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Mixed-language input and infant volubility: Friend or foe?

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Abstract

Language mixing is a common feature of many bilingually-raised children's input. Yet how it is related to their language development remains an open question. The current study investigated mixed-language input indexed by observed (30-second segment) counts and proportions in day-long recordings as well as parent-reported scores, in relation to infant vocal activeness (i.e., volubility) when infants were 10 and 18 months old. Results suggested infants who received a higher score or proportion of mixed input in one-on-one social contexts were less voluble. However, within contexts involving language mixing, infants who heard more words were also the ones who produced more vocalizations. These divergent associations between mixed input and infant vocal development point for a need to better understand the causal factors that drive these associations.

Introduction

An increasing number of children are growing up in bilingual environments. For example, 18 percent of Canadian children aged 0-9 years use at least two languages at home (Schott et al., 2022) and in Quebec, nearly 90% of young French–English bilinguals grow up with bilingual parents (Turcotte, 2019). It is common for bilingual parents to mix languages when talking to their children (Bail et al., 2015; Byers-Heinlein, 2013; Kremin et al. 2022a). 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). Moreover, although bilingual parents begin using mixed language with their children as early as 10 months old, most research on mixed input's relation with 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 infants' tendency to vocalize and has been shown to predict their future language abilities (Iyer et al. 2016; Wang et al. 2020). In the current study, we analyzed infant vocalizations and mixed-language input in naturalistic day-long recordings, to better comprehend the relation between infants' volubility and caregivers' language mixing.

1. Mixed-language input

In this study, 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). Mixed-language input 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 mixing languages 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 language mixing usually increases with children's age or language knowledge, at least in the first two years of life. Kremin and colleagues studied

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French–English bilingual parental language mixing in naturalistic day-long recordings (Kremin et al., 2022a). These parents switched languages 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 language mixing per hour had quadrupled and the frequency per 1000 words had tripled. About half of the families had at least doubled their frequency of language mixing and no family reduced their use of language mixing. The authors also coded apparent reasons for parental language mixing. Switching languages to teach new words increased remarkably as infants grew. Thus, caregivers increase their use of language mixing in tandem with and in support of their children's growing language knowledge (Bail et al., 2015; Kremin et al., 2022a).

Parents switch languages to serve certain purposes including to bolster understanding and to teach new words, and thus it does not occur in random locations (Byers-Heinlein, 2013; Kremin et al., 2022a). An evidently larger proportion of parental language mixing occurs between sentences compared to within a sentence, and this difference expands with age (Bail et al., 2015; Kremin et al., 2022a). 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, mixed-language input increases with child 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?

2. Relation between mixed-language input and children's 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).

2.1 Negative relation

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 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. 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; Byers-Heinlein et al. 2022b; Gross et al. 2019; Morini & Newman, 2019; Potter et al. 2019). The processing cost is more evident for intra-sentential switches, especially switches from the dominant language to the non-dominant language. In looking-while-listening tasks, toddlers show 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 the United States, failed to learn novel labels when the labels were heard in sentences with an intra-sentential language switch (Byers-Heinlein et al., 2022b).

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 in young infants: when a language switch occurs in their input, infants have to rapidly disengage one language and engage the other language. Preliminary results showed that more parent-reported language mixing trended with less mature brain activation of 6-month-olds during a non-linguistic attention orienting task which required the ability to engage, disengage, and attention shift (Arredondo et al., 2022).

Language mixing might also disrupt the statistical regularities in the speech stream, which makes tracking and comprehending 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 language 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 non-dominant language, since the prediction established from the preceding words is stronger for their more familiar language (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 identified other potential challenges introduced by mixed-language input. For example, a highly-unbalanced use of two languages could make the process of inhibition-activation or prediction-recovery more difficult

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(Carbajal & Peperkamp, 2020). Mixed-language input might also contain accented speech (Place & Hoff, 2016). These factors might bolster the difficulties when processing mixed-language input, which helps explain its negative relation with child language development found by some researchers. However, other researchers argued that a negative relation was found because the Language Mixing Scale (LMS) specifically measures intra-sentential code-switching which is more difficult to process (Place & Hoff, 2016). In reality, everyday mixed-language input might be less detrimental, given that, for instance, most child-directed language mixing happens between sentences (Bail et al., 2015; Kremin et al., 2022a).

2.2 Neutral relation

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 controlled, the zero-order correlation with LMS was not significant for children's receptive and 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 whether 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 30-minute BLOCK (within or across speakers) and 11-month-olds' receptive vocabulary size in both languages, different from the negative relation found when using within-SPEAKER language mixing in the same study (Carbajal & Peperkamp, 2020).

To bridge this definition gap, in the more recent study, Place and Hoff administered the LMS 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 language mixing 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 language mixing was not related to children's total conceptual 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 this type of one-on-one interaction plays an especially important role in children's language development (e.g., Ramírez-Esparza et al., 2017; Ruan, 2022; Ruan et al., 2020). 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 as to whether the social contexts where mixed-language input is received modulate its relation with children's language development.

