Infant Volubility and Bilingual Input in Naturalistic Day-long Recordings

Ruan, Yufang

School of Communication Sciences and Disorders, Faculty of Medicine and Health Sciences

McGill University, Montreal

June 2022

A thesis submitted to McGill University in partial fulfilment of the requirements of the degree of Doctor of Philosophy in Communication Sciences and Disorders (Language Acquisition).

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This dissertation is dedicated to the COVID-19 global pandemic.

福兮祸所伏，祸兮福所倚。

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List of Abbreviations

MBI	Montréal Bilingual Infants corpus
LENA	Language ENvironment Analysis
CVC	Child Vocalization Counts
AWC	Adult Word Counts
1:1	one-on-one social contexts
NHST	null-hypothesis significance testing
CET	conditional equivalence testing
EOS	every-other-segment

Abstract

Language input plays an important role in child language acquisition. Children encounter language input in different social contexts: They sometimes are directly addressed by caregivers and sometimes overhear conversations between others. For children growing up in bilingual environments, they receive input in two languages. In many cases, a bilingual child is exposed to one language more often than the other which are usually referred to as the child's dominant and non-dominant languages. Bilingual caregivers are also commonly observed mixing languages when talking to their child. How language input that varies in both quantity and quality interacts with child language development is not fully understood. As well, various units and sampling methods that have been used to measure input can impact the relation between input and language development. To assess bilingually-raised infants' speech and language development in their first year of life is challenging; in this dissertation, I deployed infant volubility which is a measurement of infants' vocal activeness and an established precursor of their future language skills.

To examine the relation between infant volubility and language input received in different social and language contexts, I analyzed infant and caregiver vocalizations in the naturalistic day-long recordings from the Montréal Bilingual Infants corpus. Twenty-one French-English bilingual families living in Montréal completed language background interviews and contributed three day-long audio recordings when their infant was 10 months old and another day-long audio recording when their infant was 18 months old. Recordings were obtained and processed by the LENA system (Language ENvironment Analysis, Boulder, Colorado). Every other 30-second segment containing adult speech was manually coded for social (one-on-one, overhearing) and language (French, English, mixed-language) contexts. Infant volubility was

assessed at two levels (1) *overall volubility*, the number of infant vocalizations produced throughout the day; and (2) *local volubility*, the number of infant vocalizations produced in the presence of a certain type of input. In Chapter 2 to 4, I examined infant overall and local volubility's relation with input in different social contexts (Chapter 2), with English- and French-only input (Chapter 3), and with mixed-language input (Chapter 4). In Chapter 5, I assessed the alignment between input measures estimated by various units (segment counts, adult word counts, speech duration) and different sampling methods (every-other-segment, top-segment). Data and analysis codes are available at http://osf.io/wjnaq.

These analyses revealed at least following findings: (1) Infant volubility and language input is robustly and positively related at global and local levels; (2) Infants' concurrent and longitudinal overall volubility has a strong association with the amount of input received in 1:1 social contexts and in their dominant language; (3) Input received in overhearing contexts and in their non-dominant language also makes unique contributions to infant overall volubility; (4) There is a complex relation between infant volubility and mixed-language input including that a higher proportion of mixed input in 1:1 social contexts is related to reduced overall volubility; (5) Input measures and their relation with infant overall volubility are consistent across different units but diverge across sampling methods.

This dissertation adds to an emerging body of research on children's bilingual language environment and their language acquisition. Findings from this dissertation have important theoretical and practical implications. First, they show a robust relation between infant volubility and language input. Second, they contribute to the current debates on the role of overheard input and mixed-language input. Last, they provide methodological suggestions to future research on the choice of input measurement units and sampling methods.

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Résumé

L’input linguistique joue un rôle important dans le développement du langage chez les enfants. Ces derniers reçoivent de l’input langagier dans différents contextes sociaux : parfois la personne qui s’occupe d’eux leur adresse directement la parole et parfois ils entendent par hasard les conversations d’autres personnes. Les enfants qui grandissent dans des environnements bilingues, quant à eux, reçoivent de l’input en deux langues. Dans de nombreux cas, un enfant bilingue est exposé à une langue plus souvent qu’à l’autre; langues qui sont habituellement considérées comme la langue dominante et la langue non dominante de l’enfant. Les parents bilingues entremêlent aussi régulièrement ces deux langues lorsqu’ils parlent à leurs enfants. Cependant, des questions subsistent quant à l’interdépendance entre la variabilité de l’input, en termes de quantité et de qualité, et le développement du langage chez les enfants. En outre, les diverses unités de mesure et méthodes d’échantillonnage qui sont utilisées pour mesurer l’input peuvent avoir un impact sur la relation entre l’input et le développement du langage. L’évaluation du développement du langage chez les enfants bilingues durant la première année de vie représente donc un défi de taille. Dans le cadre de cette thèse, j’ai utilisé l’échelle de volubilité infantile qui est une mesure de l’activité vocale des nourrissons et un précurseur de leurs futures compétences linguistiques.

Afin d’examiner la relation entre la volubilité infantile et l’input reçue dans différents contextes sociaux et langagiers, j’ai analysé les vocalisations des nourrissons et de leurs soignants dans des enregistrements naturels d’une journée du corpus de « Montréal Bilingual Infants ». Vingt-et-une familles bilingues francophones-anglophones vivant à Montréal ont réalisé des entrevues sur leurs antécédents linguistiques et ont fourni trois enregistrements audios d’une journée lorsque leur enfant avait 10 mois et un autre enregistrement lorsque leur enfant

avait 18 mois. Les enregistrements ont été recueillis et traités par le système LENA (Language ENvironment Analysis, Boulder, Colorado). Un segment de 30 secondes sur deux contenant de la parole adulte a été codé manuellement en fonction des contextes sociaux (tête à tête, entendu par hasard) et langagier (français, anglais, mixte). La volubilité infantile a été mesurée à deux niveaux : (1) *la volubilité globale (overall volubility)*, soit le nombre de vocalisations infantiles produites tout au long de la journée et (2) *la volubilité locale (local volubility)*, soit le nombre de vocalisations infantiles produites en présence d'un certain type d'input. Aux chapitres 2 à 4, j'ai examiné la relation entre la volubilité globale et locale des nourrissions et (1) l'input reçue dans différents contextes sociaux (le chapitre 2) ; (2) l'input en français et en anglais uniquement (le chapitre 3) et (3) l'input mixte (le chapitre 4). Au chapitre 5, j'ai évalué l'alignement entre les mesures d'input estimées par diverses unités de mesure (nombre de segments, nombre de mots adultes, durée de la parole) et les méthodes d'échantillonnage (tous les autres segments, top segments). Les données et les codes d'analyse sont disponibles sur http://osf.io/wjnaq.

Les résultats ont montré : (1) une relation étroite et positive entre la volubilité infantile et l'input linguistique aux niveaux global et local ; (2) que la volubilité globale actuelle et celle atteinte huit mois plus tard sont fortement associées à la quantité d'input reçue dans les contextes de tête-à-tête et dans la langue dominante ; (3) que l'input entendu par hasard ou dans la langue non dominante contribue de façon spécifique à la volubilité globale ; (4) une relation complexe entre la volubilité infantile et l'input mixte, incluant qu'une proportion plus élevée d'input mixte dans les contextes de tête-à-tête est associée à une réduction dans la volubilité globale ; (5) que les mesures de l'input et leur relation avec la volubilité globale concordent d'une unité à l'autre, mais divergent selon les méthodes d'échantillonnage.

Cette thèse s'inscrit dans le cadre d'un ensemble de recherches émergentes sur l'environnement bilingue et l'acquisition du langage chez les enfants. Les résultats ont des implications théoriques et pratiques importantes. Premièrement, ils démontrent un lien entre la volubilité infantile et l'input linguistique. Ensuite, ils contribuent aux débats actuels sur le rôle de l'input entendu par hasard et de l'input mixte. Finalement, ils suggèrent des méthodologies à appliquer aux futures recherches sur le choix des unités et des méthodes d'échantillonnage.

摘 要

语言输入（language input）在儿童语言发展中扮演了重要的角色。儿童会在不同的社会场景中接收到语言输入，有时他们的照料者会直接和他们交流，有时他们会旁听到其它人之间的对话。对于在双语环境中成长的儿童，他们会接收到两种语言的输入。大多数情况下，他们接收到其中一种语言的输入比另一种语言多，我们往往称这两种语言分别为儿童的主要语言（dominant language）和次要语言。不仅如此，双语家长们在和他们的孩子交流时还常常混合这两种语言。关于在质与量上各异的语言输入是如何与儿童语言发展相互作用的，学界还没有一个完整的答案。另外，用来测量语言输入的不同单位和抽样方法也可能对语言输入和儿童语言发展之间的关系产生影响。与此同时，测量双语儿童一岁前的言语语言发展并非易事。本文采用了婴儿发声量（infant volubility），它测量了一定时间内儿童发声的活跃度，并且已经被证明可以预测儿童未来的语言能力。

为了研究婴儿发声量和他们在不同社会和语言环境中接收到的语言输入之间的关系，本文分析了蒙特利尔双语婴儿自然全天语音语料库（Montréal Bilingual Infants corpus）中的婴儿和他们的照料者的发声量。二十一个居住在蒙特利尔地区的英法双语家庭完成了语言历史访谈并在孩子 10 个月时提供了 3 段全天候录音，在孩子 18 个月时提供了另一段全天候录音。录音的采集和分析皆通过 LENA 语言环境分析系统（Language ENvironment Analysis, Boulder, Colorado）完成。接下来，英法双语研究助理对每隔一个包含语言输入的 30 秒片段的社会（一对一（one-on-one），旁听（overhearing））和语言（法语，英语，语言混合（mixed-language））场景进行了编码。婴儿发声量则从两个层面测量：（1）整体发声量（overall volubility），指婴儿在一天内发声的次数；（2）局部发声量（local volubility），指婴儿在特定的社会和语言场景中的发声次数。本论文第二

到第四章探究了婴儿整体和局部发声量与不同社会场景中的语言输入的关系（第二章），与英语、法语单语输入的关系（第三章），以及与混合语言输入的关系（第四章）。第五章探究了不同语言输入测量单位（片段数（segment count）、字数（adult word count）、时长（speech duration））和抽样方法（间隔法（every-other-segment）、取高法（top-segment））之间的一致性。本论文数据和分析代码已在 OSF 页面开源 http://osf.io/wjnaq。

本论文至少揭示了以下五个科学发现。第一，无论是在整体还是局部层面，婴儿发声量和语言输入之间都存在紧密的、正向的联系。第二，婴儿当下的和远期的整体发声量与他们在一对一社会场景中的主要语言的语言输入相关。第三，在此基础上，婴儿旁听到的和次要语言的语言输入对婴儿的整体发声量有各自独立的影响。第四，婴儿发声量和混合语言输入的关系较为复杂，其中在一对一社会场景中接收到了较高比例混合语言输入的婴儿可能整体发声较少。第五，关于语言输入的测量以及他们和婴儿整体发声量的关系，不同测量单位之间的一致性较高，而不同抽样方法得到的结果不尽相同。

本论文为双语语言环境和语言习得这一新兴研究领域提供了新的证据。这些新证据在理论上和实践上都有重要的意义。首先，它们展示了婴儿发声量和语言输入之间的紧密联系。其次，在有关旁听到的和双语混合的语言输入对儿童语言发展的作用这些争论性议题上，本论文为学界提供了新的证据和看法。最后，本论文还向未来的研究提供了关于如何选择语言输入测量单位和抽样方法的方法学建议。

Acknowledgement

I would like to thank the families who have contributed to the Montréal Bilingual Infants corpus and the research assistants from McGill Infant Speech Perception Lab for their hard work to code and transcribe the corpus. I would also like to thank Drs. Adriel John Orena, Linda Polka, and Krista Byers-Heinlein for generously making the Montréal Bilingual Infants corpus available for this research project. I want to express my gratitude to members on my various committees, Drs. Linda Polka, Krista Byers-Heinlein, Susan Rvachew, and Nicole Yee-Key Li-Jessen, as well as my defense committee, Drs. Gigi Luk, Christopher Fennell, Meghan Clayards, and Dominique Walker (Pro-Dean), for their instrumental feedback on my thesis. I want to thank Dr. José Correa for his expert statistical consultation and Dr. Annie Gilbert for her feedback on my French writing.

I would like to give additional thanks to McGill University, the Faculty of Medicine and Health Sciences, the School of Communication Sciences and Disorders, the Interdisciplinary Language Acquisition Program, and the Centre for Research on Brain, Language, and Music for providing various resources over the last five years. I would especially like to thank my supervisor, Dr. Linda Polka, for her supervision and financial support. She has also greatly influenced my writing development to apply a more audience-oriented approach. My PhD study is generously supported by the China Scholarship Council-McGill Joint Fellowship (2017 - 2021) and Fonds de recherche du Québec – Société et culture Doctoral Research Scholarship (2021 - 2022).

This dissertation is dedicated to the COVID-19 global pandemic. On March 11, 2020, the World Health Organization declared the novel coronavirus outbreak a global pandemic. The epidemic situation escalated rapidly in Québec and forced me to alter my original research design. Still, I would like to express my thanks to the teams involved in the original project: The Proteomics at the Research Institute of the McGill University Health Centre led by Lorne Taylor and the Voice and Upper Airway Research Lab led by Dr. Nicole Yee-Key Li-Jessen. Fortunately, I had been working on a side project with Dr. Adriel John Orena and Katherine Xu using data from the Montréal Bilingual Infants corpus. I was able to expand one of the research questions which ultimately developed into the current research project. In this project, I continued my investigation of the dynamic interaction between language environment and child speech and language development, that had started in my master's thesis where I examined prenatal language exposure's impact on newborn cry. By the time that I completed this thesis, my interest in bilingualism has also grown significantly, as well as my appreciation for everything and everyone that has helped me become a multilingual.

The ongoing global pandemic not only altered my thesis project, but more importantly, it compelled my personal growth. As the physical evidence for my personal growth, I have grown two wisdom teeth since the start of this pandemic. Chinese philosopher Mencius (孟子) has taught generation after generation that one's personal growth is not always pleasant (《孟子·告子下》). I would not have arrived here without these people standing by my side: my colleagues and friends, Drs. Pegah Athari and Haruka Saito, Drs-to-be. Deidre Truesdale, Zhang Shuyi, Yang Yi, Dahlia Thompson, and many others; my thesis buddy, Dr. Jing Xiaoli; and, my therapist Mrs. Camila Velez among other consultants. My dearest thanks to my family in China for their unconditional love and support and to my little family in Montréal, Stan (大爷) and Oliver (二爷, ? – 2017/12/22 – 2022/02/11), for their faithful and agreeable companionship.

The completion of this thesis marks the start of a new chapter in my life. May the world be a peaceful, safe place for everyone to live and thrive.

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Contribution to Original Knowledge

This dissertation contributes to original knowledge in the field of language acquisition in several ways. First, this is one of the first few studies that has thoroughly examined the relation between language input and infant volubility. Second, when using infant volubility, in addition to overall volubility, this is the first study deploying *local* volubility. The merit of using local volubility is that the volubility-input relation can be examined within specific social and language contexts respectively, via which one can scope whether each context provides a stimulating environment for infants and caregivers' vocal activities. On that note, findings from this dissertation have shown that the number of infant and caregiver vocalizations are tightly correlated not only in one-on-one interactions but in all social and language contexts.

Furthermore, in addition to established knowledge about the impactful role of input received in one-on-one social contexts in child language development, findings from this dissertation highlight a significant additional contribution from overheard input, which has important theoretical implication to child language acquisition regardless of language background. Specific to children growing up in bilingual environments, overheard input might be especially important to their successful acquisition of the non-dominant language, which has not yet been discussed in the field. As for mixed-language input, I have found divergent associations with infant volubility, highlighting the complex role of mixed-language input in bilingual language development.

Finally, to the best of my knowledge, this is the first study to assess the consistency across input measurement units and the reliability of top-segment sampling methods with LENA outputs. Outcomes of this endeavor provide methodological suggestions for future studies to ensure that our research conclusions are not built on methodological biases.

Contribution of Authors

This dissertation utilized open-access data from the Montréal Bilingual Infants corpus. My role in every chapter of this dissertation involved conceptualization, formal analysis, investigation, methodology, visualization, and writing*. Drs. Linda Polka (supervisor), Krista Byers-Heinlein, Susan Rvachew, and Adriel John Orena provided instrumental feedback on conceptualization, analysis, and writing. Dr. Linda Polka also contributed to supervision and funding acquisition.

*Author contribution taxonomy adopted from CRediT (https://casrai.org/credit/).

CHAPTER 1

INTRODUCTION

An increasing number of children are growing up in bilingual environments. In Canada, 18 percent of children aged 0-9 years use at least two languages at home (Schott et al., 2022). In Québec, nearly 90% of young French-English bilinguals grow up with bilingual parents (Turcotte, 2019). Infants growing up in a bilingual family receive input in two languages and in various social contexts (e.g., Oller, 2010; Orena et al., 2020; Ramírez-Esparza et al., 2017b), which creates a natural context to examine how varied quantities of language input affect child language development within the same individual. Thus, research with bilingual infants provides an opportunity to better understand bilingual acquisition as well as fundamental aspects of language development regardless of language background. Bilingually-raised infants also receive input in mixed language, that is, the alternating use of two languages (Bail et al., 2015; Byers-Heinlein, 2013; Kremin et al., 2021). As a field, we are just beginning to understand how input experienced in different social and language contexts shapes bilingual development.

Prior work has clearly demonstrated that input received in one-on-one (1:1) social contexts and in the child's dominant language plays an impactful role in child language development, including volubility (e.g., Ramírez-Esparza et al., 2017b). However, evidence as to what extent overheard, non-dominant language, and mixed-language input impacts child language development is equivocal (Bail et al., 2015; Byers-Heinlein, 2013; Carbajal & Peperkamp, 2020; Pearson et al., 1997; Place & Hoff, 2011, 2016; Shneidman et al., 2013; Weisleder & Fernald, 2013).

Moreover, measuring bilingual input is challenging. With the rapid expansion of the ways to measure input in recent years, various units and sampling methods have been deployed to estimate bilingual input. The robustness of these methods is unknown as research has not yet examined the alignment between input measures indexed by different units and estimated in samples selected by different sampling methods (Bergelson et al., 2019; Cychosz et al., 2021; Orena et al., 2020; Ruan et al., 2022).

Although many bilingually-raised infants are exposed to bilingual input at least since birth, most research on how bilingual input is related to child language development has focused on toddlers and older children. This research gap is due in part to the challenge of objectively and rapidly assessing the language development of children under 12 months. A measure that can be deployed before infants produce their first words is *volubility* which indexes the frequency of the infant's vocalizations and predicts their future language abilities (Iyer et al., 2016; Oller et al., 2019; Wang et al., 2020).

Therefore, in this dissertation, I analyzed infant vocalizations and bilingual input in naturalistic day-long recordings, to better comprehend the relation between infant volubility and language input in different social and language contexts, as well as to assess the alignment between various input measurement units and sampling methods. Before laying out my research questions, relevant studies will be reviewed first in this chapter.

1. Infant Volubility

Infant volubility is the amount or rate of speech/speech-like vocalizations produced by an infant (Iyer et al., 2016). According to the Dual Nature Theory (Oller et al., 2019; Stark et al., 1993), infant vocalizations can be classified as either interactive (i.e., infants vocally interact with their caregivers) or endogenous (i.e., infants vocalize spontaneously as a form of exploration without a clear social intention). While infants' interactive vocalizations have been well studied, their non-interactive vocalizations have received less attention. Endogenous vocalizations present as early as two months of age and are prominent in the first year of life (Oller et al., 2019; Stark et al., 1993). Previous estimates suggested that 75% of 3- to 10-month-olds' vocalizations are produced without a clear social intention (Long et al., 2020). When researchers manipulated social settings, they found that infants under 12-month of age produced more vocalizations when their caregivers' attention was not on them (Iyer et al., 2016; Shimada, 2012). Researchers also found that the motivation behind these endogenous vocalizations appears to be less about seeking responses from caregivers and more about infants' urge of vocal exploration and interest in listening to their own vocalizations (Shimada, 2012). It is known that young infants show a listening preference for speech with infant vocal properties (Masapollo et al., 2016; Polka et al., 2014) and this auditory feedback of their own vocalizations might play an important role in early vocal development (Koopmans-van Beinum et al., 2001; Oller & Eilers, 1988; Rvachew et al., 1999).

Infant volubility has a special value in terms of assessing child vocal development's relation with language input: Language input demonstrates a language model and provides communicative opportunities (Hoff, 2006); how input provides children with communicative opportunities is difficult to assess by standardized language tests but is well reflected in an utterance-to-utterance quantitative relation with infant volubility. Through this input-volubility relation, we scope how language input stimulates infant vocalizations as well as how infant vocalizations elicit speech from caregivers. To assess this utterance-to-utterance quantitative relation between infant volubility and language input, infant volubility can be measured at two levels: *overall* and *local* volubility. Both infant volubility measures were computed by day without removing silent time. This was done so that I would not overestimate the volubility of the infants who were quieter. *Infant overall volubility* refers to the number of infant vocalizations that the infant produce throughout the day, including both during social interactions and when they are alone. Although it is possible that children inherit “talkativeness” genes from their parents (Dale et al., 2015), infants growing up in a verbally stimulating environment are also more likely to produce vocalizations both during social interactions and when alone. Therefore, it is reasonable to expect a strong association between language input and infants’ overall volubility (Ramírez-Esparza et al., 2017b; Ruan et al., 2020).

Local volubility, on the other hand, refers to the number of infant vocalizations produced in the presence of adult speech (Ruan et al., 2020). Robust evidence show that infants use their vocalizations to elicit responses from their caregivers (e.g., Goldstein et al., 2009) and likewise, caregivers’ vocalizations, especially their response to infants’ vocalizations, boost the quantity and quality of infants’ sequential vocalizations (Athari et al., 2021; Goldstein et al., 2003; Goldstein & Schwade, 2008; Gros-Louis et al., 2006, 2014, 2016; Gros-Louis & Miller, 2018; Hsu & Fogel, 2001, 2003; Lopez et al., 2020; Pretzer et al., 2019; Warlaumont et al., 2014). Infants and caregivers mutually stimulate vocalizations from each other and facilitate a social feedback loop (Warlaumont et al., 2014). In infancy, the presence of this social feedback loop is the strongest predictor of a child’s productive vocabulary later in life (Donnellan et al., 2020; Lopez et al., 2020). A positive relation between infant and caregiver vocalizations within a context may not directly indicate the presence of this social feedback loop, but it does reflect a stimulating environment for vocal engagement from *both* the child and their caregivers, which is crucial for child language development.

There are other merits of using infant volubility as a measure of early vocal development. First, infant volubility is an early precursor of language development (Gilkerson et al., 2018). A recent meta-analysis found that infant volubility outperformed adult word count and conversational turn-taking regarding their relation with children's language skills assessed by standardized tests (Wang et al., 2020). Abnormality in volubility can also suggest developmental disorders (see review in Iyer et al., 2016). Second, volubility can be measured before infants produce any words, making it possible to study child speech and language development's relation with language input as early as two months. Third, compared to standardized assessments, volubility is a more observational measure and less influenced by children's social experience. For example, standardized tests conducted by an experimenter and involving a question-and-answer format might favor children who have had more experience with this form of directed interaction with an adult and disfavor those with more experience of overhearing conversations (Shneidman & Goldin-Meadow, 2012). Lastly, bilingual infants are learning two languages simultaneously. It is challenging to measure their vocabulary knowledge in two languages given the distributed characteristic of bilingual knowledge (Oller & Pearson, 2002). However, measuring volubility does not require grouping infant vocalizations into different languages, which makes volubility a great candidate to measure bilingual children's speech and language development.

