain development and is suggestive of links between early language and brain development.

Chapter 1

Introduction

One of the most intriguing phenomena in language sciences is the rapid and homogenous development of a complex first language within a few years after birth (Brown, 1973; Clark, 2009; Diessel, 2004; Pinker, 2009). Key to this process is the interaction between early language experience and early brain development. Postnatal brain development is greatly shaped by learning and environmental factors, facilitated by early neural plasticity (Greenough, Black, & Wallace, 1987; P. R. Huttenlocher, 2002). Early language experience affects language development (Ferjan Ramírez, Lytle, & Kuhl, 2020; J. Huttenlocher, Vasilyeva, Cymerman, & Levine, 2002; Romeo, Leonard, et al., 2018; Romeo, Segaran, et al., 2018; Vasilyeva, Waterfall, & Huttenlocher, 2008), and a lack of early language experience can result in severe language deficits (Curtiss, 2014; Fromkin, Krashen, Curtiss, Rigler, & Rigler, 1974; Newport, 1990; Boudreault & Mayberry, 2006; Mayberry et al., under review).

However, it is difficult to study the specific role of early experience on language and brain development because the language learning process usually occurs simultaneously with other neural and cognitive developmental processes among typically developing children, and no animal models are available for this uniquely human function. One way to directly examine the role of early language is to look at individuals with vastly different early language experience.

Congenitally deaf individuals show large variations in their early language experience. About 10% of the deaf population was born into signing families and acquired a visual-manual language from birth, showing a different modality of language development that is nonetheless parallel with typical hearing individuals acquiring an audio-vocal language from birth. The remaining 90% of deaf individuals often did not have early access to any language and may only learn a fully accessible language, a sign language, as their first language, at a much older age than is typical. In some rare cases, deaf individuals may have extremely late language onset, after late childhood. The deaf population therefore provides an opportunity to directly examine the role of early language on brain and language development. Research on this question also has practical importance, as the findings can raise the awareness of the potential harm of missing early language, and can help identify deaf children who are at the risk of language delay due to limited early language experience.

The language development of individuals with little early language initially shows a similar trajectory to infant learners, up until the two-word stage (Ferjan Ramirez et al., 2013; Lillo-Martin & Berk, 2012), but their language outcomes often diverge from those of native signers, especially at the morpho-syntactic level (Cormier, Schembri, Vinson, & Orfanidou, 2012; Boudreault & Mayberry, 2006; Mayberry et al., under review; Newport, 1990). Given the resemblance between native and late first language development and the morpho-syntactic deficits observed in late first language outcomes, it is crucial to understand the initial syntactic development and to pin down the developmental bottleneck caused by a delayed language onset. In the meantime, neuroimaging studies show atypical activation patterns when late signers process single words (Ferjan Ramirez et al. 2014, 2016; Mayberry et al. 2018) or sentences (Mayberry et al. 2011). Because early language experience may be key to neural development for the language network, it is also important to examine the underlying brain structures that may contribute to the alternative functional activation patterns observed in this population.

The current dissertation aims to examine the effects of early language input on language and brain development by studying deaf individuals with or without early sign language input and combining observations at both behavioral and neural levels. By examining the longitudinal development, sentence processing strategies, and neural substrates of simple clausal structures in American Sign Language (ASL), with a focus on basic word order, we hope to pin down the behavioral and anatomical outcomes due to a lack of early language experience in order to explain the additional morpho-syntactic difficulties and the neural activation patterns observed among deaf late signers.

The structure of the dissertation is as follows. Chapter 2 summarizes relevant background on the role of early language (2.1), reviews the relation between early experience and language-relevant brain development (2.2), and proposes a neurodevelopmental approach to first language development (2.3). Chapter 3 is a longitudinal study on word order development. Chapter 4 is an experimental study on simple sentence processing strategies. Chapter 5 is a white matter language pathway study. Chapter 6 discusses the implications of the behavioral and neural findings as well as future directions.

Chapter 2

Background

2.1 Role of early language in typical and impoverished first language development

For the typically developing population, many studies have revealed a relation between the quality and quantity of early language experience and the rate of language development. An increased amount and complexity of early language input, either from parents or teachers, contributes to faster vocabulary development as reflected in vocabulary size and processing proficiency (Huttenlocher et al. 1991, 1998; Weisleder & Fernald, 2013; Rowe, 2012), and the use of complex syntactic structures (Huttenlocher et al. 2002; Vasilyeva et al. 2008). Ferjan Ramirez et al. (2019; 2020) showed that an early parent coaching intervention increases conversational turns and has lasting effects on later child language development. At the neural level, language exposure in the form of adult-child conversational turns, independent of socio-economic status (SES), is related to more robust connectivity in left AF-SLF, but not any other white matter tracts (Romeo et al. 2018a). As for neural activation, children with exposure to increased conversational turns mostly showed greater activation in Broca's area (Romeo et al. 2018b).

Curiously, in these studies with typically developing children, the quantity and quality of early experience seems to show fewer effects on the emergence of early syntactic milestones. In Vasilyeva et al. (2008), children with low and high SES show similar developmental trajectory with simple sentence types. Mayan children, with reduced child-directed speech from parental input (Shneidman & Goldin-Meadow, 2012), begin to produce multi-word combinations roughly around the same time as Western children with much more child-directed speech (Casillas, Brown, & Levinson, 2019).

Still, the degree of input variation among children with typical L1 from birth is limited, and children with reduced language input will eventually attain adult-like competence in their native language. In order to fully understand the role of early language on brain and language development, we need to examine extreme cases with minimal early language experience but otherwise typical social and cognitive development.

Individuals born deaf are more likely to have limited early language experience. Only about 10% of deaf children are born with deaf parents, with a fully accessible visual language, sign language, available from birth. 90% of deaf children often experience large variation in their early language environment. Some hearing parents learn some sign language and provide less optimal but accessible early language in the visual-manual modality. But more commonly, parents try hearing compensation technology such as hearing aids or cochlear implants, accompanied with speech therapy, in the hope that this will restore the children's hearing so that they can learn spoken language normally. The outcomes of these hearing compensation tools differ from person to person. When the hearing compensation fails to work properly, the spoken language experience perceived by the deaf child can be minimal. Sign language, despite it being a fully accessible language to deaf children, is sometimes considered harmful for speech training, and not always available for deaf children. In some extreme cases, when a deaf child grows up in an environment where no deaf education is available, they may be kept at home without any sign or spoken language input. Still, these individuals are often healthy and supported by their caretakers, thus with relatively typical cognitive and social development.

Mayberry and Kluender (2018) provide a detailed review on behavioral and neural outcomes of late first language development among deaf individuals. In this dissertation, a summary of early language development of deaf late learners of ASL can be found in Section 3.2.3. To briefly summarize here, when deaf individuals acquire sign language as their first language in late childhood or adolescence, they show similar characteristics in vocabulary development (Ferjan Ramirez, et al. 2014) and linguistic features during a two-word stage (Lillo-Martin & Berk 2012). Morford (2003) found continuing development in the spontaneous production of classifier structures (spatial morphology), but the comprehension of these structures still differed from native signers after 7 years of language use. As for language outcomes, simple syntactic structures are relatively unaffected, while morpho-syntactically complex structures persistently pose more challenges to deaf late L1 signers (Boudreault & Mayberry, 2006; Cormier, Schembri, Vinson, & Orfanidou, 2012; Henner, Caldwell-Harris, Novogrodsky, & Hoffmeister, 2016; Newport, 1990; Mayberry et al., under review).

Neuroimaging studies of deaf people with early language deprivation suggest that they often show decreased activation of the default language network when processing language. Using functional magnetic resonance imaging (fMRI) and an ASL grammatical judgment task, Mayberry, Chen, Witcher and Klein (2011) found that late AoA is associated with decreased activation in anterior frontal and temporal language areas, and also increased activation in left occipital visual areas. Longitudinal studies of ASL lexico-semantic processing using anatomically constrained magnetoencephalography (aMEG) found atypical neural processing patterns in two adolescent L1 learners of ASL, Carlos and Shawna, who acquired little or no language prior to being immersed in ASL around the age of 13. They showed strong activation in right occipital-parietal areas, but little in the language-related left temporal and frontal areas (Ferjan Ramirez et al., 2016). But they also showed increased activation in the temporal language areas after 4 years of exposure, especially with more familiar signed words. Using the same paradigm, Mayberry, Davenport, Roth and Halgren (2018) reported another case study, Martin, who had an even later age of onset, in his 20s, and had more than 30 years of ASL usage. Martin primarily activated bilateral dorsolateral, superior parietal and occipital areas, similar to Carlos and Shawna. Unlike the other two late learners, Martin showed almost no activation in bilateral temporal language areas, although his behavioral performance was equally accurate and fast as the native signers and the other two late learners.

These atypical behavioral and neural processing outcomes suggest that early language input may play a crucial role in establishing the neural foundations for language. In the next section, I provide some background on postnatal brain development and the role of early experience.

2.2 Brain development and the role of early experience

Development of the human cerebral cortex consists of a series of events, including neuronal proliferation, differentiation, migration, dendritic and axonal growth, synaptogenesis (formation of neuronal connections, synapses), pruning (decease of synapses), and myelination (insulation of axons to ensure faster signal processing) (Stiles & Jernigan 2010). Early processes are considered to be largely determined by genetic factors, while the postnatal processes of synaptogenesis, pruning, and myelination are more likely to be affected by external environmental factors (P. Huttenlocher, 2002).

Synaptogenesis occurs during the first year of infancy with exuberant synaptic connections, yielding a synaptic density higher than that of adults (Huttenlocher & Dabholkar, 1997). These early connections are then either maintained or removed depending on the amount of functional neural activity, with the more frequently used connections being maintained, while the seldom used synapses are deleted during the pruning process (Hua & Smith 2004). Myelination is a process when a special type of glial cells, oligodendrocyte progenitor cells (OPC), form myelin wraps around neuronal axons to provide insulation sheaths, greatly increasing the conductivity. The myelination process is also plastic and adaptive to experience (see Mount & Monje 2017 for a review). Major fiber tracts in the brain take an extended period of time to go through myelination, sometimes until late puberty (Lebel et al., 2008). Robust connectivity of these long range white matter fiber tracts is crucial for rapid information transmission between remotely connected regions. To summarize, early environmental input and learning largely determine which neuronal connections are maintained and myelinated, and these maintained wiring patterns then gradually form robust neural circuits that carry emerging cortical functions.

Apart from genetic guidance and environmental influence, another essential constraint in postnatal brain development is the temporal unfolding of developmental process, characterized as 'progressive differentiation' (Stiles 2008; Stiles & Jernigan, 2010). The development of neural elements often relies on preceding neural events. At the cortical level, different regions follow a hierarchical order in the developmental process (Guillery 2005; Huttenlocher 2002). Primary sensory regions often mature first, followed by secondary sensory regions and association regions, while the prefrontal regions that are responsible for integrating information from association regions mature last. Sensory-motor regions often show earlier pruning and myelination, while associative and higher cognitive regions show later cortical thickening and myelination (Sowell et al., 2004; Pujol et al., 2006). The development of higher cognitive functions is more sensitive to this progressive differentiation and commitment (Stiles et al. 2015), and therefore often show protracted development over an extended period of time.

Language is a highly specialized higher cognitive function and robustly recruits a default language network, often in the left hemisphere. A review of the mature neural language network for both spoken and sign language can be found in Section 5.1. Although the exact locations for specific linguistic functions are still not entirely clear from the neurolinguistics literature, there is a convergence on two language neural processing streams, one dorsal and one ventral (Friederici, 2011; Hickok & Poeppel, 2004, 2007; Price, 2012; Saur et al., 2008; Dick & Tremblay 2012), with the dorsal stream being specifically crucial for syntactic structure building (Wilson et al. 2011; Bornkessel-Schlesewsky & Schlesewsky, 2013; Hagoort & Indefrey, 2014).

Like other neural circuits, the language network in the brain also emerges gradually, driven by genetic guidance and early experience, and show progressive differentiation and commitment. Language-relevant brain structures often show protracted maturation, and the degree of maturation correlates with behavioral development. Huttenlocher (1999) looked at synaptic density in the auditory cortex (Heschl's gyrus), Wernicke's area in the left temporal cortex, and Broca's area in left inferior frontal cortex, and found that the auditory cortex shows the earliest synapse formation, followed by Wernicke's area, while Broca's area show the latest formation. Pujol et al. (2006) found earlier myelination in sensorimotor region and later myelination in language-relevant temporal and frontal regions. Also, the accelerated vocabulary development observed after 18 months relates to a rapid myelination phase in the language-related regions. Event-related potential (ERP) studies (Mills, Coffey-Corina, & Neville, 1993; Mills, Coffey-Corina, & Neville, 1997) found that children from age 13-17 months, before the vocabulary spurt, show broadly distributed activation to known words over frontal, temporal, parietal, and occipital regions of both the left and right hemispheres. After the vocabulary spurt, at age 20 months, children mainly show activation limited to temporal and parietal regions of the left hemisphere. Sowell et al. (2004) observed gray matter thickening in left inferior frontal (Broca's area) and bilateral posterior perisylvian regions among children aged 5 to 9 years old, while other areas are going through cortical thinning at this age. As cortical thickening often precedes cortical thinning during early brain development, Sowell's findings suggest late development of these language-related regions compared to other brain regions. Lu et al. (2007) found that the increase of cortical thickness in left inferior frontal gyrus positively correlates with improvement in phonological processing.

As for white matter pathways, studies using diffusion tensor imaging (DTI) show that language-relevant fiber tracts (see 5.1 for a summary) develop more slowly than other long-range tracts, especially for the inferior longitudinal fasciculi (ILF), the superior longitudinal fasciculus - arcuate fasciculus (SLF-AF), and the inferior fronto-occipital fasciculi (IFOF) (Brauer, Anwander, & Friederici, 2011; C. Lebel & Beaulieu, 2011; C. Lebel, Walker, Leemans, Phillips, & Beaulieu, 2008). In particular, the development of dorsal SLF-AF pathway, which plays a role in syntactic structure building, is associated with syntactic processing skills as evidenced by German-speaking children processing relative clauses, but such association is not found with the development of other pathways (Skeide et al. 2016). These studies all suggest language regions to show an extended period of development, likely reflecting neural plasticity from extensive language experience from the environment.

To date, few studies have examined the neural anatomical effects of early language deprivation. Pénicaud et al. (2013) using voxel-based morphometry (VBM) identified anatomical changes caused by late AoA. Late learners show decreased gray matter concentration and increased white matter in occipital visual areas, but no differences were found in the core language regions. But, due to methodological constraints of VBM, certain micro-anatomical differences may not be detected. One study examining white matter differences between deaf and hearing individuals identified differences in several language-relevant fiber tracts, such as bilateral SLF and left IFOF (Kim, Park, Kim, Lee, & Park, 2009), while other studies comparing near-native deaf signers with hearing individuals (Emmorey, Allen, Bruss, Schenker, & Damasio, 2003; Hribar, Suput, Carvalho, Battelino, & Vovk, 2014; Karns, Stevens, Dow, Schorr, & Neville, 2017; Li et al., 2012) mostly only found differences in auditory-related areas. As Kim et al. (2009) did not report the language background of their deaf participants, it is possible that the differences they detected in language-relevant tracts are due to limited early language experience.

Higher cognitive functions such as language require the wiring of the association regions, which receive input from sensory regions and feed into the motor regions, while also connect to the frontal executive regions to allow for top-down controls. Therefore, development of the cortical circuits for language likely depends on the temporal unfolding of these neural events given early language experience. The hierarchical maturation of the sub-regions (Sowell et al., 2004; Pujol et al., 2006) and the changes in functional differentiations (Imada et al. 2006; Mills et al. 1993; 1997) provides evidence for this progressive differentiation and commitment of the language network, but the details of these processes are less known, given limited studies that map behavioral and neural development during first language acquisition.

2.3 A neurodevelopmental approach to first language acquisition

By focusing on the early syntactic development, processing, and brain anatomical outcomes of a special population with impoverished early language, the current dissertation aims to adopt a neurodevelopmental approach to understand the mechanisms of first language development. Previous theoretical accounts for first language development mostly centered around how typical learners acquire their first language from birth, when language learning co-occurs with brain development. Since the earlier debates between Skinner (1957), who attributed language acquisition to reinforcement learning, and Chomsky (1959), who argued for an innate capacity specifically for language, theoretical debates have been focused on the nature vs. nurture argument. The nativist approach looks for early language uses that are considered not learnable from inconsistent input, which often reflects universal properties observed across human languages, and the process is thus considered to be guided by language-specific innate representations (Crain, 1991; Lidz, Gleitman, & Gleitman, 2003; Pinker, 2009). The non-nativist approaches look for general learning mechanisms that link between the input and the development (Aslin & Newport, 2012; Goldberg, 2009; Saffran, Newport, & Aslin, 1996; Tomasello, 2000), posing more emphasis on domain-general learning. However, the neurodevelopmental changes during early years that co-occur with language development have not been explicitly discussed under either account, and no clear contrasting predictions can be made from these theoretical accounts on the outcome of a lack of early language experience. Because first language development mostly happens during the first few years, when the infant brain is going through tremendous changes, infant learners should be considered as dynamic systems, where the learning process itself shapes subsequent learning (Omaki & Lidz, 2015). A neurodevelopmental approach to first language acquisition puts the dynamic processes of language and brain co-development in the foreground, and explicitly explores the biological foundations of human language from a developmental perspective.

Postnatal brain development is a complex process with interactions between genetic guidance and experience-driven plasticity. The biological foundations of human language, which are established during the first few years of brain and language development, are no exception (as elaborated in 2.2). In this sense, early neural plasticity, where nature meets nurture when the brain is still fast developing, should be considered as the driving force for first language development. Studies on the role of early language input quality and quantity on individual differences of first language development (Huttenlocher et al. 1991, 1998; Weisleder & Fernald, 2013; Ferjan Ramirez et al. 2019, 2020; Romeo et al., 2019a, 2019b; summarized in 2.1) have been examining this driving force of first language development. But given the limited degree of early language experience variation among typically developing children and the overall successful learning outcomes, the underlying mechanisms still remain unclear. Also, research on the neural development of language (Kuhl & Rivera-Gaxiola, 2008; Friederici, 2006; Dehaene-Lambertz et al., 2006) is still scarce, especially at the morpho-syntactic level. Given the development of neurolinguistic and psycholinguistic research on adult language processing in the past decades, many of the methods and findings can be and should be used to explore the neurocognitive basis of first language development.

The current dissertation focuses on the development and outcomes of a basic syntactic cue – basic word order in simple transitive sentences. Previous findings on late first language development of deaf individuals (as summarized in 2.1) suggest a similar developmental trajectory of early and late first language development up till two-word stage and relatively resilient outcomes of simple clausal structures, while also revealing ultimate learning deficits at more complex morpho-syntactic level as well as alternative neural activation patterns when processing language. Pinning down the developmental, processing, and neural differences or similarities between native and late signers of ASL regarding simple transitive structures serves as a means to understand the breakdown in late first language syntactic development as a result of missing early language. Simple transitive clauses often emerge early in native first language, and its underlying representation of a hierarchical structure is a hallmark of human language capacity. If late first language learners fully resemble native signers with regard to simple transitive structures in ASL, the findings will help restrict the role of early neural plasticity to hierarchically more complex structures. In contrast, if the simple clausal structures are not fully acquired by late first language learners, it will attribute the role of early language to earlier stages of syntactic development, and also provide explanations for morpho-syntactic deficits. Chapter 3 and Chapter 4 provide longitudinal and experimental data to explicitly test these hypotheses.

The current dissertation also examines the degree of connectivity of long-range white matter pathways in the brain that are relevant to efficient language processing. As demonstrated in 2.2, progressive differentiation and development of higher-order cognitive functions like language is likely to be sensitive to early experience, which may be reflected in the myelination process of long-range white matter pathways. In particular, the dorsal pathway is often associated with syntactic processing. Chapter 5 presents a study that compares the anatomical characteristics of these language-relevant pathways in deaf and hearing individuals with and without early language access from birth.

Combining behavioral observations on longitudinal development in Chapter 3 and on processing strategies in Chapter 4, together with anatomical observations on the neural substrates for syntactic processing in Chapter 5, this dissertation provides a multifaceted study on the effects of impoverished early language on syntactic development. Comparing this atypical population with typically developing individuals with robust early language on their language and brain outcomes, this dissertation can shed light on the neurodevelopmental basis of successful first language development.

Chapter 3

Longitudinal language development: the case of word order

3.1 Introduction

One crucial observation about language acquisition is that it is age constrained (Lenneberg, 1967). Children usually acquire their first language (L1) early in life with little effort. By contrast, second language (L2) learners (Bongaerts, Mennens, & Slik, 2000; Coppieters, 1987; Lardiere, 1998, 2007) as well as L1 learners with early language deprivation (Fromkin, Krashen, Curtiss, Rigler, & Rigler, 1974; Grimshaw, Adelstein, Bryden, & MacKinnon, 1998; Mayberry, 1993) all seem to face difficulties developing native-like skills. In addition, early language deprivation results in a more disrupted learning outcome compared to delayed L2 learning (Mayberry, 1993; Mayberry & Lock, 2003). This contrast between increased cognitive maturity and decreased language acquisition ability suggests there may be a critical temporal window for successful language learning, and that missing this developmental window has negative effects on language development.

Research also suggests that not all linguistic structures are equally vulnerable to age of acquisition (AoA) effects for late L1 learners who suffer from early language deprivation. Previous studies have found that simple, mono-clausal structures that are acquired early by young children seem to be acquired at any age, while complex, multi-clausal structures are not (Boudreault & Mayberry, 2006; Curtiss, 1977; Newport, 1990). This parallel between child L1 milestones and late L1 outcomes seems to suggest that even when begun later in life, syntactic development still follows a set path similar to typical child L1 development. Studies on the initial stages of late L1 development also suggest that, despite differences in cognitive skills and early language experience, late L1 learners tend to resemble native L1 learners in terms of initial lexical development and word combinations (Berk & Lillo-Martin, 2012; Ramírez, Lieberman, & Mayberry, 2013).

It remains unknown why late L1 learners fail to proceed to master more complex structures beyond basic mono-clausal structures. Thus far we have limited knowledge of what happens in-between initial child-like development and the ultimate non-native outcomes of late L1 learners. One way to fill in this gap is to investigate the developmental trajectory of late L1 syntactic development beyond the two-word stage.

Word order is a crucial linguistic device that maps thematic roles and grammatical relations in most languages, and the default word order is often acquired early in life (Brown, 1973; Pinker, 1989; Slobin & Bever, 1982). American Sign Language, ASL, uses a basic Subject-Verb-Object (SVO) order (Fischer, 1975), but also employs multiple word order variations under certain morphological and pragmatic conditions, such as sentence final pronominal subject copy (VS) and object topicalization (OV) (Fisher & Janis, 1990; Kegl, 1976; Liddell, 1980; Matsuoka, 1997; Padden, 1988; Pichler, 2001). ASL basic word order has been found to be generally intact in late L1 outcome with respect to comprehension and grammatical judgment tasks (Newport, 1990; Boudreault & Mayberry, 2006), but little is known about the use of word order in the ASL expression of late L1 learners. Previous literature has also documented ASL word order patterns at various stages in child L1 development (Berk, 2003; Hoffmeister, 1978; Pichler, 2001; Schick, 2002). Investigating the trajectory of word order development among late L1 learners offers us a unique opportunity to understand how syntactic development unfolds when the learners have more mature cognitive functions but reduced linguistic experience during childhood.