There are several potential explanations for these null results compared to the previously-reviewed negative relations. First, fewer processing costs have been reported when the most natural and common forms of language mixing that young children experience are considered (Kaushanskaya et al., 2022; Kremin et al. 2022b; Valdés Kroff et al., 2018; Vaughan-Evans et al. 2020). Inter-sentential code-switching is the most common type of language mixing found in bilingual infants' everyday input and no processing cost is associated with processing inter-sentential code-switching (Byers-Heinlein et al., 2017; Gullifer et al., 2013; Kremin et al., 2022a). Intra-sentential code-switching is relatively less frequent and usually appears in the form of a single-word insertion (e.g., Do you see the *chien* [fr. dog] on the teelo [the novel word]?) or a determiner followed by a noun in the other language (e.g., *El* nem [the novel word]). Previous research found that bilingual children had no difficulties matching a novel word with a novel object while listening to a mixed-language sentence (Byers-Heinlein et al., 2022b) or memorizing the novel words immediately after exposure (Kaushanskaya et al., 2022). In fact, children were not slower to process intra-sentential language mixing even if it occurred at a less expected syntactic locations – for example, an uninformative pronominal adjective (e.g., "Look at le bon [fr. the good] duck", Kremin et al., 2022b). Intra-sentential mixing neither compromises preschool- and school-age 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). In a touchscreen tablet task, Tsui and colleagues reported that French–English and Spanish–English 3- to 5-year-olds readily learned new words in different intra-sentential switching conditions (Tsui et al. 2022).

The absence of processing cost for various types of code-switched constructions might indicate that most children can handle 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 language mixing was related to better language abilities, while for children with lower verbal working memory, higher exposure to language mixing was associated with lower levels of language ability. However, the causality is uncertain as it could be that better working memory helps children process language mixing, or higher exposure to language mixing bolsters their working memory.

Processing costs may 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 attributed to 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, a 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.

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Potential mixing costs may also be offset by contextual factors. One study showed that when bilingual adults were habituated in a bilingual mode (wherein both languages were represented with similar frequency within a block), the switch cost observed in a monolingual mode (wherein 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 brief recent 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 fewminutes of exposure (Saffran et al., 1996), and bilinguals might be particularly adept at processing statistical regularities across two languages (Antovich & Graf Estes, 2018; Benitez et al. 2020).

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 both 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 a relatively small proportion of infants and toddlers' total input on average (Kremin et al., 2022a), which limits its interaction with child language development. In some 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., 2022b; Orena & Polka, 2019; Potter et al., 2019; Read et al., 2021; Schott et al. 2021).

2.3 Positive relation

There is also evidence suggesting a positive relation between mixed-language input and children's language development (Bail et al., 2015; Place & Hoff, 2016). Recall that Place and Hoff tagged 30-minute time blocks where both languages were used (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. Bail and colleagues also reported a positive relation between toddlers' total and conceptual vocabulary size in two languages and their parent's INTRA-sentential language mixing over a 13-minute play session (Bail et al., 2015).

Worth noting, Bail and colleagues measured parental language mixing not only in proportion, but also in frequency (Bail et al., 2015). In their study, proportions were the frequency of language mixing relative to the total number of utterances. For example, assuming that two infants, A and B, hear the same number of code-switches (n = 10), the proportion of language mixing will be different for them if Infant A hears total 100 utterances while Infant B hears 1000 total utterances during the play session – namely, 10% and 1% for Infant A and B respectively. Therefore, these two measurements quantify language mixing in different ways: the frequency reflects the absolute number of code-switches whereas the proportion reflects the density of code-switches relative to the total input. We argue that each is important when examining mixed input's relation with child language development.

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 to Kremin and colleagues' coding scheme, over 70% of parental language mixing was attributed to facilitating comprehension and translating for their child (Kremin et al., 2022a). 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., 2022a). Researchers interpreted these findings as parents' effort to support their child's successful acquisition of both languages. Indeed, research shows that presenting a word in a context instead of in isolation helps infants recognize the word (Fernald & Hurtado, 2006). For bilingually-raised children, a carrier sentence in the language that is more familiar to infants might help them recognize the target word in the less-familiar language, despite a potential processing cost (Byers-Heinlein et al., 2017; Potter et al., 2019). Indeed, a subset of preschool-age children performed better in identifying target objects (Kremin et al., 2022b) and learning novel words (Kaushanskaya et al., 2022) when the information was provided in mixed sentences. Preschoolers also benefit from language bridging in the classroom (use translation in children's first language to teach new words in the second language) and reading mixed-language books to acquire a second language (Brouillard et al., 2020; Read et al., 2021). In addition, children whose parents mixed languages frequently might become accustomed to language mixing and develop skills to navigate this linguistic situation. Evidence showed that eight- and ten-month-old infants with more mixed-language exposure were able to segment words in both languages while their peers with less mixed-language exposure only segmented words in their dominant language (Orena & Polka, 2019).