2. Language Input

A robust relation between the quantity of input and children's talkativeness and vocabulary size found in the 1990s led to a paradigm shift in language acquisition research (Hart & Risley, 1995; Huttenlocher et al., 1991). Recent studies further demonstrate that input quality also matters by showing that input received in different social contexts contributes to child language development differently (Ramírez-Esparza et al., 2017b; Shneidman & Goldin-Meadow, 2012; Weisleder & Fernald, 2013). Children raised in a bilingual family receive input in two languages. Given that the input in two languages may vary in quantity and quality, the contribution to child language development might also differ (Place & Hoff, 2011, 2016; Ramírez-Esparza et al., 2017a, 2017b; Song et al., 2012). In some bilingual families, children receive languages in different proportions across different social contexts (Oller, 2010; Orena et al., 2020); thus, the contribution of input in different languages might vary across social contexts.

2.1 Input from Different Social Contexts

Children's experience with their language environment is socially gated such that different social environments offer variable opportunities for interactions with social partners (White et al., 2002). In addition to investigations of dyadic interactions in the laboratory, the technological advancements in day-long recording and automatic analysis, such as LENA systems (Language ENvironment Analysis, Boulder, Colorado), enable researchers to study children's real-world language input. In reality, language input occurs in different contexts: one caregiver talks directly to the child (one-on-one, 1:1), or two or more caregivers talk to the child (group), or caregivers talk to each other in the presence of the child (overhearing). Features of these contexts (directiveness, responsiveness, acoustic and linguistic properties, etc.) impact how children benefit from the input.

In line with what has been found in monolinguals (e.g., Ramírez-Esparza et al., 2014; Weisleder & Fernald, 2013), language input received in 1:1 social contexts appears to be especially influential for the language development of bilingually-raised infants (Ramírez-Esparza et al., 2017a, 2017b; Song et al., 2012). Spanish-English bilingual children who received more 1:1 input in their first and second year of life showed higher volubility and larger vocabularies in each of their native languages (Ramírez-Esparza et al., 2017a, 2017b). In a previous study with French-English bilingual infants, researchers compared the number of infant vocalizations produced in different social contexts in naturalistic day-long recordings and found that infants vocalized more in 1:1 social contexts (Xu et al., 2019).

One-on-one input provides infants a great language model as well as communicative opportunities (Hoff, 2006). First, when talking to young children, caregivers are likely to use parentese, a special speech register with salient prosodic features and simplified language structure, which attracts infants' attention, triggers infants' positive emotions, and makes the speech easier to process (Polka & Ruan, 2021; Saint-Georges et al., 2013; Soderstrom, 2007). Second, independent from using parentese, caregivers' contingent responses to infants' vocalizations elicit more infant vocalizations and more developmentally advanced ones (Athari et al., 2021; Goldstein et al., 2003; Goldstein & Schwade, 2008; Gros-Louis et al., 2014, 2016; Gros-Louis & Miller, 2018; Lopez et al., 2020; Miller, 2014; Miller & Gros-Louis, 2013; Miller & Lossia, 2013; Pretzer et al., 2019; Tamis-LeMonda et al., 2001; Van Egeren et al., 2001; Warlaumont et al., 2014; Yoder et al., 2001). A meta-analysis including 214 children generated a large effect size for adult contingent responsiveness on the increases of infant vocalizations (Dunst et al., 2010). This effect of parental responsiveness has been observed as early as two months of age (Hsu & Fogel, 2001) and across cultures (Bornstein et al., 2015). Additionally, interactions often involve the sharing of joint-attention by the caregiver and the infant, which helps form an association between a word and its referent to facilitate child vocabulary growth (Akhtar, 2005a; Akhtar & Gernsbacher, 2007).

However, after taking a closer look at children's real-world language input, recent studies have discovered that children typically experience more overheard input than directed input (Orena et al., 2020; Sperry et al., 2019a). The presence of more adults (growing up in larger-sized families or attending daycares) can also significantly increase overheard speech (Place &

Hoff, 2011; Shneidman et al., 2013; Soderstrom et al., 2018). Yet only a handful of studies have quantitatively examined overheard input's contribution to language development, all of which suggested the contribution to be limited (Oller, 2010; Shneidman et al., 2013; Shneidman & Goldin-Meadow, 2012; Weisleder & Fernald, 2013). Two group studies were conducted in America, either in Latino families with low socioeconomic-status (Weisleder & Fernald, 2013) or in families where children spend the majority of their time with multiple individuals (Shneidman et al., 2013). Results from these two studies showed a non-significant contribution of overheard input to children's vocabulary development. Another group study conducted in Mayan community also showed that the input overheard by 24-month-old Mayan children did not significantly contribute to their vocabulary size at the age of 35 months (Shneidman & Goldin-Meadow, 2012).

In Shneidman & Goldin-Meadow (2012), the input was sampled at 24 months. At that age, however, Mayan children were perceived as a conversational partner in the community because of their more mature language skills and therefore experienced child-directed input in proportions similar to their American peers. It would be more informative if the input was sampled at an earlier age where the overheard input was more predominant. In general, previous studies have used relatively short recordings (90-minute, Shneidman et al., 2013; Shneidman & Goldin-Meadow, 2012), examined less fine-grained coding units (5-minute segments, Weisleder & Fernald, 2013), or excluded distant speech that can still be overheard by the child in reality (Weisleder & Fernald, 2013). Therefore, the contribution of overheard speech might have been underestimated in these studies.

In addition, in one case report, even when caregivers intentionally avoided using English when talking to the child, their daughter still managed to learn some English words from the conversations that she overheard (Oller, 2010). There is also no evidence suggesting a higher prevalence of language delays for infants growing up in cultures where young children spent most of their time overhearing conversations of others (Lieven, 1994). In fact, a growing body of research shows that infants, as young as 18 months old, can learn new labels from overheard speech equally well as from directed speech, even when they are occupied with a distractor or the labels are not introduced in a directive way (Akhtar, 2005b; Akhtar et al., 2001; Floor & Akhtar, 2006; Gampe et al., 2012; Martínez-Sussmann et al., 2011). To achieve this, evidence of world and gesture learning showed that children strategically shift and divide their attention as well as imagine themselves in a third-party conversation (Akhtar et al., 2001; Herold & Akhtar, 2008; Martínez-Sussmann et al., 2011). It may sound challenging, but research has found that children who have extensive experience with overhearing conversations between others (e.g., growing up in one of the aforementioned communities, spending significant time with multiple adults, or having an older sibling) are skilled in attention switch and are better at learning novel information from overhearing conditions compared to their counterparts (Chavajay & Rogoff, 1999; Oshima-Takane et al., 1996; Shneidman et al., 2009).

Evidence also shows that infants learn some syntactic and pragmatic aspects of language better from overhearing conversations between others (Blum-Kulka & Snow, 2002; Oshima-Takane, 1988; Oshima-Takane et al., 1996). For example, a correct model of personal pronouns ("I" and "you") is not available in directed speech: when addressing to their child, parents refer themselves as "I" and their child as "you", so children mistakenly refer themselves also as "you". In this case, overhearing conversations of others would provide a better demonstration of the correct use of these pronouns. Indeed, second-born children outperform their first-born peers

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because they have more chances to overhear conversations between their parents and older sibling (Oshima-Takane, 1988; Oshima-Takane et al., 1996).

Furthermore, some aspects of language can be partially acquired through passive exposure without paying attention. Experiments showed that 8-month-old infants who were passively exposed to an artificial language for only few minutes computed statistical regularities in the grammatical structures (Saffran et al., 1996). As well, individuals who only had passive exposure to a language in early childhood which was then disrupted due to international adoption or other reasons, still show traces of that language in their perception and production (Au et al., 2002; Pierce et al., 2014, 2015; Singh et al., 2011). Together, accumulating evidence suggests that children can benefit from overheard input.

Recognizing potentially important sources of input outside 1:1 interaction does not dismiss the importance of 1:1 input. On the other hand, by excluding consideration of other sources of input, we might miss the opportunity to obtain a comprehensive view of child language environment (Soderstrom, 2007; Sperry et al., 2019b). Therefore, in this dissertation, I considered both 1:1 and overheard input and examined the relative contribution of overheard input to infant volubility. As children's mobility and language ability develop, they are likely to have vocal exchanges in a broader array of social contexts (Ramírez-Esparza et al., 2017a; Rowe, 2012; Song et al., 2012). Thus, I also hypothesized that the input received in social contexts outside 1:1 interaction would play a stronger role in language development as children grow.

2.2 Input from Different Language Contexts

Bilingually-raised children receive input in two languages simultaneously. An extensive body of research shows that for each language, the (absolute or relative) amount of input is related to various aspects of knowledge (receptive and expressive vocabulary, grammar and syntax knowledge, etc.) in that specific language (Byers-Heinlein, 2013; Carbajal & Peperkamp, 2020; Cattani et al., 2014; Garcia-Sierra et al., 2011; Gathercole & Thomas, 2009; Hoff et al., 2012; Marchman et al., 2017; Patterson, 2002; Pearson et al., 1997; Place & Hoff, 2011, 2016; Ramírez-Esparza et al., 2017a, 2017b; Song et al., 2012). Some evidence suggests the relation is somewhat weaker for the less dominant language (e.g., Pearson et al., 1997). To test whether language dominance influences bilingual infants' volubility, researchers categorized their languages into dominant and non-dominant language according to parent-reported relative exposure to each language, and compared the number of infant vocalizations produced in the presence of each language (Xu et al., 2019). Preliminary results showed that dominant language input was accompanied with more infant vocalizations.

Furthermore, language contexts are nested in social contexts. Some bilingual parents use a different language when addressing their child and when talking to each other, while other parents use both languages regardless of addressees. Thus, bilingual children may experience each language in different social contexts (Orena et al., 2020). Only few studies have considered this. In a case study of a two-year-old trilingual child (German-Spanish-English), the majority of Germen and Spanish input was directed to her, but English input was mostly overheard (Oller, 2010). The child produced more words in Germen and Spanish than in English, suggesting that the language(s) used in directed speech clearly had a greater impact on this child's vocabulary learning. Another study was based on a group of 11- and 14- month-old Spanish-English bilingual infants (Ramírez-Esparza et al., 2017b). Although 1:1 input in both Spanish and English was related to children's vocabulary size in the corresponding language, uniquely to Spanish, the group input was also related to children's Spanish vocabulary knowledge. The authors attributed this to culture differences, as Latino families tend to spend more time in group activities. Therefore, when assessing the relation between language input and bilingual development, it is important to consider the social contexts where the input in a specific language is more often received. Assuming that 1:1 input is predominantly in the child's dominant language and the non-dominant language is mostly overheard (Oller, 2010), I hypothesized that the effect of dominant language would be greater than the non-dominant language in 1:1 social contexts and the difference would be less evident in overhearing contexts. At the same cause, non-dominant language input would make a significant additional contribution in overheard contexts, but not in 1:1 social contexts.

2.3 Mixed-language Input

In this dissertation, mixed-language input refers to the input containing code-switching which is defined as the alternating use of two languages between sentences or within a sentence (Peynirciolu & Durgunolu, 2002). It is among the "qualitative aspects of the early bilingual environment that do not have monolingual analogues" (Byers-Heinlein, 2013, p. 33). It is common for bilingual caregivers to mix languages with their young children. For example, according to a survey conducted across bilingual communities in Vancouver, Canada, more than 90% of parents reported code-switching when speaking to their 1.5- and 2-year-olds (Byers-Heinlein, 2013). Observational studies further show that the frequency of language mixing varies greatly across families (Bail et al., 2015; Place & Hoff, 2011, 2016).

The frequency of parental code-switching usually increases with children's age or language knowledge, at least in the first two years of life. Kremin and colleagues studied French-English bilingual parental code-switching in naturalistic day-long recordings (Kremin et al., 2021). These parents code-switched around 7 times per hour and 6 times per 1000 words when talking to their 10-month-olds. By the time their children reached 18 months old, the frequency of parental code-switching per hour had quadrupled and the frequency per 1000 words had tripled. About half of the families had at least doubled their frequency of code-switching and no family reduced their use of code-switching. The authors also coded apparent reasons for parental code-switching. The reason of teaching new words increased remarkably as infants grew. Thus, caregivers increase their use of code-switching in tandem with and in support of their children's growing language knowledge (Bail et al., 2015; Kremin et al., 2021).

As code-switching serves certain purposes including to bolster understanding and to teach new words, it does not occur in random syntactic locations (Byers-Heinlein, 2013; Kremin et al., 2021). An evidently larger proportion of parental code-switching occurs between sentences instead of within a sentence, and this difference expands with age (Bail et al., 2015; Kremin et al., 2021). Empirical evidence shows that inter-sentential code-switching is less effortful to process than intra-sentential code-switching, even for adults (Byers-Heinlein et al., 2017; Gullifer et al., 2013).

Taken together, language mixing is a common phenomenon in bilingual families although its frequency varies. Overall, infants and toddlers' mixed-language input increases with age and includes more inter-sentential than intra-sentential code-switching. For these young bilinguals whose language skills are rapidly evolving, how does mixed-language input interplay with their language development?

Relatively little research has studied the relation between language mixing and child language development and so far, evidence is equivocal. While some studies have found that more exposure to language mixing is related to a smaller receptive vocabulary size (Byers-Heinlein, 2013; Carbajal & Peperkamp, 2020), others suggest a neutral relation especially when considering a wide range of language skills (Bail et al., 2015; Byers-Heinlein, 2013; Place & Hoff, 2011, 2016). As well, there is evidence suggesting that infants can benefit from mixed-language input (Bail et al., 2015; Place & Hoff, 2016). These studies will be reviewed in detail in the following sections.

2.3.1 Negative relation with children's language development

In 2013, Byers-Heinlein published the Language Mixing Scale (LMS) to measure parental language mixing via five short questions (Byers-Heinlein, 2013). In that same study, the author measured children's vocabulary size in the dominant language of the community (English) and found that, when infant age, gender, percentage of English input, and language balance were held constant, a higher rate of parent-reported language mixing was linked to a smaller receptive vocabulary size in 1.5-year-old children. Carbajal and Peperkamp found a similar pattern in 11-month-olds exposed to French and another language in France: Infants who encountered more language mixing by the same speaker within in a 30-minute block tended to have a smaller receptive vocabulary in French (Carbajal & Peperkamp, 2020).

These two findings suggest a negative association between mixed-language input and children's vocabulary development (in the dominant language of the community). A negative effect of language mixing is also supported by some experimental studies: Compared to single-language input, mixed-language input can be more effortful for infants and adults to process (Byers-Heinlein et al., 2017, 2022; Gross et al., 2019; Morini & Newman, 2019; Potter et al., 2019). The processing cost is more evident for intra-sentential language switches, especially switches from the dominant language to the non-dominant language. In looking-while-listening tasks, toddlers showed higher processing efforts when the target word was spoken in a different language from the proceeding words, indexed by pupil dilation and looking time at the matched picture (Byers-Heinlein et al., 2017; Morini & Newman, 2019; Potter et al., 2019). A recent study looking at the influence of language mixing on word learning showed that bilingual 3-year-olds, from both a French-English community in Canada and a Spanish-English community in America, failed to learn novel labels when the labels were heard in sentences with an intra-sentential language switch (Byers-Heinlein et al., 2022).

According to control theories regarding code-switching production (Inhibitory Control Model, Green, 1998; Green & Wei, 2014) and comprehension (Bilingual Interactive Activation Model, Dijkstra & van Heuven, 2002; Grainger et al., 2010), the switch cost observed in such studies might arise when one language must be inhibited in order to retrieve knowledge from the other language (Byers-Heinlein et al., 2017). Thus, processing mixed-language input could increase the demand of cognitive control for young infants: When code-switching occurs in their input, infants have to disengage one language and engage with the other language in a timely manner. Preliminary results showed that more parent-reported language mixing trended with less mature brain activation in 6-month-olds during a non-linguistic attention orienting task which required the ability to engage, disengage, and attention shift (Arredondo et al., 2021).

Language mixing might also disrupt the statistical regularities in the speech stream, which makes tracking and comprehend speech more difficult. According to the PRIMIR model (Processing Rich Information from Multidimensional Interactive Representations), bilingually-raised infants use learning mechanisms like compare-contrast, statistical learning, and co-occurrence patterns as well as sentence-level cues to track and discriminate two languages (Curtin et al., 2011). Based on their prior experience where most input is exclusively in one language or the other, infants anticipate the incoming words from their bilingual caregiver to be in the same language as preceding ones. When code-switching occurs, this prediction based on statistical regularities is violated and infants need to devote efforts to recover, which might temporarily impair processing and comprehension (Place & Hoff, 2016; Potter et al., 2019). As compromised comprehension accumulates over time, children might display a smaller vocabulary size than their peers until they overcome this challenge (Byers-Heinlein, 2013; Carbajal & Peperkamp, 2020). This processing cost can be higher if the switch is from the dominant language to the non-dominant language, since the prediction established from the preceding words is stronger because the infant is more familiar with the dominant language, and the recovery from the word in the non-dominant language is harder because the infant has less knowledge of that language (Byers-Heinlein et al., 2017; Potter et al., 2019).

Researchers have also proposed other potential challenges introduced by mixed-language input. For example, the highly-unbalanced use of two languages could make the process of inhibition-activation or prediction-recovery more difficult (Carbajal & Peperkamp, 2020). Mixed-language input might also contain a large proportion of accented speech (Place & Hoff, 2016). These factors might bolster the difficulties when processing mixed-language input, which helps explain the negative relation with child language development found by some researchers. However, other researchers argued that the negative relation was found because the Language Mixing Scale specifically measures intra-sentential language mixing which is more difficult to process (Place & Hoff, 2016). In reality, everyday mixed-language input might be less detrimental, given that most language mixing happens between sentences (Bail et al., 2015; Kremin et al., 2021).

2.3.2 Neutral relation with children's language development

Contrary to previous results, some findings suggest a null or trivial association between the amount of mixed-language input and children's language development. In Byers-Heinlein's cornerstone study, when demographic and linguistic factors were not statistically controlled, the zero-order correlation with Language Mixing Scores was not significant for children's receptive or expressive vocabulary size (Byers-Heinlein, 2013). For expressive vocabulary, the correlation was not significant even after controlling the demographic and linguistic factors. Using language diary methods, Place and Hoff also did not find a significant relation between the proportion of mixed-language input and a wide range of language skills (expressive vocabulary, grammatical complexity of children's productive language, mean length of utterances, auditory comprehension) in Spanish-English bilingual 2-year-olds (Place & Hoff, 2011, 2016). Due to their methodological choice, the definition of mixed-language input in Place and Hoff's studies was broader, requiring only that both languages were used within a 30-*minute* block no matter that the two languages were used by the same speaker or different ones. Applying a similar definition, Carbajal and Peperkamp also reported a non-significant correlation between language mixing usage within the same block regardless of speakers and 11-month-olds' receptive vocabulary size in both languages (Carbajal & Peperkamp, 2020).

To bridge this definition gap, in the more recent study, Place and Hoff administered the Language Mixing Scale and computed language mixing usage in a subset of blocks where the primary bilingual caregiver (mother) used both languages with the child (Place & Hoff, 2016). Neither index of mixed input was related to any language skills in their sample. Bail and colleagues counted parental code-switching during a 13-minute play session between a Spanish-English bilingual parent and their 18- to 24-month-old child in the laboratory (Bail et al., 2015). The frequency and proportion of *inter*-sentential code-switching was not related to children's total concept vocabulary or vocabulary size in either language. Note that in these two studies, researchers measured the mixed-language input received in a specific context where *one* caregiver interacted with the child. Language input received in *one-on-one* social contexts has an especially important role in children's language development (e.g., Ramírez-Esparza et al., 2017b; Ruan et al., 2020; Weisleder & Fernald, 2013). However, because Place and Hoff did not include one-on-one mixing from caregivers other than the mother and they did not explore its relation with children's language skills before breaking down to different language categories, the question remains open whether the social contexts where mixed-language input is received modulate its relation with language development.

There are several potential explanations for these different results compared to the previously-reviewed negative relations. First, although processing intra-sentential code-switching is effortful, studies typically do not find a processing cost if the switch is from the non-dominant language to the dominant language (Morini & Newman, 2019; Potter et al., 2019). Moreover, recall that bilingual 3-year-olds did not successfully learn and recall new labels from sentences with a mid-sentence code-switch (Byers-Heinlein et al., 2022). In the learning phase of this study, however, these young bilinguals had no problem following mixed-language sentences and accurately matching the new label with the novel object. Studies with preschool- and school-aged children also suggest that intra-sentential language mixing does not affect children's offline processing: they do not make more mistakes in answering comprehensive questions when the message contains intra-sentential code-switches (Gross et al., 2019; Peynirciolu & Durgunolu, 2002). More importantly, no processing cost has been found for processing *inter*-sentential code-switching which is much more common in bilingual infants' everyday input (Byers-Heinlein et al., 2017; Gullifer et al., 2013; Kremin et al., 2021). Finally, work that looked at code-switching at other syntactic locations, for example an uninformative pronominal adjective (e.g., "Look at the *le bon* duck."), found no evidence that children are slower to process this type of code-switching (Kremin et al., 2022). In fact, a subset of children performed better in the code-switched condition.

The absence of processing cost for many types of code-switched constructions might indicate that most children can cope with the cognitive demands posed by language mixing. For instance, children's early event-related potential (ERP) and looking time while listening to code-switches reveal that young bilinguals pay greater attention to upcoming speech and they are faster in detecting language changes compared to monolinguals (Kuipers & Thierry, 2012, 2015; Mattock et al., 2010). Another study showed that the relation between parent-reported language mixing and children's language skills was modulated by children's verbal working memory (Kaushanskaya & Crespo, 2019). Specifically, for seven-year-olds with higher verbal working memory, higher exposure to code-switching was related to better language abilities, while for children with lower verbal working memory, higher exposure to code-switching was associated with lower levels of language ability. However, the causality is uncertain as it could be that better working memory helps children processing code-switching, or higher exposure to code-switching bolsters their working memory.

Potential mixing costs might also be compensated by contextual factors. One study showed that when bilingual adults were habituated in a bilingual mode (both languages were represented with similar frequency within a block), the switch cost observed in monolingual mode (the majority of utterances was in one language within a block) disappeared (Olson, 2017). In other words, bilingual adults were able to establish new statistical regularities from prior exposure to language mixing, which reduced or even eliminated processing costs. Evidence shows that infants as young as eight months can compute statistical regularities in the input after only a few-minute exposure (Saffran et al., 1996), and bilinguals might be particularly adept at processing statistical regularities from two languages (Antovich & Graf Estes, 2018; Benitez et al., 2020; Orena & Polka, 2019).

Processing costs can also be modulated by children's language knowledge. Recall the asymmetric processing demand (Byers-Heinlein et al., 2017; Potter et al., 2019), which might be caused by children's lower familiarity with the non-dominant language. Indeed, with an increase in exposure or knowledge of the non-dominant language, children's comprehension of mixed-language information also improves (Gross et al., 2019; Read et al., 2021). Thus, more balanced knowledge of two languages might reduce the prediction bias favoring the dominant language and accelerate the retrieval of lexical knowledge in the non-dominant language.