In the current study, we investigate the patterns of ASL word order preference by deaf adolescents with limited early language exposure. To do so, we first describe word order variations in ASL, how child native learners acquire these structures, and what we know about the effects of delayed language acquisition on syntactic development. Following this necessary background, we describe two studies. Study one investigates the longitudinal development of word order patterns in three adolescents acquiring language for the first time in the same linguistic environment. Study two investigates word order development in a fourth adolescent late L1 learner who was immersed in an entirely different ASL environment. The main goal of the studies is to describe in detail the word order patterns used by late L1 learners, to document changes over time in their development, and to compare their development with child L1 patterns available in the literature. The results indicate that adolescent L1 learners develop an increased preference for the basic SVO word order over time, which resembles that of child native learners. However, our findings also show that this process is prolonged in adolescent L1 learners compared with child L1 learners.

3.2 Literature Review

3.2.1 ASL word order

Languages utilize word order as the main method to mark grammatical relations and generate compositional meanings (Slobin, 1966). Word order usually refers to the relative order of a finite verb (V) and its nominal arguments, Subject (S) and Object (O). Most languages have a dominant word order (Greenberg, 1963), and typological studies show that SOV and SVO are the most common word orders across languages while other orders are relatively rare (Dryer, 2007; Tomlin, 1986). Many languages, such as Turkish, German, and Japanese, also have word order variations in addition to the default word order, and these non-canonical word orders are usually conditioned by information structure with non-obligatory prosodic cues (Reinhart, 1995), and sometimes by lexical verb class as well (Bader & Häussler, 2010).

ASL is a natural language that employs the manual modality and demonstrates linguistic features similar to those of spoken languages (Klima & Bellugi, 1979; Stokoe, 1978). According to Fisher (1975), ASL demonstrates a basic SVO order (1a). Non-canonical word order patterns are mainly derived from the basic word order and constrained by certain grammatical rules. The most common variations include sentence-final pronouns (VS, as in 1b), pre-verbal objects (OV, as in 1c), and also the so-called 'verb sandwiches' structure (VOV, Fisher & Janis, 1990, as in 1d).

(1)

a. BOY LIKE ICECREAM

'The boy likes ice cream.'

b. SLEEP IX-3

'He sleeps.'

c. BALL HIT(handling: bat)

'(Someone) hit the ball.'

d. READ BOOK READ(aspect: continuative)

'(Someone) kept reading the book.'

Padden (1988) has explained the surface VS order as being a result of subject-pronoun copy with a null subject. ASL allows sentence-final subject pronouns to serve an emphatic function (2a), and this copied pronoun usually co-occurs with a null subject, rendering the surface structure non-canonical VS (2b).

(2)

a. BABY SLEEP IX-3

'The baby it sleeps.'

b. SLEEP IX-3

'(As for the baby), it sleeps.'

As for the OV order, there is more than one trigger. First, ASL allows object topicalization, as shown in the following sentences. The underscore indicates the scope of the non-manual marker. The numbers represent the person alternations in verb agreement, with the subject person preceding the verb and the direct object following the verb. For example, 1_GIVE_3 means 'I give (something) to him/her'.

(3)

a. APPLE_topic marker, IX-1 EAT.

'As for the apple, I eat it.'

b. BOOK_topic marker 1_GIVE_3

'I give him/her the book.'

c. CANDY WANT_yes-no marker?

'Do you want candy?'

This non-canonical OV order is triggered by an object-prominent information structure, and also requires obligatory non-manual topic markers, usually raised eyebrows and chin (Aarons, 1996; Liddell, 1980). Topicalized OV order is common in verb agreement (3b) and yes-no questions (3c). Fisher (1975) suggests that word orders are more flexible when there is an agreeing verb, as the subject and the object are indicated by the agreement inflection, but the licensing conditions are less clear in the literature. Two deaf native signers we consulted confirmed that OV structure is very common with verb agreement but requires a topic marker on the fronted object.

OV structure is also grammatical when the verb is under certain modulated conditions. According to previous studies (Fisher & Janis, 1990; Hoffmeister, 1978; Kegl, 1976; Liddell, 1980; Matsuoka, 1997; Pichler, 2001), verb inflections that license the OV structure include aspectual inflection (4a), handling inflection (4b), and spatial inflection (4c).

(4)

a. TOMATO GIRL EAT(aspect: continuative)

'The girl keeps eating tomatoes.'

b. BALL HIT(handling: bat)

'(He) hits the ball with a bat.'

c. MONEY PUT(spatial: on the table)

'(He) puts money on the table.'

It is worth noting that not all ASL verbs are compatible with these three morphological modulations. Only a subset of verbs with corresponding properties can be morphologically marked, namely verbs that allow aspectual modulation, handling verbs, as well as spatial verbs. Therefore, the OV structures listed above also depend on the specific verb type. However, it is less clear from the literature to what extent these OV orders are obligatory. According to our ASL consultants, canonical word order is still preferred even when the verbs are inflected, and the information structure plays an important role in deciding which order is used.

Another word order phenomenon is the 'verb sandwich' structure, when a verb is repeated at a sentence-final position. The second verb is usually morphologically modulated, but the modulation is not obligatory. An example is given below from Pichler (2001):

(5)

SALLY TYPE PAPER TYPE(aspect: continuative)

'Sally was typing and typing her paper.'

To conclude, ASL uses a basic SVO order but also several word order variants depending upon various constraints including a VS order that requires a pronoun copy, an OV order that requires object-prominent information structure and a mandatory non-manual topic marker, or an OV order that requires specific inflections that apply to different subsets of verbs. In addition, ASL allows null arguments (Lillo-Martin, 1986), which renders surface word orders even more diverse. This means that the full picture of ASL word order is complicated.

3.2.2 ASL Word Order Development in Young Children

As described above, ASL allows various word order patterns conditioned by verb inflections and mandatory information structure markers. This raises the question of whether variable adult ASL word order input complicates the learning situation for child native learners. We now turn to research investigating the acquisition of both basic word order and word order variations in ASL by typically developing children.

At the initial stage of acquisition, when child native learners begin to produce multi-word combinations (around 2;0 - 2;6; years; months), several studies report similar findings, namely that deaf children produce a relatively high percentage of non-canonical word orders: 25%-36% VS; 41%-54% OV (Hoffmeister, 1978; Pichler, 2001; Schick, 2002). Also, the non-canonical word orders young children produce are mostly adult-like. Both Hoffmeister (1978) and Pichler (2001) observed that the subjects of non-canonical VS utterances produced by child native learners are almost always pronouns, which is compatible with the pronoun-copy rule. Still, Pichler did not find any statistically significant relationship between pronominal subjects and VS order, because young children mostly use pronouns even in the canonical subject position. Coerts (2000) also looked at the use of subject pronoun copy in Sign Language of the Netherlands (SLN), an SOV language, and found that young children were sensitive to this condition by age 2. As for OV utterances, adult-like, non-manual markers are generally missing in child ASL (Reilly, McIntire, & Bellugi, 1990). Still, Schick (2002) found that children tend to use OV order for certain verbs (e.g. EAT, SEE, DRINK, PUT-IN, LOOK-FOR, WANT, LIKE). Pichler (2001) confirmed this pattern in her data and further argued that most verbs found in child OV utterances are morphologically modulated, including aspectual, handling and spatial inflections. As described above, these verb inflections license OV order in adult ASL. One caveat in interpreting the results of these studies is that the types of verbs found in the OV utterances produced by the children were quite limited. It is unclear whether children at this stage have fully acquired the licensing morphological rules, or have acquired certain patterns of specific verbs.

As for word order development beyond the initial two-word stage, Hoffmeister (1978) found that, in contrast to the high variability in word order at the earlier stage, deaf children from 3;2 to 5;7 consistently produce more than 80% of their utterances in canonical word order. Berk (2003) reported a similar trajectory for one child native learner who produced 43% canonical word order at age 2;0, and at age 2;9, increased production of canonical word order to 74%. Newport and Meier (1985) suggested that young children rely on fixed word order to mark grammatical relations. This pattern also echoes the early fixed word order preference of children observed for some spoken languages, such as Korean (Park, 1970) and Italian (Slobin & Bever, 1982). Interestingly, some of these studies also show a brief period of time in the earliest two-word stage (before 2;6) when young children use more word order variations (Slobin & Bever, 1982). These findings indicate a cross-linguistically similar developmental trajectory. When the language employs variable word order patterns, young children sometimes begin by using word order variations, but shortly thereafter show a preference for the canonical word order. Berk (2003) also reported that one native child learner at age 4;6 produced 63% canonical word order, slightly lower than the 74% at age 2;9. The literature reports variable word order in adult ASL (Aaron, 1996; Fisher, 1975; Liddell, 1980), but the exact frequencies of variable word order use remains unknown. Palmer (2015) analyzed three child-parent sessions between deaf native parents and their hearing bilingual bimodal children aged 1;8 to 3;4 with session durations ranging between 31 to 47 minutes, and found non-canonical VS order ranging between 11% to 24%, and non-canonical OV order ranging between 3% to 15%, suggesting that adult input involves high percentage of canonical word order. Still, this limited language sample might not reflect the whole picture of adult use of variable word order. Therefore, we do not know whether the percentage of canonical word order use by young children is adult-like or not, although children seem to use the same morphological rules as used in adult ASL.

In summary, studies to date indicate that young ASL learning children initially use more variable word orders in the early multi-word stage at around age 2;0 to 2;6, and that the non-canonical word orders they produce are mostly adult-like. Shortly afterward, children rely more on canonical SVO order. There is little information on word order preferences during later stages of ASL development and how this compares to adult ASL usage.

3.2.3 AoA effects on ASL Syntactic Development

Previous studies on late L1 language outcome suggest that late L1 learners are capable of acquiring simple structures, while showing more difficulties with linguistic structures with increased morpho-syntactic complexity, such as sentences with embedded clauses (Boudreault & Mayberry, 2006; Mayberry, 1993; Newport, 1990). In terms of basic word order, Newport (1990) found that, compared with other ASL morpho-syntactic structures, deaf adults with delayed L1 onset exhibit fewer problems comprehending basic SVO order in ASL. Boudreault and Mayberry (2006) also reported better performance with basic word order by late L1 learners in a grammatical judgment task, although they still performed slightly worse when compared to native signers. Hall, Ferreira and Mayberry (2015) found native and late learners to be equally syntactically primed by basic SVO structures in ASL. As for non-canonical word orders such as the topic-comment structure in ASL, no previous studies have explicitly examined late L1 learner outcomes, but given the intricacies with various morphological, syntactic and discourse conditions, we would expect late L1 learners to show more difficulties based on their performance in other morpho-syntactically complex structures.

So far, developmental studies on late L1 development generally suggest a similar developmental trajectory when compared to young native learners, while also indicating a reduced rate of syntactic development as compared to lexical development. Ramírez, Lieberman and Mayberry (2013) examined the vocabulary development of three adolescent L1 learners, with an AoA of around 14 years, who were at the initial two-word stage of acquisition (1;0 to 2;0 years of exposure to ASL). They found few differences between adolescent late learners' vocabulary acquisition and early utterances compared with younger native learners reported in Anderson and Reilly (2002). Their findings suggest that adolescent L1 learners acquire lexical items in a fashion akin to younger native learners but at a faster rate.

Berk and Lillo-Martin (2012) examined the two-word stage of two deaf children with an AoA of 6 years old and observed a dissociation between linguistic and general cognitive abilities. Although the child late learners tended to produce more cognitively complex utterances, using mental verbs or more sophisticated semantic relations, they still used linguistic features similar to those of younger children at this stage, such as limitations in utterance length. Morford (2003) studied two deaf children with AoAs of 13;7 and 12;1, respectively, investigating their longitudinal development (2 to 31 months of exposure to ASL) of verb agreement and classifier constructions using picture description and elicited production. The adolescent L1 learners gradually improved production of these morpho-syntactically complex structures that use spatial features, but their performance on comprehension tasks after 7 years of exposure still deviated significantly from that of native signers, consistent with the results of retrospective studies of ultimate attainment in adult, late L1 learners (Boudreault & Mayberry, 2006; Mayberry, 1993; Newport, 1990).

As for word order development, Lillo-Martin and Berk (2003) gathered naturalistic language data during the initial two-word stage from two deaf children whose language onset began at 5;9 and who had been exposed to ASL for 10 to 20 months. Adopting the same methodology as in Pichler (2001), they found that these late L1 learners were somewhat more canonical and made more inflectional mistakes with non-canonical orders compared with native child learners. Their findings suggest that non-canonical word orders in ASL pose difficulties for late learners. Longitudinal development of word order was studied for one of the children in Berk (2003). This child showed word order variation after 10 months of exposure with 61% canonical word order, which subsequently became even more canonical with a rate of 80% canonical word order after 3 years and 3 months of exposure. Thus, the trajectory of this late learner's ASL word order acquisition appears to be similar to that reported for young native learners. Berk also described this late L1 learner as showing a gradual increase in canonical word order use over three years, compared with the younger native learner in her study who displayed a rapid increase in canonical word order use within one year's time after initial two-word production.

3.3 Research Questions and Hypotheses

Previous studies suggest that late L1 learners of ASL show similar, and even faster development, in the very early stages of language acquisition compared with young native learners, but subsequently encounter difficulties with morpho-syntactically complex structures. So far, the selectivity of AoA effects has yet to be explained, as few studies have looked at longitudinal syntactic development in late L1 learners after the two-word stage. The current study investigates the developmental trajectory of word order production in adolescent late L1 learners to deepen our understanding of AoA effects on syntactic development. To do so, we coded the word order patterns in their production of verb-noun combinations, calculated the percentage of canonical word order at each time point, examined their use of non-canonical word orders, examined the longitudinal changes in their word order patterns, and compared the results with findings on native, child L1 learners as reported in the literature. A key question is how late L1 learners might develop word order patterns in ASL given their cognitive maturity and early language deprivation.

With respect to the effects of cognitive maturity on syntactic acquisition, there are two possible outcomes. First, increased cognitive maturity may facilitate early syntactic development in fashion similar to its facilitation on early lexical development (Ramírez et al., 2013). If so, we would expect late learners to show faster syntactic development compared to native child learners. Alternatively, syntactic development may rely more on linguistic constraints than of cognitive maturity, as suggested in Berk and Lillo-Martin (2012). If this is the case, we would expect no facilitating effects from cognitive maturity, and the late L1 learners should develop word order patterns in a similar, if not slower, rate, compared to native L1 learners.

With respect to AoA effects, there are three possibilities. One possibility is that early syntactic development is unaltered by early language exposure. If this is the case, we would expect late learners to show a similar trajectory to that of native child learners, with a brief stage of variable order progressing to more canonical word order. In this case, the late L1 learners should be sensitive to the various conditions that license non-canonical orders in early stages of acquisition. The second possibility is that early syntactic development is unaffected by early language deprivation, but only for basic word order. If so, we would expect late L1 learners to follow a similar trajectory in terms of the use of basic word order, but their use of non-canonical word orders might be random and not explained by the adult ASL grammar. Also, they might differ from native child learners in terms of when they begin to use basic word order. Finally, a late AoA might affect early syntactic development including basic word order. If so, late learners should show different patterns of word order development compared to native child learners. For example, they may rely on verb-specific patterns to produce word order and show no increase their use of the canonical word order over time.

To test these possibilities, we conducted two longitudinal studies of ASL word order acquisition by four adolescent L1 learners. The first study investigates the ASL word order acquisition of three deaf late L1 learners whose ASL environment was the same. The second study investigates the ASL word order acquisition of a fourth late L1 learner whose ASL learning environment was different.

3.4 Study One: Adolescent L1 acquisition within a group home environment

3.4.1 Participants

The participants of the first study were three individuals who, due to varying circumstances, acquired little or no language prior to being immersed in ASL around the age of 14 in the same environment. The adolescents lived in a group home for deaf adolescents where they were fully immersed in ASL. The staff consisted of proficient signers who used ASL exclusively with the adolescents daily. The participants resided together at the group home for four years along with other deaf adolescents who were proficient signers. Before joining the group home, each participant was in a circumstance that prevented him or her from learning language.

Carlos lived with his hearing and non-signing family members in another country until he was 11 years old. He briefly enrolled in a local deaf school but soon stopped attending. He then immigrated with some of his family members to the United States and was first placed into a classroom for cognitively impaired children. He was later placed in the group home for deaf children at age 13;8. According to the staff, he knew no spoken language and very few ASL signs upon his initial placement, and mainly used pointing and gestures to communicate.

Before his placement, Cody lived with one hearing, non-signing guardian. He attended school at age 5 and was misdiagnosed as cognitively impaired. The school he attended used very limited sign language. Upon his placement in the group home at age 14;8, he knew only a few basic ASL signs. Similar to Carlos, Cody knew no spoken language and was observed to mainly use pointing and gestures to communicate.

Shawna lived with her hearing and non-signing guardians and was reported to have been kept at home until age 12. She attended several schools, both deaf and mainstream, for a total of 16 months. Upon joining the group home at age 14;7, she was reported to know no spoken language and rely primarily on behavior and limited use of gestures to communicate. She produced no ASL signs.

The adolescent L1 learners' lexical development and initial utterances are reported in Ramírez et al., (2013). Their vocabulary size, vocabulary composition, utterance length as well as complexity were similar to that of younger, deaf native ASL learners with a comparable length of ASL exposure (Anderson & Reilly, 2002).

3.4.2 Data Collection

In total, three sessions of spontaneous language samples were collected over a 3.5-year period. All three adolescent L1 learners participated in the first two sessions, which were filmed at their group home while they were having dinner with some deaf peers and deaf professionals. These filming sessions each lasted for about 50 minutes. During each filming session, the participants signed with different interlocutors on various daily topics. Instead of signing to each other, the participants mostly conversed with one to two proficient signers with whom they were familiar. The last session was filmed at the lab of the research team, and only Carlos and Shawna were filmed. During this filming session, each participant signed with a hearing researcher as well as with a deaf adult while they were having lunch. Both interlocutors were very proficient signers, and the participants were familiar with them. They conversed on various daily topics. Each participant was filmed for about 20 minutes. Table 3.1 shows their age and years of exposure to ASL at each filming session.

The videos were transcribed using the annotation system ELAN (Crasborn & Sloetjes, 2008) by a hearing researcher who is highly skilled in ASL. All of the transcriptions were re-examined for accuracy by a deaf researcher who is a native signer.

Table 3.1: The participants' age and years of exposure (YoE) to ASL at each filming session.

Participant	AoA[a]	YoE[b] $atT1$[c]	YoE at T2	YoE at T3
Carlos	13;8	2;0	3;8	5;6
Shawna	14;7	1;0	2;8	4;6
Cody	14;8	1;6	3;2	NA

a.AoA: Age of Acquisition; b. YoE: Years of Exposure to ASL; c. Filming session: T1 - Time 1, T2 – Time2, T3 – Time 3.

3.4.3 Analysis procedures

The first step of the analysis was to select all verb phrases that were associated with at least one argument. Next, we coded word order information. All previous studies of ASL word order acquisition have separated subject-verb and verb-object combinations in their analyses. Following this procedure makes it easier to compare the present results with previous findings. This is also because most utterances (87.44%, 181 out of 207) produced by the adolescent L1 learners were associated with either subject only or object only, and only 12.56% utterances (26 out of 207) had both subject and object. It is potentially interesting to analyze the word order patterns of those utterances with more than one argument, but for the purposes of the present study we do not have enough data points to perform such an analysis, as we only found around 3 such utterances per subject per session. Therefore, utterances that were associated with more than one argument, such as an SVO order, would be coded twice under the current coding scheme. For example, I LIKE DOG would be coded twice, first I LIKE as SV for the subject-verb combination, and also LIKE DOG as VO for the object-verb combination.

We first coded the relative order in subject-verb combinations. We tagged all verb phrases that were associated with a nominal subject, and then coded the relative word order between the subject and the verb. We then coded the relative order in verb-object combinations. We used all verb phrases that were intelligible and unambiguous. We tagged all nominal objects in each verb phrase, if there were any, and then coded the word order according to the relative linear order. Utterances with pointing gestures, such as pointing at a person or an entity in a picture, were excluded from the analyses. Nominal, adjectival, and classifier predicates were excluded from the analyses. Complement verbs, which take verb phrases as complements, such as WANT in I WANT EAT ICE-CREAM (‘I want to eat ice-cream’), were analyzed as involving no nominal object, because the internal argument is an embedded verb phrase instead of a noun phrase, which did not meet our criteria. Auxiliary verbs such as FINISH in I FINISH COOK MEAL (‘I finished cooking a meal’) were analyzed in a similar way. Embedded verb phrases and coordinated verb phrases, although very uncommon in the current data set, were analyzed independently.

Application of these criteria yielded our word order data set, summarized in Table 3.2. Our language sample for analysis is relatively small because the adolescent L1 learners were relatively taciturn and not particularly talkative. Also, perhaps due to being in the initial stages of ASL development, they produced more verb-only utterances and rarely used overt subjects or objects.

Table 3.2: The number of verb-argument combinations produced in each filming session by each participant.

	Verb with Subject			Verb with Object		
Participant	T1[a]	T2	T3	T1	T2	T3
Carlos	12	17	9	31	13	11
Shawna	11	13	11	21	20	15
Cody	16	10	NA	14	9	NA

a Filming session number: T1 - Time 1, T2 – Time2, T3 – Time 3.

Next, we classified the coded word orders according to whether they were canonical or not. A word order is canonical if the subject precedes the verb, or if the object follows the verb, otherwise it is considered to be non-canonical. According to Pichler (2001), VSV order is a variant of non-canonical VS order, with the verb repeated at the end of the utterance. Similarly, OVO is a variant of the non-canonical OV structure when the object is repeated for emphasis at the end, and is counted as OV. Another possible word order is the verb-sandwich order VOV, where the second verb is a copy of the first verb. We followed Pichler (2001) and analyzed VOV as a variant of VO. For the very occasional ditransitive verb phrase with both direct and indirect objects (1.72%, 4 utterances in total), we counted the word order as VO only if both direct and indirect object follow the verb, otherwise we counted the word order as OV.

After coding the relevant word order information, we analyzed the subject-verb combinations and verb-object combinations separately, following the analysis used in previous studies to facilitate later comparison. Each analysis consisted of two parts. First, we examined the trajectory of word order preference over time. We specifically made the following computations: 1) the proportion of canonical word orders and non-canonical word orders in the initial stage of acquisition, as reflected in the first filming session, 2) the proportion of word orders in later stages as reflected in the second and third (if applicable) filming sessions, 3) the trajectory of word order preferences over time within and across the participants, and finally 4) the characteristics of the participants' trajectory relative to that of native child learners reported in the literature. Second, with the help of two deaf, native ASL consultants, we examined the participants' use of non-canonical word orders and compared them to those produced by child native learners. The following results are presented according to the analyses procedures outlined above. First, we turn to the relative word order between the verb and the subject and then to the relative word order between the verb and the object.

3.4.4 Results

Relative order between verb and subject.

Recall that SV is the canonical word order in ASL and that non-canonical VS order is also allowed if the subject is a pronoun, according to the pronoun-copy rule. Figure 3.1 shows the late L1 learners' preference for the relative order between a subject and a verb.