Another possible pathway is that parents adjust their use of language mixing according to their children's language ability (Bail et al., 2015). Parents adjust 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 language mixing increases with infant age (Kremin et al., 2022a). The fact that their child is older or equipped with more language knowledge might encourage parents to mix language more often, assuming their child in possession with sufficient knowledge to sustain the conversation or balancing the acquisition of both languages (Quay & Chevalier, 2019). With children whose language skills are more advanced, parents might also generally use longer sentences which creates more opportunities for intra-sentential mixing (Bail et al., 2015).

Overall, the relation between mixed-language input and child language development is not firmly established. Some potential factors mentioned above should be considered, such as child

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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, as well as child language outcome measures.

3. Infant volubility as an outcome measure

Bilingual parents begin mixing two languages when talking to their child in their first year of life (Kremin et al., 2022a). However, research on mixed input's relation with child language development has mostly focused on 2-year-olds and older (Bail et al., 2015; Byers-Heinlein, 2013; Place & Hoff, 2011, 2016; although see Carbajal & Peperkamp, 2020). A potential reason for this research gap is that we have limited tools to assess expressive speech and language development for children under twelve months. Take expressive vocabulary as an example: parents report that children rarely produce words before their first birthday and produce only about 50 words by 18 months (Fenson et al. 1994). Furthermore, 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). Therefore, we need alternatives to measure emerging bilingual skills.

Although they produce few words in the first year of life, infants vocalize from birth (Iyer et al., 2016; Oller et al. 2019). Infants vocalize not only during social interactions, but also when they are alone (Oller et al., 2019; Shimada, 2012; Stark et al., 1993). In fact, around 75% of 3- to10-month-old infants' vocalizations are produced without clear social intentions (Long et al. 2020). The measure of infants' tendency to vocalize is called volubility. Infants' volubility is significantly associated with their future language abilities such as receptive and expressive vocabulary size (Gilkerson et al. 2018; Ramírez-Esparza et al., 2014; Wang et al., 2020). Abnormal volubility might also suggest developmental disorders (see review in Iyer et al., 2016). Moreover, measuring volubility does not require determining in which specific language (if any) infant vocalizations might be, which makes volubility a great candidate to measure bilingual development.

Given the strong association between language input and language acquisition, it is expected that input and volubility would also be related, although to date not much research has explored this possibility (Ramírez-Esparza et al., 2017; Ruan, 2022; Ruan et al., 2020). Regarding its relation with language input, infant volubility can be measured at two levels: overall and local (Ruan, 2022; Ruan et al., 2020). Infant overall volubility refers to infants' overall tendency to vocalize both during social interactions and when alone. Infants growing up in a verbally stimulating environment might more actively vocalize throughout the day. Therefore, there might be a link between features of language input such as language mixing and infants' overall vocal activeness.

Local volubility, on the other hand, refers to infants' vocalizations produced in the presence of adult speech (Ruan, 2022; Ruan et al., 2020). Robust evidence shows that infants and caregivers' vocalizations mutually stimulate more vocalizations from each other and facilitate a social feedback loop (Athari et al., 2021; Goldstein et al., 2003; Goldstein & Schwade, 2008; Gros-Louis & Miller, 2018; Saint-Georges et al., 2013; Warlaumont et al. 2014). The presence of this social feedback loop is the strongest predictor of child's productive vocabulary later in life (Donnellan et al. 2020; Lopez et al. 2020). A positive relation between infants and caregivers' vocalizations within a context may not directly indicate the presence of this social feedback loop, but it does reflect a stimulating environment for vocal activities from BOTH the child and their caregivers, which is crucial for child language development.

In our previous study, we analyzed naturalistic day-long recordings from French–English bilingual families with an infant at 10 and 18 monthsold and investigated the relation between French- or English-only input and infant volubility (Ruan, 2022; Ruan et al., 2020). As described above, infant volubility was measured at two levels: overall and local. For infant OVERALL volubility, infants who heard more speech throughout a day were also the ones who vocalized more, which replicated previously-reported associations between input and language development that was measured by standardized language assessments (e.g., Place & Hoff, 2011, 2016; Ramírez-Esparza et al., 2017). Input in the non-dominant language, despite its relatively smaller proportion, still made a significant additional contribution to infant overall volubility beyond the dominant language. Analyses of infant LOCAL volubility showed that the number of infant and caregivers' vocalizations were strongly and positively correlated within each social and language context. This means that more words produced by the caregivers, no matter in which language, were accompanied by more infant vocalizations.