Furthermore, some researchers have questioned whether a processing cost is involved at all in mixed-language comprehension. Kohnert, Bates and colleagues tested participants across a wide age range (5-year-olds to adults) with a timed picture-word verification task (comprehension) and a picture-naming task (production) in mixed- and single-language conditions (Kohnert et al., 1999; Kohnert & Bates, 2002). They found a switch cost only for the production task but not the comprehension task. In more recent systematic reviews and meta-analyses, collective evidence seems to also disfavor the involvement of switch or mixing cost in mixed-language comprehension and even production (Blanco-Elorrieta & Pylkkänen, 2018; Declerck, 2020; Gade et al., 2021).

Processing costs aside, although most bilingual parents mix languages, mixed-language input makes up, on average, a relatively small proportion of infants and toddlers' total input (Kremin et al., 2021; higher mixed input proportions reported in some studies, see Place & Hoff, 2011, 2016), which restricts its interaction with child language development. In previous empirical studies, parent-reported language mixing was not associated with children's ability to process mixed-language information, which might further explain the neutral relation between mixed-language input and child language development (Byers-Heinlein et al., 2022; Orena & Polka, 2019; Potter et al., 2019; Read et al., 2021; Schott et al., 2021).

2.3.3 Positive relation with children's language development

There is also evidence suggesting a positive relation between mixed-language input and children's language development (Bail et al., 2015; Place & Hoff, 2016). For example, Bail and colleagues reported that the frequency and proportion of *intra*-sentential code-switching over a 13-minute play session was positively related to toddlers' total and conceptual vocabulary size in two languages (Bail et al., 2015). Recall that Place and Hoff tagged 30-minute time blocks where both languages were used either within or across speakers as mixed blocks (Place & Hoff, 2016). Due to their broad definition, mixed blocks were the most frequent type of input in their sample, accounting for nearly half of total blocks. They further categorized these mixed blocks into English-dominant, Spanish-dominant, and balanced blocks. The exposure to English-dominant mixed blocks was positively linked to these 30-month-olds' English language skills. The relation remained significant after removing the effect of the English-only blocks. Thus, the authors argued that children can benefit from language exposure even when it was provided in mixed-language contexts.

At least two pathways could explain this positive association between mixed-language input and child language development. First, when mixing languages, parents do not intend to increase cognitive demands for their child and are often trying to help their child understand their conversation and learn new words. According Kremin and colleagues' coding scheme, over 70% of parental code-switching was attributed to the use of a translation equivalent or facilitating comprehension (Kremin et al., 2021). In Byers-Heinlein (2013), nearly half of the parents reported that they switched languages to teach their child a new word, which aligns with findings from observational studies (Bail et al., 2015; Kremin et al., 2021). Researchers interpret these findings as parents' effort to support their child's successful acquisition of both languages. Indeed, presenting a word in a context instead of in isolation helps infants recognize the word (Fernald & Hurtado, 2006). For bilingually-raised infants, a carrier sentence in the language that is more familiar to infants can help them recognize the target word in the less-familiar language (Gross et al., 2019), despite a potential processing cost (Byers-Heinlein et al., 2017; Potter et al., 2019). Research found that 8- and 10-month-old infants with more mixed-language exposure segmented words in both languages while their peers with less mixed-language exposure only segmented words in their dominant language (Orena & Polka, 2019). Preschoolers also benefit from language bridging in the classroom (use of translation in children's first language to teach new words in the second language) and reading code-switching books over immersive books to acquire a second language (Brouillard et al., 2020; Read et al., 2021).

Another possible pathway is that parents adjust their use of language mixing according to their children's language capability (Bail et al., 2015). It is not uncommon for parents to change the quantity and quality of their speech to adapt to their child's status and needs (see review in Saint-Georges et al., 2013). As for language mixing, previous research showed that the frequency of parental code-switching increased with infant age (Kremin et al., 2021). Parents of a child with a larger vocabulary size might use more code-switching, assuming their child is equipped with sufficient lexical knowledge to process and comprehend their conversation. Parents might also generally use longer sentences which creates more chances for intra-sentential code-switching (Bail et al., 2015).

Overall, the relation between mixed-language input and child language development is complex and the existing, limited data shows mixed findings. Some potential impactors mentioned above should be considered, such as child age, input collection approaches (questionnaire or recording), input measurement (frequency, proportion, or parent-reported score), language balance, social contexts where mixed-language input is received, and measures of child language outcome. Therefore, in this dissertation, I investigated the relation between infant volubility and mixed-language input indexed by parent-reported scores as well as proportions and raw counts in global and one-on-one social contexts observed in naturalistic day-long recordings. I also examined mixed-language input's unique contribution beyond demographic and linguistic factors including child age, language balance, and total input that was accessible to infants. The complex nature of the relation between mixed-language input and child language development as well as the mixed findings in previous studies prevented me to make a strong prediction of my analysis.

3. Input Measurements

Measuring language input, especially for infants growing up in bilingual environments, is challenging. Some researchers have used diaries and questionnaires completed by caregivers to estimate the proportion of each language in a child's input (Carbajal & Peperkamp, 2020; Place & Hoff, 2011, 2016). Other researchers have documented children's real-world language input using audio- or video-recordings. In recent years, a growing number of researchers and clinicians have adopted the LENA system (Language ENvironment Analysis, LENA Research Foundation, Boulder, CO) to obtain and process day-long audio recordings of language input in bilingual households (Marchman et al., 2017; Orena et al., 2020; Ramírez-Esparza et al., 2017a, 2017b; VanDam et al., 2016). The LENA system includes a recorder which children can wear in a vest and algorithms that automatically process and estimate language input by adult word counts (AWCs) or speech duration. Researchers have tested LENA's accuracy in different languages and have found most LENA estimates to be reliable (Cristia et al., 2020, 2021; Orena et al., 2020).

Although the ways to measure input have expanded rapidly, there are many unresolved issues. First, various units have been used to measure bilingual input. Some researchers, using diary or recording methods, divide the time in a day into equal-sized segments and count the number of segments or segment durations where each language was used (e.g., Place & Hoff, 2011, 2016; Ramírez-Esparza et al., 2017a, 2017b). However, bilingual caregivers do not always use the same language for a given segment. Thus, some researchers ask caregivers to estimate the proportion of time that each language was used within a segment (Carbajal & Peperkamp, 2020). This approach still overlooks the fact that caregivers might not continuously speak for the length of a segment. With the introduction of algorithms, more fine-grained units, such as speech duration or AWCs extracted from recordings, have been used in some studies (e.g., Marchman et al., 2017; Ruan et al., 2020). It is, however, unclear how (or if) the specific unit impacts input estimation as research has not yet examined how well these measures align with each other.

Another unresolved issue is that algorithms are so far unable to automatically and reliably categorize bilingual input into two languages; this task therefore requires manual coding. Manually coding day-long recordings is laborious. Thus, there is an urgent call to find an effective and reliable sampling method which allows researchers and clinicians to achieve their goals by processing only a portion of their data. Research showed that the proportion of input in each language estimated in a periodically-selected (e.g., every-other-segment) sample was correlated with parental estimation (Orena et al., 2020). A decent portion of randomly-selected data also reached a stable estimation of bilingual exposure (Cychosz et al., 2021). Other more conscious sampling methods have also been used. For example, researchers selected 40 temporally-scattered segments with the highest AWCs each day and composed a sample of around 160 top segments across four days for each child (Ramírez-Esparza et al., 2017b). However, there are concerns whether children's typical language exposure is accurately represented in the recordings of peak hours where speakers are the most active (Bergelson et al., 2019; Tamis-LeMonda et al., 2017).

Accuracy aside, researchers and clinicians may deploy peak hours for different objectives. For many bilingual children, input in their dominant and non-dominant language naturally differs in quantity, thus it can be difficult to tease apart qualitative (i.e., dominancy) from quantitative aspects of each language when examining bilingual input's relation with children's language skills. However, selecting the same number of segments and selecting the ones with the densest input for each language, strategically controls for quantity and enables researchers and clinicians to focus on how input's quality interacts with language development (Xu et al., 2019).

Therefore, in this dissertation, I examined the alignment between input measures indexed by different units (Adult Word Counts, speech duration, segment counts) and using different sampling methods (every-other-segment, top-segment). I also compared infant overall volubility's relation with input measured by each approach.

4. The Current Study

In this dissertation, to examine the relation between infant volubility and language input received in different social and language contexts, I analyzed infant vocalizations and language input in the naturalistic day-long recordings from the Montréal Bilingual Infants (MBI) corpus

(Orena et al., 2020). In Chapter 2 to 4, I studied infant overall and local volubility's relation with input in different social contexts (Chapter 2), with English- and French-only input (Chapter 3), and with mixed-language input (Chapter 4). In Chapter 5, I assessed the alignment between input measures estimated by different units and sampling methods.

CHAPTER 2

INFANT VOLUBILITY AND INPUT IN DIFFERENT SOCIAL CONTEXTS

In Chapter 2, my goal was to examine the relation between infant volubility and language input received in different social contexts. I examined language input's relation with the number of infant vocalizations produced in the presence of adult speech within a specific social context (i.e., local volubility) as well as with the number of infant vocalizations produced throughout the day (including both interactive and endogenous vocalizations, i.e., overall volubility). With infants' overall volubility, I also examined how this volubility-input relation varied across different social contexts (1:1 v.s. overhearing) and whether overheard input made additional contribution beyond 1:1 input. I also looked at infant overall volubility's longitudinal relation with language input over an eight-month time lag.

Locally, I expected the correlation between infants' and caregivers' vocalizations produced in the same context to be strong and significant, given that infants and caregivers mutually stimulate vocalizations from each other (Goldstein et al., 2003; Hsu & Fogel, 2001; Warlaumont et al., 2014). Based on previous findings using standardized language assessments and volubility (Ramírez-Esparza et al., 2017b; Xu et al., 2019), I expected correlations with infant overall volubility to be significant for children's global and 1:1 input. As well, given the empirical evidence showing that children can benefit from overhearing conversations between others (Akhtar, 2005b; Floor & Akhtar, 2006), I expected that overheard input would make a significant *additional* contribution to infant overall volubility, especially at 18 months when infants have more mature mobility and language skills. Lastly, based on previous longitudinal evidence (Ramírez-Esparza et al., 2017b; Song et al., 2012), I expected longitudinal relations to follow the same pattern as the concurrent ones.

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Methods

Participants. I analyzed data from twenty-one bilingual families in the Montréal Bilingual Infants (MBI) corpus (Orena et al., 2020). Families were first recruited when the infant was 10 months old for another experiment at our laboratory (13 males, 8 females; Age *Mean* = 303 days, *Range* = 289 – 319 days). Sixteen of these families participated again when the child was at 18 months (10 males, 6 females; Age *Mean* = 576 days, *Range* = 551 – 635 days). Families were from mid- to high-socioeconomic backgrounds (*Mean* = 52.2, *Range* = 31 – 66, out of a possible score of 66, Hollingshead, 1975). Parental consents were obtained during their initial visit. Parents declared no auditory and neurocognitive disorders for their child.

Procedure and Measures.

***Language Background*.** The Language Exposure Questionnaire (Bosch & Sebastián-Gallés, 2001) was administrated via Multilingual Approach to Parent Language Estimates (MAPLE, Byers-Heinlein et al., 2019) to obtain language background information for each child. All caregivers had knowledge of both French and English and their self-rated proficiency was high for French (Mean = 9.4, Range = 5.7 – 10) and for English (Mean = 9.2, Range = 6.3 – 10). According to parents, every child had at least 20% exposure to French and to English. Four families reported a very small amount of exposure (< 5%) to a third language (Arabic, Kannada, Portuguese, and Spanish). Previous analyses showed that caregivers reliably estimated children's proportional language input in day-long recordings (Orena et al., 2020). In the 10-month-old sample, twelve infants were raised in a French-dominant environment and nine were English-dominant. At 18 months, eight were French-dominant and eight were English-dominant (see Orena et al., 2020 for details).

Naturalistic Day-long Recordings. Naturalistic audio recordings were collected by a LENA digital language processor which the infant wore in a vest for 16 hours per day. Parents were instructed to leave the device on until it automatically stopped recording after 16 hours. Three full-day recordings (two weekdays and one weekend day) were made when infants were 10 months old. Previous analyses showed that the proportions that caregivers used each language were consistent on weekdays and weekend (Orena et al., 2020). For 16 of these families, a fourth recording was completed on a weekend day when infants were 18 months old. A weekend day was chosen at 18 months because at this age most of the infants were enrolled in a daycare during weekdays. In total, the families provided 1,264 hours of audio recordings (21 families at 10 months × 3 days × 16 hours + 16 families at 18 months × 1 day × 16 hours). Recordings were then processed by LENA algorithms which derived Child Vocalization Counts (CVCs) and Adult Word Counts (AWCs).

*Infant Volubility***.** Infant volubility was estimated by LENA-generated CVCs. A child vocalization is defined as a speech/speech-like sound produced by the key infant that is preceded and followed by 300 milliseconds of silence or nonspeech. Infant cries, vegetative, and other fixed signals are excluded from this estimate. Infant volubility was measured at two levels: overall and local. I summed CVCs in the entire LENA recordings for each child on each day as infant *overall* volubility (Figure 1). Thus, overall volubility includes infant vocalizations produced in the presence of adult speech and when alone. *Local* volubility referred to the number of vocalizations that an infant produced in the presence of a certain type of input (see below for how different types of input were coded).

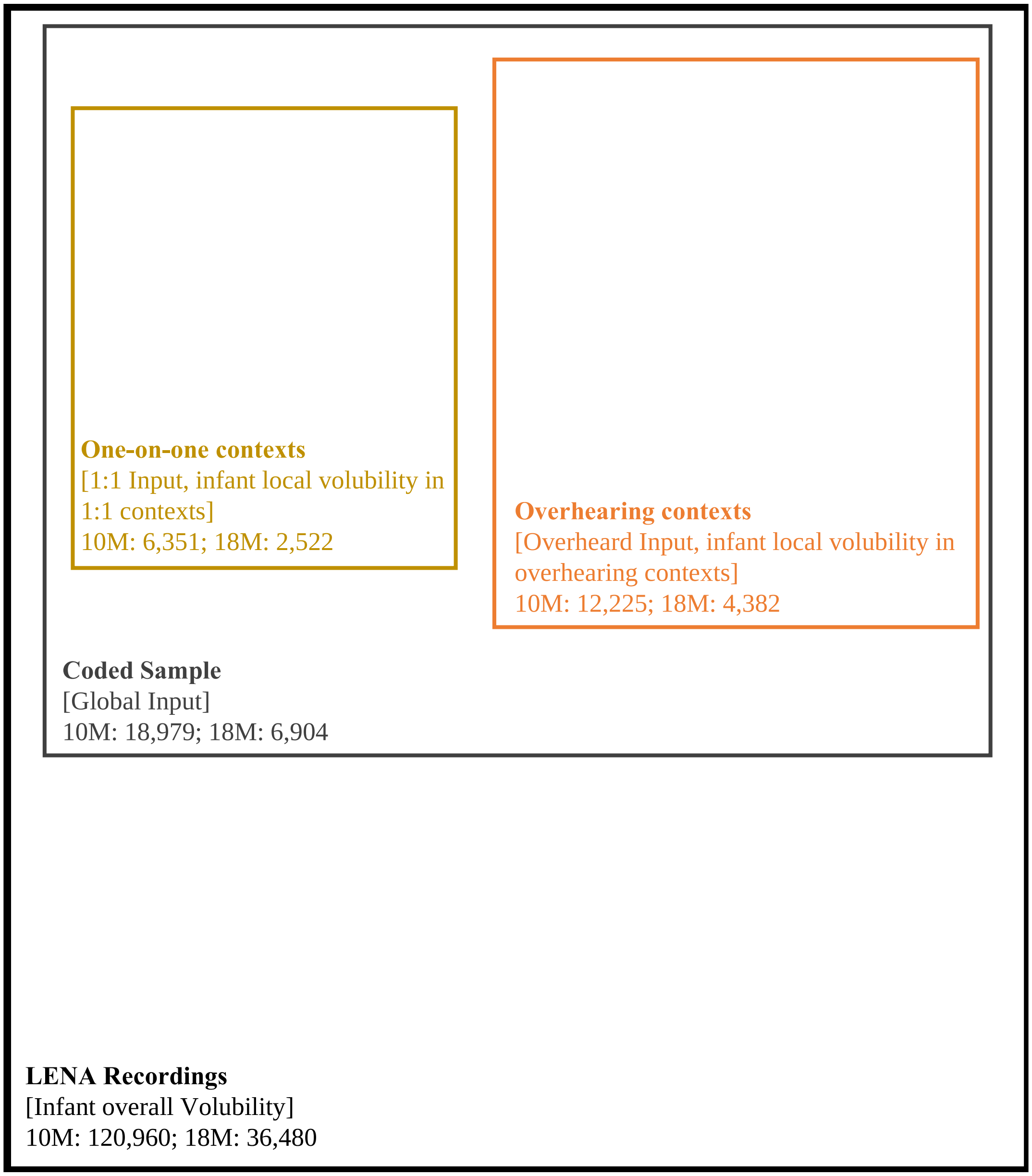

Figure 1

The structure of the Montréal Bilingual Infants corpus, the number of segments included in each sample, and variables used in Chapter 2 (10M: 10 months; 18M: 18 months; note that the boxes are not scaled to accurately show the relative size of the samples).

*Language Input in Different Social Contexts***.** LENA algorithms also estimate the number of words spoken near the key child (Adult Word Counts, AWCs). I used AWCs to index input in this chapter because it is a fine-grained unit that has been used in other studies (e.g., Marchman et al., 2017). As the input in the MBI corpus were bilingual, previous research showed that LENA algorithms reliably estimate AWCs in both English and French (Orena et al., 2019).

To prepare for data coding, the recordings were re-organized into 30-second segments and then were matched with LENA-generated measures. As the research goal was to code caregivers' speech, I focused on the segments containing AWCs (Figure 1). Previous study suggested that coding a sample that included every other segment was representative of a child's full-day exposure (Orena et al., 2019). Thus, in the next step, trained English-French bilingual research assistants manually coded every other segment. They listened to each segment and coded for social contexts (i.e., how many speakers and listeners, who was speaking and to whom) and language contexts (i.e., what language was being spoken). Seven research assistants completed this work after each of them successfully completed a training file. Inter-coder reliability in the training file was high across coders (on average 94.2% match for speaker contexts and 92.4% match for language contexts; see Orena et al., 2020 for details). In total, 18,979 and 6,904 segments were completely coded for 10- and 18-month sample respectively. A summary of the number of segments in each sample and context can be found in Figure 1.

Global social contexts included all speech in the coded sample. In *One-on-one (1:1)* social contexts, one caregiver (mother, father, nanny, older siblings, and others) talked to the infant. *Overhearing* social contexts were where caregivers talked in the presence of the infant but were not directly addressing the infant. The coding also included a group context where two or more caregivers talked to the infant. However, I observed very few segments with group input

(403 in the 10-month sample, 0 in the 18-month sample). This might be due in part to that when others (outside the immediate family) were present, parents were asked to obtain their consent, which may have discouraged group activity for some families on the recording day. Thus, group context was not included in the social context comparisons.

Statistical analysis.

Statistical analysis was conducted at R platform (v4.1.2, R Core Team, 2021), using packages including lme4 (v1.1-27.1, Bates et al., 2021), effectsize (v 0.6.0.1, Ben-Shachar et al., 2020), cocor (v1.1-3, Diedenhofen & Musch, 2015) and ppcor (v1.1, Kim, 2015). All volubility and input measures at 10 months were standardized to "per day" (i.e., divided by three days) to be comparable to those at 18 months. Although the CVCs at both ages was not normally distributed (Shapiro-Wilk $Ws = 0.83$, $p < .05$), I decided to proceed with Pearson's correlations to retain the real size of variation. Spearman's correlations were used when the input measure also failed the normality test. The *p*-values reported in the Chapter 2 and 3 were adjusted using method of Benjamini & Hochberg (1995). Data and analysis codes are available at http://osf.io/wjnaq.

Local analysis. First, I examined how well caregivers' input was related to infants' vocalizations produced within the same context. Thus, for each child at each age, I summed the CVCs and AWCs in the coded sample by social contexts (1:1 and overhearing). Correlations between these *local* volubility and input measures were then computed within each context. Cohen suggested that *r* values of 0.1, 0.3, and 0.5 represented small, medium, and large effect sizes, respectively (Cohen, 1988), and I followed this convention.

Concurrent analysis. Next, I investigated how input was related to infants' overall volubility, the measure of infant vocalizations produced in the presence of adult speech and when infants were alone. Infant overall volubility was correlated with the total amount of coded input (global input) at each age.

Comparisons between social contexts. Infant overall volubility was correlated with input received in 1:1 and overhearing social contexts respectively at each age. Correlation coefficients were then compared between social contexts at each age, using Fisher's z transformation followed by Z tests (Meng et al., 1992).

Next, I tested the additional contribution of overheard input to infant overall volubility beyond 1:1 input at each age. To do so, I compared the linear regression model including both 1:1 and overheard input to the model with only 1:1 input. I computed the change in the variations explained by the models (ΔR^2) as the unique contribution of overheard input to infant overall volubility and its effect size f^2 (Cohen, 1988). Cohen suggested that f^2 values of 0.02, 0.15, and 0.35 represented small, medium, and large effect sizes, respectively (Cohen, 1988).

Longitudinal analysis. I used infants' volubility at 10 months to predict the amount of input they received at 18 months, as well as the amount of input received at 10 months to predict infant volubility at 18 months. The corresponding input measure or infant volubility at 10 months was statistically controlled.

Results

Descriptive results are presented in Table 1. Exploratory analyses showed that at each age, infant volubility and language input was not correlated with infants' age (in days), sex, or socioeconomic status (p-values were above adjusted α). Correlations between *local* volubility and input within different social contexts were first presented (Figure 2). I then reported the concurrent relation between language input and infant *overall* volubility. These correlations were compared between 1:1 and overhearing social contexts (Table 2). Lastly, I reported findings from longitudinal analyses.

1. Local relations

Infant local volubility is the sum of vocalizations that infants produced in the presence of adult speech in a specific social context (1:1 or overhearing). I correlated infant local volubility with the amount of input received in the same context. Significant correlations with large effect sizes were observed for both social contexts and at both ages (Figure 2). These findings suggested that infants and caregivers' vocalization produced locally within the same context were positively and strongly correlated.

2. Concurrent relations

Infant overall volubility, the number of infant vocalizations (per day) in entire LENA recordings at each age, was correlated with coded input (per day) received at the same age. As shown in Table 2 (Global), infant overall volubility was significantly and positively correlated with their global input at both ages. The effect sizes of these correlations were uniformly large. The finding suggested that globally, infant volubility and language input was positively and strongly correlated.

3. Concurrent relations: comparisons across social contexts

The correlation with infant overall volubility was large in effect size for 1:1 input at both ages and overheard input at 10 months (Table 2). The adjusted *p*-value reached the significance for 1:1 input at 10 months. Correlations were not reliably different across social contexts at either age. Follow-up linear regressions showed that overheard input explained an additional 18% and 43% of the variation in infant overall volubility beyond 1:1 input at 10 and 18 months respectively, and the adjusted *p*-value reached significance at 18 months. These findings suggested that more 1:1 input was related to higher infant overall volubility at 10 months and overheard input made a unique contribution to infant overall volubility at 18 months.