All the participants generally preferred canonical word order SV across all filming sessions (Fig. 1). In addition, they produced more non-canonical VS orders in earlier sessions (both first

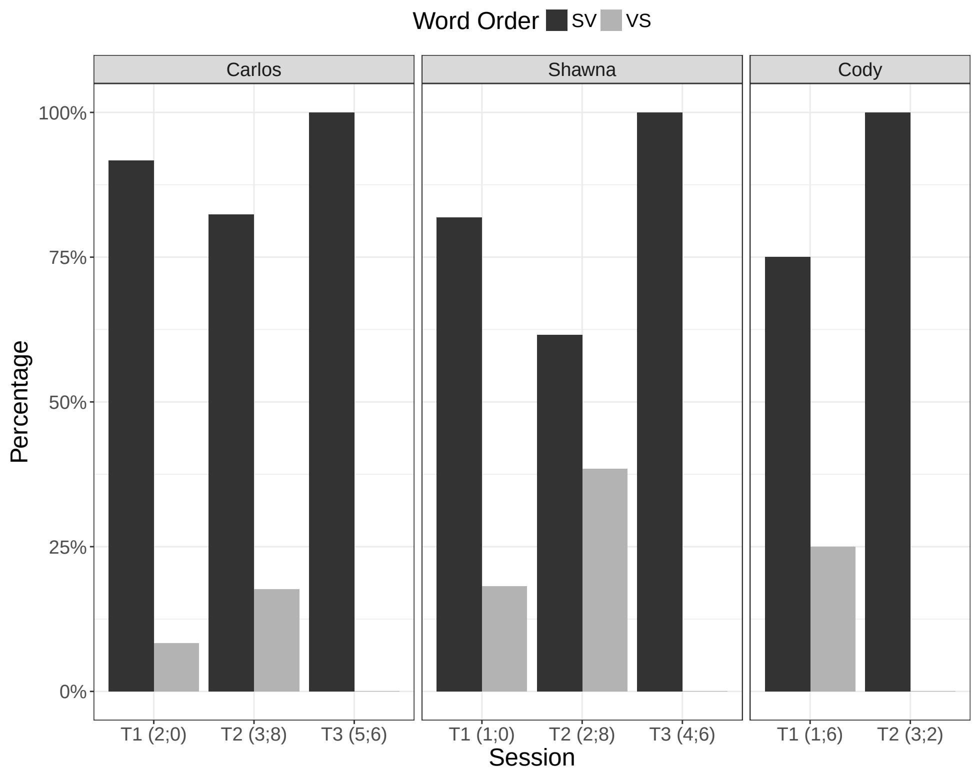

Figure 3.1: Percentage of canonical SV and non-canonical VS orders produced by the adolescent L1 learners during each session as a function of years of ASL exposure (shown in the parenthesis following the session number).

and second sessions for Carlos and Shawna, the first session for Cody). All three participants tended to become more canonical with more ASL exposure. By the time of their last filming sessions (after 5;6 years of ASL exposure for Carlos, 4;6 years of exposure for Shawna, and 3;2 years of exposure for Cody), all three participants used only SV order. We note that Shawna produced more non-canonical word order VS in her second filming session (38.46%, 5 out of 13) compared to her first filming session (18.18%, 2 out of 11). As she had less ASL exposure compared with Carlos and Cody during her second filming session, this indicates her continued preference towards variable word order during her early developmental stages. The percentage of non-canonical VS order the adolescent L1 learners used is comparable to that reported for child native learners, both in the initial stage around ages 2;0 to 2;6 (25% in Hoffmeister, 1978; 34% in Schick, 2002; 36% in Pichler, 2001), and also in the later stages beyond age 3;2 (8% - 14% in

Hoffmeister, 1978). Both child native learners and adolescent L1 learners share the ASL word order characteristic of becoming more canonical over time, although the adolescent learners are more conservative and use only canonical SV order with a longer ASL exposure period compared with deaf native children.

Next, we take a further look at the non-canonical VS structure produced by these participants. All the subjects produced by Carlos and Shawna in VS structures were pronouns. Two examples are listed below, (6) produced by Carlos during the second filming session, and (7) produced by Shawna during the first filming session.

(6)

COOK IX-1.

'I cooked.'

(7)

BRING FOOD IX-3.

'She brought food.'

We compared the proportion of pronominal subjects in SV and VS structures to determine if Carlos and Shawna showed a tendency to use sentence-final pronouns. For Carlos, 64.71% of the subjects in SV structures (34 in total) were pronouns, while 100% of the subjects in his VS structures (4 in total) were pronouns. This difference is not significant according to a Fisher's Exact test ($p = 0.287$) and suggests that the consistent use of pronoun in those VS utterances by Carlos may be a mere coincidence. The difference is more obvious for Shawna, as only 39.29% of her subjects in SV structures (28 in total) were pronouns, while 100% of her VS structures (7 in total) had pronominal subjects, which was a significantly different use of pronouns in SV and VS structures (Fisher Exact test $p = 0.008$). This suggests that Shawna consistently used pronominal subjects in the VS structure but less so in the SV structure.

By contrast, for Cody we found only 1 pronominal subject in the VS structure (8a). The other 3 VS utterances he produced all used the same noun, MOM, as the subject. One example is shown in (8b). This use of VS order is not adult-like, and could not be a copied form from adult input. He also used MOM several times in SV orders, as shown in (8c). This indicates that he is not consistently adopting VS order for this specific noun, MOM, but instead shows more random patterns in his production.

(8)

a. FORGET IX-1 FORGET

'I forget.'

b. BUY MOM.

'Buy mom.'

Intended meaning: 'Mom buys (something).'

c. MOM BUY DOG.

'Mom bought the dog.'

To summarize the results thus far, similar to child native learners, all three late L1 learners produced more non-canonical VS order in the initial stage of ASL acquisition after 1 to 2 years of exposure and became more canonical at a later stage after 3 or more years of exposure, although their percentage of initial non-canonical VS order was slightly lower compared to child native learners. Two late L1 learners, Carlos and Shawna, consistently produced adult-like non-canonical VS orders with pronominal subjects, while Cody appeared to be more random in his production of the VS order. Next, we examine word order preference in verb-object combinations.

Relative order between verb and object

The issue of verb-object order in ASL is more complicated than that of subject-verb order. Recall that the most common word order in ASL is the canonical VO order. A non-canonical OV order is also possible. There are basically two conditions that license OV order. One is topicalization, which requires a clear non-manual marker, and the other is when the verb is morphologically modulated, with spatial, handling, or aspectual inflection. As mentioned above, despite morphological modulation, agreement inflections are more related to topicalized structures, and non-manual topic markers on the object are required for OV orders with agreement verbs. Figure 3.2 shows the proportion of different word order patterns produced by the adolescent learners during each session.

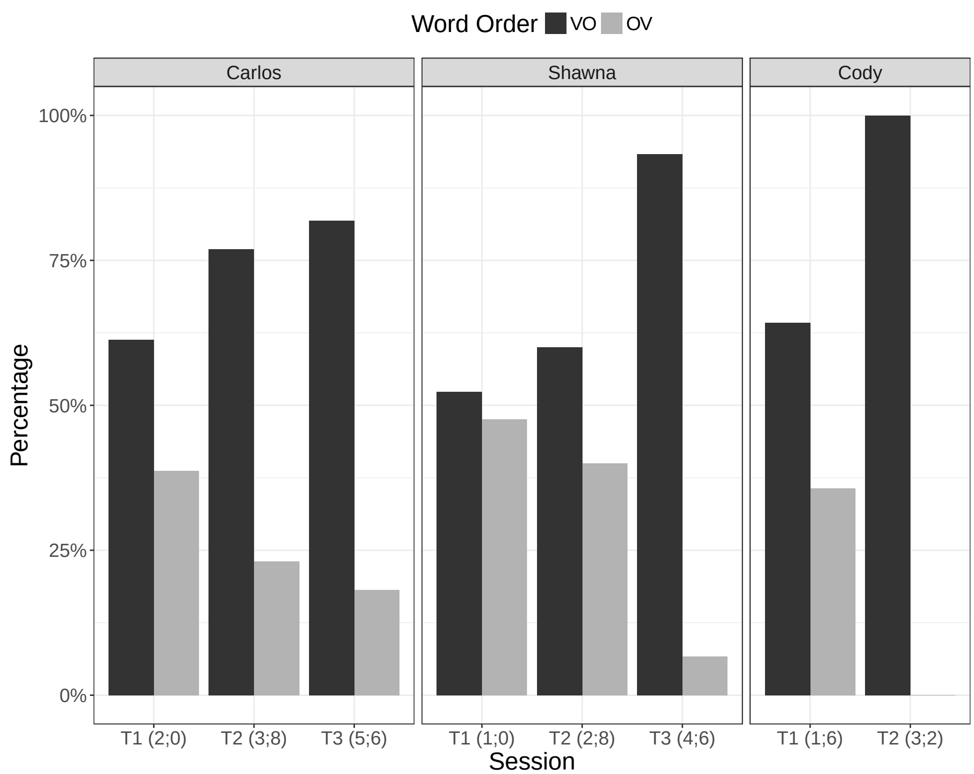

Figure 3.2: Percentage of canonical VO and non-canonical OV order produced by the learners during each session as a function of length of ASL experience (shown in the parenthesis following the session number).

At the first filming session after 1 to 2 years of exposure to ASL, all participants showed more flexible word order patterns and produced more than 40% of their utterances using non-canonical order. During the second session, Shawna continued to produce more flexible word order after 2 years and 8 months of exposure, while Carlos and Cody, each with more than 3 years of exposure to ASL, showed a clear increase in their use of canonical word order. Cody especially produced no OV order at all after 3 years and 2 months of exposure to ASL. During the third session after 4 to 5 years of exposure to ASL, both Carlos and Shawna produced fewer than 20% utterances in non-canonical OV order. These results indicate that the adolescent L1 learners were quite similar in becoming more canonical over time.

For the late L1 learners, their percentage use of the non-canonical OV order in the initial stage after 1 year to 2 years and 8 months of exposure (more than 40%) was relatively close to what is reported for child native ASL learners at age 2;0 t0 2;6: 41% (Hoffmeister, 1978); 44% (Schick, 2002); and 54% (Pichler, 2001). This also held true for the later stages after more than 3 years of exposure. According to Hoffmeister (1978), the percentage of non-canonical OV order produced by native child learners beyond age 2;9 ranged from 12% to 20%. Therefore, native child learners and late L1 learners appear to share a similar trajectory and become more canonical over time. It is less clear when Carlos and Cody shifted to the more canonical word order pattern, given the long intervals between their first and second sessions. However, Shawna continued to use varied word order patterns at her second session, after 2 years and 8 months of exposure. Given the fact that these late L1 learners started producing multi-word utterances very early on (Ramírez et al., 2013), her use of varied word order pattern seems to have lasted for more than at least two years, which differs from that of the child native learners described in Berk (2003) and Hoffmeister (1978), who entered this stage only 9 months to 1 year after beginning to produce multi-word utterances.

Next we take a closer look at the adolescent learners' utterances with both canonical word order and with word order variations to determine if they were similar to child native learners in producing non-canonical word orders with OV-prominent structures. To do so, we grouped their utterances into six categories. The first three categories were verb inflections that allow OV order, namely, aspectual, spatial and handling inflection (Pichler, 2001). The fourth category was agreement verbs, which are commonly associated with topicalization and require the object to be marked by an eyebrow-raising non-manual marker. The fifth category was yes-no questions, which is also common in OV order in adult ASL. Similar to native child learners (Reilly et al., 1990; Pichler, 2001), late L1 learners rarely produce the non-manual eyebrow-raising marker, making it hard to detect any obvious topicalization structure in their production. This means that their production of agreement verbs and yes-no questions were less adult-like due to the lack of an appropriate topic marker. Nevertheless, given that verb agreement structures and yes-no questions are more often associated with topicalization, we would expect these structures to be OV prominent as well. Thus, the five categories listed above are considered to be OV-prominent in adult ASL. Other utterances that did not fit in the above categories were grouped into the 'other' category. While it is still possible that OV utterances that fall into the 'other' category are actually topicalized and conditioned by information structure, we have insufficient evidence to examine such a possibility from our data set, due to the lack of non-manual discourse markers among late L1 learners.

Table 3.3 summarizes the different conditions that were sensitive to word order variations in non-canonical OV utterances produced by the late L1 learners over time, while Table 3b shows the distribution in their canonical VO utterances.

Table 3.3: Distribution of word order sensitive conditions in OV utterances – token number (type number)

participant	Carlos			Shawna			Cody	
Session	T1	T2	T3	T1	T2	T3	T1	T2
(Years of exposure)	(2;0)	(3;8)	(5;6)	(1;0)	(2;8)	(4;6)	(1;6)	(3;2)
Utterance Type								
Aspectual	0	0	0	3(1)	0	1	0	0
Spatial	0	0	0	3(1)	0	0	0	0
Handling	1	0	1	0	5(3)	0	0	0
Agreement	8(3)	0	0	1	1	0	2(2)	0
Yes-no question	2(2)	1	0	1	0	0	0	0
Others	1	2(2)	1	2(2)	2(2)	0	3(3)	0
OV total count	12(7)	3(3)	2(2)	10(6)	8(5)	1	5(5)	0

As shown in Table 3.3, we observed individual differences in sensitivity to OV-prominent structures. In addition, Carlos seemed to be more sensitive to the topic-prominent conditions,

Table 3.4: Distribution of word order sensitive conditions in VO utterances – token number (type number)

participant	Carlos			Shawna			Cody	
Session	T1	T2	T3	T1	T2	T3	T1	T2
(Years of exposure)	(2;0)	(3;8)	(5;6)	(1;0)	(2;8)	(4;6)	(1;6)	(3;2)
Utterance Type								
Aspectual	0	0	0	0	1	0	0	0
Spatial	0	1	0	1	1	1	4(2)	3(2)
Handling	3(1)	0	0	0	0	0	0	0
Agreement	5(1)	2(2)	0	3(2)	0	2(1)	3(1)	0
Yes-no question	0	0	0	1	0	0	0	0
Others	11(9)	7(7)	9(5)	6(2)	10(7)	11(6)	2(2)	6(6)
OV total count	19(11)	10(10)	9(5)	11(6)	12(9)	14(8)	9(5)	9(8)

especially with agreement verbs, but he also produced a few OV utterances with the handling inflection. In contrast, Shawna produced more OV orders with adult-like verb inflections, including aspectual, spatial and handling, during both the first and the second sessions. By comparing Table 3.3 with Table 3.4, we observe that in the first session, Carlos produced more OV-prominent types in his OV utterances than in his VO utterances (Fisher Exact test $p = 0.008$). This is also observed in Shawna's second session (Fisher Exact test $p = 0.019$), but not in her first session (Fisher Exact test $p = 0.183$). Cody also produced two OV utterances with agreement verbs in the first session, but no preference for OV-prominent types is found in his OV utterances (Fisher Exact test $p = 0.266$). The numbers of OV utterances produced by Carlos in the second and third session, Shawna in the third session, and Cody in the second session were too few to perform a meaningful test. In general, all three late learners produced very few unaccounted ('Others') OV utterances.

Notably, we also observed that the OV utterances the adolescent L1 learners produced during the first session were always associated with a small set of verbs. For example, Carlos produced 8 OV utterances with 3 agreement verbs, namely PAY (9a), SEND (9b) and SHOW (9c).

(9)

a. COACH FIRST PAY_3.

‘(I) first pay the coach.’

b. MY SISTER IX-3 SEND_3 EMAIL_3.

‘(I) send my sister (something), I email (her).’

c. CD IX-1 SHOW_2 FAMILY MANY FAMILY

‘I show the CD (to you), family, many (photos), family.’

During the first filming session, Carlos also produced the same verb PAY in canonical word order several times. Also, although his production of PAY often associates only with one object, either the direct object (e.g. COACH) or the indirect object (e.g. MONEY), it seems that neither is associated with a fixed word order pattern. Therefore, it seems that when producing utterances associated with this specific ditransitive verb, Carlos was random in his production.

Similarly, all the OV utterances Shawna produced with spatial and aspectual inflection were always associated with a certain verb for each inflection type, namely spatial BRING (10a) and aspectual SEARCH (10b).

(10)

a. FOOD BRING(spatial: there)

‘(I) brought food.’

b. BATTERY SEARCH(aspectual: durative).

‘(I) searched for the battery.’

These patterns suggest that, instead of mastering the underlying rules, it is possible that the late L1 learners are initially learning whole phrases as a constructional template.

Compared with child native learners, we found that although Carlos and Shawna used more OV-prominent verbs in their OV utterances, there still seemed to be a difference between child and adolescent L1 learners in terms of the types of OV-prominent utterances they produced. According to Pichler (2001), most of the OV orders produced by young children are associated with the handling inflection as well as the spatial inflection; only a few utterances are associated with the aspectual inflection, and very few are licensed by the agreement inflection. In contrast, OVs with the handling inflection as well as with the spatial inflection were less common in the adolescent L1 learners' productions, especially for Carlos and Cody, but all the adolescent L1 learners produced some OV utterances associated with agreement verbs. Because the adolescent L1 learners are much older and cognitively mature, we might speculate that agreement verbs are conceptually more difficult for child native learners compared with adolescent L1 learners who may be able to link experience with home sign or gesture to the spatial modulation of such verbs.

At the same time, we also note that adolescent L1 learners and child native learners share the use of certain verbs in OV utterances, such as WANT and LIKE. As discussed earlier, adults commonly use these two verbs in yes-no questions with topicalization. This suggests that both adolescent L1 learners and child native learners are sensitive to the adult input for specific verbs.

In sum, these results indicate that adolescent L1 learners are similar to child native learners in terms of word order preferences and developmental trajectory. Also, there is some evidence that they may enter the canonical stage later compared to child native learners.

Although highly informative, there are some limitations of the present study that weaken these implications. First, the language samples we collected from the adolescent L1 learners were relatively small, which means that the patterns we found across three participants could be due to chance, although this is unlikely. The limited sample size also makes it difficult to directly compare results found at different time points, as the set of verbs being produced might influence word order choice as well. Also, with the present dataset, it is difficult to interpret the change in word order preference, given the few tokens of non-canonical utterances produced in the later filming sessions. Finally, because all three participants were living in the same group home, it is difficult to exclude the possibility that the word order patterns we found were prompted by mutual influence among the adolescent L1 learners. More utterances from other adolescent L1 learners acquiring ASL in different environments are required to confirm these findings. In study 2, we analyze the word order development patterns of a fourth adolescent L1 learner of ASL who met these criteria.

3.5 Study Two: Adolescent L1 acquisition in a family environment

3.5.1 Participant

The L1 learner in the second study has the pseudonym Chris. Chris was born and grew up until the age of 12 in Indo-China. He was the only deaf person in his hearing family who used no sign language. He attended no school until he moved to North America at the age of 12;10. Upon his arrival, Chris was illiterate and could neither speak nor lip-read. He was placed into a foster home with foster parents who were fluent signers, one of whom was deaf, where he was exposed to accessible language for the first time. He was also enrolled in a deaf residential school, where he was exposed to both ASL and English. Chris was thus fully immersed in an ASL environment at home and school. According to his foster parents, when they first met him, Chris mainly used gestures, facial expressions and loud vocalizations to communicate.

3.5.2 Data Collection

Two sessions of spontaneous language samples were collected from Chris. The first session occurred when Chris was aged 15;9, 2 years and 11 months after he was first exposed to ASL. The language samples were collected during spontaneous conversations about various daily topics between Chris and a deaf native ASL signer. The filming took place in a university laboratory. The second session was filmed when he was aged 18;8, which was 5 years and 10 months after his first exposure to ASL. Similar to the first filming session, Chris conversed with the same deaf native ASL signer about various topics in a university laboratory. The videos were first transcribed by a native deaf signer, and later checked by a hearing researcher who is highly skilled in ASL and coded using the Child Language Data Exchange System (CHILDES, MacWhinney, 2000).

3.5.3 Analysis Procedures

We used the same analysis procedures as those described in Study 1. Table 4 shows the number of analyzable argument-verb combinations we found in the spontaneous language samples.

Table 3.5: Number of argument-verb combinations produced by Chris during each filming session – token number (type number).

Type	T1 (2;11)[a]	T2 (5;10)
Verb with Subject	77	146
Verb with Object	51	59

a Filming session number: T1 - Time 1; T2 - Time 2. Years of exposure to ASL shown in the parentheses (Year; Month).

Compared with the data available for analysis in Study 1, significantly more data was available for analysis in Study 2. This is because the filming sessions with Chris consisted of several conversations throughout an entire day, while in Study 1 only one conversation was filmed for each session during one meal. Also, Chris was more talkative than the adolescent L1 learners who participated in Study 1.

As shown in Table 3.5, Chris generally produced more subjects than objects, especially during the second filming session. But this bias does not affect our analyses as we separate the verb-subject combinations from the verb-object combinations when calculating the percentages.

3.5.4 Results

Figure 3.3 shows the proportion of canonical and non-canonical word order patterns produced by Chris during each session.

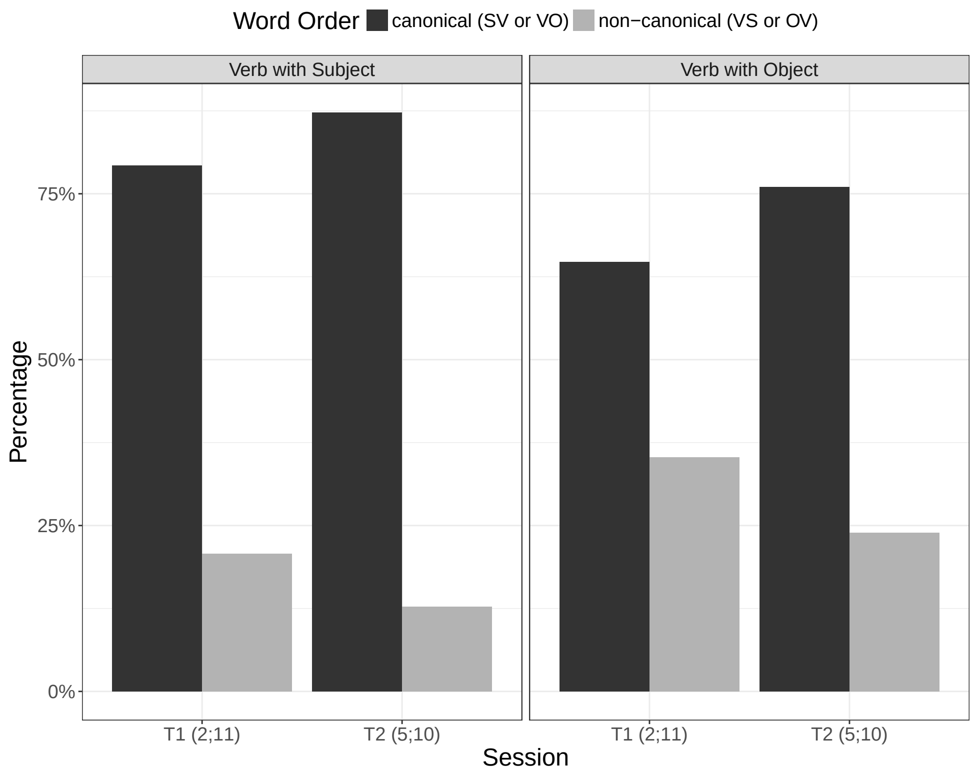

Figure 3.3: Percentage of canonical (SV or VO) and non-canonical (VS or OV) utterances produced by Chris during each session as a function of length of ASL experience (shown in the parenthesis following the session number).

Considering the relative order between verb and subject, Chris preferred canonical SV order in both the first filming session (79.27%) and the second filming session (87.26%), using slightly more SV order in the second filming session. This is similar to the results from Study 1. One pattern to note is that Chris appeared to show less change over time, but this pattern is more apparent than real considering the fact that he had nearly three years of ASL exposure in the first filming session compared with the one and one and a half years of experience for Shawna and Cody respectively and the two years of exposure for Carlos during their first filming session.