In the current study, we used the same recordings as our previous study (Ruan, 2022; Ruan et al., 2020) to investigate mixed-language input and its relation with infants' overall and local volubility. We also asked caregivers to estimate their use of language mixing via the Language Mixing Scale (Byers-Heinlein, 2013). Our first approach, following previous research (Bail et al., 2015; Byers-Heinlein, 2013; Place & Hoff, 2011, 2016), was to measure language mixing by a parent-reported score or as a proportion of input. Thus, in Study 1a, we computed parent-reported mixing from the Language Mixing Scale (i.e., LMS) and PROPORTIONS of language mixing in day-long recordings (measured both globally and in one-on-one contexts). Unique to studies using recordings, we could also measure language input in an absolute metric alongside proportions. Thus, we also computed RAW COUNTS of 30-second recording segments containing language mixing (again, both globally and in one-on-one contexts). We then examined each mixed input measure in relation to infant OVERALL volubility. For any significant relations, we examined the same relation while controlling for demographic and linguistic factors in Study 1b. Given the diversity of findings in previous studies reviewed above, we did not have a clear hypothesis regarding the relation between infant overall volubility and different mixing metrics (scores, proportions, and counts). However, in case of any significant relation between mixed input and volubility, we expected that it would attenuate after controlling for demographic and linguistic factors. In Study 2, we investigated the relation between adult word counts and infant LOCAL volubility within mixed-language contexts; we expected this relation to be positive and strong given our previous findings on local input-volubility relations in single language input contexts (Ruan, 2022; Ruan et al., 2020).

Study 1a. Infant overall volubility and language mixing estimated by parental reports and in day-long recordings

Methods

Participants

We analyzed data from the Montréal Bilingual Infant corpus (Orena et al., 2020). This corpus consists of naturalistic day-long

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Table 1. Demographic information, reported language balance, and observed overall input at two time points of data collection. Median and Interquartile range (Quartile 1 – Quartile 3).

			Age (day)		Reported Language Balance[1] (%)		Observed Global Input[2] (AWC)		Observed 1:1 Input[2] (AWC)	
Time Points	N	Sex	Median	Q1–Q3	Median	Q1–Q3	Median	Q1–Q3	Median	Q1–Q3
10 months	21	8F, 13M	301	295–311	23	16–40	7123	5120– 8482	1960	1282–2171
18 months	16	6F, 10M	573	557–593	23	12–35	9966	7453–12129	2462	1812–4474

Notes:
[1]Parents estimated percentages of time their child exposed to English and French, the difference between which indexed language balance.
[2]Observed global and one-on-one (1:1) input was estimated by LENA-generated Adult Word Count (AWC).

recordings from 21 French–English bilingual families in Montréal, Canada. Data were collected from the same families at two time points, when the child was 10 and 18 months old (Table 1). Five families withdrew at the second time points and thus, our 18-month dataset was based on 16 families. All of the families were from mid-to-high socioeconomic background (Mean = 52.2, Range = 31 – 66, out of a possible score of 66, Hollingshead, 1975). All caregivers had knowledge of both languages and their self-rated proficiency was high for both French (Mean = 9.4, Range = 5.7 – 10) and English (Mean = 9.2, Range = 6.3 – 10). According to parental reports, each child had at least 20% exposure to each language. Four families reported a small proportion of exposure to a third language (Arabic, Kannada, Portuguese, and Spanish, < 5%). Twelve out of 21 families reported using a "one-person-one-language (OPOL)" strategy (De Houwer, 1998; Quay & Chevalier, 2019); however, parents from these families did not have lower parent-reported mixing scores or observed (raw counts or proportions) 1:1 mixing than other parents (Mann-Whitney tests, ps > .05). This could be because few families that had planned to follow OPOL strictly maintained this strategy in practice (Carbajal & Peperkamp, 2020; Quay & Chevalier, 2019). Consent was obtained during the initial laboratory visit. Parents declared no auditory and neurocognitive disorders for their child.

Procedure and measures

In-home recordings

We used the Language ENvironment Analysis system (LENA, LENA Research Foundation, Boulder, CO) to record infants' vocal activity and their language exposure. Infants wore a LENA digital language processor in a vest. Parents were instructed to have the processor on for the entire day, until the device automatically stopped after 16 hours. Three day-long recordings (two weekdays and a weekend day) were made when the infant was 10 months old, and a fourth recording was completed on a weekend day when the infant was 18 months old (see Orena et al., 2020 for details). A weekend day was chosen at 18 months because at this age some infants were enrolled in a daycare during weekdays, and recording at daycares would have significantly complicated consent procedures. In total, the families provided 1,264 hours of audio recordings (21 families at 10-month × 3 days × 16 hours + 16 families at 18-month × 1 day × 16 hours).

Infant overall volubility

The recordings were processed by LENA algorithms to extract Child Vocalization Counts (CVCs) which we employed as an estimate for infant volubility. A child vocalization is defined as a speech or speech-like sound produced by the key child that is preceded and followed by 300 milliseconds of silence or non-speech. Cries, vegetative, and other fixed signals are excluded from this estimate. To index OVERALL volubility, we summed the number of CVCs by day for each child at each age. Our definition and measurement of local volubility will be introduced in Study 2.