4. Longitudinal relations

So far, I have examined the volubility-input relation when both variables were measured at the same age. Here, I investigated this relation longitudinally. When input received in corresponding social contexts at 10 months was statistically controlled, higher overall volubility at 10 months was related to less overall 1:1 input (r (13) = – .76, $p < .001$) but more overheard input at 18 months (r (13) = .64, $p = .011$). Other partial correlations were not significant. I also used the input received at 10 months to predict infant overall volubility at 18 months when infant volubility at 10 months was statistically controlled, but none of the partial correlations reached significance.

Table 1

Summary of infant volubility and language input measures in different social contexts. Means (Range) are provided at each age (10 months: N = 21, 18 months: N= 16).

Age	**Infant Volubility (CVCs, *per day*)**	
	Overall Volubility *(per day)*	
10-Month	1071 (706 – 2472) [1]	
18-Month	2005 (899 – 6968) [1]	
	Local Volubility *(per day)*	
	One-on-one	**Overhearing**
10-Month	138 (44 – 555) [1]	182 (75 – 587) [1]
18-Month	432 (85 – 1157)	455 (99 – 2184) [1]
Age	**Language Input (AWCs, *per day*)**	
	Global Social Contexts	
10-Month	7119 (3225 – 13831)	
18-Month	10784 (3399 – 26096)	
	One-on-one Social Contexts	
10-Month	1830 (652 – 3416)	
18-Month	3916 (283 – 10018)	
	Overhearing Social Contexts	
10-Month	5163 (1784 – 11420)	
18-Month	6181 (1582 – 21242) [1]	

Note:

[1] Median is reported for this variable which failed the normality test.

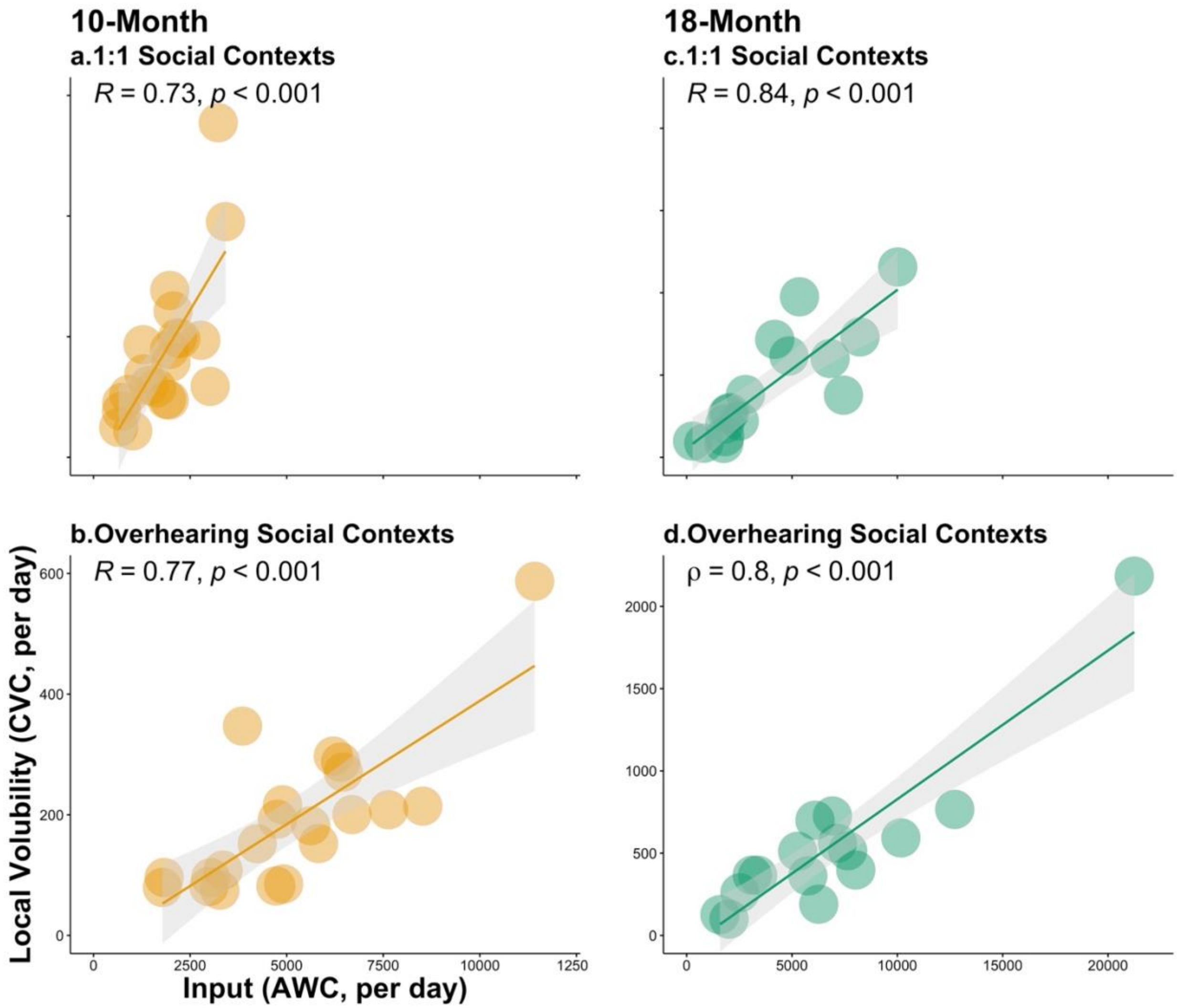

Figure 2

Local relations between infant local volubility and language input in function of social contexts (One-on-one (1:1): a & c; Overhearing: b & d) and age (10 months: a & b, 18 months: c & d). Yellow dots represent 10-month-olds and green dots represent 18-month-olds.

Table 2

Concurrent correlations between infant overall volubility and input in different social contexts at each age (10 months: N = 21, 18 months: N= 16).

	Social Context Comparison						
	Global	**One-on-one**	**Overhearing**	**Comparison**	**Additional contribution from overheard input?[4]**		
				z	F	ΔR^2	f^2
10-Month	.61*	.52*	.50	.10	5.79	18%	.32
95% CI[1]	[.24, .82]	[.12, .78]	[.08, .77]	[− .61, .68]			
p-values[2]	.011	.037	.050	.942	.057		
18-Month	.81***	.50	.19[3]	.85	17.55**	43%	1.35
95% CI	[.53, .93]	[.01, .80]		[− .47, 1.18]			
p-values	<.001	.089	.581	.518	.004		

Note: * $p < .05$; ** $p < .01$; *** $p < .001$.

[1] 95% CI – 95% confidence intervals. 95% CI is only available for Pearson's correlations, but not for Spearman's rank correlations.

[2] *p*-values are adjusted using method of Benjamini & Hochberg (1995).

[3] Spearman's rank correlation: *rho* = .19, Pearson's correlation: r (14) = .61, p = .012.

[4] To test the additional contribution of overheard input to infant overall volubility beyond 1:1 input, I compared the linear regression model including both 1:1 and overheard input to the model with only 1:1 input. ΔR^2 is the difference between the variation in infant overall volubility explained by the independent variables included in these two models.

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Discussion

In summary, the analyses in this chapter revealed at least the following findings: (1) At both ages, I found a robust association between infant local volubility and language input within each social context; (2) With respect to overall volubility, higher concurrent volubility was related to more global input at both ages and more 1:1 input at 10 months; (3) Overheard input at 18 months made a unique contribution to infant overall volubility; (4) When input received in the corresponding social context at 10 months was statistically controlled, higher overall volubility at 10 months was related to less overall 1:1 input but more overheard input at 18 months.

The results indicate a robust association between language input and infant volubility throughout infancy and toddlerhood. First, within both social contexts, more infant vocalizations (i.e., local volubility) are coupled with more vocalizations from caregivers. This finding aligns with previous research that independently from using parentese or contingency, more parental responses is related to increased rate of infant vocalizations (e.g., Goldstein et al., 2003; Goldstein & Schwade, 2008). The local analyses extend the existing findings by showing that this tight and positive association emerges not only in 1:1 interaction but also in overhearing contexts.

Recall that in local analyses, only infant vocalizations produced in the presence of adult speech were considered. When considering both interactive and endogenous vocalizations, namely *overall* volubility, this strong and positive volubility-input relation stands. These findings together supplement our existing knowledge by showing that language input from caregivers links not only to infants' volubility during dyadic interaction (e.g., Goldstein et al., 2003; Goldstein & Schwade, 2008) but also to their general vocal activeness. This input-volubility relation particularly emphasizes the communicative values of infants and caregivers' vocalizations (Hoff, 2006). This utterance-to-utterance quantitative relation between language input and infant vocalizations cannot be established otherwise.

I also found that more input in 1:1 social contexts at 10 months was related to higher concurrent overall volubility. It aligns with previous findings focused on bilingual children's vocabulary development (Ramírez-Esparza et al., 2017a, 2017b). The 1:1 input is particularly impactful because during the dyadic interaction, caregivers and infants are more likely to share the same attentional focus and positive emotions (Polka & Ruan, 2021; Saint-Georges et al., 2013; Soderstrom, 2007), as well as to respond to each other's vocalizations (Athari et al., 2021; Goldstein et al., 2003; Goldstein & Schwade, 2008; Gros-Louis et al., 2014, 2016; Gros-Louis & Miller, 2018; Lopez et al., 2020; Miller, 2014; Miller & Gros-Louis, 2013; Miller & Lossia, 2013; Pretzer et al., 2019; Tamis-LeMonda et al., 2001; Van Egeren et al., 2001; Warlaumont et al., 2014; Yoder et al., 2001).

Findings from this chapter highlight the unique contribution of overheard input to infant overall volubility. As expected, overheard input makes a significant and large-sized contribution to infant volubility beyond 1:1 input at 18 months. Overheard input might contribute to infant volubility in a different way from 1:1 input. Studies found that infants produced more vocalizations when their caregivers' attention was not on them (Iyer et al., 2016; Shimada, 2012). Thus, overhearing contexts might provide children a space for spontaneous vocal exploration. Overhearing contexts also contributes to child language development by being a ubiquitous source of language input for young children. In the 18-month sample, overheard input is nearly twice as much as 1:1 input (Table 1). These findings echo empirical research which has shown that infants can benefit from overheard input through tuning in to the attentional focus of others (Akhtar, 2005b; Akhtar et al., 2001; Floor & Akhtar, 2006; Gampe et al., 2012; Martínez-

Sussmann et al., 2011; Oshima-Takane, 1988; Oshima-Takane et al., 1996; Shneidman et al., 2009) or simply by passive exposure (Au et al., 2002; Pierce et al., 2014, 2015; Saffran et al., 1996; Singh et al., 2011). Compared to previous studies that suggested a limited contribution of overheard input (Shneidman et al., 2013; Shneidman & Goldin-Meadow, 2012; Weisleder & Fernald, 2013), in this dissertation, I adopt a different approach to assess overheard input's role by quantifying its *relative* contribution beyond 1:1 input. Moreover, I argue that overheard input might have been more accurately measured in the current study as I used day-long recordings and fine-grained coding units (30-second segments), and kept all distant speech captured by LENA recorders.

Furthermore, findings suggest that the relative role of overheard input appears to be more salient with age. There are two possible interpretations. First, 18-month-olds might have accumulated more experience of overheard input, which help them benefit from overhearing conversations among others (Chavajay & Rogoff, 1999; Oshima-Takane et al., 1996; Shneidman & Woodward, 2016). Second, infants' mobility and language skills have improved at 18 months, so they are more likely to expand their active zone and seek opportunities of being part of polyadic interactions which presents more chances to overhear conversations between others. Together, the recognition of additional contribution from overheard input can help us obtain a comprehensive picture of language environment and build a better understanding of the language acquisition process for children regardless of language backgrounds (Soderstrom, 2007; Sperry et al., 2019b).

Longitudinally, higher volubility at 10 months old was related to less 1:1 input and more overheard input at 18 months, when caregivers' verbal activeness in the same language and social contexts at 10 months was statistically controlled. These findings are exploratory but I may speculate that one's vocal behaviour can influence the other's vocal behaviour not only at concurrent, but also across an eight-month time lag (Hsu & Fogel, 2003). Caregivers might adjust their communicative strategy according to their child's vocal activeness. When they perceive their 10-month-old as verbally active and mature, caregivers might reduce their time in dyadic interactions and give their child more space for self-exploration. Alternatively, it might be these verbally-active children who lead this change via actively seeking opportunities to take a part in polyadic interactions. Analyses in this dissertation cannot answer which party or both parties is/are driving this change. Future studies could answer this question by closely examining the recordings across two ages or by interviewing caregivers. Limitations and future directions will be discussed in Chapter 6.

In conclusion, findings from this chapter indicate a strong and robust association between language input and infant local and overall volubility. Consistent with previous research, 1:1 input appears to be particularly impactful to infant language development. Findings from this chapter further highlight the significant additional contribution of overhearing input.

All of the infants participated in the MBI corpus were growing up in bilingual families and were receiving input in two languages simultaneously. For some children, they heard languages in different proportions across different social contexts (Orena et al., 2020). My discoveries as how input in different languages is related to infant local and overall volubility and how this relation varies across social contexts will be presented in Chapter 3.

CHAPTER 3

INFANT VOLUBILITY AND INPUT IN DIFFERENT LANGUAGE CONTEXTS

In Chapter 3, my goal is to examine the relation between infant volubility and input in the child's dominant and non-dominant languages. Same as in Chapter 2, I examined language input's relation with the number of infant vocalizations produced in the presence of adult speech within a specific language context (i.e., local volubility) as well as with the number of infant vocalizations produced throughout the day (i.e., overall volubility). With infants' overall volubility, I compared the volubility-input relation between the dominant and non-dominant language in different social contexts (global, 1:1, and overhearing) and investigated whether non-dominant language input made an additional contribution beyond dominant language input. I also examined these volubility-input relations over an eight-month time lag.

Locally, I expected the correlation between infants' and caregivers' vocalizations produced in the same context to be strong and significant, given that infants and caregivers mutually stimulate vocalizations from each other (Goldstein et al., 2003; Hsu & Fogel, 2001; Warlaumont et al., 2014) and the significant local relations found in Chapter 2. Based on previous findings using standardized language assessments and volubility (Ramírez-Esparza et al., 2017b; Xu et al., 2019), globally, I expected correlations with infant overall volubility to be significant for the amount of input in the infant's dominant language. Assessing the effect of language dominancy across different social contexts is exploratory. However, assuming that 1:1 input was predominantly in the infant's dominant language and the non-dominant language was mostly overheard (Oller, 2010), I expected infant overall volubility's relation with dominant language input to be stronger (than the non-dominant language) in 1:1 contexts whereas the relation with non-dominant language input to be stronger in overhearing contexts. At the same cause, the additional contribution of non-dominant language would be significant in global and overhearing contexts but not in 1:1 contexts. Lastly, based on previous longitudinal evidence (Ramírez-Esparza et al., 2017b; Song et al., 2012), I expected longitudinal relations to follow the same pattern as the concurrent ones.

Methods

Participants and Procedure. Identical as described in Chapter 2.

Measures.

***Language Dominance*.** The Language Exposure Questionnaires (Bosch & Sebastián-Gallés, 2001) was administrated via Multilingual Approach to Parent Language Estimates (MAPLE, Byers-Heinlein et al., 2019) to obtain language background information for each child. For each child, their *dominant* language was the language (French or English) that they had higher exposure to according to *parental reports*. Previous analyses showed that caregivers reliably estimated children's language input in day-long recordings (Orena et al., 2020). In the 10-month-old sample, twelve infants were raised in a French-dominant environment and nine were English-dominant. At 18 months, eight were French-dominant and eight were English-dominant (see Orena et al., 2020 for details).

***Naturalistic Day-long Recordings*.** Identical as described in Chapter 2.

*Infant Volubility***.** Identical as described in Chapter 2.

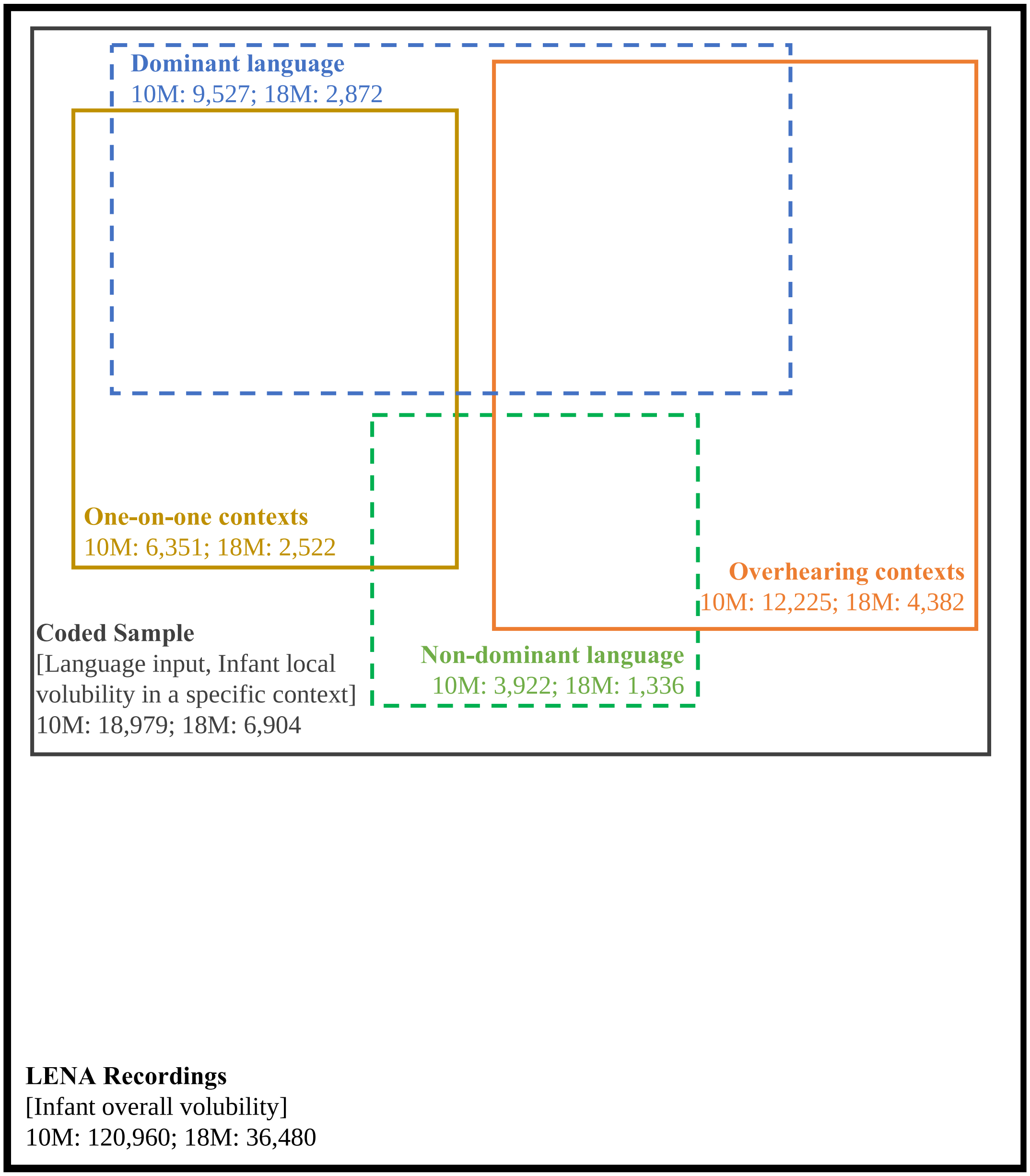

Figure 3

The structure of the Montréal Bilingual Infants corpus, the number of segments included in each sample, and variables used in Chapter 3 (10M: 10 months; 18M: 18 months; note that the boxes are not scaled to accurately show the relative size of the samples).

Language Input in Different Language Contexts. Language input in day-long recordings was processed and coded in the same way as in Chapter 2. Trained English-French bilingual research assistants manually coded every other segment with adult speech in the MBI corpus. They listened to each segment and coded for social contexts (i.e., how many speakers and listeners, who was speaking and to whom) and language contexts (i.e., what language was being spoken). Segments coded as “English” or “French” were renamed as “dominant language” or “non-dominant language”, with dominance assigned according to the *parental report* for each child at each age (Figure 3). Mixed-language input will be examined separately in Chapter 5. Language input in each language was indexed by adult word counts (AWCs). The AWCs were summed by the child’s dominant and non-dominant language respectively for each child at each age.

Statistical analysis.

Statistical analysis was conducted at the same platform using the same packages as described in Chapter 2. Data and analysis codes are available at http://osf.io/wjnaq.

Local analysis. First, I examined how well caregivers’ input was related to infants’ vocalizations produced within the same context. Thus, for each child at each age, I summed the CVCs and AWCs in the coded sample by language contexts (dominant and non-dominant). Correlations between these *local* volubility and input measures were then computed within each context.

Concurrent analysis. Next, I investigated how input was related to infants’ overall volubility.

Comparisons between language contexts. Infant overall volubility was correlated with the input in the dominant and the non-dominant language respectively. I repeated the same analysis within global, 1:1, and overhearing social contexts at each age. The coefficients between language contexts were compared using Z tests at each age, following the same process as social contexts comparisons in Chapter 2.

Next, I tested the additional contribution of non-dominant language input to infant overall volubility beyond dominant language input within each social context at each age. To do so, I compared the linear regression model including input in both languages to the model with only dominant language input. I then computed ΔR^2 as the unique contribution of non-dominant language input to infant overall volubility and its effect size f^2, following the same process as described in Chapter 2

*Longitudinal analysis***.** Identical as described in Chapter 2.

Results

Descriptive results are presented in Table 3. Correlations between *local* volubility and input within each language context were first presented (Figure 4). I then reported the concurrent relation between language input and infant *overall* volubility. These correlations were compared between dominant and non-dominant language input within different social contexts (global, 1:1, and overhearing, Table 4). Lastly, I reported findings from longitudinal analyses.

Table 3

Summary of infant volubility and language input measures in the child's dominant and non-dominant language within each social context. Means (Range) are provided at each age (10 months: N = 21, 18 months: N= 16).

Age	**Infant Volubility (CVCs, *per day*)**	
	Overall Volubility *(per day)*	
10-Month	1071 (706 – 2472) [1]	
18-Month	2005 (899 – 6968) [1]	
	Local Volubility *(per day)*	
	Dominant Language	**Non-dominant Language**
10-Month	144 (56 – 577) [1]	74 (4 – 200)
18-Month	426 (55 – 912)	128 (11 – 764) [1]
Age	**Language Input (AWCs, *per day*)**	
	Dominant Language	**Non-dominant Language**
	Global Social Contexts	
10-Month	3323 (607 – 7331)	1468 (46 – 2962)
18-Month	4061 (499 – 9771)	1686 (41 – 7556) [1]
	One-on-one Social Contexts	
10-Month	1121 (215 – 2738)	298 (27 – 1336) [1]
18-Month	2222 (103– 6005)	255 (14 – 2648) [1]
	Overhearing Social Contexts	
10-Month	2135 (117 – 5424)	1023 (5 – 2361)
18-Month	1840 (39 – 4324)	1090 (7 – 6182) [1]

Note:

[1] Median is reported for this variable which failed the normality test.

1. Local relations

Infant local volubility is the sum of vocalizations that infants produced in the presence of adult speech in a specific language (dominant or non-dominant). I correlated infant local volubility with the amount of input received in the same context. Significant correlations with large effect sizes were observed for both languages and at both ages (Figure 4). These findings suggest that infants and caregivers' vocalizations produced locally within the same language context are positively and strongly correlated.