In Chris' first filming session, we found 76% of the subjects in utterances with VS order to be pronouns, higher than the proportion in utterances with SV order, which was 59.04%, but the difference was not significant (Fisher Exact test p = 0.159). In the second filming session, there were 84.61% of pronoun subjects in VS utterances, while in SV utterances the percentage was 74.86%; the difference was again not significant (Fisher Exact test $p = 0.333$). Therefore, although Chris produced more pronouns in his VS utterances, there is no clear evidence that he was sensitive to the pronoun-copy rule in ASL.

Similar to Study 1, only 12.71% utterances (15 out of 118) in the first filming session and 11.21% utterances (23 out of 205) in the second filming session were produced with both subject and object. In the first filming session, only 40% followed the canonical SVO word order. In the second filming session, 65.21% utterances followed the canonical SVO order. This increase is not statistically significant (Fisher Exact test $p = 0.185$), but might indicate an increased preference of canonical word order even when the utterance has more than one argument.

Next, we examined his relative order pattern between verb and object. The general pattern was again similar to our results from Study 1. During the first filming session, Chris showed more variation in his word order patterns, with 64.71% canonical VO order. In the second filming session, the proportion of canonical word order increased to 76.06%. Similar to Shawna in Study 1, Chris already had 2 years and 11 months of exposure to ASL at the time of the first filming session, but he still showed a relatively varied word order pattern. This again may suggest a prolonged development of late L1 learners compared to native child learners. Chris also produced a number of OV utterances in his second filming session, which enables us to analyze changes in the distribution of his OV production over time. Table 3.6 summarizes his use of each category of verb-object combinations in the first (T1) and second (T2) filming sessions.

As Table 3.6 shows, in the first filming session, Chris showed a slight tendency to prefer OV-prominent categories in his OV utterances (33.33%) than in his VO utterances (9.09%), and this difference is marginally significant (Fisher Exact test $p = 0.052$). In the second filming session, we observe an increased use of OV-prominent categories in his OV utterances (58.82%), which is significantly different (Fisher Exact test $p < 0.001$) from the low percentage in his VO utterances (14.81%).

Table 3.6: Distribution of word order sensitive conditions in VO and OV utterances – token number (type number).

Session[a]	T1		T2	
(Years of exposure)	(2;11)		(5;10)	
Word Order	VO	OV	VO	OV
Utterance Type				
Aspectual	0	0	0	1
Spatial	0	2(2)	2(1)	0
Handling	0	1	0	1
Agreement	2(2)	3(3)	2(2)	7(4)
Yes-no question	1	0	4(4)	1
Others	30(19)	12(11)	46(23)	7(5)
Total count	33(22)	18(17)	54(30)	17(11)

a Filming session number: T1 - Time 1, T2 – Time2.

These results suggest that instead of applying the canonical word order to all verbs, Chris shows an increased sensitivity to OV-prominent conditions in ASL. Therefore, it appears that Chris continued to learn the specific rules that allow non-canonical word order in ASL, but increased his use of canonical word order in other utterances. Nevertheless, the non-canonical OV utterances produced by Chris in the second filming session are also associated with a small set of verbs, such as ASK and SEND, similar to the patterns found in Carlos and Shawna's data.

Despite different childhood backgrounds and ASL learning environments, we found that Chris showed a developmental trajectory similar to those of Carlos, Shawna and Cody. We next summarize the results across all four adolescent L1 learners, and examine word order preferences over time.

3.6 Word Order Preferences as a Function of Length of ASL Exposure

To further explore the relation between years of ASL exposure and word order preference, we plotted word order preferences as a function of years of exposure for each participant at each language sampling session allowing us to compare findings across the two studies.

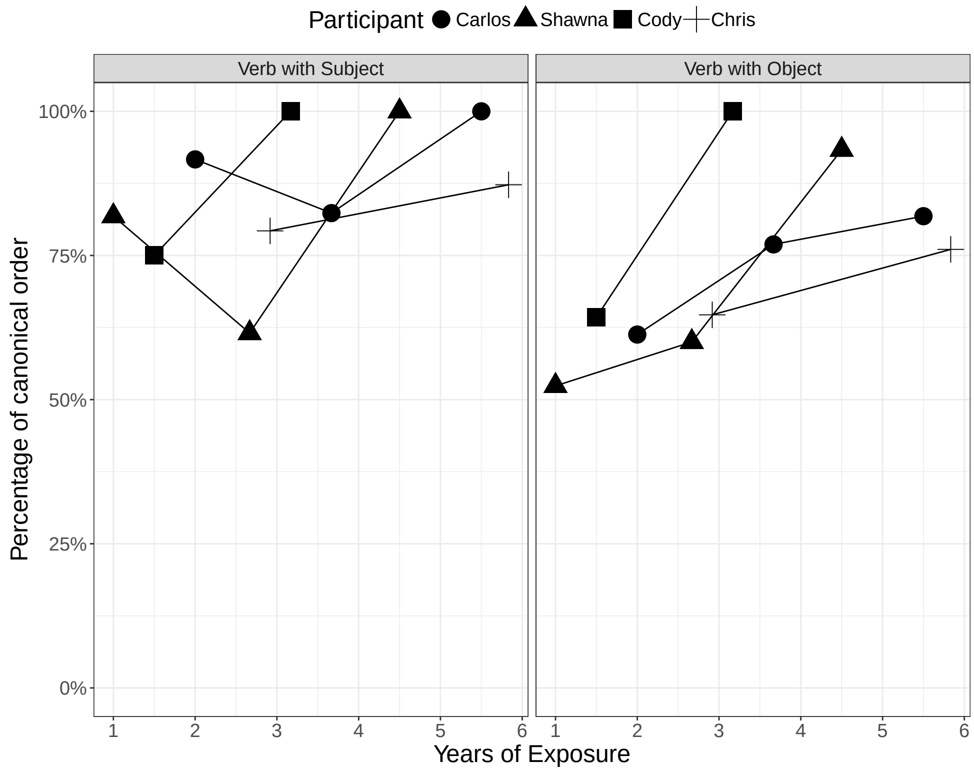

Figure 3.4: Percentage of canonical word order (SV or VO) produced by each participant as a function of years of ASL exposure.

All four late L1 learners display a similar learning trajectory of word order acquisition as shown in Figure 3.4. For the verb-subject combinations, the late L1 learners tended to use more canonical word order from the beginning of ASL acquisition, becoming more canonical with increased years of exposure. For the verb-object combinations, the late L1 learners produce more variable word orders during the earlier stage of acquisition, and after two to three years of exposure to ASL converge on a more canonical word order pattern over time.

These patterns are very similar to the findings reported for child native learners (Berk, 2003; Hoffmeister, 1978), although there is some evidence, as discussed in previous studies, that adolescent L1 learners tend to spend more time using variable word order despite their early production of two-word utterances after approximately one year of ASL exposure (Lillo-Martin

& Berk, 2003; Ramírez et al., 2013). It seems that late L1 learners may require up to 2 years from the initial two-word utterance stage to proceed to the canonical word order stage, more than twice the time child native learners need to enter this stage from their first multi-word utterances, around 9 months to 1 year.

We do observe some individual differences, however. Shawna produced only 61.54% canonical SV order in her second filming session after two years of ASL exposure, which differed from other participants. We speculate that this may be because Shawna, unlike other late L1 learners, tended to restrict the use of pronominal subject to the sentence-final position during this stage, as described above in Study 1. Also, Cody showed an earlier stage of canonical word order preference after 3 years and 2 months of exposure to ASL, while other three adolescent L1 learners, Shawna, Carlos, and Chris, showed more variability with similar years of exposure. Cody had attended school prior to being exposed to ASL. Although he showed little evidence of language acquisition from this schooling, it may have had an effect on his subsequent language acquisition. He also showed faster vocabulary development compared to Carlos and Shawna (Ramírez et al., 2013), and faster lexical development is related to an earlier onset of early morpho-syntactic development in English speaking children (Marchman & Bates, 1994). This may explain why he entered the canonical stage earlier than other adolescent L1 learners.

3.7 Discussion

In two studies, we found that for both verb-subject combinations and verb-object combinations, adolescent L1 learners showed word order variation in the initial stage of ASL acquisition, after 1 year to 2 years and 11 months of exposure to ASL (first session for Carlos, Cody and Chris, and both first and second sessions for Shawna). This result is highly consistent with those reported for child native learners who also produce more flexible word order at this stage with similar amounts of ASL exposure, at ages 2;0 to 2;6 (Hoffmeister, 1978; Pichler, 2001; Schick, 2002). We also found that adolescent L1 learners became more canonical after about three years of language exposure. This second finding again parallels the word order patterns observed for young native children beyond age 2;6, when they also show a preference for canonical word order (Berk, 2003; Hoffmeister, 1978). In addition, like young child L1 learners, the adolescent L1 learners seldom produced unaccountable non-canonical utterances. That is, they often used pronominal subjects in the sentence-final position, and also showed sensitivity to the various object-first conditions. Together these results indicate a similar developmental trajectory of ASL word order acquisition for adolescent and child L1 learners. However, there is some evidence that adolescent L1 learners take longer to progress to the canonical stage.

For our main research question, we asked about the effects of cognitive maturity and early language deprivation on syntactic development. First, we did not observe faster acquisition by adolescent L1 learners in early syntactic development, suggesting that cognitive maturity does not facilitate syntactic development. The trajectory of word order acquisition in ASL thus appears to be constrained by the learning mechanisms of grammatical structure for the first time rather than by cognitive maturity. One thing we noticed is that compared to native L1 learners, late L1 learners produced more utterances with cognitively more complex verbs, for example agreement verbs, early in their syntactic development. They also showed some sensitivity to the OV-prominent features of these verbs, along with other types of verbs, similar to native L1 learners. These findings extend previous findings for the initial stages of adolescent L1 lexical acquisition (Ramírez et al., 2013) and the two-word stage in child late L1 learners (Berk & Lillo-Martin, 2012), confirming that the content and trajectory of early language development is not altered by increased cognitive maturity.

As for AoA effects, we considered three possibilities: no effects, effects on non-canonical orders only, and effects on both basic and non-canonical word orders. According to our results, late L1 learners showed a developmental trajectory similar to that of child, native L1 learners with varied word order in the beginning and more canonical word order later on. Also, they seem to show sensitivity to the various syntactic conditions that trigger non-canonical word orders, such as sentence-final pronominal subjects and various verb-specific object-first conditions. Similar to child native L1 learners, from very early on, adolescent L1 learners seldom produce unaccountable non-canonical word orders. Among the late L1 learners, Chris showed increased sensitivity to non-canonical conditions over time. In this sense, these findings seem to favor the first prediction, that early language deprivation does not affect early syntactic development in general.

However, we also garnered some evidence suggesting a prolonged developmental stage for basic word order for late L1 learners. Although the mechanisms underlying early syntactic development appear to be intact when language acquisition is delayed until adolescence, the developmental duration of syntactic acquisition appears to be significantly prolonged relative to the fast rate observed for their early lexical development (Ramírez et al., 2013).

Previous studies on native L1 grammatical development (Pinker, 1989; Brown, 1973; Slobin & Bever, 1982), emerging sign languages (Sandler, Meir, Padden, & Aronoff, 2005), early language deprivation (Boudreault & Mayberry, 2006; Curtiss, 2014; Newport, 1990), and gestural communicative systems developed by deaf children without sign language (Susan Goldin-Meadow & Mylander, 1998), have all suggested that simple form-meaning mappings, such as unit combinations with basic constituent order, are salient to children, even when environmental input is varied, insufficient, severely delayed, or absent. Our findings confirm that basic word order is relatively resilient from the effects of late language exposure from a developmental aspect.

The present study was an initial attempt to fill the gap between the native-like developmental trajectory shown by the adolescent L1 learners in previous studies (Berk & Lillo-Martin, 2012; Morford, 2003; Ramírez et al., 2013), and the morpho-syntactic and complex syntax deficits observed in ultimate attainment studies of delayed L1 acquisition (Boudreault & Mayberry, 2006; Newport, 1990). Our findings suggest that the trajectory of syntactic development is not altered when it starts later in life, but the learning process is likely to be significantly slowed, even for the most common structures such as basic word order. It is also important to note that crucial morphological markers, such as the non-manual topic marker, were always missing from late learners' utterances. Thus, it appears that ultimate language outcomes are likely affected by selective learning difficulties at the morpho-syntactic level of language structure. A protracted rate of word order development may be one symptom that the underlying mechanisms of grammatical learning are adversely affected by a late start to the language acquisition process. Future studies are required to determine whether such learning difficulties cause representational differences in language outcome, or rather indicate increased processing difficulties that affect their task performance, as proposed by Morford (2003).

The nature of longitudinal studies of a less-studied language (ASL) of a special population (adolescent L1 learners) poses several limitations. First of all, given our limited knowledge of adult ASL patterns, it is difficult to determine if the relatively high proportion of canonical word order use observed in the later sessions of the present studies are adult-like or not. It remains possible that late L1 learners as well as child native L1 learners rely on canonical word order more than necessary due to a failure to fully acquire more complex morphological and syntactic structures. More longitudinal data is necessary to determine whether and when late L1 learners and child native L1 learners start to produce adult-like word order patterns. The lack of this information does not affect the interpretation of our present findings, however, as we only compared late L1 learners with native L1 learners in the early stages of syntactic acquisition. More information on adult input patterns would greatly increase our understanding of late L1 syntactic acquisition.

Another caveat regarding our findings is that, because the non-canonical OV orders in ASL are often associated with a subset of verbs in ASL, we do not know if the OV utterances expressed by the late L1 learners are generated by morphological rules, or instead are acquired on a verb-specific basis. For example, most of the non-canonical OV utterances produced by Carlos, Shawna and Chris were always associated with a small set of agreement verbs or morphologically modulated verbs. This was also true for the morphologically modulated verbs observed in Pichler

(2001). Experiments involving less common verbs with similar morphological features would clarify this question.

We do not know the complexity of the home sign systems these learners may have used before their exposure to ASL. Studies on home sign systems (Goldin-Meadow & Feldman, 1977; Goldin-Meadow & Mylander, 1998) suggest that deaf children without natural sign language input usually develop their own gesture systems, and they demonstrate certain patterns in their two gesture combinations, such as constituent expression and ordering as a function of argument type. Because all four late L1 learners showed similar word order acquisition patterns despite their different cultural backgrounds and ASL learning environments, it seems likely that the task of learning ASL grammar itself overrides any pre-existing differences in the late L1 learners' use of homesign.

Finally, when analyzing the available spontaneous data, it was not always easy to interpret the late learners' intended information structure to determine how change in information prominence might have affected their word order preference. Answering this question would require careful control of information structure using experimental designs, which would be a fruitful direction for future research.

In sum, the current studies find that adolescent late L1 learners show a developmental trajectory in their ASL word order production similar to what has been observed for child native ASL learners. The present results also show that the process of word order acquisition when language acquisition begins for the first time at or after the age of 13 is significantly prolonged. Importantly, the present findings suggest that initial syntactic development follows a similar trajectory even with delayed language onset and increased cognitive maturity. These results confirm previous findings that L1 AoA effects are selective: simple syntactic structures are relatively more resilient to perturbations in the age-onset of language acquisition than morpho-syntactically complex structures. These findings also suggest that the learning process of early morpho-syntactic development appears to be sensitive to the age-onset of language acquisition unlike early lexical development. More research is required to discover precisely how a late onset of language exposure affects the mechanisms of syntactic acquisition and processing.

Chapter 3, in full, is a reprint of the material as it appears in Cheng, Q., Mayberry, R. I. (2019). Acquiring a first language in adolescence: the case of basic word order in American Sign Language. Journal of Child Language, 46(2), 214-240. The dissertation author was the primary investigator and author of this paper. Reprinted with permission.

Chapter 4

Sentence comprehension strategies: when event plausibility overrides word order

4.1 Introduction

Individuals born deaf are at risk of a lack of accessible language in either signed or spoken modality during childhood (Mayberry, Lock, & Kazmi, 2002). Studies on deaf individuals acquiring American Sign Language (ASL) as a first language (L1) at ages past infancy have found multiple effects on linguistic structures, with more difficulties on complex structures (Boudreault & Mayberry, 2006). Case studies of deaf individuals with extreme delay in the onset of language experience suggest that late L1 development resembles typical L1 development from the standpoints of: 1) initial vocabulary development (Ferjan Ramírez, Lieberman, & Mayberry, 2013); 2) linguistic characteristics during a two-word stage (S. Berk & Lillo-Martin, 2012); and 3) basic word order development (Cheng & Mayberry, 2019; Lillo-Martin & Berk, 2003). However, syntactic development beyond the two-word stage appears to be protracted in very late L1 learners, and developmental outcomes appear to be limited to basic clausal structures. The language production of these case studies is characterized by a small mean length of utterance

(MLU) with little increase over time (Ferjan Ramírez, Lieberman, & Mayberry, 2013). Late L1 learners show limited acquisition of non-canonical word order patterns (Berk, 2003; Cheng & Mayberry 2019), and low comprehension of complex structures such as verb agreement and classifier constructions (Morford, 2003). Studies investigating the language outcomes of late L1 learners of ASL have found high performance levels on simple structures, such as mono-clausal sentences with canonical word order, but not on more complex structures such as sentences with embedded clauses (Boudreault & Mayberry, 2006; Cormier, Schembri, Vinson, & Orfanidou, 2012; Henner, Caldwell-Harris, Novogrodsky, & Hoffmeister, 2016; Newport, 1990). A recent comprehension study (Mayberry et al., under review) tested late L1 outcomes at different clausal levels, following the typical emergence order of sentence structures. The findings show that late L1 learners perform better with mono-clausal sentence structures, which often emerge early in typical L1 development, but much worse with bi-clausal and inter-sentential structures, which emerge much later.

This parallel between late and native L1 development and difficulties at later stages suggest a plateau in late L1 syntactic development restricted to basic sentences. Investigating this plateau can provide insights on the role of early language input on L1 syntactic development, which is difficult to study among typically developing children. Here we investigate the nature of late L1 sentence processing when the age onset of accessible language begins after early childhood, focusing on non-linguistic strategies children use beyond the two-word stage prior to their development of word order.

Beyond the two-word stage, typically developing young children who experience language from infancy go through a transitional stage from simple, context-bound, and more pragmatically or semantically based language use, to an abstract, rule-based, and morpho-syntactically structured use of language. This transition during early language development is manifested by rapidly increased MLU (Brown, 1973), over-generalization of morpho-syntactic rules (Bybee & Slobin, 1982; Marcus et al., 1992; Pinker, 2009), the emergence of complex structures (C.Chomsky, 1969; Diessel, 2004; Vasilyeva, Waterfall, & Huttenlocher, 2008), and more robust reliance on abstract linguistic rules (Akhtar & Tomasello, 1997; Akhtar, 1999; Bates et al., 1984; Berko, 1958; Strohner & Nelson, 1974).

One crucial developmental phenomenon in this transitional stage is the robust use of basic linguistic cues such as word order. Although children show sensitivity to word order from very early on (Brown, 1973; Gertner, Fisher, & Eisengart, 2006; Hirsh-Pasek & Golinkoff, 1991, 1996; Naigles, 1990), they are more likely to use other extra-linguistic cues such as event probability and animacy as heuristic strategies during early stages of language development, especially when there are inconsistencies across the cues. Younger children show a strong reliance on animacy hierarchy as a way to infer thematic roles before they can fully rely on abstract syntactic frames (Chapman & Kohn, 1978; Dodson & Tomasello, 1998). Using acting-out tasks with plausible and implausible sentences in English, Strohner and Nelson (1974) found that 3-year-olds performed above chance with reversible and plausible sentences such as 'the boy is chasing the girl'. But for sentences with implausible meanings such as 'A ball is throwing a boy', children consistently preferred the reverse interpretation which is more probable in the real world. By contrast, older children between the ages of 4 to 5 years rely more on basic word order to arrive at the implausible meaning. This pattern of relying more on plausible meaning than on linguistic structure during the early stages of language development has been replicated in English and in other languages (Chan, Lieven, & Tomasello, 2009; Chapman & Miller, 1975; Lindner, 2003).

Robust form-meaning mappings based on linguistic cues at the mono-clausal level can serve as a steppingstone for more complex form-meaning mappings in complex sentences. Because early processing skills constrain the intake of linguistic information during syntactic development (Omaki & Lidz, 2015), it is likely that the shift from context-bound grammar to complex grammar is partially driven by an increased ability to robustly process simple clausal structures using syntactic cues. In addition, the robust use of syntactic cues is a prerequisite for the learning mechanism of syntactic bootstrapping (Fisher, Gertner, Scott, & Yuan, 2010; Naigles, 1990). This enables the subsequent learning of new verbs that can take subordinate clauses such as attitude verbs (White, Hacquard, & Lidz, 2016), and the acquisition of late developing, more complex sentence structures (Diessel, 2004).

Similar to other languages, ASL makes use of word order to mark grammatical relations. ASL adopts a basic word order of SVO (Fischer, 1975; Kegl, 1996), while also allowing alternative surface word orders such as topicalized objects with non-manual markers and verb spatial, aspectual, or handling markings (Aarons, 1994; S. Fischer & Janis, 1990; Hoffmeister, 1978; Kegl, 1976; Liddell, 1980; Matsuoka, 1997; Pichler, 2001), and sentence-final pronominal subject repetition (Padden, 2016). Previous studies on late L1 development have found basic word order to be relatively resilient to conditions of inaccessible early language input, for both spontaneous production (Berk, 2003; Cheng & Mayberry, 2019) and comprehension (Boudreault & Mayberry, 2006; Newport, 1990). Unknown, however, is whether this basic linguistic cue is sufficiently developed to provide the foundation for further syntactic development. Mayberry et al. (under review) found that although late L1 signers performed above chance with SVO sentences, their performance is still much worse compared to the native signers. Also, simple reversible SVO sentences with two animate arguments such as 'BOY PUSH GIRL ' used in previous comprehension tasks are insufficient to test the robustness of this linguistic cue.

Language onset after late childhood may be too late for the transition from using event knowledge to using abstract word order in sentence comprehension. This would predict that sentence comprehension would be limited to simple and context-bound cues, despite extended experience with ASL. This could also explain the limited MLU development observed over an extended period of 5 years observed for very late L1 learners (Ferjan Ramírez, Lieberman, & Mayberry, 2013), and additional difficulties with morpho-syntactically complex structures (Boudreault & Mayberry, 2006; Cormier, Schembri, Vinson, & Orfanidou, 2012; Henner, Caldwell-Harris, Novogrodsky, & Hoffmeister, 2016; Mayberry et al., under review; Newport, 1990). If, like very young children, late L1 learners of ASL also rely on extra-linguistic cues such as event plausibility, rather than on word order, they should show less consistent use of basic word order when it conflicts with event plausibility cues. A weaker version of this hypothesis is that late L1 learners may not fully rely on word order, but may show sensitivity to animate first nouns, since first noun animacy appears to be a precursor of the syntactic position of a subject (Dodson & Tomasello, 1998; Slobin, 1985).

Alternatively, the bottleneck in late L1 syntactic development may not be caused by fragile foundations at the basic clausal level, but instead may be due to additional difficulties at the complex clausal level. If this is so, then the basic word order cue may be fully resilient for very late L1 learners, and we would expect them to robustly rely on basic word order even when it conflicts with event probability.

In the current study, we aim to examine these two possibilities in order to better understand sentence comprehension in late L1 syntactic development. Using a sentence-picture matching paradigm, we investigate the use of word order during simple sentence comprehension when language experience begins in late childhood, by contrasting basic word order cues with event probability and animacy cues., We also test a group of deaf native signers of ASL as one control asking if word order is a robust linguistic cue in ASL, since this information is not available from previous literature. By including a group of hearing individuals learning ASL as a an L2 later in life, we further ask whether late L1 and late L2 differentially affect the use of word order versus event probability and animacy cues for comprehension of simple transitive sentences.