Observed Language Mixing

Speech spoken near the child was also captured by the LENA system. To prepare for annotation, the recordings were organized into 30-second segments and then were matched with LENA-generated measures such as Adult Word Counts (AWCs), an estimate of the number of words spoken near the key child. As our purpose was to annotate input, we focused on segments containing AWCs. Previous analyses showed that coding every other segment was representative of a child's full-day exposure (Orena et al., 2019; Ruan, 2022; Ruan et al., 2022, 2023). Thus, we manually coded every other segment. Trained English-French bilingual research assistants listened to each segment and 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). Seven research assistants completed this work, and each completed a training file before coding the data. Inter-coder reliability in the training file was high across coders (94.2% and 92.4% match for speaker and language annotation respectively, Orena et al., 2020). In total, 18979 and 6180 segments were annotated in the 10- and 18-month dataset respectively (Figure 1). There were significantly fewer annotated segments per day in the 10-month dataset than the 18-month dataset (Segment counts: 301.3 versus 386.3, F (1, 60.4) = 9.5, p = .003), but no significant difference across three days in the 10-month dataset (F (1, 41) = 1.5, p = .228).

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 540 in the 10- and 18-month datasets respectively (Figure 1).

We examined LENA-based quantification of language mixing both in terms of global mixing (the number of annotated segments containing language mixing) and one-on-one mixing (1:1 mixing, the number of annotated segments where one caregiver talked to the infant in mixed-language, Figure 1). The

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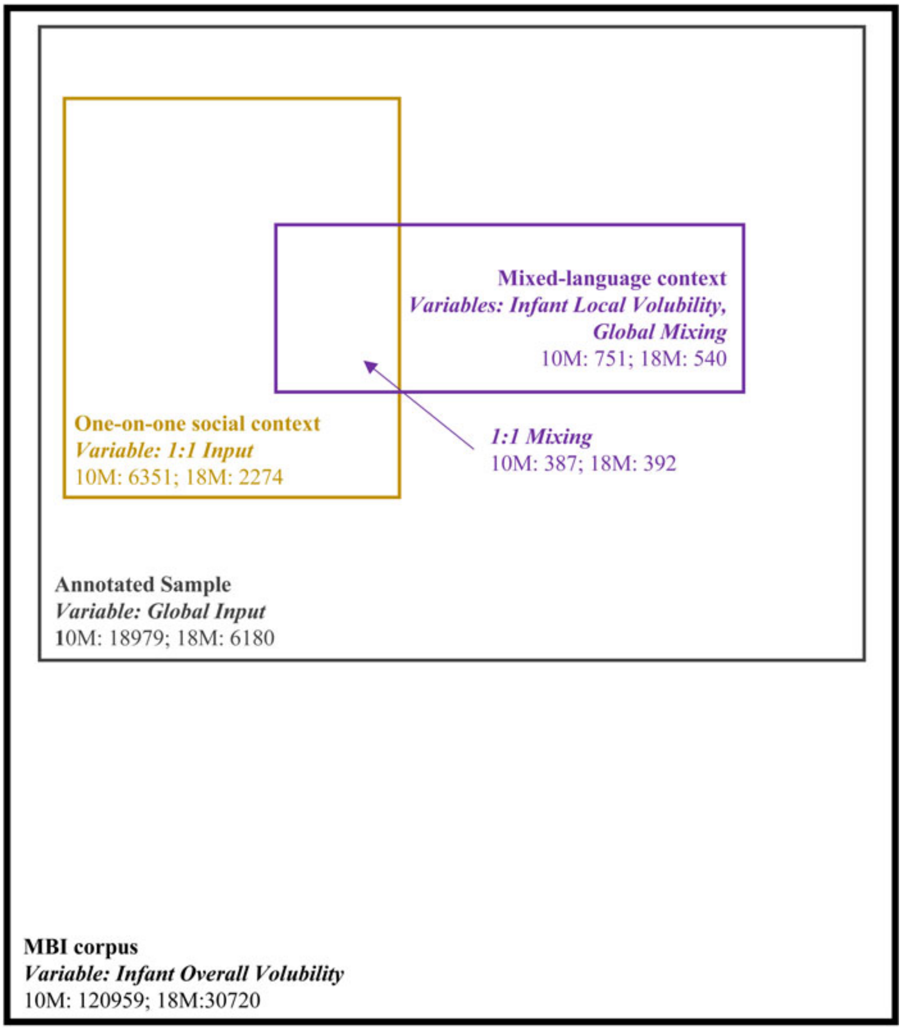

Figure 1. The structure of the Montréal Bilingual Infant corpus, LENA-based variables used in this study, and the number of segments included in each sample. 10M: 10 months; 18M: 18 months. Note that the boxes are not scaled to accurately show the relative size of the samples.

quantification was based on 30-second segments, for two reasons: (1) counting segments yields a close approximate of the frequency of language mixing as previous estimates suggested that, on average, parents code-switched once in a 30-s segment in our corpus (Kremin et al., 2022a); (2) preliminary analyses showed consistent results when using other measures such as AWCs or durations (Ruan, 2022; Ruan et al., 2022, 2023). In addition to raw segment counts, mixing variables were computed as PROPORTIONS. Specifically, the proportion of global mixing was calculated as the number of mixed segments divided by the number of annotated 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 annotated 1:1 segments for a given day of recording.