2. Concurrent relations: comparisons across language contexts

I correlated infants' overall volubility with the amount of input in their dominant and non-dominant language respectively and compared the correlations between languages. The same analyses were repeated in global, 1:1, and overhearing social contexts. Language dominance was determined according to the *parental report* for each child at each age.

Global social contexts. Globally, the correlation between infant overall volubility and dominant language input had a medium effect size at 10 months and a large effect size at 18 months, but the adjusted p-value did not reach significance at either age (Table 4 – Section A. Global Social Contexts). Correlations with non-dominant language input were smaller and not significant. Correlations were not reliably different across language contexts at either age. Follow-up linear regressions showed that in addition to dominant input, non-dominant input explained 16% and 29% of the variation in infant overall volubility at 10 and 18 months respectively, and the adjusted p-value reached significance at 18 months.

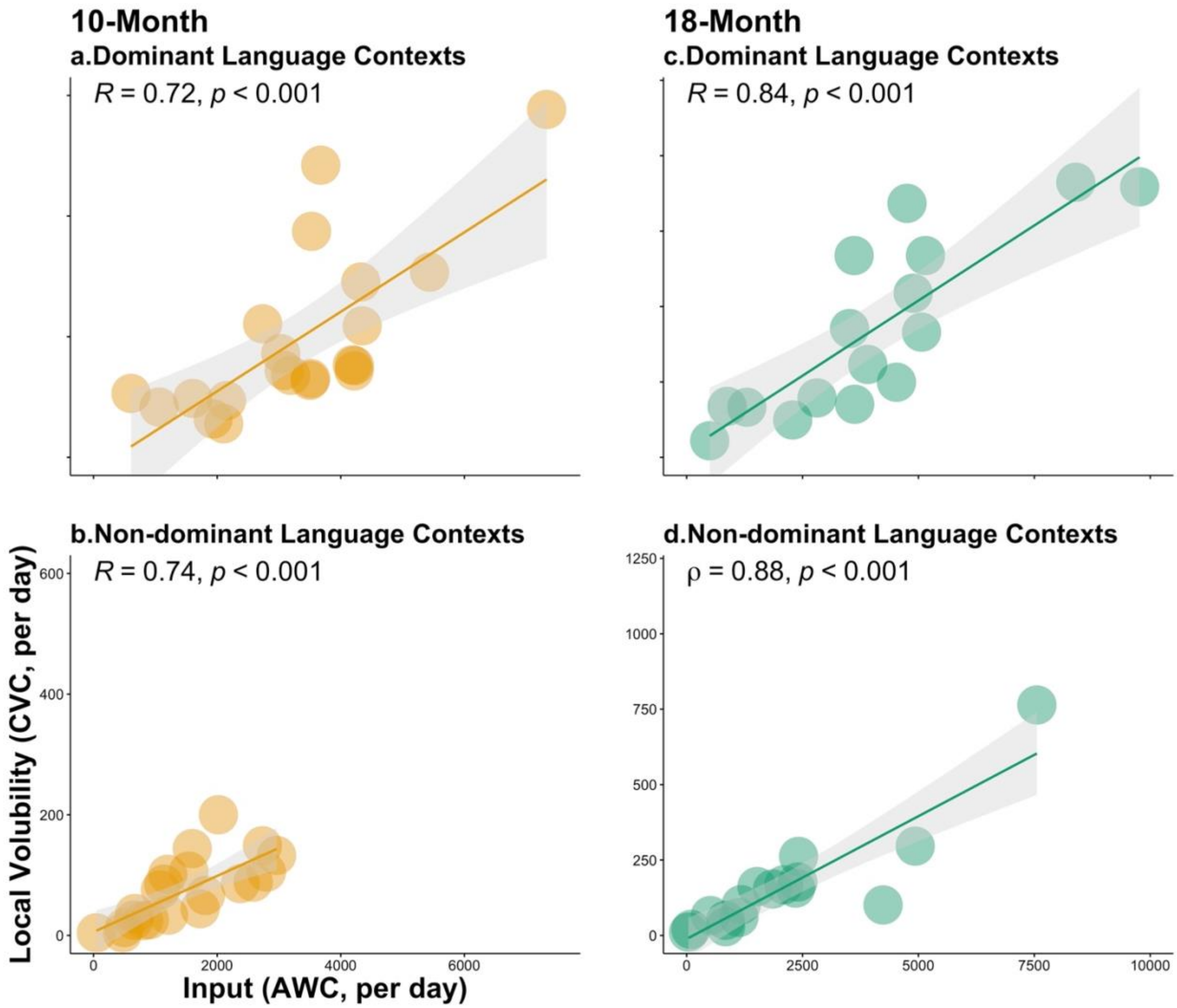

Figure 4

Local relations between infant local volubility and language input received in the same context, in function of language contexts (Dominant language: a & c; Non-dominant language: b & d) and age (10 months: a & b, 18 months: c & d). Yellow dots represent 10-month-olds and green dots represent 18-month-olds.

Table 4

Concurrent correlations between infant overall volubility and input in different language contexts at each age (10 months: N = 21, 18 months: N= 16).

Language Context Comparison						
	Dominant Language	**Non-dominant Language**	**Comparison**	**Additional contribution from non-dominant language input?** [3]		
			z	***F***	ΔR^2	f^2
A. Global Social Contexts						
10-Month	.42	.37	.14	4.48	16%	.25
95% CI[1]	[– .02, .72]	[– .07, .69]	[– .65, .75]			
p-values[2]	.104	.153	.938	.089		
18-Month	.56	.19	1.04	9.57*	29%	.74
95% CI	[.09, .83]		[– .39, 1.27]			
p-values	.054	.589	.419	.026		
B. One-on-one Social Contexts						
10-Month	.75***	– .15	2.96*	.594	1%	.03
95% CI	[.47, .89]		[.38, 1.87]			
p-values	<.001	.599	.011	.574		
18-Month	.54	.31	.93	.125	0.7%	.01
95% CI	[.06, .82]		[– .31, .88]			
p-values	.063	.366	.478	.806		
C. Overhearing Social Contexts						
10-Month	.07	.55*	– 1.49	8.45*	32%	.47
95% CI	[– .37, 49]	[.15, .79]	[– 1.26, .17]			
p-values	.818	.026	.210	.026		
18-Month	.28	– .02	.64	4.18	22%	.32
95% CI	[– .25, 68]		[– .56, 1.09]			
p-values	.419	.952	.599	.104		

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Note: * $p < .05$; ** $p < .01$; *** $p < .001$.

[1] 95% CI – 95% confidence intervals. 95% CI is only available for Pearson's correlations, but not for Spearman's rank correlations.

[2] p-values are adjusted using method of Benjamini & Hochberg (1995).

[3] To test the additional contribution of non-dominant language input to infant overall volubility beyond dominant language input, I compared the linear regression model including input in both languages to the model with only dominant language input. ΔR^2 is the difference between the variation in infant overall volubility explained by the independent variables included in these two models.

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One-on-one social contexts. The correlation between infant overall volubility and 1:1 input in the dominant language at 10 months was positive and significant with a large effect size (Table 4 – Section B. One-on-one Social Contexts). It was also significantly larger than the correlation between infant overall volubility and non-dominant language input. The effect size of the correlation with 1:1 dominant language input was also large at 18 months, but the adjusted *p*-value did not reach significance. Follow-up linear regressions showed that in 1:1 social contexts, non-dominant input made negligible contribution to infant volubility beyond dominant input at both ages.

Overhearing social contexts. As for overheard input, the correlation between infant overall volubility and non-dominant language input at 10 months was positive and significant with a large effect size (Table 4 – Section C. Overhearing Social Contexts). Correlations did not differ across language contexts at either age. Follow-up linear regressions showed that in addition to overheard dominant language input, overheard non-dominant language input explained 32% and 22% of variation in infant overall volubility at 10 and 18 months respectively, and the adjusted *p*-value reached significance at 10 months.

Together, findings from language context comparisons showed that: (1) more 1:1 dominant language input and more overheard non-dominant language input was related to higher infant overall volubility at 10 months; (2) overheard non-dominant language input at 10 months and total non-dominant language input at 18 months made a unique contribution to infants' concurrent overall volubility. In addition to the absolute measure, I also computed the proportions for each language by using AWCs of input in one language divided by the total input in the corresponding social context (Table 5). Correlations between infant overall volubility and proportional measures of input in each language did not suggest additional relations (Table 6).

3. Longitudinal relations

So far, I have examined the volubility-input relation when both variables were measured at the same age. Here, I investigated this relation longitudinally. When variability related to individual differences in infant overall volubility at 10 months was statistically controlled, more 1:1 dominant language input at 10 months was related to higher overall volubility at 18 months (r (13) = .73, p = .002). When input received in corresponding social and language contexts at 10 months was statistically controlled, higher overall volubility at 10 months was related to less 1:1 dominant language input (r (13) = – .85, p < .001). Other partial correlations are not significant.

Table 5

Summary of language input measures in the child's dominant and non-dominant language within each social context. The measures are expressed as proportional values by dividing the AWCs in each language by the total AWCs in the corresponding social contexts for each infant at each age. Means (Range) are provided at each age (10 months: N = 21, 18 months: N= 16).

Age	**Proportion of Language Input *(AWC, per day)***	
	Dominant Language	**Non-dominant Language**
	A. Global Social Contexts	
10-Month	46% (19 – 76%)[1]	21% (1 – 43%)
18-Month	40% (6 – 81%)	18% (1 – 52%)
	B. One-on-one Social Contexts	
10-Month	60% (21 – 91%)	18% (3 – 73%)[2]
18-Month	57% (25 – 93%)	13% (1 – 36%)
	C. Overhearing Social Contexts	
10-Month	42% (6 – 88%)	20% (0.2 – 51%)
18-Month	22% (1 – 82%)[2]	20% (0.3 – 63%)

Note:

[1] Observational percentage for input in the dominant language may not exceed 50% for some families because household dominant language was determined by parental reports and recordings with language mixing or unknown language were also included in general analyses.

[2] Median is reported for this variable which failed the normality test.

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Table 6

Concurrent correlations between infant overall volubility and proportional measures of input in different language contexts at each age (10 months: N = 21, 18 months: N= 16).

Language Context Comparison						
	Dominant Language	**Non-dominant Language**	**Comparison**	**Additional contribution from non-dominant language input?** [2]		
			z	$\boldsymbol{F}$	ΔR^2	f^2
A. Global Social Contexts						
10-Month	– .10 / – .16[1]	.004 / .16	– .22	.04	0.1%	.02
18-Month	.07 / .46	– .09 / – .48	.31	.60	1%	.05
B. One-on-one Social Contexts						
10-Month	.50 / .50	– .31 / – .34	1.87	.68	2%	.04
18-Month	.11 / .13	.23 / .0002	– .25	.12	0.7%	.01
C. Overhearing Social Contexts						
10-Month	– .39 / – .40	.34 / .38	– 1.66	.12	0.5%	.007
18-Month	.23 / .29	– .16 / – .29	.74	.75	4%	.06

Note: * $p < .05$

[1] The first *r*-value is zero-correlation between infant volubility and input and the second *r*-value is partial correlation when total amount of input in the corresponding social context is statistically controlled.

[2] The additional contribution from non-dominant language input was computed by comparing the linear regression model including input in both languages to the model with only dominant input. The total amount of input in the corresponding social context, indexed by adult word counts, was statistically controlled in all models.

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Discussion

In summary, the analyses in this chapter revealed at least the following findings: (1) At both ages, I found a robust associations between infant local volubility and input received in the same language context; (2) More 1:1 dominant language input at 10 months was related to higher concurrent and longitudinal overall volubility; (3) Overheard non-dominant language input at 10 months as well as total non-dominant language input at 18 months made a unique contribution to infant overall volubility.

The results of infant local volubility corroborate findings in Chapter 2 where I also found a strong and positive relation between the number of infant and caregiver vocalizations produced within each social context. Together, they show that the robust association between infants and caregivers' vocal activeness found in previous studies (e.g., Goldstein et al., 2003; Goldstein & Schwade, 2008) emerges not only in dyadic interaction, but in various social and language contexts.

As for infant overall volubility, findings from this chapter indicate that more dominant language input in 1:1 social contexts at 10 months is related to higher overall volubility at 10 and 18 months. The great impact of 1:1 social contexts has been discussed in Chapter 2. Within 1:1 contexts, as expected, the volubility-input correlation is significantly stronger for the dominant language than the non-dominant language. It is likely to be driven by the fact that infants experience more 1:1 input in their dominant language: In the MBI corpus, on average, two thirds of input that the 10-month-olds heard during dyadic interactions was in their dominant language (*Mean* = 60%, *Range*: 21 – 91%).

Furthermore, in addition to the unique contribution of overheard input discussed in Chapter 2, findings from this chapter suggest that overheard input might play a special role in bilingual development, especially for the development of the non-dominant language. In the MBI corpus, at both ages, infants experienced non-dominant language input more often in overhearing contexts (see Table 3 & Table 5). At 10 months, overheard non-dominant language input is positively and closely related to infant overall volubility, and makes significant and large-sized contribution beyond overheard dominant language. I speculate that overhearing conversations among others helps infants accumulate experience and knowledge of the non-dominant language especially at a young age, so that at a later stage, they can respond to non-dominant language input regardless of social contexts, as the significant additional contribution of global non-dominant language observed for 18-month-old infants in this chapter. These intertwined effects of language and social contexts are exploratory and need to be tested in future studies. Limitations and future directions will be discussed in Chapter 6.

In conclusion, findings from this chapter add more evidence to the robust association between infant and caregiver vocalizations produced in the same context. The relation with infant overall volubility is particularly strong for 1:1 input in the child's dominant language and overheard input in the child's non-dominant language. This chapter also highlights the unique contribution of non-dominant language input to bilingual language development.

When talking to their children, bilingual parents do not always use one language at a time. In fact, they are commonly observed to mix languages when addressing their child (Bail et al., 2015; Byers-Heinlein, 2013; Kremin et al., 2021). However, only a handful of studies have investigated how language mixing is related to children's language development and existing findings are equivocal (Bail et al., 2015; Byers-Heinlein, 2013; Carbajal & Peperkamp, 2020; Place & Hoff, 2011, 2016). Therefore, in Chapter 4, I will present findings on the relation between infant volubility and mixed-language input indexed by parent-reported scores, as well as proportions and raw counts in naturalistic day-long recordings.

CHAPTER 4

INFANT VOLUBILITY AND MIXED-LANGUAGE INPUT

In Chapter 3, I investigated the relation between infant volubility and French- or English-only input. In this chapter, my goal is to examine infant volubility's relation with mixed-language input. Mixed input was estimated in the naturalistic day-long recordings from the MBI corpus. Caregivers were also asked to estimate their use of language mixing via the Language Mixing Questionnaire (Byers-Heinlein, 2013). First, I attempted to replicate findings from previous studies where mixed input was measured by parent-reported scores or proportions (Bail et al., 2015; Byers-Heinlein, 2013; Place & Hoff, 2011, 2016). Thus, in Study 4.1a, I computed parent-reported mixing from the Language Mixing Questionnaire and *proportions* of mixing in day-long recordings (measured both globally and in one-on-one contexts), then examined their relations with infant overall volubility. For any significant relations, I examined the same relation while controlling for demographic and linguistic factors in Study 4.1b.

Unique to studies using recordings, language input could also be measured in raw counts. Thus, in Study 4.2, I computed *raw (segment and word) counts* of mixed input (again, both globally and in one-on-one contexts) and examined their relation with infant overall volubility. I also investigated the relation between raw word counts of mixed input and infant *local* volubility within mixed-language contexts. Based on findings in the literature (Bail et al., 2015) and previous chapters, I expected a positive relation of raw counts of mixed input with both infant overall and local volubility.

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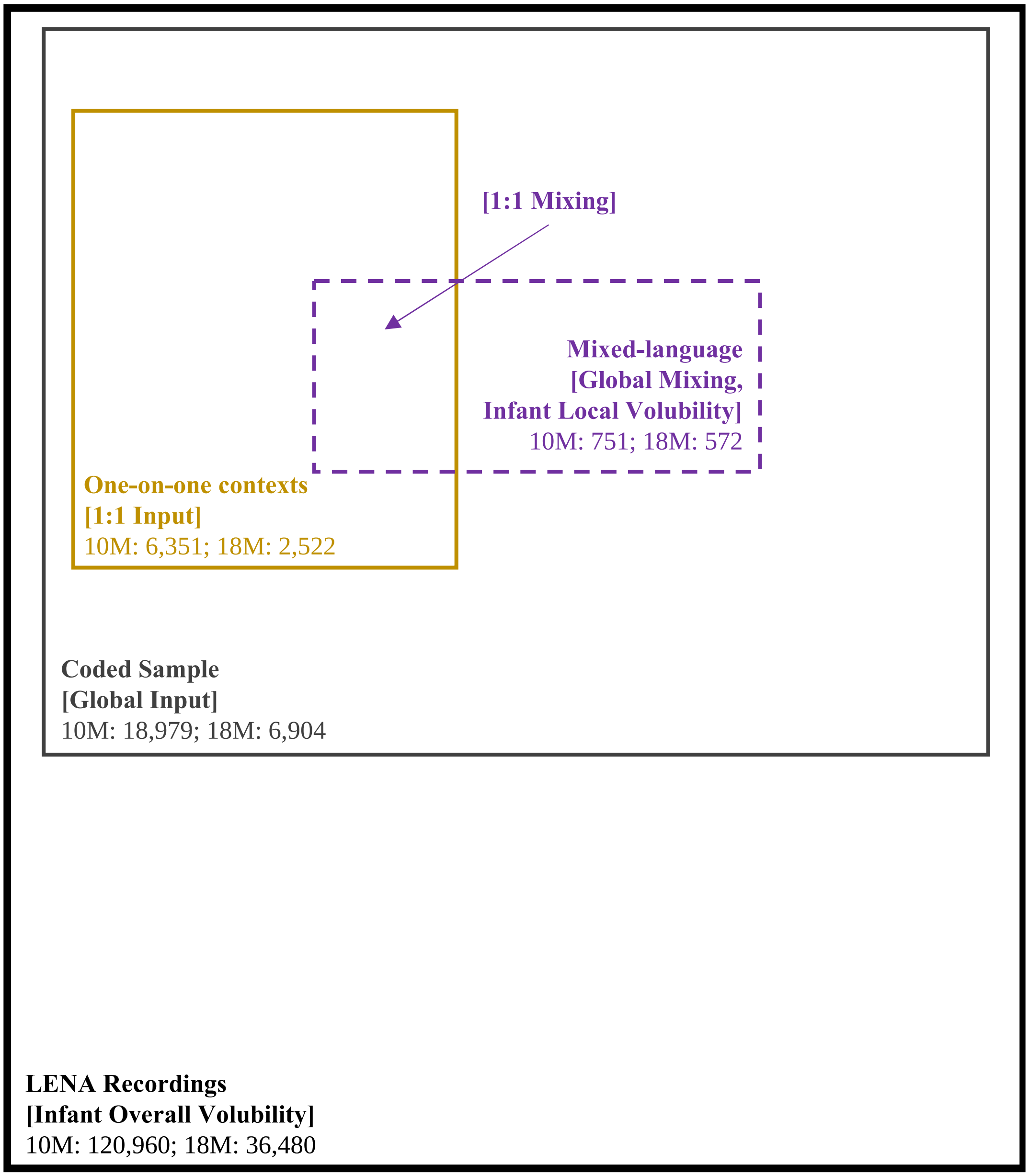

Figure 5

The structure of the Montréal Bilingual Infants corpus, the number of segments included in each sample, and LENA-based variables used in Chapter 4 (10M: 10 months; 18M: 18 months; note that the boxes are not scaled to accurately show the relative size of the samples).

Study 4.1a. Infant overall volubility and language mixing estimated by parental reports and proportions in day-long recordings

Methods

Participants and Procedures. Identical as described in Chapter 2.

Measures. Measures used in this chapter are summarized in Figure 5.

Infant Overall Volubility. Identical as described in Chapter 2. Local volubility will be introduced in Study 4.2.

Proportions of Mixed-language Input. Naturalistic day-long recordings were obtained and processed as described in Chapter 2. Every other 30-second segment that contained AWCs was manually coded for language (i.e., what language(s) was/were being spoken) and social contexts (i.e., how many speakers and listeners, who was speaking and to whom). The language context of a segment was tagged as "mixed" if the *same* speaker used two languages addressing the same listener within that 30-second segment. Segments were not tagged as "mixed" if the same speaker used different languages to address different listeners, or different speakers used different languages. Although language mixing could include alternating use of any two languages, most cases were French-English mixing. The total number of segments tagged as mixed were 751 and 572 in the 10- and 18-month dataset respectively (Figure 5).

I examined LENA-based quantification of language mixing both in terms of global mixing (the number of coded segments containing language mixing) and one-on-one mixing (the number of coded segments where one caregiver talked to the infant in mixed-language, Figure 5). Different from previous chapters, the quantification of mixed-language input was based on segment counts. This was done because compared to AWCs, segment counts were a closer approximate of the *frequency* of language mixing. Two mixing variables were computed as *proportions*. Specifically, the proportion of global mixing was calculated as the number of all mixed segments divided by the number of coded segments for a given day of recording. Likewise, the proportion of 1:1 mixing was calculated as the number of 1:1 mixed segments divided by the total number of coded 1:1 segments for a given day of recording.

Parent-reported Language Mixing. The Language Mixing Questionnaire was administered at each age, to assess parent-reported usage of language mixing (Byers-Heinlein, 2013). Parental responses to five questions with Likert scales were re-coded (0 = infrequent language mixing; 6 = frequent language mixing) and summed, which yielded a possible score from 0 to 30, a higher score indicating a higher frequency of language mixing. I computed the score for each parent and then averaged across two parents for each infant at each age. Two infants' score at 10 months was based on one parent because the score from their mother (n = 1) or father (n = 1) was missing.

Statistical Analysis.

Statistical analysis was conducted at R platform (v4.1.2, R Core Team, 2021) using packages including lme4 (v1.1-27.1, Bates et al., 2021), lmerTest (v. 3.1-3, Kuznetsova et al., 2017), TOSTER (v0.4.0, Campbell & Lakens, 2021), and effectsize (Ben-Shachar et al., 2020). Data and analysis codes are available at http://osf.io/wjnaq.

Given that the number of mixed segments was considerably low compared to single-language segments, I pooled data collected at two ages (Byers-Heinlein et al., 2021). Separate analyses were conducted for parent-reported mixing and two LENA-based estimates of mixing: proportion of global mixing and proportion of 1:1 mixing. For parent-reported mixing, each infant contributed one data point per age, which generated 21 + 16 = 37 observations. I employed linear mixed-effect models with a random intercept by infant and age group (10- or

18-month). For each LENA-based estimate of mixing, each infant provided three data points at 10 months and another one at 18 months, which generated $3 \times 21 + 1 \times 16 = 79$ observations. I employed linear mixed-effect models with random intercepts by infant and age group. Independent variables were rescaled by centering and dividing by two standard deviations (Sonderegger, 2022).

To evaluate the significance of fixed effects, I fitted models using restricted maximum likelihood (REML) and estimated degrees of freedom by Kenward-Roger approximations. The combination of these two approaches produces Type 1 error rates that are closest to 0.05 for smaller samples, suggested by a simulation study (Luke, 2017). I also reported effect sizes, partial eta-squared (${\hat{\eta}_p}^2$). Cohen suggested that ${\hat{\eta}_p}^2$ values of 0.01, 0.06, and 0.14 represented small, medium, and large effect size (Cohen, 1988), and I followed this convention.