4.2 Current Study

4.2.1 Test Design

We created a sentence-picture verification experiment to test the mapping from syntactic positions to semantic roles during simple sentence comprehension. The participants first watched an ASL utterance consisting of three signs. Next, they saw a line drawing that either matched or mismatched the previous utterance. The mismatched drawings show reversed semantic roles for the target SVO sentences, or mismatched features in the filler condition. For example, when presented with the sentence ‘DOOR PAINT BOY’, the matched picture would be an animated door painting a boy, while the mismatched picture would be a boy painting a door. Next, the subjects responded to the picture by pressing the ‘yes’ button if the picture matched the meaning of the previous utterance, or by pressing the ‘no’ button if the picture did not. Before beginning the experiment, each participant performed a practice session with 6 trials to ensure they fully understood the testing procedures. The experiment was conducted in two counter-balanced blocks; participants were able to take a break between the blocks, although none did so. The full experiment took approximately 30 minutes. Figure 4.1 illustrates the experimental procedure.

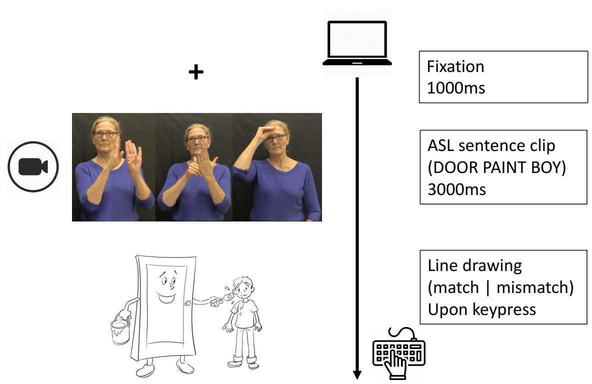

Figure 4.1: Experimental procedures of the sentence-picture verification task.

Transitive sentences of four types were created for the present experiment. The design controlled for two factors: event plausibility, and subject animacy. First, we have two critical sentence types with implausible sentence meaning, where the sentence meanings were more plausible when interpreted in reverse. These two sentence types contrast in the animacy of the subject noun: Condition 1 sentences consisted of animate subjects and animate objects (Impl-AA), such as DUCK CARRY CLOWN; Condition 2 sentences had inanimate subjects and animate

(Impl-IA), such as BANANA BITE BOY. The semantic cue of subject animacy may provide extra information for semantic role assignment of the implausible events. In addition to these two critical conditions, we also created two baseline conditions that were the reversed and plausible versions of the implausible sentence conditions, matched in verb and noun types: Condition 3 consisted of plausible sentences with animate subjects and animate objects (Plau-AA), such as WOMAN FEED HORSE; Condition 4 consisted of plausible sentences with animate subjects and inanimate objects (Plau-AI), such as GIRL KICK CHAIR. Each condition consisted of 24 stimuli, 12 with matched pictures and 12 with mismatched pictures, yielding 96 stimuli in total. Eleven transitive ASL verbs were used in the experiment, including CARRY, HUG, KICK, PUSH, BITE, LICK, PAINT, FEED, DRAW, RIDE-ON, and EAT, all signed in plain form without any spatial modification or extra linguistic markers. Figure 4.2 illustrates the conditions and their stimulus pictures. Note that during the experiment, each sentence appeared only once, either with a matched or a mismatched picture, to avoid potential priming effects. We also used an equal number of fillers consisting of noun phrases with adjectives such as BIG CUTE DOG, or intransitive verb phrases such as GOOD BOY SLEEP. For the mismatched pictures of the filler condition, we changed either the adjective, the event, or the entity. The fillers show that the participants are paying attention to the task and understand single argument intransitive verbs. In order to respond correctly, the participant had to comprehend the lexical items in the sentence and combine them into a unified meaning. The fillers also served to mitigate any potential syntactic priming effects.

We began by creating 96 sentence stimuli which we then asked 8 fluent signers to rate on a plausibility scale of 1 to 5. Stimuli designed to be plausible but eliciting an average score lower than 4, and sentences designed to be implausible but receiving an average score above 2 were excluded and replaced with a set of newly calibrated sentences (n = 17). An illustrator then provided line drawings for all the corresponding picture stimuli. The experiment was programmed with OpenSesame (Mathôt, Schreij, & Theeuwes, 2012) on a Mac notebook. The keyboard was

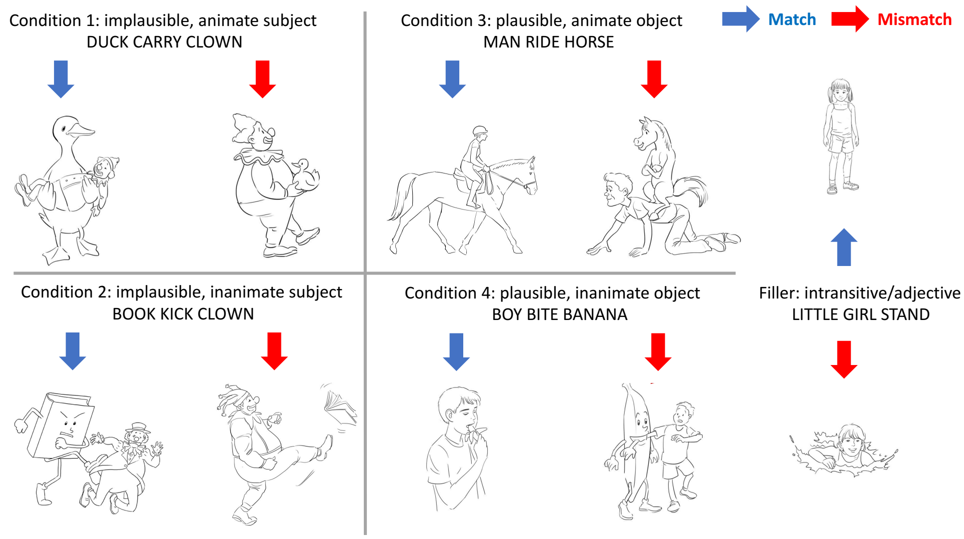

Figure 4.2: Examples of test conditions, with sentences and matched/mismatched pictures.

used to collect responses. Response accuracy was recorded for each trial. Data analyses were conducted in R, and statistical models were implemented using the lme4 package (D. Bates, Maechler, & Bolker, 2012). All the lexical signs used in the task are early-acquired, simple signs selected from the ASL Communicative Developmental Inventory (CDI) list (Anderson & Reilly, 2002), and typically produced by 3-year-old native ASL signers.

4.2.2 Participants

We collected data from three groups of signers: the target group consisted of 7 late L1 learners each of whom first acquired ASL after 9 years of age and had a minimum of 9 years of ASL experience. One control group shows differences in late L1 versus late L2 development and consisted of 7 hearing L2 signers of ASL with intermediate proficiency. A second control group was native deaf signers who show differences between late L1 vs early L1 development of ASL and consisted of 7 native signers who were born deaf to deaf signing families. Table 4.1 shows the background characteristics of the groups.

The deaf late L1 participants are all healthy adults who were profoundly or severely deaf from birth. Due to various conditions, these individuals were not exposed to a sign language from birth, nor did they have sufficient residual hearing to access spoken language. Five late L1 participants were born and raised in countries outside the USA where deaf education was either unavailable, or mostly oral based and prohibited the use of sign language, or they did not have access to a local deaf community and therefore did not acquire the local sign language. The first formal language immersion experience they had with ASL was after they immigrated to the USA. Two late L1 participants were born in the US but were enrolled in kindergartens and elementary schools with oral communication only and received no ASL support until the age of 9. They later acquired ASL either by transferring to a deaf school with formal ASL instruction, or by fully immersing with the local Deaf community and taking ASL classes in the community. These individuals are rare cases with extreme delay in their age onset of language experience with a minimum of 9 years of ASL exposure. Thus, the size of the group is necessarily limited to a small number given the rarity of this population.

The hearing L2 participants were all healthy adults who are native English speakers and late L2 learners of ASL. Most of them are college students who took at least four terms of daily ASL classes and had at least two years of ASL experience. Their ASL proficiency is mostly at the intermediate level.

The deaf native L1 participants are all healthy adults who are profoundly deaf from birth. Unlike the late L1 group, these individuals all acquired ASL from birth from their deaf signing family members.

Table 4.1: Background information of the participant groups.

Group	N	Age (mean; range)	ASL onset (mean; range)	ASL Duration (mean; range)
Deaf late L1	7	34.57; 19-56	16.14; 9-30	18.42; 9-41
Hearing late L2	7	21.14; 20-25	16.71; 13-19	4.42; 2-8
Deaf native L1	7	39.57; 27-64	birth	same as age

4.2.3 Hypotheses and analyses

Our main question is whether the age of initial language experience affects the ability to use syntactic cues even when they conflict with event plausibility. A secondary question is whether semantic cues such as subject animacy can serve as an additional cue when there is a conflict between event knowledge and the syntactic cues. For the late L1 learners, we consider four main possible outcomes. If their ASL development is similar to that of young children, they should rely more on event plausibility than word order during sentence comprehension; then their accuracy would be lower than chance for both implausible conditions. However, if they do show some sensitivity to the animacy of the first noun, then we would expect them to perform more accurately in Condition 1 (Impl-AA) with animate subjects when compared with Condition 2 (Impl-IA) with inanimate subjects. Alternatively, if late L1 signers robustly rely on word order, then they should show performance levels higher than chance in all conditions, although potentially still lower than that of the native L1 signers and late L2 signers, due to perceptual or cognitive limitations. Finally, if sentences are being comprehended by random assignment of semantic roles independent of word order or event knowledge cues, then we would expect them to show chance-level performance across all conditions except for the fillers. For the late L2 learners, given that previous studies (Jackson, 2007) often suggest early reliance on word order cues during L2 acquisition, we expect them to be fully reliant on syntactic cues for all conditions, especially given that their native language, English, is a language that relies heavily on word order. Another possibility is that as native English speakers, they may rely more on basic word order compared to the native signers, if, for example, basic word order in ASL is not as robust a linguistic cue in the presence of other cues. If basic word order is a robust linguistic cue in ASL as in other languages, we would expect the native signers to perform at ceiling level for the target implausible conditions. Alternatively, if basic word order is not as robust in ASL given other choices of grammatical markings, then we would expect the native signers to perform worse in the implausible conditions, especially in the inanimate subject condition.

4.3 Results

The results are described at the group level, at the statistical level, and in terms of individual patterns of the late L1 learners.

4.3.1 Descriptive statistics

Figure 4.3 shows the mean accuracy across conditions as a function of group.

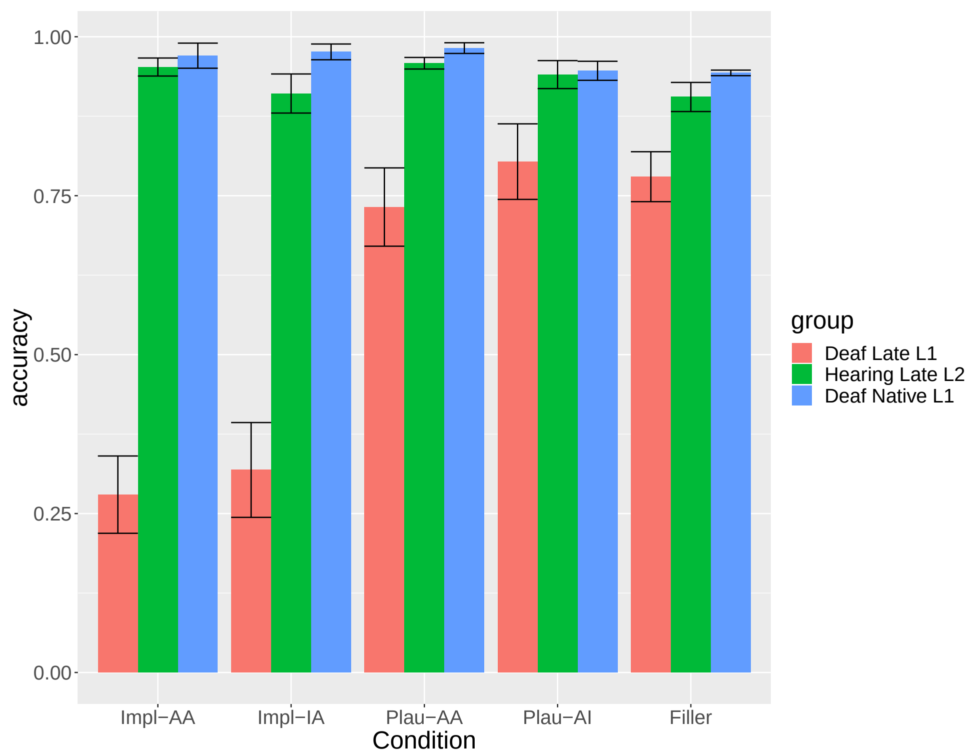

Figure 4.3: Group comparisons of mean accuracy and standard error under each condition. Cond.1 Impl-AA: implausible sentence with animate subject, e.g. DUCK CARRY CLOWN; Cond.2 Impl-IA: implausible sentence with inanimate subject, e.g. BOOK KICK CLOWN; Cond.3 Plau-AA: plausible sentence with animate object, e.g. MAN RIDE HORSE; Cond.4 Plau-AI: plausible sentence with inanimate object, e.g. BOY BITE BANANA.

The deaf native signers performed well in the plausible baseline conditions (Cond. 3 Plau-AA: 98.24%; Cond.4 Plau-AI: 94.64%) and also in the implausible target conditions (Cond. 1 Impl-AA: 97.02%; Cond. 2 Impl-IA: 97.61%). Their performance in the experimental conditions was similar to their performance in the filler condition (94.31%), with minimal variation within the group. The hearing L2 learners also performed well in both implausible (Cond. 1 Impl-AA: 95.23%; Cond. 2 Impl-IA: 91.07%) and plausible (Cond. 3 Plau-AA: 95.83%; Cond. 4 Plau-AI: 94.04%) conditions, as well in the filler condition (90.52%), again with minimal variations within the group. By contrast, the deaf late L1 group showed very different patterns. First, their mean accuracy for the filler condition, 77.98%, is lower than both control groups, NS and L2, but still higher than chance (50%). Similarly, their performance in the two plausible baseline conditions (Cond.3 Plau-AA: 73.21%; Cond.4 Plau-AI: 80.35%) are lower than the control groups, but above chance (50%). However, their average accuracy for the implausible conditions, Cond.1 Impl-AA (27.97%) and Cond.2 Impl-IA (31.85%), are much lower than that of the control groups and also below chance (50%). Event plausibility was a stronger cue to sentence meaning for the late L1 learners than was the basic word order and the animacy of the subject noun. In addition, there is more individual variation within the late L1 group, for the fillers (standard error = 3.92%) and even more so for the test conditions (standard errors around 6%).

4.3.2 Statistical analyses

To further examine the observations from the descriptive statistics, we conducted several statistical tests to explore our questions. First, because the primary research question asks if late L1 learners consistently rely on word order regardless of sentence plausibility, we used a generalized linear mixed model to examine the interaction between group and sentence plausibility for the test conditions (fillers excluded). We used the accuracy of each individual response as a categorical dependent variable, included group and plausibility and their interaction as fixed effects, targeted response (match vs. mismatch) as a covariant to control for potential yes-bias, and individual items, individual subjects, and their interactions as random errors. The maximal model did not converge, however, so we dropped random error factors in a step-wise fashion until the model converged and individual subjects and its interaction with individual items were excluded from the current model. For the group factor with 3 levels, the NS group was set as the base level. We found a significant group difference with the late L1 group showing lower accuracy compared to the NS group ($z = -6.729$, $p < 0.001$) while L2 did not differ significantly from the NS group ($z = -0.957$). Sentence plausibility did not show a significant main effect ($z = 0.696$), but it significantly interacted with sentence plausibility and group. The interaction was due to the late L1 group ($z = -5.26$, $p < 0.001$) using plausibility cues while the hearing L2 group did not ($z = -1.122$). These results confirm our descriptive observations detailed above, namely that overall the late L1 group performed worse than the other two groups, but particularly so in the implausible conditions.

To better understand the cues used to comprehend ASL sentences, it is important to know whether the late L1 group performed above, at, or below chance, for each experimental condition given that chance performance on our task was 50%. To this end, we conducted five statistical tests to examine late L1 group performance on the fillers as well as on the four test conditions. We used generalized linear mixed models with the intercept as the only fixed effect, and individual items, individual subjects, and their interaction as random errors. Again, the maximal model did not converge, so we dropped random error factors step-wise until the model converged, resulting in the interaction between item and individual subjects being excluded from the models. These models test whether the overall performance is different from chance level for each condition. The results indicate, importantly, that the late L1 learners performed above chance on the filler sentences ($z = 5.627$, $p < 0.001$), the plausible sentences with animate objects ($z = 3.018$, $p = 0.002$), the plausible sentences with inanimate objects ($z = 3.082$, $p = 0.002$), but below chance for the implausible target sentences with animate subjects ($z = -3.187$, $p = 0.001$) and the implausible target sentences with inanimate subject ($z = -2.256$, $p = 0.024$). We again see that event plausibility is a significant cue to sentence meaning for late L1 learners, exerting a greater effect than basic word order.

Since our secondary research question is to further explore the role of subject animacy when the sentence is implausible, we conducted another statistical test to specifically investigate whether animacy modulated performance in the two implausible conditions. Selecting the dataset with implausible sentences and late L1 learners only, we fit a generalized linear model with the accuracy of each individual response as a categorical dependent variable, subject animacy as a fixed effect, targeted response (match vs. mismatch) as a covariate to control for yes-bias effects, and individual items, individual subjects, and their interactions as random errors. The maximal model did not converge, so we dropped random error factors step-wise until the model converged, and individual items and its interaction with individual subjects were excluded from the current model. The model showed no significant difference between animate and inanimate subjects for the late L1 learners ($z = 0.838$, $p = 0.40$). This suggests that the semantic cue of an animate subject does not override the strong influence of event plausibility.

4.3.3 Individual differences

Given the variations observed within the late L1 group, and because the language experience is not as homogeneous within this group, due to varying age of language onset and years of language exposure, we further examined the individual differences within this group.

For each condition, we have 24 items with 2 potential responses (match vs. mismatch). The probability of a performance accuracy greater than 16 items correct, or fewer than 8 items wrong, by chance alone is lower than 0.05. By plotting the individual accuracy by condition and linking it to chance performance (0.05), shown in Figure 4.4, we find only one late L1 learner to be slightly below the upper 0.05 chance level for the filler condition, while all others were above this significant chance level. For the transitive sentence target conditions, two individuals were within the chance-level range for all four conditions and more so for the implausible conditions; two participants were above or marginally below the upper chance-level boundary for the plausible conditions, and both performed below the lower chance-level boundary for the implausible condition with animate subjects, but were within the chance-level range for the implausible condition with inanimate subjects (Cond.2 Impl-IA); the last three participants consistently scored above change-level for both plausible conditions, and below chance-level for both implausible conditions.

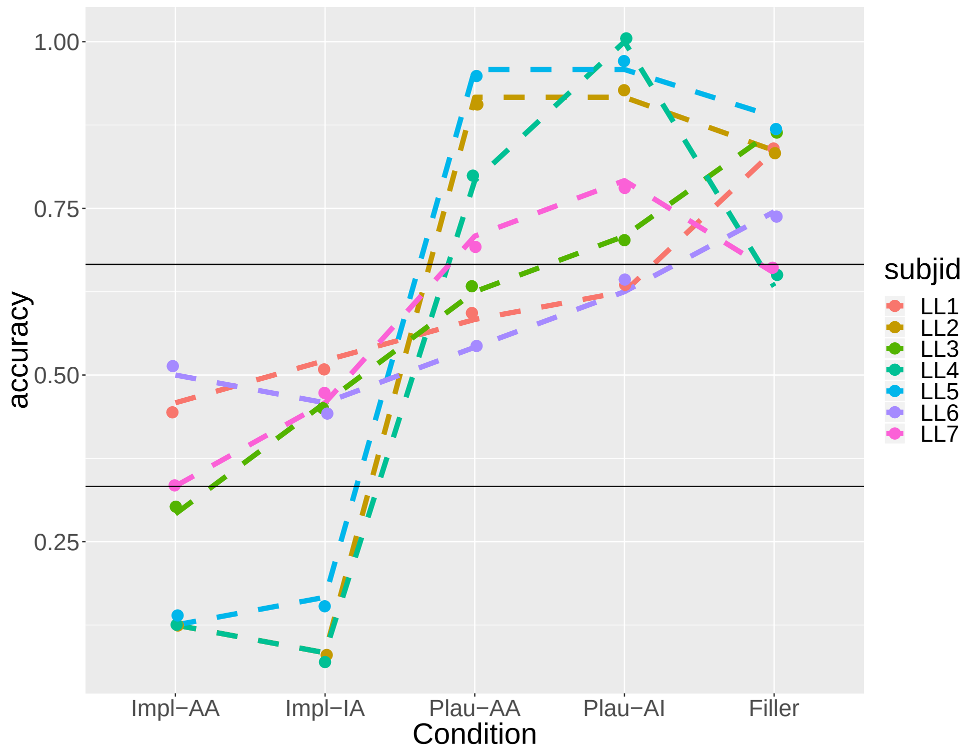

Figure 4.4: Late L1 signers individual performance under each condition. Cond.1 Impl-AA: implausible sentence with animate subject, e.g. DUCK CARRY CLOWN; Cond.2 Impl-IA: implausible sentence with inanimate subject, e.g. BOOK KICK CLOWN; Cond.3 Plau-AA: plausible sentence with animate object, e.g. MAN RIDE HORSE; Cond.4 Plau-AI: plausible sentence with inanimate object, e.g. BOY BITE BANANA.

To further investigate the nature of these performance differences as a function of event plausibility and subject noun phrase animacy, we looked at the late L1 learners' responses to the matched and the mismatched pictures separately. The results suggest that instead of showing chance-level performance on both matched and mismatched trials, those two individuals with overall chance-level performance (LL1, LL6) showed a yes-bias in all four sentence conditions, resulting in high accuracy in all matched trials and low accuracies in all mismatched trials, but less so in the filler conditions. Still, their overall performance in the implausible conditions was slightly lower than that for the plausible conditions. As for those two individuals with chance-level performance only for the implausible condition with inanimate subjects (Cond.2 Impl-IA), LL3 demonstrated a similar yes-bias pattern for this condition, although to a lesser degree. In contrast, LL7 was at chance level for both matched and mismatched trials. These individual differences suggest that late L1 signers may adopt different strategies to comprehend simple transitive sentences, but word order is not among them. We will discuss more about possible interpretations of these individual patterns in the discussion section.

4.4 Discussion

In the current study, our main research question was whether early language deprivation affects the ability to use word order as a cue to map semantic roles in simple transitive sentences, even when it conflicts with the event plausibility. Our secondary question was whether subject animacy plays an additional role in resolving the conflicting cues if word order is not as robust as it should be because it has not been fully developed.

First, we discuss the performance of native L1 signers, because it provides information on the typical sentence processing strategies of simple transitive events in ASL, and such experimental evidence is not available in the literature. The results suggest that native L1 signers consistently used basic word order across all event plausibility and subject noun phrase animacy conditions, even when word order conflicted with the event plausibility cue. These findings provide direct evidence that sequential processing is available and highly robust when no other linguistic cue is present for native signers of ASL which uses variable word order patterns depending upon sentence structure.