Parent-reported Language Mixing

The Language Mixing Scale was administered at each age, to assess parent-reported usage of language mixing (Byers-Heinlein, 2013). Parents were instructed to reflect on their language mixing behaviour during interactions with their child. Their 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 (LMS) from 0 to 30, a higher score indicating a higher frequency of language mixing. We computed the LMS 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 in R (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 effect size (Ben-Shachar et al., 2020).

Given our relatively small sample size, we pooled data collected at two ages (Byers-Heinlein et al., 2022a). Separate analyses were conducted for parent-reported mixing and four LENA-based estimates of mixing: segment count of global mixing, proportion of global mixing, segment count of 1:1 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. 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. We employed linear mixed-effect models with a random intercept by infant and time point of data collection (10- or 18-month). Considering parent-reported and LENA-based mixing were on distinct scales,

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we rescaled our independent variables by centering and dividing by two standard deviations (Sonderegger, 2022). Note that this rescaling does not change the results of statistical tests. For a robustness check, we also performed analyses averaged by infant, which yielded similar results (Supplementary Material Table S2).

To evaluate the significance of fixed effects, we fitted our 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). We also reported effect sizes using 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 sizes (Cohen, 1988).

Null-hypothesis significance testing (NHST) asks whether we can reject the null hypothesis that population proportion of variance accounted for (P^2, hereafter "the effect") is equal to zero. In cases where we cannot reject the null hypothesis, NHST does not inform us whether the effect is absent or extremely small. Thus, we performed conditional equivalence testing (CET) against medium-sized $\hat{\eta}_p^2$ of 0.06 (Campbell & Lakens, 2021; Lakens et al., 2018). 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., there is insufficient data to support either finding. Both the original and adjusted p-values using method described in Benjamini and Hochberg (1995) were reported. The data and code that support the findings of this study are available at https://osf.io/aq9n2/.

Results

Descriptive results are summarized in Table 2 (descriptive results by two ages are available in Supplementary Material S1). Results from linear regression analyses are presented in Table 3. When mixed input was indexed by raw segment counts, the relation between infant overall volubility and global or 1:1 mixing showed a small-to-medium effect size. 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 the segment counts of mixed-language input 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.

However, the relation between infant overall volubility and the proportion of 1:1 mixing was significant, with a medium-to-large effect size (Estimate = −393.9, 95% CI [−716.2, −43.6], F (1, 76.7) = 5.06, $\hat{\eta}_p^2$= .07, p_1 = .027, Figure 2a). This significant result remained marginally significant (p < .10) after correcting for multiple NHSTs. For every two-standard-deviation increase in the proportion of 1:1 mixing, the number of infant vocalizations per day decreased by 393.9. This relation was significant at 10 months (Estimate = −698.8, 95% CI [−1139.4, −269.2], F (1, 60.3) = 9.58, $\hat{\eta}_p^2$= .14, p_1 = .003), but inconclusive at 18 months (Estimate = −130.6, 95% CI [−747.5, 486.4], F (1, 14) = 0.21, $\hat{\eta}_p^2$= .01, p_1 = .657, p_2 = .214). The corrected p-value remained significant at 10 months.

The relation with infant overall volubility was also significant for parent-reported mixing, with a large effect size (Estimate = −498.9, 95% CI [−930.8, −16.5], F (1, 25.3) = 4.97, $\hat{\eta}_p^2$= .17, p_1 = .035, Figure 2b). This significant result remained marginally significant after correcting for multiple NHSTs. For every two-standard-deviation increase in the LMS, the number of infant vocalizations per day decreased by 498.9. This relation was inconclusive at 10 months (Estimate = −269.8, 95% CI [−757.5, 217.9], F (1, 19) = 1.34, $\hat{\eta}_p^2$= .07, p_1 = .261, p_2 = .482), but significant at 18 months (Estimate = −893.3, 95% CI [−1724.4, −62.3], F (1, 14) = 5.32, $\hat{\eta}_p^2$= .28, p_1 = .037). The corrected p-value remained marginally significant at 18 months.

Table 2. Descriptive results for infant volubility, observed mixing, and parent-reported mixing, averaged across two time points and four days.