Because many previous studies reported a neutral association between mixed input and child language skills (Bail et al., 2015; Byers-Heinlein, 2013; Carbajal & Peperkamp, 2020; Place & Hoff, 2011, 2016), it was possible that null results would also emerge in this chapter. Therefore, I conducted a series of conditional equivalence testing (CET) against medium-sized ${\hat{\eta}_p}^2$ of 0.06 to ensure the robustness of null results (Campbell & Lakens, 2021; Lakens et al., 2018). Specifically, null-hypothesis significance testing (NHST) asks whether one can reject the null hypothesis that population proportion of variance accounted for (P^2, hereafter "the effect") is equal to zero. In cases where one cannot reject the null hypothesis, NHST does not indicate whether the effect is absent or extremely small. Under the CET scheme, if the p-value obtained from NHST (p_1) is less than α (0.05), one can conclude that the effect is greater than zero. However, if p_1 is larger than α but the p-value obtained from CET (p_2) is less than α, one can conclude that the effect is small and negligible. If both p-values are larger than α, the result is inconclusive, i.e., insufficient data to support either finding. Note that p-values reported in this chapter were adjusted using method described in Benjamini and Hochberg (1995).

Results

Descriptive results are summarized in Table 7. Results from linear regression analyses are presented in Table 8. For the relation between infant overall volubility and parent-reported mixing, the effect size was medium. As p-values from *both* NHST and CET were large, the result was inconclusive, i.e., it was not possible to reject the hypothesis that the relation between infant overall volubility and parent-reported mixing differ from either zero or a medium-sized effect. The result was also inconclusive for the relation between infant overall volubility and the proportion of global mixing observed in day-long recordings.

However, the relation between infant overall volubility and the observed proportion of 1:1 mixing was significant with a medium-to-large effect size (Figure 6). For every two-standard-deviation increase in the proportion of 1:1 mixing, the number of infant vocalizations per day decreased by 604.9. This relation was significant at 10 months (Estimate = −701.0, 95% CI [− 1139.2, − 273.6], F (1, 60.2) = 9.74, $\hat{\eta}_p{}^2 = .15$, p = 021), but inconclusive at 18 months (Estimate = −524.0, 95% CI [−1645.6, 597.6], F (1, 14) = 1.00, $\hat{\eta}_p{}^2 = .07$, p_1 = .426, p_2 = .509). For a robustness check, I also performed analyses averaged by infant, which yielded similar results (Table 9 & Table 10).

Table 7

Descriptive results for infant volubility, observed mixing, and parent-reported mixing, averaged across two ages and four days. Median (Interquartile Range).

Infant Volubility *(per day)*[1]	
Overall Volubility	1322 (970– 1862)
Local Volubility	14 (6 – 28)
Mixed-Language Input *(per day)*	
Global Mixing	
Segment Counts	12 (7 – 21)
Proportions	4% (2 – 7%)
Adult Word Counts	285 (153 – 649)
1:1 Mixing	
Segment Counts	5 (2 – 11)
Proportions	6% (2 – 13%)
Parent-reported Mixing	
LMS[2]	12 (6 – 16)

Note:

[1] Infant volubility was estimated by LENA-generated Child Vocalization Count (CVC). Local volubility is the number of infant vocalizations within the mixed segments.

[2] Averaged between maternal and paternal Language Mixing Score (LMS).

Table 8

Relation between infant overall volubility and parent-reported mixing and observed proportion of global and 1:1 mixing (N = 21, Study 4.1a).

Mixed Input Measures	**Parent-reported Mxing**[1]	**Global Mixing %**[1]	**1:1 Mixing %**[1]
Observations	37	79	79
Estimate	– 555.8	– 339.4	– 604.9
95% Confidence Interval	[– 1286.3, 262.7]	[– 770.0, 127.3]	[– 1025.4, – 149.7]
F	2.18	2.14	7.02
$\hat{\eta}_p^{\ 2}$	.08	.03	.09
NHST[2] p_1	.290 [3]	.290	.045*
CET[2] p_2	.575	.333	–

Note:

[1] $Overall\ Volubility = Mixing + (1|Infant) + (1|Age\ Group)$

[2] NHST: Null-hypothesis Significance Test (H_0: $P^2 = 0$). CET: Conditional Equivalence Testing (H_0: $1 > P^2 > .06$).

[3] *p*-values were adjusted using method of Benjamini & Hochberg (1995).

% – Proportions; 1:1 – One-on-one social contexts.

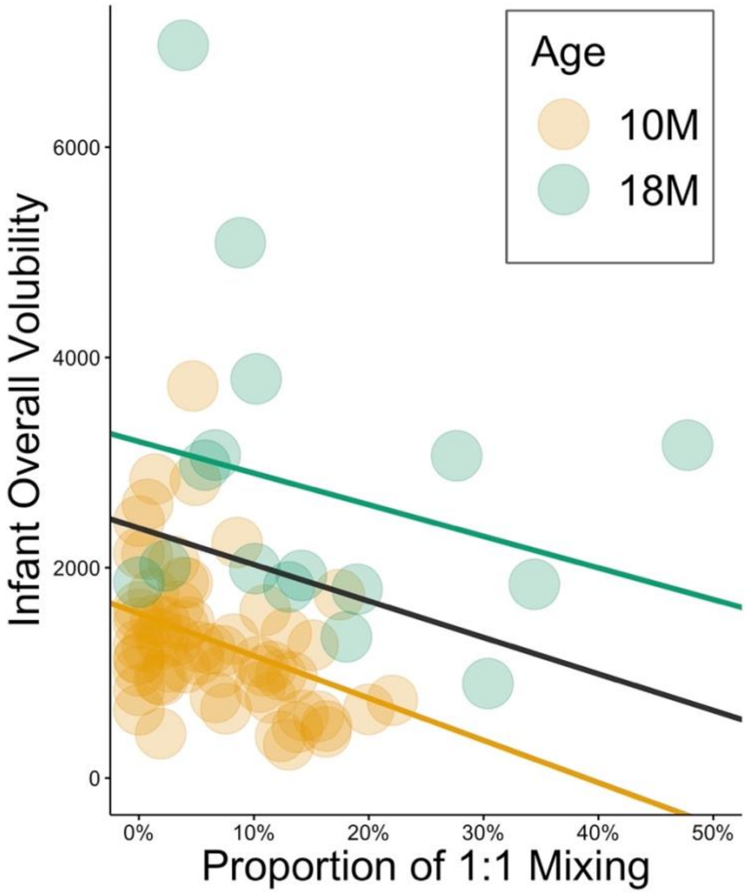

Figure 6

The relation between infant overall volubility and the proportion 1:1 mixing across two ages (black line), at 10 months (yellow line), and at 18 months (green line) respectively. Yellow dots represent 10-month-old infants. Green dots represent 18-month-old infants.

Table 9

Descriptive results of infant volubility and mixed input at each age. Mean (Range).

	10-Month ($N = 21$)	**18-Month** ($N = 16$)
	Infant Volubility *(per day)*[1]	
Overall Volubility	1070.7 (706.0 – 2472.3) [2]	2005.0 (899.0 – 6968.0) [2]
Local Volubility	13.3 (2.0 – 36.0) [2]	65.5 (5.0 – 352.0) [2]
	Mixed-Language Input *(per day)*	
	Global Mixing	
Segment Counts	11.9 (2.0 – 26.0)	28.0 (1.0 – 115.0) [2]
Proportions	4% (1 – 10%)	6% (0.2 – 25%)[2]
Adult Word Counts	343.4 (75.0 – 746.4)	1155.1 (9.2 – 3476.9)
	1:1 Mixing	
Segment Counts	5.3 (0.7 – 20.7) [2]	19.5 (0 – 112.0) [2]
Proportions	5% (1 – 15%)[2]	2% (0 – 48%)
	Parent-reported Mixing	
LMS[3]	11.0 (1 – 21.5)	12.6 (2 – 22.0)

Note:

[1] Infant volubility was estimated by LENA-generated Child Vocalization Count (CVC). Local volubility is the number of infant vocalizations within the segments involving mixed-language input.

[2] Median is reported for this variable that failed the normality test.

[3]Averaged between maternal and paternal Language Mixing Score (LMS).

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Table 10

Relation Between Infant Overall Volubility and Mixed Input (Infant-based [1]).

	Mixed Input				
Overall Volubility	**Reported Mixing**	**Global Mixing %[2]**	**1:1 Mixing %[2]**	**Global Mixing[2]**	**1:1 Mixing[2]**
10-month (N = 21)	– .25 / – .34 [3]	– .38 / – .29	– .54* / – .56**[4]	– .10	– .33[4]
18-months (N = 16)	– .35 / – .18	– .26 / – .39[4]	– .26 / – .28	.20[4]	.11[4]

Note: * $p < .05$, ** $p < .01$

[1] One datapoint for each infant at each age. At 10 months, infants' volubility and input were average across three days.

[2] Observed Mixed input was indexed by segment counts. Proportions (%) were computed as the number of mixed segments divided by the number of coded segments in the corresponding social context.

[3] Pearson's correlations. The first *r*-value is zero-correlation between infant volubility and input. The second *r*-value is partial correlation when total amount of input in the corresponding social context is statistically controlled. For parent-reported mixing, I controlled for the total amount of global input.

[4] Spearman's correlation, because both volubility and input measures failed the normality test.

% – Proportions; 1:1 – one-on-one social contexts.

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Interim discussion

Results from the Study 4.1a support either a negative or a null relation between infant overall volubility and parent-reported mixing or observed proportions of global mixing. The effect size was medium for parent-reported mixing and small-to-medium for the observed proportion of global mixing, but insufficient statistical power prevents drawing a clear conclusion.

However, a significant negative relation was found between infant overall volubility and the proportion of 1:1 mixing, whereby infants who heard a higher proportion of 1:1 mixing produced fewer vocalizations. This result aligns with Byers-Heinlein (2013) where a negative relation was found between parent-reported mixing and children's receptive vocabulary. This study differs from Byers-Heinlein (2013) in two critical ways: (1) Infant volubility used in this study is an expressive measure; (2) Mixed input has been measured in day-long recordings and has included both inter- and intra-sentential code-switching from all caregivers.

This finding also further highlights the impactful role of 1:1 input. In Chapter 2 and 3, infant overall volubility was found to be significantly related to the total amount of 1:1 input and the amount of 1:1 dominant language input. Here, although mixed input only accounts for a relatively small proportion of 1:1 input, it is still linked to infant overall volubility. However, this finding does not align with two other studies that also considered language mixing in 1:1 social contexts (Bail et al., 2015; Place & Hoff, 2016). I argue that mixed input might be more precisely measured in the current study. Mixed input was estimated in the previous studies by either asking parents to keep language diaries or observing one parent's language mixing over a 13-minute play session in the laboratory, while this study considered all caregivers' language mixing over a much longer and more naturalistic input sample.

Although the estimates were uniformly negative, the relation between infant overall volubility and the proportion of 1:1 mixing was significant at 10 months but inconclusive at 18 months. The inconclusive results at 18 months might be due to the reduced sample size (*N* = 16) or because the relation between the proportion of 1:1 mixing and volubility fades with age. Effect size estimates are more consistent with this latter explanation. As infants' exposure and knowledge in both languages accumulates with age, processing mixed input might become less effortful (Gross et al., 2019; Read et al., 2021). In Byers-Heinlein's study (2013), the negative relation between parent-reported mixing and child vocabulary size was only observed for 1.5-year-olds but not for 2-year-olds. In addition to age, as discussed in Chapter 1, other variables could also influence the relation between mixed input and language outcomes, such as the language balance between two languages and the total amount of input accessible to infants. The total amount of input is uniquely available in day-long recordings and how it impacts the relation between mixed input and language development has not yet been studied. Therefore, I introduced these demographic and linguistic factors as fixed effects into linear models and explore the unique contribution of the proportion of 1:1 mixing to infant volubility beyond these factors.

Study 4.1b. Unique contribution of the proportion of 1:1 mixing

Methods

Participants and Procedures. Identical as described in Study 4.1a.

Measures. Infant overall volubility and proportions of 1:1 mixing were measured as described in Study 4.1a.

Demographic and Language Background Information. Demographic and language background information was collected at each age. Thirteen families with a boy and eight families with a girl participated when the child was 10 months old (*Mean* = 303 days, *Range* =

289 – 319 days). Ten boys and six girls participated again at 18 months (*Mean* = 576 days, *Range* = 551 – 635 days).

Recall that to collect language background information, the Language Exposure Questionnaire (LEQ, Bosch & Sebastián-Gallés, 2001) was administrated via Multilingual Approach to Parent Language Estimates (MAPLE, Byers-Heinlein et al., 2019). Parents estimated percentages of time that their child was exposed to English and to French, the difference between which indexed language balance. For instance, if the parents reported that an infant received language input in English for 40% of time and French for 60% of the time, then language balance for that infant was |40% – 60%| = 20%. A smaller score indicates a more balanced input. Language balance was computed for each child at each age. On average, language balance was 28% (*Range* = 10 – 57%) and 25% (*Range* = 0.3 – 57%) at 10 and 18 months respectively.

Statistical Analysis.

I performed linear mixed-effect regressions at R platform using the same packages as described in Study 4.1a. In addition, I conducted model comparisons using pbkrtest (v0.5.1, Halekoh & Højsgaard, 2014). Data and analysis codes are available at http://osf.io/wjnaq.

The control variables included infant sex, infant age (continuous variable indexed by day, instead of categorical (10- or 18-month) in Study 4.1a), parent-reported language balance, as well as global and 1:1 input in the day-long recordings (Figure 5). Infant sex was considered because sex differences have been associated with infant volubility in prior work (Oller et al., 2020). I included infant age and language balance as they might influence the relation between infant volubility and mixed input. Observed global and 1:1 input were considered here because both of them were found to be related to infant volubility in previous chapters.

Like in Study 4.1a, all independent variables were rescaled (Sonderegger, 2022): Continuous variables (infant age, language balance, global input, 1:1 input, and proportions of 1:1 mixing) were standardized by centering and dividing by two standard deviations; Binary variables (infant sex) were contrast coded such that they have mean of 0 and difference of 1 between values (i.e., girl = – 0.5, boy = 0.5). Collinearity diagnostic tests indicated no collinearity between independent variables included in the same model (Condition Numbers < 6.0, Baayen & Shafaei-Bajestan, 2019; Belsley et al., 1980). Note that I did not compute the significance for each variable to reduce the number of NHST.

Next, I fitted our rescaled independent variables into linear mixed-effect models with a random intercept by infant. I then compared models with and without the proportion of 1:1 mixing to test its *additional* contribution to infant overall volubility beyond the control variables. Instead of using χ^2 tests, I used Kenward-Roger approximations for estimating degrees of freedom to perform *F* tests which is considered to be more suitable for small samples (Halekoh & Højsgaard, 2014). I then computed corresponding effect sizes ($\hat{\eta}_p{}^2$). When the *F* test was not significant, I followed up with a CET for robustness check as described in Study 4.1a.

Results

I first explored the additional contribution of the proportion of 1:1 mixing to the variance in infant overall volubility beyond the total 1:1 input. Model comparison between Model 1a and 1b indicated that the proportion of 1:1 mixing made a significant additional contribution to infant overall volubility beyond 1:1 input (Table 11). After controlling for 1:1 input, the direction of the relation between the proportion of 1:1 mixing and infant overall volubility remained negative (Model 1b). When infants' sex, age, and language balance were added into models (2a & b), the results were inconclusive. Results were also inconclusive for the proportion of 1:1 mixing's contribution beyond the global input (Model 3a & b).

Interim discussion

The results from Study 4.1b extend findings from Byers-Heinlein (2013) by showing that the proportion of 1:1 mixing made a unique contribution to infant volubility, even while controlling for the total amount of 1:1 input. There was insufficient data to draw a clear conclusion about the proportion of 1:1 mixing's contribution to infant overall volubility beyond demographic and linguistic factors or global input; however, the effect size of the proportion of 1:1 mixing was not negligible, either close-to-medium ($\hat{\eta}_p{}^2$ = 0.05) or medium-to-large ($\hat{\eta}_p{}^2$ = 0.08). It is consistent with what I have found for input in children's non-dominant language in Chapter 3: Despite making up a relatively smaller proportion of children's total input, non-dominant input still makes its unique contribution to infant volubility. Similarly, even while it might be rare, mixed-language input is linked to infant overall volubility.

Table 11

Unique contribution of proportion of 1:1 mixing to infant overall volubility (N = 21, Study 4.1b).

Variables [2]	**Infant Overall Volubility (*obs.* = 79, *N* = 21)** [1]					
	Model 1a	**Model 1b**	**Model 2a**	**Model 2b**	**Model 3a**	**Model 3b**
(Intercept)	1794.1	1895.8	1340.4	1403.8	1889.7	1980.7
Infant Sex			398.8 [–58.4, 851.8]	299.3 [–147.9, 744.1]		
Infant Age (day)			659.2 [350.6, 981.3]	827.4 [491.5, 1175.7]		
Language Balance			485.4 [55.8, 923.0]	412.6 [–3.7, 835.7]		
Global Input					884.5 [515.9, 1290.0]	840.6 [477.3, 1240.6]
1:1 Input	1165.0 [812.4, 1571.1] [3]	1116.8 [777.9, 1494.1]	1075.4 [715.2, 1421.0]	1062.7 [714.6, 1399.1]		
% 1:1 Mixing		–524.9 [–869.2, –139.3]		–384.5 [–738.9, –35.9]		–490.5 [–859.9, –79.9]
Additional Contribution from Proportion of 1:1 Mixing						
Model Comparison (*F*)	7.62		4.16		5.73	
df	(1, 75.9)		(1, 72.7)		(1, 66.2)	
$\hat{\eta}_p^2$	0.09		0.05		0.08	
NHST[4] p_1	.042* [5]		.148		.075	
CET[4] p_2	–		.508		.615	

Note.

[1] Model 1a, 1b, 3a, & 3b: $Overall\ Volubility = Variables + (1|Infant) + (1|Age\ Group)$; Model 2a & 2b:

$Overall\ Volubility = Variables + (1|Infant)$

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[2] All independent variables were rescaled: binary variables (Infant Sex) were contrast coded to have mean of 0 and difference of 1 between values and other continuous variables were standardized by centering and dividing by two standard deviations.

[3] 95% Confidence Intervals.

[4] NHST: Null-hypothesis Significance Test (H_0: $P^2 = 0$). CET: Conditional Equivalence Testing (H_0: $1 > P^2 > .06$).

[5] *p*-values were adjusted using method of Benjamini & Hochberg (1995).

Obs. – Observations; 1:1 – One-on-one social contexts; % – Proportions.

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So far, I have examined the relation between infant overall volubility and mixed input indexed by parent-reported scores or observed *proportions* in global and 1:1 contexts. Uniquely to recordings, mixed input can also be measured in raw counts. Next, I examined their relation with infant overall volubility and then with infant local volubility which refers to the number of infant vocalizations produced in the mixed segments.

Bail and colleagues found a positive relation between the frequency of parental intra-sentential code-switching and infants' vocabulary size (Bail et al., 2015). Thus, I also expected a positive relation between raw counts of mixed input and infant overall volubility. In turn, based on the positive relation between infants and caregivers' vocalizations produced locally in the segments with English-only and French-only input found in the previous chapters, I expected the volubility-input relation also to be positive and significant within segments involving mixed-language input.

Study 4.2. Raw counts of mixing and infant overall and local volubility

Methods

Participants and Procedures. Identical as described in Study 4.1a.

Measures. Infant overall volubility was measured as described in Study 4.1a.

Infant Local Volubility. To derive a measure of *local* volubility, I summed the number of child vocalizations (CVCs) only from the mixed segments. Local volubility was computed by day for each infant at each age.

Raw Counts of Mixed-Language Input. Global and 1:1 mixing were indexed by raw counts of 30-second segment and LENA-derived adult word counts (AWCs) in these segments. Raw counts of mixed input were computed by day for each infant at each age.

Statistical Analysis.

I conducted the analyses at R platform using the same packages as described in Study 4.1a. First, I investigated the relation between infant overall volubility and raw counts of global or 1:1 mixing. As in Study 4.1a and 4.1b, I pooled data collected at two ages; thus, I had a total of 79 observations from 21 infants. I employed linear mixed-effect models with random intercepts by infant and age group. Segment counts or AWCs were rescaled by centering and dividing by two standard deviations. I fitted the models, computed effect sizes, and performed NHST and CET as described in Study 4.1a.

Next, at local level, I examined the relation between infants and caregiver's vocalizations within mixed segments. Due to the small variation in local volubility, I could not fit a linear mixed-effect model without overfitting the model. Therefore, I fitted a linear fixed-effect model with infant-based data (i.e., one datapoint per infant) for 10 and 18 months separately. To do so, I averaged CVCs and AWCs in mixed segments at each age for each infant. Data and analysis codes are available at http://osf.io/wjnaq.

Results

Results were inconclusive as to whether infant *overall* volubility is related to caregivers' global or 1:1 mixing indexed by segment counts or AWCs, although all estimates were positive (Table 12).

With respect to *local* volubility, there was a positive correlation between the number of infants and caregivers' vocalizations within mixed segments at both 10 months (Estimate = .04, 95% CI [.03, .05], F (1, 19) = 37.6, $\hat{\eta}_p^{\,2} = .66$, $p < .001$, Figure 7a) and 18 months (Estimate = .09, 95% CI [.07, .11], F (1, 14) = 113.8, $\hat{\eta}_p^{\,2} = .89$, $p < .001$, Figure 7b).

Interim discussion

When mixed input was indexed by raw (segment or word) counts, there was insufficient evidence to reject the hypotheses that the mixed input makes either zero or medium-sized contribution to infant overall volubility. However, analyses with infant local volubility at both ages suggest a robust and positive relation between the number of infant and caregiver vocalizations produced within the contexts where language mixing occurs. Unlike overall volubility which is the number of vocalizations produced throughout the day, local volubility in this chapter specifically refers to the number of infant vocalizations produced *in the presence of mixed input*. Therefore, this positive association between infant local volubility and mixed input indicates that mixed-language contexts create a stimulating environment for vocal activities from both the child and caregivers, which has been proved to facilitate language development (Donnellan et al., 2020; Lopez et al., 2020; Warlaumont et al., 2014). This tight volubility-input association at the local level also replicates findings with English- or French-only input in previous chapters.

Table 12

Relation between infant overall volubility and observed raw counts of language mixing (N = 21, Study 4.2).

Mixed Input Measures [1]	**Global (segments[2])**	**1:1 (segments)**	**Global (AWC[2])**	**1:1 (AWC)**
Observations	79	79	79	79
Estimate	250.0	199.6	344.3	310.6
95% Confidence Interval	[– 183.5, 742.4]	[– 253.4, 713.0]	[– 79.7, 833.1]	[–139.3, 831.0]
F	1.09	0.65	2.12	1.56
$\hat{\eta}_p^{\ 2}$	0.02	0.01	0.03	0.02
NHST[3] p_1	.405 [4]	.508	.290	.333
CET[3] p_2	.290	.213	.333	.290

Note.

[1] $Overall\ Volubility = Observed\ Mixing + (1|Infant) + (1|Age\ Group)$

[2] Mixed input was indexed by segment counts or adult word counts (AWCs).

[3] NHST: Null-hypothesis Significance Test (H_0: $P^2 = 0$). CET: Conditional Equivalence Testing (H_0: $1 > P^2 > .06$).

[4] p-values were adjusted using method of Benjamini & Hochberg (1995).

1:1 – One-on-one social contexts.