Next, we turn to the hearing late L2 signers group to understand the sentence processing strategies used in late L2 learning in a different modality when robust language processing skills were previously established in an infant L1. We found that, similar to the native signers, the hearing L2 signers also robustly relied on basic word order in ASL even when it conflicted with event plausibility. One caveat of the interpretation of these results is that all the hearing L2 signers are native English speakers, where canonical word order is a very robust cue, and the canonical word order in English is the same as in ASL. It is possible that they were relying on their default L1 word order pattern instead of the result truly reflecting L2 acquisition outcomes. Future research needs to test L2 learners with different kinds of first languages where word order patterns are either more variable or at least different from ASL and English. Another important question is the learning of spatial linguistic features that mark grammatical relations in ASL, such as verb agreement inflections, in L2 learners.

Finally, we turn to the findings regarding deaf late L1 signers, our main research group in this study. We are interested in this population because they provide a unique opportunity to examine the effects of early language deprivation on morpho-syntactic development, which can also shed light on the mechanisms underlying the rapid processing of typical L1 morpho-syntactic development. We are particularly interested in their basic phrasal processing, because it can inform the morpho-syntactic deficits observed in late L1 learners.

The results showed that, unlike native signers and hearing L2 signers, very late L1 signers do not robustly rely on basic word order when comprehending implausible transitive sentences. Rather, they rely more on event plausibility. This is evidenced by their above-chance performance with the plausible baseline sentences and below-chance performance with the implausible target conditions. As for subject animacy, the results show no significant performance difference between the two implausible conditions, one with an animate subject and the other with an inanimate subject. This finding suggests that subject animacy, which is internally related to agency and could be an intermediate stage of word order development, did not play a facilitative role the sentence processing of late L1 learners when word order conflicts with event plausibility.

One caveat in interpreting this result is that we did not specifically distinguish event plausibility and animacy hierarchy, as these two cues are often closely related. That is, a noun with higher animacy hierarchy, for example human, is often more likely to be the agent. In both implausible conditions, the intended patient is usually higher in the animacy hierarchy than the intended agent. Therefore, although we did not find additional use of subject animacy in the implausible conditions by late L1 learners, this might be due to the fact that the event plausibility or the animacy hierarchy cue is too strong and overshadows the effect of subject animacy in these learners. We are addressing these issues in new experiments that foreground these factors.

Also, we observed some individual differences in terms of task-related performance. Two late L1 learners showed a yes-bias in their responses, which resulted in a general chance-level performance for sentence conditions. Still, for these individuals, the yes-bias was less obvious for the filler condition. One possibility is that, because it takes more cognitive effort to give 'no' responses, especially when there is no obvious conflict present in the sentence conditions. Another possibility is that if word order is not being used to generate a unidirectional interpretation of the three-sign utterance, these late L1 signers may constantly allowing sentence interpretations in both canonical and reversed ways, therefore responding yes to both matched and mismatched pictures regardless of the conditions. Future experiments using other tasks, such as selecting between two pictures, can shed more lights on these possible task-related individual differences. Still, individual variation did not affect the group level observation that word order is not robustly used when it conflicts with event plausibility when language experience begins in late childhood.

Altogether our findings support our original hypothesis that late L1 learners do not fully rely on the basic word order cue, but in general favor event plausibility when comprehending simple sentences. Subject animacy does not offer additional information to solve the conflict regarding which noun is the agent. Given the highly varied early life and ASL learning experience across these late L1 learners, it is striking that the group showed this unique and homogeneous pattern of simple sentence processing, consistent with previous findings (Mayberry et al. under review).

Returning to our main question as to whether a breakdown in morpho-syntactic developmental occurs at the simple clause level, or at the complex clause level, these findings support the former hypothesis for very late L1 learners. Word order alone is not a robust cue for late L1 learners, even after years of ASL experience. They appear not to successfully map semantic roles onto syntactic ones in transitive clauses. The results suggest that late L1 learners primarily use event knowledge, or a context-bound interpretation of transitive verbs, at the simple clause level. This pattern is similar to that of young children before they can fully use word order cues (Strohner & Nelson, 1974). Unlike the native deaf and hearing L2 signers, the very late L1 learners who participated here do not appear to have transitioned from a context-bound interpretation of verb arguments to the abstract use of basic word order, despite 9 years and sometimes decades of daily ASL use. These results indicate that language must be present in the young child's environment for the developmental leap from context-bound to abstract syntax to occur. The results also provide evidence that successful language development is a phenomenon tied to early childhood.

The present results can potentially explain why late L1 learners perform at low accuracy levels on more complex morpho-syntactic structures (Boudreault & Mayberry, 2006; Cormier, Schembri, Vinson, & Orfanidou, 2012; Henner, Caldwell-Harris, Novogrodsky, & Hoffmeister, 2016; Mayberry et al., under review; Newport, 1990). Extra-linguistic or semantic cues are insufficient to derive the appropriate meanings from sentences with more complex mapping relations and shared arguments. The consistent use of these heuristic processing strategies at the basic clausal level may impede subsequent syntactic learning. Without developing basic word order, late L1 learners may not have access to the powerful learning mechanisms of syntactic bootstrapping, and other linguistic statistical patterns. The heuristic processing strategies used by late L1 learners are similar to those found among young children (Chapman & Kohn, 1978; Dodson & Tomasello, 1998; Strohner & Nelson, 1974). This similarity provides additional evidence that the process of language development is similar regardless of the age when it first begins (Ferjan Ramírez, Lieberman, & Mayberry, 2013; Mayberry et al, under review). How physical maturation disrupts this process is a matter of speculation.

Deaf individuals who grow in an environment of sparse accessible language show reduced neural activation in the default language regions when performing language tasks (Ferjan Ramírez et al., 2014, 2016; Mayberry et al., 2011). They also show less robust connectivity in the left arcuate fasciculus, a core pathway for syntactic processing, when compared to deaf and hearing individuals with language from birth (Cheng et al., 2019). It is possible that the inability to learn basic sentence structure relates in some way to underdevelopment of core pathways in the default neural language system. Younger children also show less robust connectivity in this dorsal language pathway; the degree of pathway connectivity correlates with syntactic processing skills in young German learning children (Skeide, Brauer, & Friederici, 2016). We are currently investigating the question.

To conclude, using a sentence-picture verification paradigm, we found that, very late L1 signers rely more on event plausibility when comprehending simple transitive sentences in ASL, than on the linguistic cue of basic word order. By contrast, native deaf signers and hearing L2 learners show a robust reliance on word order to comprehend transitive sentences. These results indicate that a prolonged absence of accessible language experience during early childhood impedes development of syntactic structure at the single clause level, possibly preventing the development of more complex sentence structures.

Chapter 4, in full, has been submitted and may appear as a publication in Cheng, Q., Mayberry, R. I. When event knowledge overrides word order in sentence comprehension: Learning a first language after childhood. The dissertation author was the primary investigator and author of this paper.

Chapter 5

Effects on brain structures: Connectivity of language pathways

5.1 Introduction

Human language is a highly complex cognitive system that relies on a distributed neural network. One crucial question regarding the neurobiology of human language is the role of language experience during development. Early neural plasticity allows environmental experience and learning to shape postnatal brain development (P. R. Huttenlocher, 2002) and is often limited to a critical period (Hensch, 2005). Although a similar critical period has been suggested for language development (Lenneberg, 1967), it remains unclear how experience within a critical time window contributes to language acquisition. The question is difficult to investigate because neural changes at different levels occur simultaneously during the first few years of postnatal development in typically developing children.

One approach to the question is to compare populations with different early language experience. Although spoken language is ubiquitous for children who hear normally, congenitally deaf children do not have access to it from birth. Approximately 10% of the deaf children are born into deaf families who use sign language as their main communication method. Sign languages are natural languages with linguistic features similar to spoken languages (Klima & Bellugi, 1979; Stokoe, 1978), and the developmental milestones for sign language are similar to those of spoken languages (Reilly et al. 1990; Anderson and Reilly 2002; Pichler 2002; Mayberry & Squires 2006). Deaf children with deaf parents who sign with them thus experience language from birth, like typically developing children with normal hearing. But their early language experience occurs via the visual-manual modality in contrast to the auditory-oral modality of hearing children's language experience. However, the majority of deaf children are born into hearing families. Some families learn sign language to communicate with their deaf children. Some families prefer to use oral communication with their deaf children, often using hearing compensation technologies such as cochlear implants or hearing aids, together with speech training. Under certain conditions, neither spoken language nor sign language is accessible to deaf children resulting in early language deprivation. Thus, congenitally deaf individuals vary in their early language environment, offering a rare opportunity to investigate the role of early language experience in the development of the neural language network. Research on this question is also crucial to raise the awareness of the potential negative sequelae of early language deprivation in deaf children.

Recent neurolinguistics models (Friederici, 2009; Hickok & Poeppel, 2004, 2007; Parker & Brorson, 2005; Price, 2012; Saur et al., 2008) have identified two information streams, the dorsal and ventral streams, as being crucial for maintaining the dynamic language network. The dorsal stream involves the temporal-parietal-frontal connections mainly via the superior longitudinal fasciculus (SLF) - arcuate fasciculus (AF) complex (Catani & Mesulam, 2008). The ventral stream runs through the extreme capsule (EmC) linking middle-posterior STG to the anterior IFG; the inferior fronto-occipital fasciculus (IFOF) that establishes the occipital-temporo-frontal connection; the inferior longitudinal fasciculus (ILF) connecting the occipital lobe and the temporal lobe; and the uncinate fasciculus (UF) connecting anterior temporal to inferior frontal areas (see Dick and Tremblay, 2012, for a review on the anatomy and functions of each fiber tract).

The dorsal stream is often considered to be responsible for an auditory–motor integration function, carrying acoustic speech signals from the auditory cortex to articulatory representations in the frontal lobe, while the ventral stream is more responsible for speech recognition, and involves structures in the superior and middle temporal lobe that are crucial for meaning and comprehension (Hickok & Poeppel, 2004, 2007; Saur et al., 2008). The dorsal stream has been identified in several studies as also being relevant to complex syntactic processing (Caplan, Vanier, & Baker, 1986; Meyer, Cunitz, Obleser, & Friederici, 2014; Skeide et al., 2016; Verhoeven et al., 2012; Wilson et al., 2011). It is unclear if deficits at the syntactic level of language are secondary to deficits in other lower-level functions mediated by the dorsal pathways, such as auditory-motor integration and working memory. In addition, previous studies have consistently found a left-ward lateralization pattern, with greater volume, more streamlines, and greater microstructural integrity in the left AF compared to the right AF (Büchel et al. 2004; Catani et al. 2007; Glasser and Rilling 2008; Ocklenburg et al. 2013; Takao et al. 2013; Eichert et al. 2018). This lateralization pattern is found in children and adolescents as well as in adults (Catherine Lebel & Beaulieu, 2009). Eichert et al. (2018) compared the laterality of dorsal AF with the ventral IFOF in humans and macaque monkeys. In humans, the dorsal AF but not the ventral IFOF pathway is left-lateralized, while neither tract is lateralized in macaques. Panesar et al. (2018) also found strong left-lateralized connectivity patterns for ILF in humans. Variability is observed in the exact laterality of UF across studies (Danielian, Iwata, Thomasson, & Floeter, 2010; Hasan et al., 2009; Jahanshad et al., 2010; Malykhin, Concha, Seres, Beaulieu, & Coupland, 2008; Ocklenburg, Hugdahl, & Westerhausen, 2013b; Takao et al., 2013; Yasmin et al., 2009). Less information on laterality is available for EmC.

These language-related pathways mature relatively late in development (Brauer et al., 2011; C. Lebel et al., 2012, 2008; Perani et al., 2011), and their degree of maturation correlates with language development. Compared to sensorimotor regions, language-related temporal and frontal regions in the left hemisphere show protracted myelination development (Pujol et al., 2006). Accelerated vocabulary development after the age of 18 months relates to a rapid myelination phase in the language-related regions. Children aged 5 to 9 years show a delayed gray matter thinning process in left IFG (Broca's area) and bilateral posterior temporal regions (Sowell et al. 2004). At age 7 children show immature AF-SLF and IFOF pathways compared to adults (Brauer, Anwander, Perani, & Friederici, 2013), and the degree of maturation of the AF-SLF pathway from the ages of 3 to 10 years correlates with children's comprehension of complex sentences (Skeide et al., 2016). The protracted maturation of the language-related pathways might indicate an extended plastic period that can be shaped by language in the environment.

The majority of studies on language pathways have been conducted with hearing individuals who use spoken languages. To date few studies have directly examined the white matter pathways for sign language in deaf native signers. An empirical question is whether the sensory-motor modality of language affects the connectivity of the language network.

Existing studies on white matter connectivity in congenitally deaf individuals have generally found decreased white matter volume or altered white matter microstructure mostly restricted to auditory-related areas, such as bilateral Heschl's gyrus (HG), planum temporale (PT), and STG, but not in long range language pathways (Emmorey et al., 2003; Hribar et al., 2014; Karns et al., 2017; Li et al., 2012). One study comparing white matter microstructure in deaf and hearing individuals found additional differences in several language-relevant fiber tracts, such as bilateral SLF and left IFOF (Kim et al., 2009). One factor that may account for the inconsistencies across studies is variation in the developmental onset of language experience among deaf individuals. Because Kim and his collaborators did not report the language acquisition backgrounds of their deaf participants, it is possible that the differences they observed between the deaf and hearing participants were due to effects related to early language deprivation. Deaf individuals who first acquire language later in life show low levels of language proficiency across levels of linguistic structure compared to deaf individuals who experience language from birth (Boudreault & Mayberry, 2006b; Mayberry & Eichen, 1991; Mayberry & Lock, 2003; Elissa L Newport, 1990). Deaf individuals who experienced language deprivation also show altered neural activation patterns compared to deaf individuals with typical language development (Ferjan Ramirez et al., 2014, 2016; Mayberry et al., 2011; Mayberry, Davenport, Roth, & Halgren, 2018), for both lexical and sentence processing. Still, little is known about how early linguistic experience affects the connections between crucial language regions.

In the present paper, we investigate two contrasting factors in early language experience, namely, the sensory-motor modality of early linguistic experience, and the presence/absence of early linguistic exposure. We report the results of a diffusion tensor imaging (DTI) study with 12 hearing native speakers of English who were L2 learners of ASL, 12 deaf native signers of ASL who were L2 learners of English (mostly in the written form), and 3 deaf individuals who experienced extreme language deprivation throughout childhood and who experienced ASL as their first language in adolescence or early twenties.

There are two alternative hypotheses for the effects of the sensory-motor modality of language. One possibility is that deaf native signers establish both dorsal and ventral neural pathways for language processing, with the ultimate size and strength being indistinguishable from that of hearing speakers. Despite the modality difference, the neural correlates for sign language processing are very similar to those for spoken language processing. Lesion studies show that left perisylvian regions are required for sign language use (Atkinson, Marshall, Woll, & Thacker, 2005; Hickok, Kirk, & Bellugi, 1998). In addition, neural imaging studies show that sign language tasks also activate fronto-temporal regions, especially the left IFG and the left posterior superior temporal lobe (Petitto et al. 2000; MacSweeney et al. 2002; Sakai et al. 2005; Mayberry et al. 2011; Leonard et al. 2012), which is similar to the language network reported for spoken language. Thus, it is likely that dorsal and ventral language pathways connecting IFG and the temporal cortex are also crucial for sign language processing. Alternatively, since sign languages use the visual modality to process linguistic information, there might be structural plasticity of language-related white matter connectivity, which may yield alternative pathways for sign language processing. If so, we would expect deaf native signers to show less robust connectivity for those pathways crucial for spoken language processing, such as AF-SLF and UF, but potentially more robust connectivity for pathways that link the visual cortex and the language regions, such as ILF and IFOF.

For the effects of early language experience, given that late L1 learners show deficits in morpho-syntactically complex structures (Boudreault & Mayberry, 2006b; Mayberry & Eichen, 1991; Mayberry & Lock, 2003; Elissa L Newport, 1990), we might expect to find main differences to be located within the dorsal pathways that are thought to be crucial for complex sentence development and processing. Alternatively, it is possible that both ventral and dorsal pathways are affected, considering the findings from Kim et al. (2009). Another less likely possibility is that development of the language pathways is solely biologically predetermined and unaffected by early language experience. If so, we would not observe any differences between late L1 learners and deaf native signers in terms of white matter connectivity.

5.2 Materials and Methods

5.2.1 Participants

Twenty-seven adults participated in the study. The protocol was approved by the Institutional Review Board (IRB) of the University of California San Diego.

Two groups of deaf and hearing individuals with robust early language experience were scanned to examine the effects of sensory-motor modality in their early language experience. The group of deaf native signers consisted of twelve participants who were all born severely to profoundly deaf and acquired ASL as their first language from birth from their deaf parents (Table 1). The group of hearing participants consisted of twelve participants who were native

English speakers and had taken 40 to 50 weeks of college-level ASL instruction (Table 1). All participants were right-handed adults with no history of neurological or psychological impairment. The hearing L2 signers speakers serve as a sensory-motor modality contrast for the deaf native signers. Like the native signers, they experienced language from birth albeit in the auditory-vocal modality instead of the visual-manual one. Because previous research has consistently shown insignificant white matter changes during young adulthood (Brickman et al. 2006; Good et al. 2001; Lebel and Beaulieu, 2011), we did not strictly control for age in these two groups. We compare the deaf native signers to the hearing L2 ASL signers, instead of monolingual English speakers, because the deaf native signers are all also bilingual in ASL and English (mostly in the written form).

Three individuals also participated in the current study as special cases, allowing us to examine how the presence/absence of early language experience affects the language pathways. These individuals were born deaf and experienced severe language deprivation throughout childhood. Their pseudonyms are Carlos, Shawna, and Martin. Due to various circumstances, these otherwise healthy deaf individuals were mainly raised at home with hearing, non-signing family members during childhood and so acquired neither spoken nor sign language and were illiterate. Carlos and Shawna began learning ASL at the age of 13 and 14, respectively, when they were immersed in the same sign language environment for the first time. They had fewer years of ASL exposure at the time of testing compared with Martin who began learning ASL in his 20s and had 30 years of ASL experience at the time of testing.

Carlos was born into a hearing and non-signing family in another country and received no special services for deaf children, including schooling. He immigrated with family members to the United States at age 11. He was placed into a group home for deaf teenagers at age 13 years and 8 months, which was his first exposure to American Sign Language (ASL). At the time of scanning, he was 16 years and 10 months old, with 3 years and 2 months of daily exposure to ASL.

Shawna was raised by hearing and non-signing guardians and kept at home until the age of 12. She sporadically attended several schools, both deaf and mainstream, for a total of 16 months. At the age of 14 years and 7 months, she was placed into the same group home as Carlos, which marked her first language immersion experience. Shawna was 16 years and 9 months old at the time of scanning, with 2 years and 2 months of daily exposure to ASL.

Martin was born into a hearing and non-signing family in rural Mexico and attended no school until age of 21 when he learned some Mexican Sign Language at a school for deaf children. He immigrated to the United States at age 23, where he learned ASL. Since then, he has used ASL daily with deaf signers, including his wife, co-workers, and friends. At the time of scanning, he was 51 years old, with 30 years of sign language experience.

Elsewhere we have reported in detail on the language development and neurolinguistic processing of these case studies. Despite wide variation in their early home environments, these three cases of childhood language deprivation showed similar patterns of ASL acquisition ((Ramirez et al. 2013; Cheng and Mayberry 2019). They can comprehend some basic syntactic structures but show difficulties with morpho-syntax and complex sentence structures. Their neural activation patterns in response to single ASL signs primed with pictures was imaged with anatomically constrained Magnetoencephalography (aMEG). All three cases showed atypical localization patterns for single signs in comparison to deaf native and hearing L2 signers (Ferjan Ramirez et al., 2014, 2016; Mayberry et al., 2018).

Table 1 summarizes the demographic information of the deaf native signer group, the hearing L2 group, and each deaf individual with delayed L1 onset.

5.2.2 Image acquisition

MRI scans were performed at the UCSD Radiology Imaging Laboratory on a General Electric 1.5 Tesla EXCITE HD scanner with an eight-channel phased-array head coil. Four scans

Table 5.1: Summary of demographic information for each group.

Group	Number (female)	Age (sd)	L1 Modality	L1 Onset	L1Duration (years)
Deaf Native Signers	12 (5)	33.33 (4.1)	Visuo-manual	Birth	Same as age
Hearing L2 Signers	12 (11)	24.2 (3.9)	Auditory-oral	Birth	Same as age
Deaf Late Signers	Carlos[a]	16	Visuo-manual	13	3
	Shawna	16	Visuo-manual	14	2
	Martin	51	Visuo-manual	21	30

a. For the deaf late signers, each special case is listed by pseudonym.

were conducted, including one conventional three-plane localizer, one T1 weighted anatomical scan using IR-SPGR sequence with prospective motion (PROMO) correction, one diffusion-weighted scan using single-shot echo-planar sequence with isotropic 2.5 mm voxels and 30 diffusion gradient directions using b-value of 1000s/mm2 (TE/TR 80.4ms/14,300ms), and one non-diffusion-weighted (T2) scan using fast spin echo sequence with prospective motion correction.

5.2.3 Image processing and fiber tracking

For preprocessing, T1-weighted images were corrected for nonlinear warping (Jovicich et al. 2006) and spatial sensitivity inhomogeneities (Hagler et al. 2009) using customized processing stream written in MATLAB. As for the diffusion-weighted images, we performed four pre-processing steps, including motion correction (Hagler et al. 2009), eddy current correction (Zhuang et al., 2006), b0 distortion correction (Chang, Janciauskas, & Fitz, 2012), and gradient non-linearity correction (Jovicich et al., 2006).

We fit the diffusion tensors (DTs) and diagonalized the DT matrices using singular value decomposition to obtain three eigenvectors and their corresponding eigenvalues. We then calculated the fractional anisotropy (FA) ratio from the eigenvalues.

We used a probabilistic tract atlas (Hagler et al. 2009) to identify tracts of interest. We chose to use a probabilistic fiber tracking method instead of a deterministic method because it can better handle the problem of crossing fibers and stray fibers and avoids the subjectivity involved in manually selecting ROI seeds. This atlas has been used across different populations including healthy adults with an age range of 21 to 80 (Perry, McDonald, Jr, Neuropsychologia, & 2009), epilepsy patients (Hagler et al. 2009), young children and adolescents with an age range of 3 to 20 (Jernigan et al. 2016), and typical and autistic toddlers with an age range of 1 to 4 years (Solso et al. 2016).

The atlas used manually identified three-dimensional maps of streamline fiber counts in 42 individuals together with their T1-weighted images to create co-registered, normalized, average fiber density maps, which provide probabilistic information about the locations and orientations of 23 fiber tracts. Fiber tracts were first manually identified for each individual in DTI Studio (Mori, Wakana, Zijl, & Nagae-Poetscher, 2005) using multiple ROIs to select a population of streamlines that followed the paths known from anatomy (Wakana, Jiang, Nagae-Poetscher, van Zijl, & Mori, 2004), mainly following a 2-ROI approach with the addition of subsequent multiple 'NOT' ROIs to remove extraneous fibers that are not a part of the pathway. The goal is to reliably reconstruct fiber bundles that are anatomically accurate with a focus on the core of the fiber bundle. Next, normalized and averaged three-dimensional maps of streamline fiber counts were generated as fiber density maps and co-registered with the common T1 space. Cross-subject average tensors were calculated to provide information about the range of possible diffusion orientations at each location in atlas space. The atlas therefore provides probabilistic information about the locations and orientations of each fiber tract.

Based on previous studies (Dick and Tremblay, 2012; Hickok and Poeppel 2004; Parker and Brorson 2005; Hickok and Poeppel 2007; Saur et al. 2008; Friederici 2009; Price 2012), we selected four fiber tracts from the atlas as relevant long-range pathways for language, namely AF (the direct long segment of the SLF-AF complex), IFOF, ILF and UF.