Variables	Median (Q1-Q3)
Infant Volubility *(per day)*[1]	
Overall Volubility	1322 (961–1862)
Local Volubility	14 (6–28)
Mixed-Language Input *(per day)*	
Global Mixing	
Segment Counts	12 (7–19)
Proportions	4% (2–7%)
Adult Word Counts	285 (153–600)
1:1 Mixing	
Segment Counts	5 (2–11)
Proportions	6% (2–13%)
Parent-reported Mixing	
LMS[2]	12 (6–16)

Notes:
[1]Infant volubility was estimated by LENA-generated Child Vocalization Count (CVC). Overall volubility is the number of infant vocalizations produced in a day while local volubility is the number of infant vocalizations produced within the segments involving language mixing.
[2]Averaged between maternal and paternal Language Mixing Scores (LMS).

Interim discussion

A significant negative relation with infant overall volubility was found for the parent-reported mixing and the proportion of 1:1 mixing, whereby infants who had a higher score on parent-reported mixing, or a higher proportion of 1:1 mixing, tended to produce fewer vocalizations throughout a day. When examining the relation with parent-reported mixing for two time points separately, the result was significant for 18-month-olds. These results corroborated findings from Byers-Heinlein (2013) where a negative relation was found between parent-reported mixing and 18-month-olds' receptive vocabulary. Worth noting, our results reached significance without introducing control variables (such as age, gender, English proportion, language balance as in Byers-Heinlein, 2013) and the correlations from by-infant analyses (Supplementary Material Table S2) were numerically larger than the ones reported in Byers-Heinlein (2013). These differences might be attributed to: (1) the outcome measurement wherein the current study used infant volubility, an observational and expressive measure of infant vocal development regardless of languages, while Byers-Heinlein (2013) used a parental checklist of receptive (and productive) vocabulary in the community language (i.e., English); (2) the characteristics of participants' language background – that the participants in our study were from a French–English balanced bilingual community (Montreal) and

Table 3. Relation between infant overall volubility and observed global and 1:1 mixing as well as parent-reported mixing ($N = 21$, Study 1a).

Input Measures[1]	Global Mixing #	1:1 Mixing #	Global Mixing %	1:1 Mixing %	Reported Mixing
Observations	79	79	79	79	37
Estimate	229.4	313.5	−164.0	−393.9	−498.9
95% CI	[−87.2, 585.3]	[−19.1, 689.2]	[−496.4, 197.5]	[−716.2, −43.6]	[−930.8, −16.5]
F	1.74	3.01	0.85	5.06	4.97
$\hat{\eta}_p^2$	.03	.04	.01	.07	.17
NHST[2] p_1	.192[3]	.087	.360	.027*	.035*
CET[2] p_2	.191	.312	.094	–	–

Notes:
[1]*Overall Volubility* ∼ *Mixed Input Measure* + (1|*Infant*) + (1|*Time Point*). Independent variables were rescaled by centering and dividing by two standard deviations.
[2]NHST: Null-hypothesis Significance Test (H_0: $P^2 = 0$). CET: Conditional Equivalence Testing (H_0:$1 > P^2 > .06$).
[3]Original *p*-values. The two significant results remained marginally significant ($ps < .10$) after correcting for multiple NHSTs.
– Segment Counts; 1:1 – One-on-one social contexts; % – Proportions; CI – Confidence Interval.

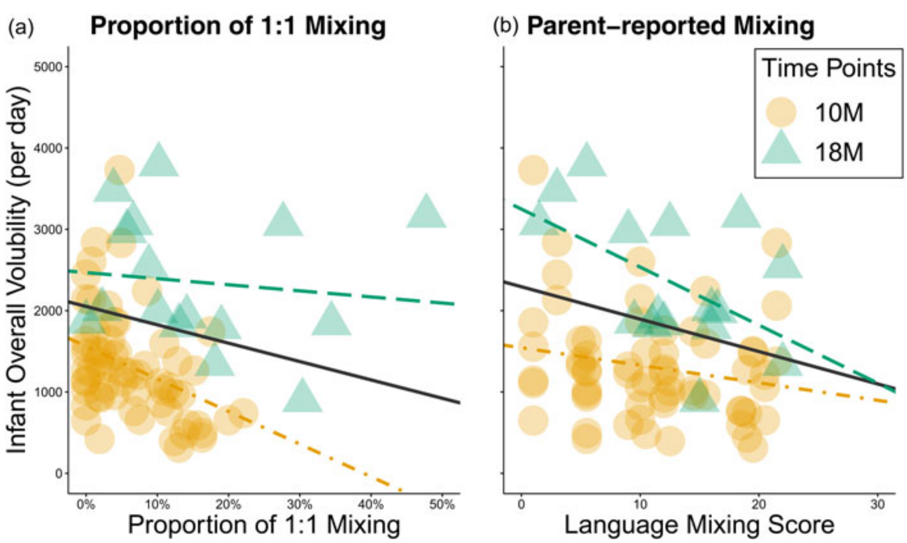

Figure 2. Infant overall volubility's relation with (a) observed proportion of 1:1 mixing and (b) parental-reported mixing, across two time points (black solid line), at 10 months (10M, orange dot-dashed line), and 18 months (18M, green dashed line). Orange dots and green triangles represent observations at 10 and 18 months respectively.

the participants in Byers-Heinlein (2013) lived in an English-dominant community (Vancouver).