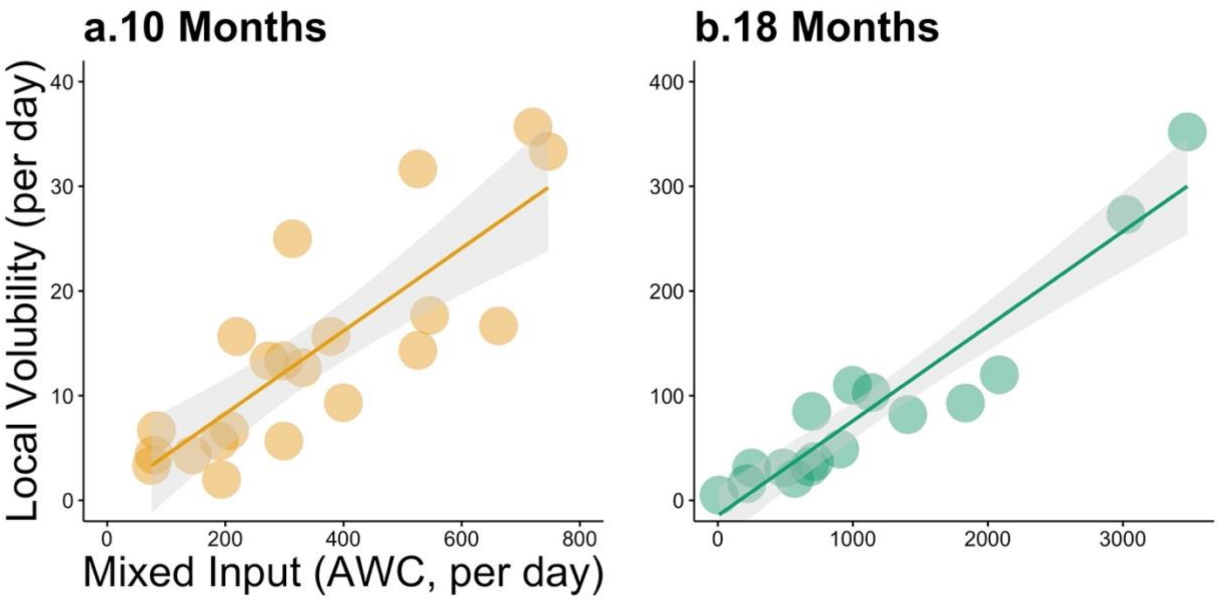

Figure 7

Correlations between infant local volubility and mixed input indexed by adult word counts (AWCs) at 10 months (a) and 18 months (b). Yellow dots represent 10-month-old infants. Green dots represent 18-month-old infants.

Discussion

In summary, I investigated the relation between infant volubility and mixed-language input estimated by parent reports (scores) and direct observation from day-long recordings (proportions and raw counts). First, I observed that infants who heard a greater proportion of 1:1 mixing produced fewer vocalizations. The proportion of 1:1 mixing made a unique contribution to infants' overall volubility beyond the total amount of 1:1 input. However, within the mixed segments, infants who heard more adult vocalizations vocalized more often themselves.

In previous studies, a negative relation was observed between mixed input and infant vocabulary size (Byers-Heinlein, 2013; Carbajal & Peperkamp, 2020). Unlike vocabulary size, infant volubility is a measure of infants' vocal activeness and a precursor of future language skills (Gilkerson et al., 2018; Iyer et al., 2016; Wang et al., 2020). Therefore, the negative relation observed in this study with infant overall volubility might help connect the missing dots between more parental language mixing and smaller vocabulary size. I propose two potential pathways. First, empirical evidence suggests that language mixing might be more effortful for young children to process (Byers-Heinlein et al., 2017, 2022; Gross et al., 2019; Morini & Newman, 2019; Potter et al., 2019), due to higher cognitive demands (Byers-Heinlein et al., 2017) and/or statistical regularity violations (Potter et al., 2019). Therefore, infants who receive a higher proportion of language mixing during 1:1 interaction, might expend more cognitive effort in processing language mixing and vocalize less. This might then slow down their rate of vocabulary growth. The impact can also be in the reversed direction: Caregivers of children who are less vocally active may switch languages more frequently during dyadic interaction. It is not uncommon for parents to adjust their language usage according to their child's development and behaviour (Saint-Georges et al., 2013). Parents with a quieter child might mix languages more often to provide novel stimuli in the hope of gaining their child's attention and eliciting more vocalizations from their child (Bail et al., 2015). Parents might also switch languages to provide translation equivalents in the other language to facilitate comprehension and teach words (Kremin et al., 2021).

Results from Study 4.2 seems to disfavor the first pathway. Within contexts involving mixed input, infants produced more utterances when they received more words from their caregivers. Processing input with language mixing does not seem to impede infants from vocalizing. Worth noticing, infants and caregivers' vocalizations within mixed segments were correlated as strongly as within segments involving input in children's dominant and non-dominant language reported in the previous chapters: Statistical comparisons indicate no difference between these three language contexts (Zs > 1.96). This supports views of everyday code-switching comprehension that downplay processing costs (Kohnert et al., 1999; Kohnert & Bates, 2002). Kremin and colleagues found in the MBI corpus that most code-switching happened between sentences (Kremin et al., 2021). It is crucial because empirical evidence suggests no processing cost for comprehending inter-sentential code-switching in infants (Byers-Heinlein et al., 2017; Gullifer et al., 2013). Even if language mixing is more effortful to process, infants might have developed strategies from their ample bilingual experience to help them successfully navigate mixed input. These strategies include greater attention to upcoming speech, faster detection of language changes, and larger verbal working memory (Kaushanskaya & Crespo, 2019; Kuipers & Thierry, 2012, 2015; Mattock et al., 2010; Olson, 2017). However, within mixed segments, I cannot rule out the possibility that there is a delay of mixed input's impact on infants' vocal activeness. It is also possible that single-language speech adjacent to code-switches drove the positive relation between caregiver and infant vocalizations.

To test the hypothesis that children's vocal activeness drives caregivers to change their verbal behaviour, as suggested in the second pathway, I need more direct evidence. For example, similar to how researchers studied the mother-infant vocal interaction, one could analyze sequences of caregiver and infant vocalizations to investigate how bilingual parents adjust their frequency of language mixing according to their child's vocal activeness (e.g., Goldstein et al., 2003; Goldstein & Schwade, 2008; Warlaumont et al., 2014). Nevertheless, existing evidence suggests that language mixing can sometimes help infants process bilingual information, especially information in the non-dominant language (Gross et al., 2019; Orena & Polka, 2019; Read et al., 2021; Schott et al., 2021). Children who receive more mixed input show a larger vocabulary size and more sophisticated language skills (Bail et al., 2015; Place & Hoff, 2016). Therefore, the negative relation observed between language mixing and children's language skills might not necessarily indicate that code-switching is detrimental to language development; instead, bilingual caregivers might switch languages to help their children successfully acquire both languages (Byers-Heinlein et al., 2017; Kremin et al., 2021).

Some of the results were statistically inconclusive. There are two possible explanations. First, the sample size was relatively small, largely because the laborious work involved in manual coding limited the sample size. However, the corpus consists of 1,264 hours of recordings. I have also tried to increase statistical power by conducting analyses based on days rather than infants and results from both analyses are consistent. Second, although a higher proportion of mixing was reported in other studies (Place & Hoff, 2011, 2016) and the frequency of mixing varies greatly across families, on average, mixed input makes up a relatively small proportion of children's input in the MBI corpus (Table 7). This might constrain mixed input's interaction with infant volubility, compared to French- and English-only input. However, it does not mean that mixed input is insignificant to child language development: Results from this chapter indicated that mixed input had a medium-sized relation with infant overall volubility, even while statistically controlling for demographic and linguistic factors. Limitations and future directions will be discussed in Chapter 6.

Taken together, I observed that a greater proportion of mixed input in 1:1 social contexts was related to reduced overall volubility. At the same time, within contexts involving language mixing, more adult words were related to more infant vocalizations. Therefore, when talking to the child, bilingual parents and educators should be less concerned about mixing languages and focus on creating a verbally stimulating environment.

In this chapter, mixed-language input was estimated by segment counts as they are a close approximation of the frequency of language mixing. Meanwhile, in Chapter 2 and 3, single-language input was estimated by adult word counts (AWCs), a fine-grained unit. Other measurement units (e.g., speech duration) are also available. Moreover, because of the laborious work involved in manual coding, only a sample of every other segment that contains adult speech in the MBI corpus was manually coded. More selective sampling methods (e.g., sampling top segments with the highest AWCs) have been used in other studies (Ramírez-Esparza et al., 2017b). Whether the choice of units and sampling methods impacts input estimation is unknown as research has not yet examined how well these approaches align with each other. Therefore, in Chapter 5, I will present the results on the alignment between input measures indexed by different units (AWCs, speech duration, segment counts) and using different sampling methods (every-other-segment, top-segment). I will also report the comparison of infant overall volubility's relation with input estimated by each approach.

CHAPTER 5

COMPARING LANGUAGE INPUT MEASURES

In Chapter 2 and 3, I analyzed the LENA recordings from the MBI corpus and investigated the relation between infant overall volubility and their French-English bilingual input in different social (1:1, overhearing) and language (dominant, non-dominant) contexts when infants were 10 and 18 months old. Input in these two chapters was estimated by adult word counts (AWCs) in a sample of every other segment that contained adult speech in the corpus. In this chapter, I examined whether the input measures reported in Chapter 2 and 3 aligned with measures derived using different units and sampling methods. I also compared infant overall volubility's relation with input measures estimated by each approach (see a summary of variables in Table 13). Specifically, I aimed to answer three research questions (RQ) and had the following hypotheses:

RQ1. How well do input measures using different units and sampling methods align?

I considered three measurement units: AWCs, speech duration, and segment counts. I expected the correlation between AWCs and speech duration to be large while their correlation with segment counts to be smaller, as segment count is less precise compared to the other two fine-grained units. When counting segments, one loses information like how verbally active the speaker was and the extent to which the speaker consistently used the same language for the entire segment.

As for sampling methods, I compared input measures derived from the entire corpus (LENA), sampling of every other segment (EOS), sampling of the top 150 segments with highest AWCs (Top150), and sampling of the top 40 or 20 segments with the highest AWCs in specific social and language contexts (Top40/20). Two top sampling methods were used for different purposes. Top150 was to examine the reliability of a simple top-sampling method. In Top40/20 sampling, annotated input was used to draw equal-duration and high-density samples from specific social and language contexts; this approach provided a way to tease apart quantitative and qualitative aspects of input. I expected a close relation between input estimates based on the entire LENA corpus and the EOS sample but a weaker relation with top samples given that top samples provide a narrow snapshot of the child's exposure landscape (Bergelson et al., 2019).

RQ2. Do proportions of input in different social and language contexts align across different sampling methods?

I computed proportions of input in different social (1:1, overhearing) and language (dominant, non-dominant) contexts in EOS and Top150 samples (context coding was not available for LENA corpus and the segment counts of different types of input was identical in Top40/20 samples). Given that a previous study found differences of input features in daylong and peak-hour recordings (Bergelson et al., 2019), I expected the input proportions to diverge across sampling methods.

RQ3. Does the input unit or sampling method change input's relation with infant volubility?

I compared infant overall volubility's relation with input estimated by different units and sampling methods. Following the same predictions for RQ1 and RQ2, I expected volubility's relation with input indexed by segment counts to be deviant from AWCs and speech duration and large discrepancies between correlations when different sampling methods were used.

Table 13

Variables and descriptions.

Variables	Descriptions
Infant Language Development	
Infant overall volubility	LENA-derived child vocalization counts (CVC) across the entire LENA corpus.
Language Input	
Measuring Units	
AWCs	LENA-derived estimates of the number of words spoken near the child.
Duration	The sum of LENA-derived Adult Female Speech Duration and Adult Male Speech Duration.
Segment Counts	The number of 30-second segments.
Sampling Methods	
Every-other-segment sampling	A periodic sampling method selecting every other 30-second segment containing adult speech.
Top sampling	A sampling method selecting a certain number of segments with the highest AWCs.
Samples	
LENA recordings	The entire Montréal Bilingual Infants corpus, consisted with 1,264 hours of audio recordings (21 families at 10 months × 3 days × 16 hours + 16 families at 18 months × 1 day × 16 hours).
EOS sample	The sample of every other segment (EOS) containing adult speech. Every segment was coded for speaker(s), listeners(s), and language usage. Also called "the coded sample" in previous chapters.
Top150	The sample of the top 150 coded segments with the highest AWCs.
Top40/20	Samples of the top 40 coded segments with the highest AWCs in a specific social context (one-on-one, overhearing). Samples of the top 20 coded segments with the highest AWCs in a specific language context (dominant, non-dominant).
Social and Language Contexts	
Global	All input in the sample.
One-one-one (1:1)	One caregiver (mother, father, nanny, older siblings, and others) talked to the infant.
Overhearing	Caregivers spoke with the presence of the infant but not exclusively addressing the infant.
Dominant language	Parent-reported language (French or English) that the infant has more exposure to at each age.
Non-dominant language	The language other than the dominant language (English or French).

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Methods

Participants. Identical as described in Chapter 2.

Procedure and Measures.

Naturalistic audio recordings were collected and processed as described in Chapter 2. The recordings were re-organized into 30-second segments and then were matched with LENA-generated measures, such as Child Vocalization Counts (CVCs) and Adult Word Counts (AWCs). Measures used in this chapter are summarized in Table 13. I estimated infant overall volubility as described in Chapter 2, by summing the CVCs in entire LENA recordings for each child at each age.

Input units (AWCs, Durations, Segment Counts). LENA algorithms estimate the number of words spoken near the key child (Adult Word Counts, AWCs). Previous research showed that LENA algorithms were reliable at estimating AWCs in both English and French (Orena et al., 2019). Algorithms also estimate the duration of these words and derive Adult Female Speech Duration and Adult Male Speech Duration. For each infant, the sum of Adult Female and Male Speech Duration derived an approximation of speech duration (Duration). Segment Counts refers to the number of 30-second segments.

LENA recordings. This consists of all the recordings in the corpus for each infant, including three recordings obtained at 10 months and one recording obtained at 18 months (Figure 1). As the recording length, i.e., Segment Counts, were identical for all infants, I focused on AWCs and Duration measures.

Every-Other-Segment (EOS) sample. As I was interested in caregivers' input, segments in the LENA recordings that did not contain any adult speech were first removed. With the remaining segments containing adult speech, trained English-French bilingual research assistants manually coded *every other segment*. As described in Chapter 2 and 3, they listened to each segment and coded for social contexts (i.e., how many speakers and listeners, who was speaking and to whom) and language contexts (i.e., what language was being spoken). In total, 18,979 and 6,904 segments were completely coded for the 10- and 18-month datasets respectively (Figure 1). The EOS sample was also referred to as "the coded sample" in the previous chapters.

As the number of segments with adult speech varied across infants, there was considerable variation in Segment Counts in the EOS sample. Thus, I utilized all three input measures: Segment Counts, AWCs, and Duration. For each child at each age, I summed the total input in the EOS sample (global) and computed input measures by social contexts (1:1, overhearing) and language contexts (dominant, non-dominant). Due to its low quantity, mixed-language input was not considered separately as a level of language contexts.

Top150 sample. Following the work of Ramírez-Esparza and colleagues (Ramírez-Esparza et al., 2017a, 2017b), in the 10-month EOS sample, I selected the top 50 segments with the highest AWCs each day across three days of recordings and thus I had a total of 150 segments for each child. For 18 months, despite having only one day of recording, I sampled the top 150 segments with the highest AWCs in the EOS sample for each child. This was done for the purpose of examining whether the size of top samples relative to the original sample can affect input estimation. The global input in the Top150 sample was indexed in both AWCs and Duration (Segment Counts were identical for all infants, n = 150). For input in each social and language context, I computed input in all three units (Segment Counts, AWCs, and Duration).

Top40/20 sample. Segments in the EOS sample at each age were categorized by social (1:1 or overhearing) and language (dominant or non-dominant) contexts. For the two social contexts, the top 40 segments with the highest AWCs in each context were sampled for each child at each age. I chose 40 segments to maximize the number of infants that were eligible for the analysis. One child at 18 months was excluded from 1:1 context analysis for having less than 40 segments. For the two language contexts, the top 20 segments with the highest AWCs in each language were sampled for each child at each age. Again, I chose 20 segments to maximize the number of infants included in the analysis. One child at 10 months and two children at 18 months were excluded from the non-dominant language analysis for having less than 20 segments. Segment Counts were identical for all infants, so input was indexed by AWCs and Duration.

Statistical Analysis.

Results and plots were generated using packages including PerformanceAnalytics (v2.0.4, Peterson et al., 2020) and ggplot2 (Wickham, 2016) in R (R Core Team, 2021). To examine the alignment between different input units and sampling methods (RQ1), correlations between input measures were calculated. Pearson's correlations were used to retain the real-size variation in each variable. Significance of these correlations was not tested because I was interested in the degree of alignment which was well-reflected by the correlation magnitudes.

To examine whether the proportions of input in different social and language contexts changes with sampling methods (RQ2), I computed the proportions of input by social and language contexts in the EOS sample and Top150 sample. In each sample, I used AWCs in a specific context divided by the total AWCs in that sample. I compared proportions across sampling methods using Wilcoxon signed-rank tests. All *p*-values were adjusted using method of Benjamini & Hochberg (1995).

To test whether input's relation with infant volubility changes with how input is estimated (RQ3), I computed correlations between infant overall volubility and language input when input was indexed by different units and sampling methods. I repeated the analysis in different social and language contexts at two ages. The original *p*-values are reported because (1) The purpose of this set of analyses is not to test the hypothesis that infant overall volubility is related to language input, but to compare the consistency across different input measures; (2) I have tried to mimic the reality where researchers and clinicians would only select one measure of input and there would not be any *p*-value adjustment at the level of input measurement. Data and analysis codes are available at http://osf.io/wjnaq.

Results

1. How well do input measures using different units and sampling methods align?

The correlations between different input measures are plotted in Figure 8, in the global context (a) as well as within each social (b & c) and language (d & e) contexts. Results for 10-month samples are plotted in the top triangle and results for 18-month samples, in the bottom triangle. The colour of cells, from yellow to red, indicates the strength of the correlation, from weak to strong. A video-animated guide for Figure 8 and exact correlation coefficients are available at Video-animated Guide for Figure 8.mp4.

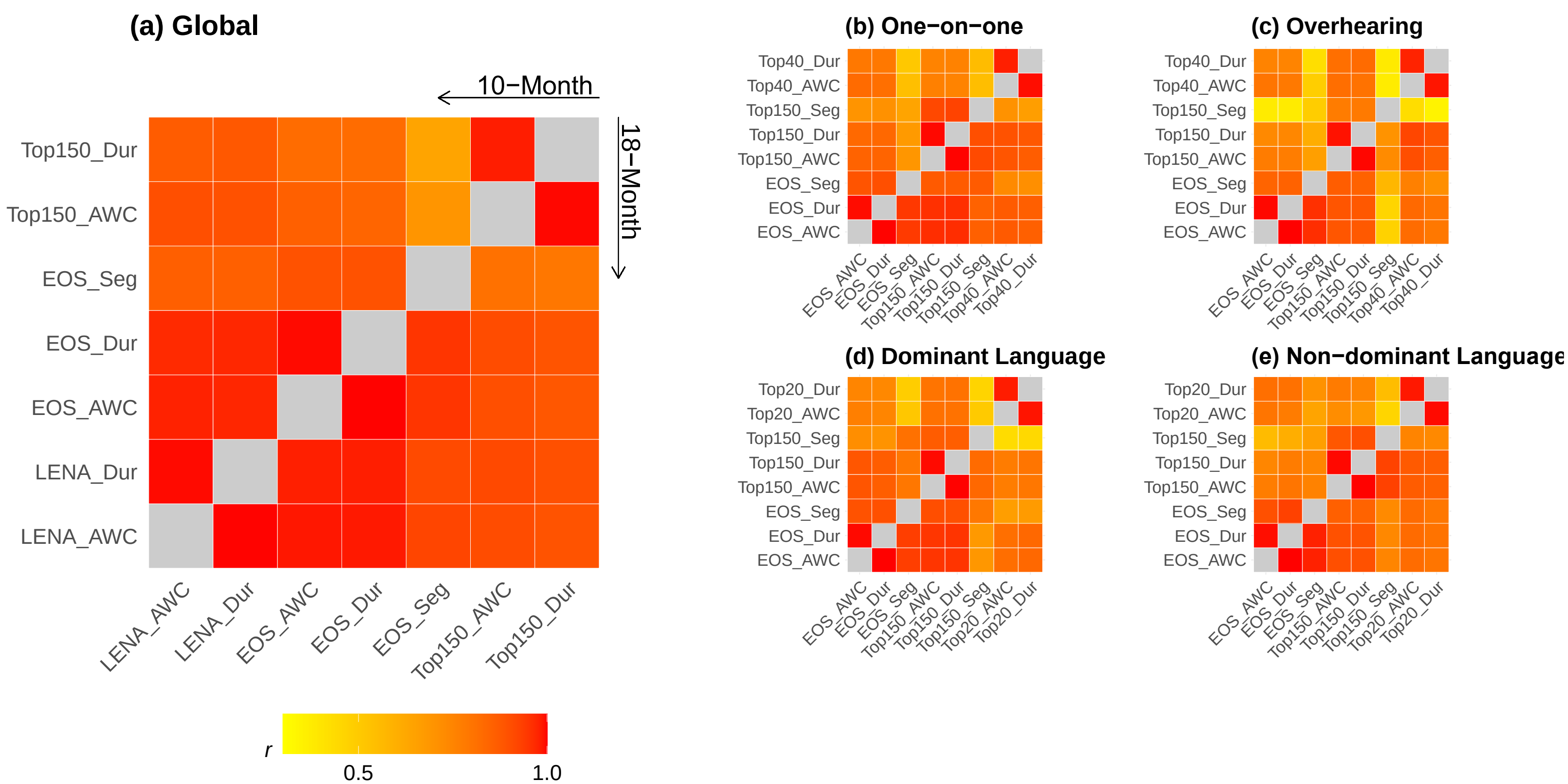

Figure 8

Correlations between different language input measures in (a) global, (b) one-on-one and (c) overhearing social contexts, and (d) dominant and (e) non-dominant language contexts. Upper triangle: 10-month-old sample; Bottom triangle: 18-month-old sample. LENA: the entire corpus. EOS: every-other-segment sample. Top150: top 150 coded segments with the highest adult word counts (AWCs). Top 40: top 40 coded segments with the highest AWCs in one-on-one or overhearing social contexts. Top 20: speech in top

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20 coded segments with the highest AWCs in the dominant or non-dominant language. AWC: LENA-derived adult word counts. Dur: Duration, the sum of LENA-derived female and male speech duration. Seg: Segment Counts, the number of 30-second segments.

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First, I compared across different units (AWCs, Duration, and Segment Counts). Across all contexts (a - e), samples, and ages, I observed the same pattern: AWCs and Duration were perfectly correlated with magnitudes close to 1.00; their correlation with Segment Counts was slightly smaller but all magnitudes were above .70. These results suggested a high alignment among three input units.

Next, I compared across different sampling methods. In global context (a), input measures derived from the EOS sample (every-other-segment sampling) was perfectly correlated with input measures in the entire LENA corpus. However, the correlations were slightly weaker with input measures derived from the Top150 sample (top sampling). This difference between the EOS sample and the top-segment samples (Top150 and Top40/20) became more evident within each social and language context (b - e). The alignment across sampling methods appeared to be weaker for larger samples, for example 10-month dataset (3-day recordings compared to 1-day recording for 18-month dataset), overhearing contexts, and dominant language contexts. These results suggested while samples selected by every-other-segment sampling was representative of the full recordings, less tight correlations were observed for top sampling methods.