So far there is no consensus on the anatomical classification of the SLF-AF complex, and different subcomponents have been proposed, but their functions are still under debate. In the current study, we only looked at the long segment that directly connects the frontal and the temporal regions, as described in the delineation methods, because this is the classic dorsal AF pathway that has been extensively studied in terms of anatomical structures and functions.

One ventral pathway, EmC, was not included here. There are limited anatomical studies on the human EmC, and it is difficult to reliably reconstruct this fiber tract and delineate it from neighboring tracts such as the external capsule, IFOF, and UF. This pathway is not available in most major DTI atlases due to a lack of reliable means to identify it using the 2-ROI approach. Therefore, we omitted this pathway in the current study to ensure that we could delineate the correct fiber tracts.

Below we describe how the selected fiber tracts were manually delineated in DTI Studio based on the documentation from the probabilistic tract atlas.

The AF was manually delineated by the following steps. First, the most inferior axial slice in which the fornix could be seen as a single structure was identified. On the same axial slice, the anterior-posterior midpoint of the posterior limb of the internal capsule was identified, and a coronal slice at this midpoint was chosen. On this slice, an 'OR' ROI was selected by choosing the superolateral area just lateral to the posterior limb of the internal capsule including all superior and lateral gyri coming from this core. Next, the midpoint of the splenium of the corpus callosum in a coronal slice was identified, and an 'AND' ROI was drawn around the entire ipsilateral hemisphere. In addition, 'NOT' ROIs were selected to avoid fibers extending into the external capsule, fibers extending inferiorly through the brainstem, and fibers extending through the cingulum. Next, the anterior commissure was identified in an axial slice and the visible fibers lateral to the sagittal striatum were selected as an 'AND' ROI, while 'NOT' ROIs were selected to avoid fibers extending superiorly to the parietal lobe and through the cingulum.

The IFOF was manually delineated by the following steps. First, the anterior-posterior midpoint in a coronal slice between the posterior edge of the splenium of the corpus callosum and the occipital pole was identified. An 'OR' ROI was drawn around the occipital lobe, inferior to the parietal-occipital sulcus. Next, the most anterior edge of the genu of the corpus callosum was identified in a coronal slice, and an 'AND' ROI was drawn around the entire ipsilateral hemisphere. In addition, 'NOT' ROIs were selected to avoid fibers extending superiorly and posteriorly beyond the parietal-occipital sulcus and extending through the thalamus.

The ILF was delineated by the following steps. First, the most posterior coronal slice in which the cingulum was visible was selected, and an 'OR' ROI around the entire hemisphere was selected. Next, the most posterior coronal slice in which the temporal lobe was visibly distinct from the frontal lobe was selected, and an 'AND' ROI was drawn around the entire temporal lobe. In addition, 'NOT' ROIs were selected to avoid fibers extending to the contralateral hemisphere at the mid-sagittal line, fibers extending superiorly to the parietal lobe beyond the parietal-occipital sulcus, and fibers extending anteriorly that terminate in the frontal lobe.

The UF was delineated by the following steps. First, the most posterior coronal slice in which the temporal lobe was visibly distinct from the frontal lobe was selected, and an 'OR' ROI was drawn around the entire temporal lobe, and another 'AND' ROI was drawn around the external capsule. In addition, 'NOT' ROIs were selected to avoid fibers extending posteriorly from the main bundle of the uncinate and short fibers at the temporal stem that did not fully extend into the temporal and frontal lobes.

Using Freesurfer (Dale et al. 1999), we first non-linearly morphed individual T1-weighted images to align with the atlas space using the method of discrete cosine transforms (Friston et al., 1995). Diffusion-weighted images were first rigid-body-registered to corresponding T1-weighted images resampled to atlas space, and then further registered using joint probability density function (JPDF) method (Leventon & Grimson, 1998). Next, a-posteriori probability of a voxel belonging to a given fiber tract was estimated given the first eigenvector derived from DT calculations together with the location information (i.e., fiber probability given location alone) and the orientation information (i.e., fiber probability given the DT first eigenvector and the atlas average of DTs rotated and warped into single subject space) from the co-registered and normalized fiber density maps. A probability threshold (relative fiber probability ¿ 0.08) was applied following Hagler et al. (2009) to derive regions of interests (ROIs) for each target fibers. This threshold was determined in Hagler et al. (2009) by testing a range of thresholds and choosing the threshold that provided the smallest difference in fiber volumes between manually selected and atlas-derived fiber masks across all subjects and fibers. Finally, the weighted averages of FA was calculated for each fiber tract (Hua et al., 2008). More details of this automated white matter tracking method can be found in Hagler et al. (2009).

Figure 5.1 shows the locations of these fiber tracts in the left hemisphere found in a deaf native signer participant. We examined these tracts in both right and left hemispheres to examine for possible lateralization effects.

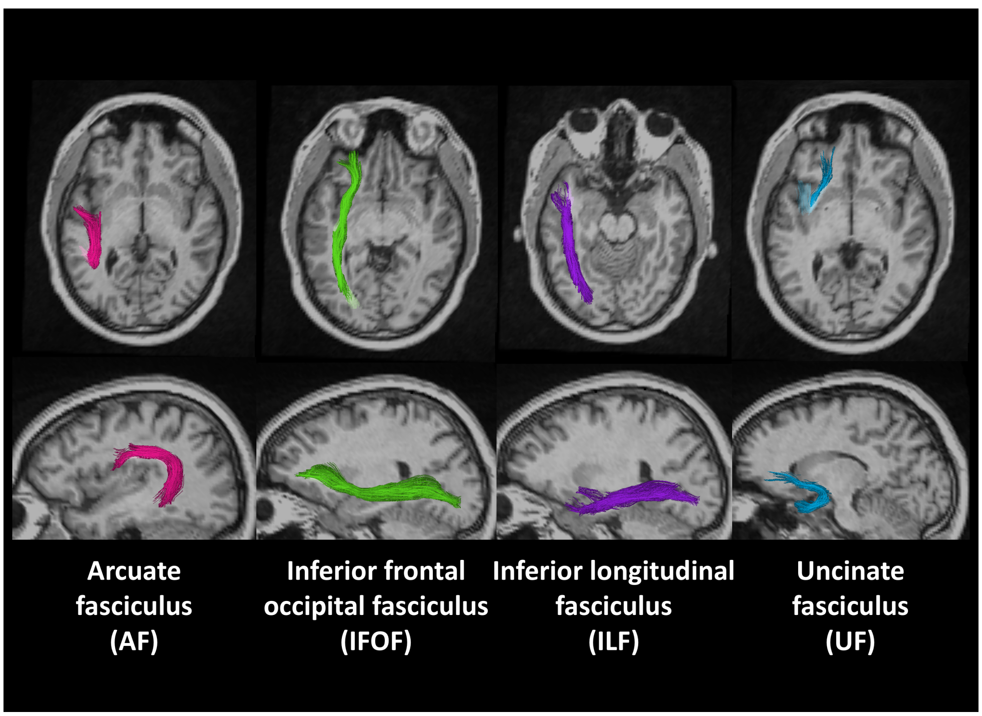

Figure 5.1: Region of interests (ROIs) of four fiber tracts derived using probabilistic tract atlas in the left hemisphere of one deaf native subject.

5.2.4 Statistical analyses

We used the lme4 package (D. Bates et al., 2012) in R (R Core Team, 2012) to conduct analyses of variance (ANOVA) tests between the deaf and hearing infant-language experience groups, using the mean FA values of each fiber tract of each individual. We also calculated the z-scores of mean FA for the deaf participants in R.

5.3 Results

5.3.1 Effects of early language modality

First, we investigated the effects of the sensory-motor modality of language by comparing the data from the deaf native signers with that of the hearing native English speakers, L2 signers. The deaf and hearing participants show very similar FA values in all fiber tracts in both hemispheres, with close median values and a similar degree of variance (Figure 5.2). Also, for both groups the FA values in the left hemisphere appear to be higher than those in the right hemisphere. We conducted an Analysis of Variance (ANOVA) test with FA value as the dependent measure, group as the between-subjects fixed effect, fiber tract and hemisphere as within-subjects fixed effects, and gender and age as between-subjects covariates. After controlling for gender ($F(1, 174) = 2.596$, $p = 0.108$) and age ($F(1, 174) = 2.924$, $p = 0.089$) effects, the results showed a significant difference among fiber tracts ($F(3, 174) = 60.770$, $p < 0.001$), a difference between hemispheres ($F(1,174) = 14.689$, $p < 0.001$) with lower FA in the right hemisphere, a trend toward interaction between fiber tract and hemisphere ($F(3, 174) = 2.389$, $p = 0.070$), but no difference between the groups ($F(1, 22) = 0.094$, $p = 0.759$), and no interactions between group and fiber tract ($F(3,174) = 0.261$, $p = 0.853$), group and hemisphere ($F(1, 174) = 0.036$, $p = 0.848$), or between group, fiber tract and hemisphere ($F(3,174) = 0.173$, $p = 0.914$).

These results indicate that, in general, there is left lateralization of language-relevant tracts in deaf and hearing participants alike, despite differences in the sensory-motor modality of their infant language experience. In addition, the trend for interaction between fiber tract and hemisphere suggests that the degree of lateralization might be slightly different for each fiber tract.

To examine the nature of this trend, we conducted ANOVA tests for each fiber tract with FA as the dependent measure, group as the between-subjects fixed effect, hemisphere as within-subjects fixed effects, and gender and age as between-subjects covariates. We found a strong left lateralization effect for AF ($F(1, 42) = 10.842$, $p = 0.002$) and ILF ($F(1, 42) = 8.832$, $p = 0.004$), but no lateralization effect for IFOF ($F(1, 42) = 2.210$, $p = 0.144$) and UF ($F(1, 42) = 0.004$, $p = 0.949$). Again, no group or interaction effects between group and hemisphere were observed in any of the tracts.

These findings confirm in the present data set that the dorsal AF shows left lateralization reported in the literature. In addition, we found one ventral pathway, ILF, to also show left lateralization, while the other two ventral pathways appear to be more bilateral. Crucially, these lateralization patterns are shared by both deaf and hearing participants, suggesting that language modality is not a factor in these laterality effects.

One observation worth noting is that for the dorsal AF, two individuals from the deaf native signer group and one individual from the hearing speaker group, were below the 1.75 interquartile range of their respective group, but only in the left hemisphere. After examining their individual profiles, we noticed that these individuals all had higher FA values in the right hemisphere for the dorsal AF pathways. According to the literature (Catani et al. 2007; Lebel & Beaulieu, 2009), there are individual differences in the lateralization patterns of this pathway. Therefore, we speculate that these individuals show lower FA in the left hemisphere due to a right lateralization pattern.

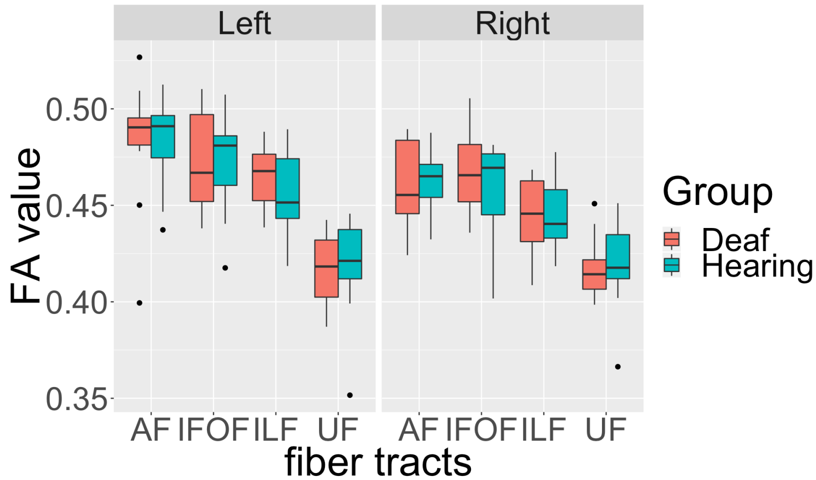

Figure 5.2: Individual average fractional anisotropy (FA) values of hearing and deaf participants in arcuate fasciculate, AF, inferior frontal occipital fasciculus, IFOF, inferior longitudinal fasciculus, ILF, and uncinate fasciculus, UC, as a function of hemisphere showing no significant differences between the groups. The top of the box plot shows the higher quartile (25%), the black bar shows the median (50%), and the bottom of the box shows the lower quartile (75%); the black dots show outliers outside the 1.75 interquartile range.

5.3.2 Effects of early language deprivation

Next, we investigated the effects of early language experience on language-relevant fiber tracts by first comparing the data from each of the three deaf case studies who matured without language to the deaf native signers and hearing native speakers who had language experience from birth. We used z-scores and interquartile ranges to estimate the differences between the language deprived cases and the two infant-language experience control groups. We then summarized the similarities and differences across these three cases.

Table 5.2 shows the z-scores of each deaf case study when calculated within the sample of both deaf native signers and hearing native speakers, 24 individuals in total who experienced language from birth. All three case studies showed decreased FA values in the dorsal AF pathway when compared to the language-from-birth control groups, while their FA values in the ventral pathways showed more individual variation.

Table 5.2: z-scores of three deaf case studies compared to the infant-language experience groups (N = 24).

Case Name	AF		IFOF		ILF		UF	
	left	right	left	right	left	right	left	right
Carlos	-1.723*	-2.257*	0.083	-0.634	0.495	0.349	0.432	-0.544
Shawna	-0.903	-0.674	-0.343	0.462	0.735	1.391	1.898*	1.048
Martin	-1.110	-0.825	-0.7	-0.452	-2.65**	-1.652*	-0.777	-1.426

*: One-tailed p value <0.05; **: one-tailed p value <0.01

Figure 5.3 shows the FA values of each deaf case in comparison to the interquartile range of the infant-language experience control group, including both deaf native signers and hearing native speakers. The FA values of all three late learners fell outside the infant-language experience control groups' 1.75 interquartile range for left dorsal AF pathway. Their FA values for AF in the right hemisphere were also lower than the infant-language experience control groups' interquartile range; only the FA values for Carlos fell outside the 1.75 interquartile range. As for the ventral pathways, the FA values of the case studies were either within normal range or showed more individual variations. Their FA values for bilateral IFOF were all within the interquartile range. For ILF, only the FA values for Martin were below the 1.75 interquartile range in both hemispheres. For UF, Shawna showed an FA value in the left hemisphere above the 1.75 interquartile range. Carlos showed normal FA values in both hemispheres. Martin showed FA values below the interquartile range in the left hemisphere and below the 1.75 interquartile range in the right hemisphere.

As discussed above in 5.3.1, some individuals from the infant-language experience control groups also showed decreased FA values in the left dorsal AF due to atypical lateralization patterns. Given that all three late learners showed slightly higher FA values in the left hemisphere for this pathway, and FA values in the right hemisphere that were closer to the interquartile range,

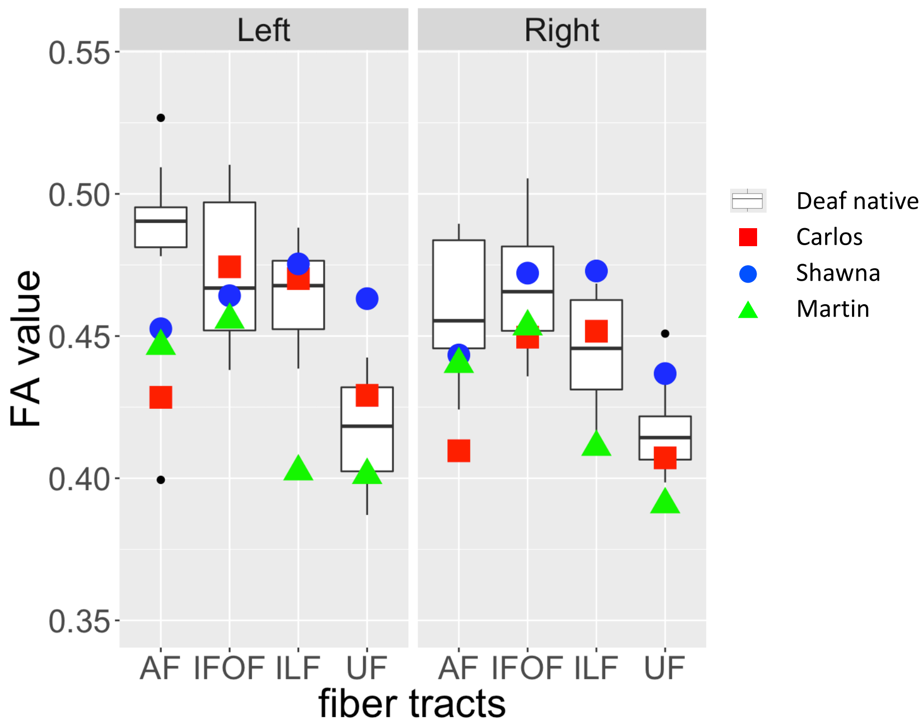

Figure 5.3: Fractional anisotropy (FA) values for three deaf individuals with severe early language deprivation as a function of pathway and hemisphere. The box plots represent the distribution of FA values of the infant-language experience control groups (both native deaf signers and hearing native English speakers, N =24); the plotted shapes show the values for each late L1 learner: Carlos – filled square; Shawna – filled circle; Martin – filled triangle. (Carlos: AoA 13;8 with 3;2 years of experience; Shawna: AoA 14;7 with 2;2 years of experience; Martin: AoA 21 with 30 years of experience). The top of the box plot shows the higher quartile (25%), the black bar shows the median (50%) and the bottom of the box shows the lower quartile (75%); the black dots show outliers outside the 1.75 interquartile range.

we interpret their reduced FA values as revealing a lack of lateralization pattern due to early language deprivation in comparison to the outliers in the infant-language experience control groups who show right lateralization for these tracts.

5.4 Discussion

With respect to the sensory-motor modality of language, we asked if deaf native signers and hearing native speakers would show similar microstructure of the language pathways despite differences in the sensory-motor modality of their early language. We observed no differences between the deaf and hearing groups for any of the four language-relevant pathways. This lack of differences supports the hypothesis that language modality does not affect the connectivity between major language regions when language acquisition begins in infancy.

Effects of neural cross modal plasticity due to sensory (auditory) deprivation among deaf individuals have been reported for some cognitive functions, such as general visuo-spatial working memory (Ding et al. 2015; MacSweeney and Cardin 2015; Cardin et al. 2018). With respect to language processing when a first language is acquired early on, however, the default language network is unaffected by language modality or sensory (auditory) deprivation (Leonard et al., 2012; MacSweeney et al., 2002; Mayberry et al., 2011; Petitto et al., 2000; Sakai, Tatsuno, Suzuki, Kimura, & Ichida, 2005). Our findings provide further evidence for the amodal nature of the language network when infants experience sufficient language during development and further extends them by showing that deafness per se does not affect development of the language pathways.

Our findings are also the first to demonstrate left lateralization of two language pathways, dorsal AF and ventral ILF, in deaf native signers, similar to the lateralization that has been consistently found for hearing native speakers (Büchel et al. 2004; Catani et al. 2007; Takao et al. 2013; Glasser & Rilling, 2008; Ocklenburg et al. 2013; Eichert et al. 2018; Panesar et al. 2018). We also found similar bilateral patterns for ventral IFOF and ventral UF in both the deaf and hearing control groups, findings that are also consistent with the literature (Hernando et al.; Kubicki et al. 2002; Takao et al. 2013; Ocklenburg et al. 2013b; Eichert et al. 2018).

Crucially, by comparing the data from the language-from-birth control group with that of the three case studies, we found specific effects of early language deprivation on the language pathways. Decreased FA values (below the 1.75 interquartile range) in the left dorsal AF pathway were observed in each of the three cases when compared to the language-from-birth control groups. Given the strong left lateralization patterns observed among the language-from-birth control groups, it appears that the lower FA values in left AF in each case study are due to reduced laterality.

These findings are also consistent with the literature on the relation between the dorsal pathway and the ability to learn and process complex linguistic structures. As explained in the introduction, the dorsal stream is often associated with syntactic processing performance as previously found for typically developing children (Skeide et al. 2016), children with specific language impairment (Verhoeven et al. 2012), and aphasic patients (Wilson et al. 2011). The present study extends these findings to deaf people with early language deprivation, suggesting that their limited syntactic performance may be associated with connectivity deficits in dorsal pathways.

As for the ventral pathways, we observed more individual variations. Martin showed decreased FA values (below the 1.75 interquartile range) in bilateral ILF and in right UF compared to the language-from-birth control groups, while Carlos and Shawna did not show such effects. There are several possibilities for the individual variation in these ventral pathways. One possibility is that the ventral pathways are not as sensitive to a lack of early language experience as the dorsal pathways and remain plastic even after puberty. Martin did not begin to learn language until the age of 21. Carlos and Shawna both began to learn language at the ages of 13 and 14 respectively. In a neuroimaging study of lexico-semantic processing, Carlos and Shawna showed some activation in perisylvian language areas to familiar ASL signs primed with pictures (Ferjan Ramirez et al., 2016). By contrast, Martin showed almost no activation in bilateral temporal language areas, despite performing nearly as accurately and quickly as the deaf native signers, hearing L2 signers, and the other case studies (Mayberry et al. 2018).

Thus, it is possible that these individual differences reflect a gradient effect of the duration of language deprivation in childhood and adolescence on the development of the ventral language pathways that potentially mediate lexico-semantic processing. Another possibility for the lack of clear effects of early language deprivation across ventral pathways is that they can be shaped by non-linguistic experience. Because ventral pathways are often associated with constructing meaning, as well as other non-linguistic functions such as complex object processing, late L1 learners may have gradually established these pathways through non-verbal communication and conceptual learning through daily life experience despite the lack of language in the environment. Future studies with a larger sample size and longitudinal observations are required to test these hypotheses.

One caveat in interpreting the present results is that the age of all three late signers was either younger or older than that of the control groups, falling at either the lower or the higher ends of the age range of stable white matter microstructure. However, given the facts that the IFOF often shows a similar trajectory of FA change as a function of age compared to other tracts (C. Lebel et al., 2008), and that all three cases had normal FA values in bilateral IFOF, we interpret the differences between the cases and the control groups as being more likely due to early language deprivation than simply age.

Another caveat is that Carlos and Shawna only had 2 to 3 years of ASL experience at the time of scanning, so that further neural plasticity induced by late language acquisition might still be possible. We plan to conduct follow-up DTI scans to address this issue. Still, given their limited ultimate attainment of ASL after substantially longer years of exposure, we expect less plasticity in their language pathways even with increased years of language use.

Research has found that deaf children with no formal sign language input often develop their own gestural system to communicate with their family members known as homesign (S Goldin-Meadow & Feldman, 1977; Susan Goldin-Meadow & Mylander, 1998). Whether the sophistication of the homesign system the deaf child develops with the family is related to their subsequent sign language development is unknown. Martin reported communicating with a hearing sister with gesture when living at home (Mayberry et al., 2018). Neither Carlos nor Shawna were reported by the knowledgeable professionals working with them to use homesign when they were initially placed in a residential sign language situation (Ferjan Ramirez et al. 2014), but doing so may not have been communicatively useful for them. Although homesign has been found to share some linguistic properties with language (S Goldin-Meadow, 2005), it has also been observed to be used primarily as an expressive means of communication by the deaf child whose family members may neither fully comprehend nor use it in the same way (Carrigan and Coppola 2017), thus limiting its potential to circumvent the effects of a lack of linguistic experience for the developing child (Morford and Hänel-Faulhaber 2011).

The present findings also provide an explanation for some inconsistencies in the literature on white matter connectivity in deaf individuals. Kim et al. (2009) identified more extensive regions with white matter deficits, including non-auditory regions within language-related pathways, while Li et al. (2012) and Karns et al. (2017) found differences only within auditory regions. By explicitly comparing deaf native signers and well-studied cases of extreme delay in the onset of language experience, our findings suggest that the variable results of previous studies are likely due to the diverse language backgrounds that would be characteristic of any randomly selected sample of deaf individuals. Given that Kim et al. (2009) did not report the language backgrounds of their deaf participants, and they also found FA deficits in language-related pathways such as SLF, it is highly probable that their deaf participants experienced language deprivation during childhood, similar to the cases we studied here.

Our findings also shed light on the potential mechanisms of critical period effects for language development. Previous studies have reported selective critical period effects on morphologically and syntactically complex structures (Boudreault & Mayberry, 2006b; Cormier et al., 2012; Mayberry & Lock, 2003; Elissa L Newport, 1990) as well as decreased functional activation in several language regions (Ferjan Ramirez et al. 2014, 2016; Mayberry et al. 2018;

Mayberry et al. 2011). However, it remained unclear how these language and neural outcomes were being influenced by early language experience. The present study shows that the case studies who suffered language deprivation during childhood developed less robust connections between language regions, especially in the dorsal stream. Given the association between dorsal pathways and syntactic processing, a coherent interpretation of the linguistic and neural activation data across these studies is that early language experience is crucial for the growth of the dorsal stream for language processing, linking various functional language regions, and thus facilitating the acquisition and processing of complex syntactic structures. Missing the critical time window for linguistic experience appears to affect development of the dorsal stream, which, in turn, creates deficits in language and neural outcomes, especially with respect to complex morpho-syntactic structures.

To conclude, in the present study we examined white matter microstructure of two groups of individuals with infant language experience, deaf native signers and hearing native speakers who were L2 signers, with three individual cases of childhood language deprivation, individuals who had little access to any kind of language until puberty or after. Our findings indicated that these cases had altered microstructure in some language-related pathways, especially in the left AF, when compared to deaf native signers. At the same time, deaf native signers of ASL showed similar connectivity within language-related pathways compared with hearing native speakers of English. Together these findings suggest that full growth of the brain language pathways requires early language experience during childhood. Language experience in early life appears to be crucial for the language system to become robustly connected as observed in the canonical mature state, regardless of its sensory-motor modality.

Chapter 5, in full, is a reprint of the material as it appears in Cheng, Q., Roth, A., Halgren, E., Mayberry, R. I. (2019). Effects of early language deprivation on brain connectivity: Language pathways in deaf native and late first-language learners of American Sign Language. Frontiers in human neuroscience, 13, 320. The dissertation author was the primary investigator and author of

this paper.

Chapter 6

General Discussion

This dissertation focused on early syntactic development and learning outcomes of deaf late first language learners of ASL. Previous literature reported that initial language development, up to two-word stage, is similar to that of native first language learners, while the outcomes differ tremendously, especially at the complex morpho-syntactic level, and the neural activation during language processing also appears to be atypical. To explain this gap between initial typical development and ultimate atypical morpho-syntactic outcomes and brain responses, the current dissertation examined the developmental trajectory following two-word stage, with a focus on a fundamental linguistic structure – basic word order in transitive events. The development and processing strategy of this key structure reflects early syntactic development, serving as a bridge to the development of mopho-syntactically complex structures, and we know very little about how impoverished early language affects this early developmental process. Combining longitudinal, processing, and anatomical evidence of the developmental outcomes of deaf individuals with impoverished early language, this dissertation revealed profound effects of impoverished early language on syntactic development even during early stages, and discovered potential neurodevelopmental correlates of these behavioral effects.

Chapter 3 to 5 each provided a study on one aspect of the effects of impoverished early language on early syntactic development. Chapter 3 presented longitudinal data of spontaneous word order production patterns of four deaf individuals with extremely late ASL onset. The results showed consistent increase in using basic ASL word order patterns (subject preceding verb, object following verb) during later filming sessions for each deaf individual. However, unlike native deaf learners who showed rapid increase in using basic word order but soon move on to use more variable word order patterns with appropriate linguistic markers, the late L1 signers showed much limited development regarding the use of word order. This is evidenced by a protracted period of the transition from varied word order pattern to canonical word order pattern, and the missing of a stage where varied word order pattern reoccur, and the absence of obligatory linguistic markers for the non-canonical order.

Chapter 4 used a sentence-picture verification task to examine the sentence processing strategies used by deaf late L1 signers to comprehend simple transitive sentences. We found that when the word order cue conflicts with real world event plausibility, deaf late L1 signers often rely on event plausibility instead of word order to interpret the sentence meaning. This pattern is very different from both native signers and late second language learners of ASL, who consistently relied on word order to comprehend simple transitive sentences in ASL regardless of the event plausibility.

Chapter 5 examined the anatomical differences between deaf late L1 signers and deaf and hearing individuals with robust first language experience from birth. Using diffusion tensor imaging (DTI), we measured the degree of connectivity of major language-relevant pathways in both hemispheres of three deaf individuals with severe impoverished early language, and compared them with two groups of individuals with robust early language: deaf native signers of ASL, and hearing native speakers of English. The results suggested that when early language experience is missing, a crucial language pathway responsible for structure building, left arcuate fasciculus, showed less robust connectivity, while other language pathways showed relatively normal development.

Altogether, these findings suggest that deaf late L1 signers did gradually learn to use basic word order following a similar trajectory as native L1 signers, but their generalization process took longer, was limited to an early stage, their use of the word order cue was not robust when processing sentences with competing plausibility cues, and the neural development of a crucial language pathway responsible for structure building was also affected. These findings help fill in the gap of late L1 language and brain development, providing potential explanations to the ultimate morpho-syntactic difficulties and atypical neural activation patterns associated with impoverished early language.

In the following sections, I discuss the implications of the current dissertation on the effects of impoverished early language on syntactic development, on language processing and learning, and on the neurodevelopmental foundations of human language. I also discuss the caveats and the future directions, and provide a brief conclusion to the dissertation.

Effects of impoverished early language on syntactic development

Existing literature on late first language development poses a gap on the exact role of early language on syntactic development. Impoverished early language often results in ultimate morpho-syntactic difficulties, while simple sentence types such as basic word order appear to be less affected (Boudreault & Mayberry, 2006; Newport 1990). Early syntactic milestones and simple sentence types among typically developing L1 learners also seems to emerge very early, independent of the quantity and quality of early language input (Casillas, Brown, & Levinson, 2019). But, even with relatively reduced input, these typical L1 learners still have enormous amount of language experience from birth, unlike the extremely impoverished language environment faced by deaf late L1 signers. In the meantime, few studies have explicitly examined the trajectory of early syntactic development of a late first language beyond two-word stage. Therefore, it is less clear whether early syntactic development is truly resilient to impoverished early language input.

Results from the current dissertation shed light on the role of early language in several ways. First, the findings showed similar developmental trajectory between native and late first language development after two-word stage. Chapter 3 showed that, similar to native L1 learners of ASL, late L1 signers also started with variable word order patterns in their spontaneous production, and switched to canonical word order patterns later, showing a generalization process. Results from Chapter 4 indicate persistent use of heuristic sentence processing strategies among deaf late L1 signers, which is very similar to the strategies adopted by younger children before they can fully rely on word order (Strohner & Nelson, 1974). The over reliance on word order during production among late L1 signers in Chapter 3 and the use of heuristic strategies instead of word order during comprehension as revealed in Chapter 4 also resembles the production-comprehension asymmetry commonly observed among younger children. These results confirm the findings from previous studies on earlier stages of late L1 development (Berk & Lillo-Martin, 2012; Berk, 2003; Ferjan Ramırez, Lieberman, & Mayberry, 2013) that the cognitive maturation of the older learners does not alter the path of development of linguistic knowledge. Results from the current dissertation extend these findings to early syntactic development, suggesting a continuation of late first language learning across the domains of early vocabulary, two-word combinations, and simple clausal structures, all follow similar developmental trajectory as young children's L1 development. The development of early syntactic structures such as the use of word order remains unchanged even with extremely impoverished early language.

However, findings from the current dissertation also indicate an early plateau of syntactic development as a result of impoverished early language. Chapter 3 found that despite a similar generalization process for basic word order, late L1 signers appeared to spend longer time using variable word order in the beginning, indicating a prolonged generalizing phase. Also, their word order development seemed to be limited to the early stages only. While very young native L1 signers continue to acquire word order variations with appropriate linguistic cues, late L1 signers did not show this later development despite extended years of language use. Chapter 4 showed that after at least 9 years and sometimes decades of language use, deaf late L1 signers still predominantly rely on heuristic strategies rather than purely linguistic rules to comprehend simple transitive sentences, while young children often transition through this stage and show robust rule-based language use by age 4. Related to these behavioral observations, the anatomical outcomes of Chapter 5 found a reduced degree of connectivity in a core language-relevant pathway, left arcuate fasciculus. Given that this language pathway takes extended years to develop to its mature state (Lebel & Beaulieu, 2011), and is sensitive to the quality and quantity of early language experience (Romeo, Segaran, et al. 2018), the anatomical differences between late and native L1 signers may reflect limited brain development as a result of a lack of early language experience and missing the sensitive period of maximal neural plasticity. Therefore, both behavioral and brain indicators of syntactic development seem to be limited in this population to a rudimentary level, as a result of impoverished early language.

These findings also provide potential explanations to the morpho-syntactic difficulties (Newport, 1990; Boudreault & Mayberry, 2006; Mayberry et al., under review) and atypical neural activation patterns (Ferjan Ramirez et al. 2014, 2016; Mayberry et al. 2011, 2018). In Chapter 3, the generalization process at simple sentence level took longer for late L1 learners, in contrast to their initial rapid development of vocabulary (Ferjan Ramirez, Lieberman, & Mayberry, 2013) and two-word combinations (Berk & Lillo-Matin, 2012). This suggests specific effects of impoverished early language on syntactic development from the beginning, with additional difficulties when generalizing abstract syntactic rules, even in the simplest forms. Chapter 4 revealed persistent use of heuristic sentence processing strategies by deaf late L1 signers, even after substantial years of language use. The heuristic strategies, such as relying on animacy or event plausibility, may be useful to correctly interpret simple transitive sentences, but are not sufficient for mapping semantic roles in more complex sentence structures, such as relative clauses. In addition, their less robust use of basic linguistic cues such as word order may prevent them from accessing the powerful learning tool of syntactic bootstrapping, which may be crucial for the subsequent learning of new verbs that can take subordinate clauses such as attitude verbs, and as a result, may affect the acquisition of late developing, more complex hierarchical structures. The anatomical differences in left arcuate fasciculus as reported in Chapter 5 further provide neurodevelopmental explanations to difficulties at the morpho-syntactic level. The left AF is crucial for syntactic processing (Meyer et al., 2014; Verhoeven et al. 2012; Wilson et al. 2011); its full development is prolonged and sensitive to environmental input (Lebel & Beaulieu, 2011; Romeo, Segaran, et al., 2018), and its development is associated with increase in syntactic processing skills (Skeide et al. 2016). The reduced connectivity in this crucial pathway, most likely due to impoverished early language and reduced neural plasticity, may thus explain the slower and plateaued early syntactic development as reported in Chapter 3 and 4, the additional difficulties with more complex syntactic structures, and the atypical neural activation patterns during language processing.

Another thing worth mentioning is that, across all three studies, we found strikingly similar patterns across deaf late L1 signers, in terms of developmental trajectory, sentence processing strategies, and neural anatomical profiles. Given the very diverse early life environments (some had a big family while some did not, some lived in rural and underdeveloped regions while some lived in developed urban regions, etc), and also the very different language learning settings (e.g. adopted by signers with immersive ASL environment; group homes with deaf social workers; schools for deaf children; or, immersion within the Deaf community), these similarities in language and brain outcomes again suggests profound effects of impoverished early language.

To summarize, the current dissertation showed profound effects of impoverished early language at the basic clausal level and also on the anatomical features of a crucial language pathway. These findings contribute to the literature by pinning down the early deficits in morpho-syntactic development and providing a neurodevelopmental explanation, that bridges the gap between native-like early development and the limited ultimate morpho-syntactic outcomes reported in previous literature.

Implications on language learning and processing

The current dissertation also bears implications on some general aspects of language learning and processing.

As summarized in the previous section, late L1 syntactic development resembles typical L1 development in early stages. In particular, findings from Chapter 3 and Chapter 4 together revealed a production-comprehension asymmetry, as they showed strong reliance on basic word order in production and weak reliance on word order during comprehension. This production-comprehension asymmetry is also observed among typical L1 learners (Hendriks Koster, 2010). Many hypotheses have been proposed to explain this asymmetry, including experimental artifact, lack of pragmatic knowledge during comprehension, general cognitive limitations, two separate grammars, and direction-sensitivity of grammar knowledge. Given that late L1 signers are cognitively more mature than young children, and pragmatic knowledge is not relevant in the current experiment, the most likely reason for late L1 signers and young children to show such asymmetry is that they may show different ranking of linguistic and non-linguistic constraints during sentence comprehension, as the linguistic representations are still less stable.

Non-linguistic cues can override linguistic cues for proficient native when facing increased cognitive burden or noise during language comprehension (Gibson et al., 2013). Agrammatic aphasic patients also show similar reliance on non-linguistic cues when comprehending syntactically complex sentences (Caramazza Zurif, 1976; Gibson et al., 2016), despite their good performance when making grammatical judgement (Linebarger, Schwartz, Saffran, 1983). That is to say, the selective deficits in sentence comprehension during L1 development for both native and late learners do not necessarily mean fundamental differences in grammatical representations, but may rather reflect the strength of the representations in comparison to other competing cues.

Research comparing different comprehension tasks (Chan et al. 2010) found effects of verb familiarity and task effects for younger children but not for children above 3 years old, suggesting early representations to be weak and task dependent, but they become stronger over time. The question is, how young children keep strengthening the syntactic representations and get past this production-comprehension asymmetry, while late L1 learners persist with this pattern, despite of the extended years of language use. One possibility is that native L1 learners show continuous parser development (Omaki Lidz, 2015), supported by early neural plasticity. Processing skills during language comprehension are crucial for language learning. First, processing determines the amount of linguistic intake for further learning. Young children with immature parser may have limited capacity to correctly process adult language input (Trueswell et al. 1999), causing a discrepancy between the input and their intake. Second, processing serves as a learning mechanism itself. Many studies using the visual world paradigm demonstrated that young children show incremental processing skills, just like adult language users (Altmann Kamide, 1999; Huettig, Rommers, Meyer, 2011). Although negative feedback is claimed to be rare and inefficient when young children produce ungrammatical utterances themselves, incremental and anticipatory processing during sentence comprehension can provide implicit feedback for the learner to adjust their internal representations, thus facilitates learning. Parser development can also explain why young children move on from the over-generalized representations to acquire exceptional forms and other syntactic variations, while late L1 signers show fossilization.

So far, we still know very little about how late L1 signers process sentences, but findings from Chapter 4 suggest that their processing may be very limited and different from the native signers, even at the mono-clausal level. Future studies are required to explicitly test the characteristics of their sentence processing skills. If late L1 signers show reduced incremental processing during sentence comprehension, then it will support the role of parser development in rapid native L1 syntactic development. If late L1 signers do show typical incremental processing during sentence comprehension, then the reason for native L1 success may be attributed to other learning mechanisms.

Findings from the dissertation also suggest cascading effects of less robust sentence processing on later syntactic development in general. Other populations with developmental language issues, such as children with specific language impairment (Evans MacWhinney, 1999;

Lindner, 2003) and late talkers (Thal Flores, 2001), also show an extended period of over-reliance on extra-linguistic cues such as animacy during sentence comprehension. Lindner (2003) showed that typically developing German learning children use agreement in their production from age 2, but predominantly relied on animacy during comprehension before age 3 and switched to agreement and case markers by age 4, while children with specific language impairment still rely on animacy by age 6. Given our reasoning on the role of robust linguistic cues on further morpho-syntactic learning, other morpho-syntactic difficulties faced by these populations may also result from this fragile processing foundation.

The current dissertation demonstrated that late L1 development appears to be delayed and fossilized, but not deviant from typical L1 development. This implies shared language learning mechanisms regardless of cognitive maturity, and emphasizes the importance of early neural plasticity and co-development of language and the brain on early syntactic processing, which serves as a stepping stone for further syntactic development.

Neurodevelopmental foundations of human language

The rapid and homogeneous development of a complex first language among young children has been one of the most intriguing unsolved questions in language science, and is considered to be the key to understanding the biological foundations of this uniquely human higher-level function (Lenneberg 1967). By looking at an atypical population with extremely impoverished early language, we can map the behavioral ad neural deficits of lacking early language. By comparing the findings with typical language use and the brain network, we can thus infer the role of early co-development of language and brain on the biological foundations of human language.

Firstly, the current dissertation confirms previous findings on profound effects of impoverished early language, and extends the effects to both basic syntactic structures and brain anatomical structures, as discussed in the previous section. These findings emphasize the role of early neural plasticity, when language and brain co-develop during the first few years of life, as the driving force of rapid and homogeneous first language development. Chapter 3 and 4 showed that, even for a very basic linguistic device, word order, missing the early sensitive period can result in irreversible disadvantages in the learning process, resulting in very limited and fragile use of linguistic cues. In comparison, young children often acquire this basic linguistic device at a very young age (Brown, 1973; Berk 2003; Hirsh-Pasek & Golinkoff, 1991, 1996; Hoffmeister 1978), and predominantly rely on the linguistic cues by age 4 (Bates et al., 1984; Strohner & Nelson 1974). Despite the more mature cognitive functions of the adolescent late L1 signers and their better general capacity to navigate everyday tasks, their capacity to learn language is much more limited compared to younger children. Therefore, unlike other motor skills such as playing the piano or swimming, language does seem to be a specific domain that cannot be learned at a later age, but has to be acquired during early life when the brain is still fast developing.

Because of the role of early experience on brain development and the progressive differentiation of association regions, early neural plasticity for language is likely to be realized through crucial early neural events during postnatal development, such as the myelination of long-range pathways. Findings from Chapter 5 provided evidence for this speculation, showing relations between impoverished early language and decreased degree of connectivity in left arcuate fasciculus which links crucial language regions. This further confirms the association between the dorsal pathway and syntactic processing, as previously observed among primary progressive aphasic patients (Wilson et al. 2011), typically developing children (Skeide et al. 2016), and children with specific language impairment (Verhoeven et al. 2012), and emphasizes the neurodevelopmental origin of this association. In addition, Chapter 5 also reported no difference between deaf native signers and hearing native speakers in all language-relevant pathways. This result suggests that sufficient early language from birth, regardless of its modality, is key for a distributed and highly efficient language network in typical brain development.

The findings from the current dissertation provide a neurodevelopmental approach to understanding the role of nature and nurture in first language development. Given the highly specialized brain network of language and the reduced degree of connectivity and language function when early language is missing, it is likely that some aspects of the immature default language network are predetermined to learn certain features from linguistic experience. Structure building during rapid temporal processing is potentially one of those features. On the other hand, early linguistic input serves as the expected experience for the default language network to emerge, and general mechanisms such as statistical learning and predicative encoding may play a crucial role in realizing the non-linear neural computations and learning from the input, thus providing the experience-dependent plasticity required to learn a specific language.

Finally, the current dissertation also sheds light on the language universals observed across human languages regarding abstract linguistic structures. All languages employ some abstract linguistic cues, be it word order, case marking, verb agreement, to map semantic roles. These linguistic cues allow for abstract structural building independent of meaning, which contribute to the productivity of human language. Results from the current dissertation suggest that, when early language is missing, late L1 signers tend to rely on real world event plausibility cues, even after many years of ASL use. Therefore, the tendency to rely on abstract rules may root from early language development. These findings also resonant with findings on emerging sign languages (Senghas & Coppola, 2001; Senghas, Kita & Ozyurek, 2004) and infant acquisition of ASL from inconsistent input (Singleton & Newport, 2004), emphasizing the role of young children in the emergence of core linguistic features. In a broader sense, the neurodevelopmental foundations of human language, arising from early neural plasticity and shaped by early language experience, may have partially contributed to the language universals that restrict the degree of variations of human languages among all possible communicative systems.

Caveats and future directions

The current dissertation provides initial attempts to combine longitudinal development, processing, and neural anatomical evidence in examining the role of early language in first language syntactic development. Still, there are many limitations of the current dissertation that can benefit from future studies.

First, the cases examined in the current dissertation had extremely late language onset. Whether earlier language onset show similar or different effects on language and brain development is less clear. Different language regions or sub-circuits may have different developmental time windows. In addition, the default language network co-develops with sensory-motor and higher cognitive networks, and the progressive differentiation nature of post-natal development suggests high interactions between these individual systems. Examining the language and brain profiles of deaf individuals with variation in their age of first language onset can help illuminate this question. Also, typical deaf children often experience less impoverished early language and with earlier language onset. Research with this population can provide more practical implications on identifying and helping deaf individuals who are at risk of language learning difficulties due to limited early language experience.

Also, we focused on one linguistic device, basic word order, but did not examine other linguistic devices and domains that are potentially also affected by impoverished early language. Many other linguistic domains may be susceptible to limited development, given the dorsal pathway differences observed in Chapter 5. Phonological processing and verbal working memory are more likely to be affected. Other crucial linguistic domains, such as the syntax-semantics interface and formal semantics, may also require early language to fully develop. Understanding the learning outcomes of late first language development at different linguistic levels is necessary to get a complete picture of the effects of missing early language on first language development.

The current dissertation identified behavioral and neural outcomes of lacking sufficient early language, but how impoverished early language affect language and brain development is still less clear. The nature of progressive differentiation and commitment during postnatal brain development and the co-development of language and other neural systems allows for several ways for early language to shape the designated language network, either within the language domain, or through interactions with other neural systems. Examining the exact ways early language interacts with brain development will reveal the underlying mechanisms of rapid and homogeneous first language development. Here are some potential directions: the establishment of a language-specific sensory-motor integration pathway that may serve further roles in abstract structure building in phonological and syntactic processing; the interaction between language and conceptual networks; the interaction between language and social cognition/joint attention; and the interaction between language and the cognitive control network. Studying individuals with various early language profiles, such as native deaf children with visual-manual language from birth, deaf children with delayed language onset, children with developmental language delay (DLD), preterm children, children with early brain injury, and congenitally blind children, can distinguish some of these factors and be beneficial for this purpose.

Finally, more studies on the neural and behavioral changes in language processing during first language development using psycholinguistic and neurolinguistics paradigms are highly desirable, in order to fully understand how early neural plasticity shapes the language-specific brain network. The current dissertation revealed key neural and processing changes that accompany typical L1 for syntactic development that are missing in late L1 due to limited early language. Studying when and how such key changes happen among typically developing children can add to our understanding of the processes of first language development.

To conclude, the current dissertation combined longitudinal, processing, and anatomical observations from a group of deaf individuals with extremely late first language onset, with a focus on the early syntactic development of basic word order in transitive sentences, in order to reveal the effects of impoverished early language on syntactic development as well as brain development for language. These findings suggest profound effects on both language and brain development, evidenced by similar yet slower and limited early syntactic development restricted to the simple clausal level, with less robust use of basic linguistic cues, and less robust connectivity in a core language pathway for structure building. We related these findings to the previous findings on morpho-syntactic difficulties regarding late L1 development, discussed the implications on typical first language development and the biological foundations of human language, and proposed future directions for a neurodevelopmental approach to first language development.

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