2. Do proportions of input in different social and language contexts align across different sampling methods?

Due to the discrepancies observed between sampling methods in RQ1, I compared proportions of input in different social and language contexts between EOS sample and Top150 sample (segment counts of different social and language input are identical in Top40/20 sample). Some differences between two sampling methods were observed, but they were not substantial (Wilcoxon test adjusted-*p*s > .05, Table 14).

Table 14

Comparison of proportions of language input in different social and language contexts in Every-other-segment (EOS) and Top150 samples. In each sample, AWCs of input in a specific context were divided by the total AWCs in that sample.

Samples	EOS		Top150		Difference		Wilcoxon *V*
	Median	Range	Median	Range	Median	Range	
				Social Contexts			
10M: One-on-one	25%	9 – 59%	19%	3 – 66%	7%	0.3 – 18%	183#
10M: Overhearing	73%	35 – 91%	81%	29 – 97%	6%	2 – 18%	43#
18M: One-on-one	34%	8 – 86%	33%	8 – 83%	3%	0.2 – 8%	64
18M: Overhearing	66%	14 – 92%	67%	17 – 92%	3%	0.3 – 8%	72
				Language Contexts			
10M: Dominant	51%	19 – 76%	46%	12 – 68%	5%	0.2 – 11%	174
10M: Non-dominant	21%	0.6 – 43%	21%	1 – 51%	2%	0.1 – 10%	80
18M: Dominant	35%	6 – 81%	33%	4 – 82%	2%	0.2 – 6%	97
18M: Non-dominant	15%	0.9 – 52%	15%	0.4 – 53%	0.9%	0.3 – 4%	84

Note: # p <.10. p-values were adjusted using method of Benjamini & Hochberg (1995).

10M: 10-month sample; 18M: 18-month sample.

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3. Does the input unit or sampling method change input's relation with infant volubility?

Correlations between infant overall volubility and input estimated by different units and sampling methods are presented in Table 15. In the EOS sample, correlations across different units (AWCs, Duration, and Segment Counts) were consistently in the same direction, with similar magnitudes, and at the same significance with a few exceptions involving Segment Counts.

However, correlations across two sampling methods (EOS and Top150) did not consistently align. At the global context, the magnitude of correlations based on the Top150 sample was slightly smaller compared to the EOS sample, but still in the same direction and at the same significance. In social and language contexts, the Top150 correlations were markedly smaller and sometimes in the opposite direction (all involving Segment Counts).

The correlations based on EOS and Top40/20 samples were more consistent. They were in the same direction and more than half of them were at the same significance, despite that most of the Top40/20 correlations tended to be slightly smaller in magnitude than EOS correlations.

Table 15

Comparison among correlations between infant volubility and input estimated by different units and sampling methods.

Correlations \ Input Measures	Every-other-segment sampling			Top sampling				
				Top150			Top40/20[1]	
	Segment	AWC[2]	Duration	Segment	AWC	Duration	AWC	Duration
10M: Global	.67***	.61**	.62**	-	.48*	.48*	-	-
10M: One-on-one Contexts	.50*	.52*	.51*	.20	.37	.35	.41	.40
10M: Overhearing Contexts	.41	.50*	.51*	–.16	.19	.18	.35	.39
10M: Dominant Language	.31	.42	.41	.15	.34	.34	.34	.37
10M: Non-dominant Language	.29	.37	.37	–.08	.09	.07	.40	.40
18M: Global	.87***	.81***	.81***	-	.59*	.57*	-	-
18M: One-on-one Contexts	.48	.50*	.50*	.20	.35	.37	.55*	.56*
18M: Overhearing Contexts	.59*	.61*	.62*	–.20	.23	.23	.31	.32
18M: Dominant Language	.42	.56*	.56*	.11	.37	.39	.54*	.54*
18M: Non-dominant Language	.51*	.49	.49	–.10	.14	.13	.27	.24

Note: * $p < .05$; ** $p < .01$; *** $p < .001$.

[1] Top 40 segments with the highest AWCs in one-on-one or overhearing social contexts were sampled. One child at 18 months was excluded from the analysis of one-on-one contexts for having less than 40 segments. Top 20 segment with the highest AWCs received in dominant or non-dominant language were sampled. One child at 10 months and two children at 18 months were exclude from the analysis of non-dominant language for having less than 20 segments.

[2] Results reported in Chapter 2 and 3.

10M: 10-month-old; 18M: 18-month-old; Segment: segment counts; AWC: adult word counts.

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Discussion

In summary, the analyses in this chapter yield the following findings: (1) Different input units (AWCs, Duration, and Segment Counts) are strongly correlated with each other and yield similar results regarding their relation with infant overall volubility; (2) Input measures in the EOS sample are tightly related to input measures based on the entire LENA corpus, while their correlations with input measures in top samples are less tight; (3) Regarding input's relation with infant overall volubility, results do not fully align across sampling methods, even though the EOS and Top150 samples arrived at similar proportional measures of input in different social and language contexts.

Measures of language input using different units (AWCs, Duration, and Segment Counts) and their relation with infant volubility are highly consistent, especially between AWCs and Duration. AWCs and Duration's correlations with Segment Counts are slightly smaller and compared to AWCs and Duration, the magnitude of Segment Counts' correlations with infant overall volubility is slightly different. First, these findings confirm the robustness of the results reported in the previous chapters when input was indexed by AWCs. Second, findings from this chapter have important implications on how researchers and clinicians assess bilingual exposure, as counting segments is a common practice in previous bilingualism research (e.g., Place & Hoff, 2011, 2016; Ramírez-Esparza et al., 2017a, 2017b). When counting segments, one loses information such as how verbally active the speaker is and how consistently the speaker uses the same language throughout the entire segment. Some researchers have tried to address the latter by asking caregivers to estimate the time that each language was used within a segment (Carbajal & Peperkamp, 2020). In future studies, researchers can also estimate the time caregivers are actively speaking within a segment to quantify the input more precisely, when fine-grained units like AWCs and speech duration are not available.

As expected, results based on the EOS and Top150 samples do not align well. The correlations between input measures in the EOS and Top150 samples are less tight, and their relations with infant volubility diverge. This deviation might be caused by two reasons. One is biased sampling. The Top150 sample consists with segments containing the highest AWCs, essentially the moments when caregivers are the most verbally active around the child (talking to the child or others). Although input proportions observed in different social and language input in the EOS and Top150 samples are consistent, other aspects of the input in the recordings of peak hours might differ from infants' language experience throughout the day. For example, researchers found more denser noun input in peak hours (Bergelson et al., 2019). This might lead to different conclusions regarding input's relation with infant volubility.

The other possible reason is the relative size of Top150 sample compared to the original sample. One-hundred-fifty segments, i.e., 75-minute recordings, only account for 0.8% and 2% of total coded segments in the 10- and 18-month datasets respectively. Because the 10-month dataset contains a larger sample (3-day recordings), top segments account for a smaller proportion of the 10-month dataset. Top sampling with a fixed number of segments seems to be more problematic for larger samples, such as overhearing and dominant language contexts. For a given number of top segments, the larger the original sample is, the smaller proportion of segments are selected, and therefore more likely to be less representative.

The correlation between input measures in the EOS and Top40/20 samples are still not very strong, but their relation with infant volubility are relatively more consistent. When examining infant volubility's relation with input in different languages, I first categorized all coded segments by language and then selected the top 20 segments with the highest AWCs for dominant and non-dominant language respectively. The same process was applied to social context analysis. This way, I have a comparable sample, with equal duration and maximum density, for each language or social context, which enables me to examine the quality of input independently from the quantity. Results from this chapter suggest that this research goal can be achieved with a relatively small portion of recordings.

Taken together, while the methods to estimate children's language input has been expanding rapidly in recent years, it is important to know that our research conclusions are not built on methodological biases. Results from this chapter suggest that deriving input measures from day-long recordings using different units appears to yield consistent results. However, caution should be taken when choosing sampling methods. When downsizing their dataset, researchers and clinicians might consider increasing the size of selected samples according to the size of the original sample, i.e., using fixed-*proportion* instead of fixed-*number* of segments when selecting samples. When it is not possible, they might want to use random or periodic sampling instead of top sampling (Cychosz et al., 2020; Orena et al., 2019). If their research goals involve comparisons across different types of input, results from this chapter suggest selecting the same number of top segments for each type of input can reach a reliable conclusion with a relatively small portion of data. These findings together highlight the need for our field to direct more attention to the exact measures used to estimate language input and to be thoughtful when selecting sampling methods. Limitations and future directions will be discussed in Chapter 6.

CHAPTER 6

GENERAL DISCUSSION

Summary of Results

Analyses in this dissertation have revealed at least five findings: (1) Infant volubility and language input is robustly and positively related at global and local levels; (2) Infants' concurrent and longitudinal overall volubility has a strong association with input received in 1:1 social contexts and in their dominant language; (3) Input received in overhearing contexts and in their non-dominant language makes unique contributions to infant overall volubility; (4) There is a complex relation between infant volubility and mixed-language input including that a higher proportion of mixed input in 1:1 social contexts is related to reduced overall volubility; (5) Input measures and their relation with infant overall volubility are consistent across different units but diverge across sampling methods.

First, the robust and positive relation between infant overall volubility and language input found throughout this dissertation adds more confirmative evidence to the classic literature on the bidirectional impact between language input and child language acquisition (e.g., Hart & Risley, 1995; Huttenlocher et al., 1991). In previous research, children's speech and language development were measured by standardized language tests (e.g., Carbajal & Peperkamp, 2020; Place & Hoff, 2011, 2016; Ramírez-Esparza et al., 2017a, 2017b). However, infant volubility used in this dissertation presents the unique opportunity to establish an utterance-to-utterance quantitative correlation between infant and caregiver vocalizations and emphasizes the communicative values of these vocalizations.

Another merit of using volubility as an outcome measurement is that one can examine the utterance-to-utterance quantitative correlation between infant and caregiver vocalizations within various social and language contexts respectively. By deploying infant *local* volubility (i.e., the number of infant vocalizations produced in the presence of a certain type of input), I found a strong and positive relation between infants and caregivers' vocalizations within every social (1:1, overhearing) and language (dominant, non-dominant, mixed-language) context. This suggests that all social and language contexts create a stimulating environment for vocalizations from *both* infants and their caregivers.

Second, findings from Chapter 2 confirm the impactful role of language input received in 1:1 social contexts (Oller, 2010; Ramírez-Esparza et al., 2014, 2017a, 2017b; Song et al., 2012; Weisleder & Fernald, 2013). Findings further highlight a significant role of overheard input beyond 1:1 input, especially for older infants with more mature language and mobility skills. It is possible that overheard speech contributes to infant volubility in a different way from 1:1 input by leaving children a space for spontaneous vocal exploration (Iyer et al., 2016; Shimada, 2012). Infants can also learn from overheard speech as a growing body of experimental evidence has shown that infants can acquire some aspects of language(s) from overhearing conversations of others (Akhtar, 2005b; Akhtar et al., 2001; Floor & Akhtar, 2006; Gampe et al., 2012; Martínez-Sussmann et al., 2011; Oshima-Takane, 1988; Oshima-Takane et al., 1996) and sometimes from passive exposure (Au et al., 2002; Pierce et al., 2014, 2015; Saffran et al., 1996; Singh et al., 2011). This ability of learning from overheard speech can be enhanced by social experience: infants with more overhearing experience are more skilled in learning from overhearing conversations between others (Chavajay & Rogoff, 1999; Oshima-Takane et al., 1996; Shneidman et al., 2009).

The conclusions drawn so far can be applied to language acquisition of children regardless of language background (monolingual, bilingual, etc.). Specific to children growing up in bilingual families, exploratory analyses in Chapter 3 showed an impactful role of 1:1 dominant language input and overheard non-dominant language input. These results are likely to be driven by the relative amount of input in each language received in different social contexts: The 1:1 input was predominantly in children's dominant language while non-dominant language was mostly overheard (Oller, 2010). For bilingual children, overheard input might be particularly important for their accumulation of experience and knowledge in the non-dominant language at a young age, so that at an older age, they can respond to non-dominant language input regardless of social contexts.

Furthermore, results from Chapter 4 corroborate previous findings (Byers-Heinlein, 2013; Carbajal & Peperkamp, 2020) by showing that a higher proportion of mixed-language input in 1:1 social contexts is related to reduced volubility. Meanwhile, a positive relation was found between the number of infant and caregiver vocalizations within contexts where language mixing occurred. These divergent associations between mixed input and infant vocal activeness highlight the complex role of language mixing to child language development and point for a need to better understand the causal factors that drive these associations. For instance, although intra-sentential code-switching is usually accompanied with a processing cost found in the laboratory (Byers-Heinlein et al., 2017, 2022; Gross et al., 2019; Morini & Newman, 2019; Potter et al., 2019), everyday mixed input might not be more effortful for infants to process compared to single-language input. Everyday mixed input is dominated by *inter*-sentential code-switching which does not typically incur a processing cost in laboratory tasks (Bail et al., 2015; Byers-Heinlein et al., 2017; Gullifer et al., 2013; Kremin et al., 2021). Even if language mixing is more effortful to process, children raised in bilingual families might have developed strategies from their ample bilingual experience to successfully navigate mixed input (Kaushanskaya &

Crespo, 2019; Kuipers & Thierry, 2012, 2015; Mattock et al., 2010; Olson, 2017). Bilingual caregivers might also switch languages as a linguistic strategy to support their children's successful acquisition of both languages (Kremin et al., 2021).

Lastly, findings from Chapter 5 confirm the robustness of results reported in the previous chapters. Moreover, this is one of the pioneer studies examining the alignment between different LENA input measurement units (adult word counts, speech duration, and segment counts). Results have also shown the consistency between input estimated in the entire corpus and a sample of every other segment, but discrepancies with samples of top segments where caregivers were the most talkative. Suggestions on how to choose input units and sampling methods are provided.

Limitations and Future Directions

This dissertation has at least the following limitations which can be addressed in future research. First, many results throughout this dissertation failed to reach significance despite their large effect sizes, possibly caused by the relatively small sample size (N = 21 and 16 for 10- and 18-month respectively). The sample size was small largely because the laborious work involved in manual coding limited the number of families that can be included in the corpus. However, the corpus consists of 1,264 hours of recordings and 25,883 coded segments. For the mixed-language context which consists of less segments, I have tried to increase statistical power by conducting analyses based on days rather than infants and results from both analyses are consistent.

Second, LENA algorithms may generate errors when estimating child and adult vocalization counts, but a thorough evaluation suggested the LENA-derived CVCs and AWCs to be highly accurate (Cristia et al., 2021). The alignment between input measurement units shown in Chapter 5 also confirms the robustness of results reported in this dissertation.

Next, according to the Dual Nature Theory (Oller et al., 2019; Stark et al., 1993), infant vocalizations can be classified as either interactive or endogenous. It is still unclear to what extent language input interacts with infants' interactive and endogenous vocalizations respectively. Results from this dissertation cannot provide a robust answer to this question largely because with audio recordings alone and no images, it is difficult to reliably classify infant vocalizations. For example, when one hears an infant vocalization in the audio recording, they cannot be certain whether the infant was alone or with adult(s) who was/were not talking at that moment. Future research that aims to address this research question should consider including video recordings as infant vocalizations might be more reliably classified with the help of images (e.g., Long et al., 2020).

In future studies, nuances in the volubility-input relation should also be examined, for example, the structure of infant vocalizations (e.g., Gros-Louis & Miller, 2018; Ramírez-Esparza et al., 2014), word types in language input (Huttenlocher et al., 1991; Rowe, 2012), how many times caregivers code-switch, and in which direction (Bail et al., 2015; Kremin et al., 2021). One could also study caregiver-infant vocalization sequences to better understand how bilingual parents adjust their vocal behaviour (e.g., their frequency of language mixing) according to their child's vocal activeness and vice versa (Lopez et al., 2020; Pretzer et al., 2019; Warlaumont et al., 2014). When examining caregiver-infant vocalization sequences, one could include contexts that contain mixed-language input and single-language input to investigate whether bilingual parents and infants engage in different patterns of vocal behaviors across these contexts. The timing (how quickly each follows the other), contingency patterns (who initiates, who follows), and quality of the infant vocal responses may differ across these contexts. All these efforts will lead the field to a deeper understanding of the relation between infant volubility and language input.

To obtain a comprehensive picture of the relation between language input and child language development, infants' cognitive skills, such as statistical learning and auditory processing speed, should also be tested in future studies, as they determines to what extent infants can benefit from language input (Garcia-Sierra et al., 2011; Marchman et al., 2017; Weisleder & Fernald, 2013).

Furthermore, the recordings in the MBI corpus provide a good snapshot of a child's in-home language environment but they do not capture the child's language input received outside the home. This is especially relevant to 18-month-olds as most of them went to a daycare on weekdays. Activities at settings outside the home may change the landscape of infants' language input (Larson et al., 2020; Soderstrom et al., 2018), which can influence the conclusions regarding infant volubility's relation with input in different social and language contexts, as well as the consistency across sampling methods (Bergelson et al., 2019; Tamis-LeMonda et al., 2017). Therefore, future studies should expand to settings outside the home.

Regarding input sampling methods, although manually coding every-other-segment sample halves the work of coding the full corpus, it is still laborious. Future studies could investigate the reliability of other periodic but less dense sampling methods, for example, sampling one minute every hour. Moreover, when Ramírez-Esparza and colleague composed their sample using top sampling method, the authors made the effort to ensure selected segments were 3-minute apart (Ramírez-Esparza et al., 2017a, 2017b). Whether this effort would improve the representativeness of top samples remains to be tested.

In this dissertation, volubility-input relations were only examined linearly, and they were correlational, not causational. Intervention programs could inform us more about (if any) the causal relation between infant and caregiver vocalizations. For instance, home-visiting programs that provide parents knowledge about early childhood development, including the importance of enrichment of home language environments (Leung et al., 2022; Leung & Suskind, 2020) and professional development programs that coach preschool educators how to improve language environment to facilitate child development (The LENA Foundation, 2022).

Lastly, cautions should be taken when generalizing conclusions from this dissertation. First, I took a dichotomous view of bilingual exposure while it forms a continuum in reality (Kremin & Byers-Heinlein, 2021). Second, some of the analyses were exploratory, for example, intertwined effects of language and social contexts and longitudinal relations between 10-month-olds' volubility and their language input at 18 months. Finally, all families that contributed to the MBI corpus were from mid-to-high socioeconomic background and a homogeneous and balanced bilingual community. Conclusions from this dissertation need to be tested in other bilingual communities (Byers-Heinlein et al., 2022).

Conclusions

In this dissertation, I analyzed naturalistic day-long recordings of bilingual families when their infant was 10 and 18 months old and investigated the relation between infant volubility and language input in different social and language contexts. The volubility-input relation found in this dissertation supplements our understanding of the dynamic interaction between child language development and language input with an emphasis on the communicative values of infants and caregiver vocalizations. The robust and positive relation between infant and caregiver vocalizations produced locally within each social and language context suggests all contexts create a stimulating environment for vocalizations from both parties. In addition to confirming the impactful role of 1:1 and dominant language input, findings from this dissertation highlight the unique contribution of overheard input, especially for older infants and for bilingual infants' acquisition of the non-dominant language. This dissertation also further highlights the complex role of mixed-language input in child language development. Methodologically, while input measures are consistent across different units, cautions should be taken when selecting sampling methods.

Together, I hope findings from this dissertation could ease the mind of individuals who are involved in rearing a bilingual child, such as caregivers, educators, and clinicians. When being around the child, they could be less anxious about which language(s) to use in which social context and focus on creating a verbally stimulating environment to support the child's successful acquisition of both languages. This dissertation is an invitation for more research to understand the dynamic relation between language input and language acquisition of children growing up in diverse language environments.

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APPENDIX

SCIENCE OUTREACH

Baby Scientists, by Ruan Yufang and Jihane Mossalim

Material: Acrylic on canvas, graphite on paper

Dimensions: Paintings: 3, 20”x16” canvases and 3, 20”x12” canvases

Drawings: 2- 11”x14” papers and 2- 8 ½” by 11” papers

Artwork description

Baby Scientists is an art demonstration of how we learn. In Part I, we reproduce infants’ language learning process through an experiment where someone who is naïve to painting learns how to paint from a professional painter in unsupervised (learning from observation) and supervised (learning from directed instruction) manners. The naïve painter painted on a smaller dimension to mimic the relative smaller size of infants’ vocal tract. Babies and their parents have been chosen as the composition's subject to acknowledge their generous contribution to our knowledge about learning. In Part II, to explore future-oriented learning approaches, two online learning conditions, “YouTube” and “Zoom”, have been tested. The contents have been chosen to commemorate the COVID-19 global pandemic which occured during the time these paintings were created. The painting progression and follow-up interviews were filmed for each condition in order to provide a more comprehensive view of the learning process and to add dynamic images to the final static paintings. The project is part of the Convergence Initiative led by Dr. Cristian Zaelzer and Bettina Forget. This work is on display at McGill Bicentennial SciArt200 virtual exhibition https://hubs.mozilla.com/MPYZzT5/sciart200/ (Curator: Milton Riaño), presented by McGill’s Faculty of Science and Redpath Museum.

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Connection to this dissertation

Learning from overheard speech is a form of unsupervised learning. Findings from this dissertation, along with previous experimental evidence, suggested that infants can benefit from overheard speech that was not addressed to them. In line with these scientific findings, this artwork showed that, in both modalities (in-person or online), the naïve painter was able to capture gross features of the professional painter's painting from observation. Recognizing that one can learn in an unsupervised fashion (overhearing or observing) does not dismiss the importance of supervised learning which is dominated in one-on-one interactions. Results from this dissertation supported previous findings by showing an impactful role of input received in one-on-one interactions. This artwork further demonstrated the importance of one-on-one interactions in acquiring the nuances. For example, the naïve painter did a significantly better job in portraying the baby's head in the supervised condition with directed instructions from the professional painter. In the online modality, again, the naïve painter imitated the professional painter's drawing better during the interactive session on Zoom, despite that the nurse was much more complicated to draw. Together, while acknowledging the remarkable differences between infants and the naïve painter (an adult), through this science outreach work, I intimately experienced my research subjects' learning process in different social contexts, which gives me more confidence in the research findings from this dissertation.

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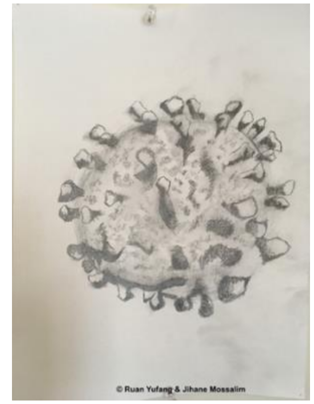
Part I: Unsupervised Learning (in-person)	
Professional painter	**Naïve painter**
	
3, 20’’x16’’ canvases	3, 20’’x12’’ canvases
Part I: Supervised Learning (in-person)	
Professional painter	**Naïve painter**
	
3, 20’’x16’’ canvases	3, 20’’x12’’ canvases

Part II: Unsupervised Learning (YouTube)	
Professional painter	**Naïve painter**
	
2- 11''x14'' papers	2- 8 ½'' by 11'' papers
Part II: Supervised Learning (Zoom)	
Professional painter	**Naïve painter**
	
2- 11''x14'' papers	2- 8 ½'' by 11'' papers

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