Both the parent-reported mixing and the observed proportion of 1:1 mixing estimate caregivers' language mixing behaviour during 1:1 interactions with the child. Therefore, our findings also highlighted the well-known importance of caregiver-infant interactions to child vocal development (e.g., Ramírez-Esparza et al., 2017; Ruan, 2022; Ruan et al., 2020). However, our findings do not align with two other studies that also considered language mixing in 1:1 social contexts (Bail et al., 2015; Place & Hoff, 2016). We 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. Secondly, the pair of languages used by the families in our study has a more balanced sociolinguistic status in the community (French and English in Montreal, Canada) compared to the pair of languages in other studies (English and Spanish in the United States). Thirdly, infants included in our sample were younger than those in the previous studies. 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). Our analyses by age supported this assumption by showing that the relation between infant overall volubility and the proportion of 1:1 mixing was significant at 10 months but inconclusive at 18 months. Meanwhile, we need to keep in mind that this age comparison might not be fair as only one day of recording was obtained at 18 months compared to three days of recording at 10-months.

Furthermore, significant results were found when language mixing was indexed by parent-reported scores and observed proportions, but not raw segment counts. This finding shows that when estimating language input, relative (scores, proportions) and absolute (segment counts) measures tell different stories (Marchman et al. 2017; Orena et al., 2020). For instance, Infant #214 and #310 respectively received 12 and 3 segments containing 1:1 mixing when they were 18 months old. Even though Infant #214 heard more 1:1 mixing in absolute measurement, these segments accounted for smaller proportions of Infant #214's total input than Infant #310 (6% versus 13%). Infant #214 also produced more vocalizations than Infant #310 (2976 versus 1818). Therefore, when converting into proportions, the higher 1:1

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mixing segment count for Infant #214 was "diluted" by the infant's total 1:1 input (209 versus 23 segments). In other words, it is important to consider the total amount of language input when examining the effect of mixed input. The total amount of input is uniquely available in day-long recordings and how it impacts the relation between mixed input and child development has not yet been studied. Therefore, in Study 1b, we introduce total input along with other demographic and linguistic factors as fixed effects into the linear models and explore the unique contribution of mixed input to infant volubility beyond these factors.

Study 1b. Unique contribution of mixed input

Methods

Participants

Same as Study 1a.

Procedure and measures

In-home recordings

Same as Study 1a. As described in Study 1a, 18979 and 6180 segments were annotated in the 10- and 18-month dataset respectively (Figure 1). Among these segments, 6351 and 2274 segments in the 10- and 18-month dataset respectively were tagged as one-on-one social contexts. Adult words contained in these segments, estimated by LENA algorithms, served as our measure of total global and 1:1 input, which were reported in Table 1.

Parent-reported Language Mixing

Same as Study 1a.

Demographic and language background information

Demographic and language background information was collected at each age (Table 1). To collect language background information, we administrated a Language Exposure Questionnaire (LEQ, Bosch & Sebastián-Gallés, 2001) via Multilingual Approach to Parent Language Estimates (MAPLE, Byers-Heinlein et al. 2020). Parents estimated percentages of time their child exposed to English and French, the difference between which indexed language balance. For instance, if parents reported that their infant's language input was in English for 40% of time and in French for 60% of the time, then language balance for that infant would be |40% – 60%| = 20%. A smaller score indicates a more balanced input. Language balance was computed for each child at each age. The median of language balance was 23% for both 10 and 18 months.

Statistical analysis

We performed linear mixed-effect regressions at the same platform using the same packages as Study 1a. In addition, we conducted model comparisons using pbkrtest (v0.5.1, Halekoh & Højsgaard, 2014).

Our control variables included infant sex, infant age (continuous variable indexed by day, instead of the categorical variable for time points (10- or 18-month) used in Study 1a), parent-reported language balance, as well as global and 1:1 input observed in our day-long recordings. Infant sex was considered because sex differences have been associated with infant volubility in prior work (infant boys were more vocal than infant girls, Oller et al., 2020). We 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 each was related to infant volubility found in our previous study (Ruan, 2022; Ruan et al., 2020).

Like in Study 1a, all independent variables were rescaled (Sonderegger, 2022): continuous variables (infant age, language balance, global input, 1:1 input, and proportion of 1:1 mixing) were standardized by centering and dividing by two standard deviations; Binary variables (infant sex) were contrast coded such that there was a 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 we did not compute the significance for each variable to reduce the number of NHSTs.

Next, we fitted our rescaled independent variables into linear mixed-effect models with a random intercept by infant and time point (10 or 18 months). Time point was not included as a random intercept when the model had infant age as a control variable. We then compared models with and without the variable of interest (the parental-reported mixing or 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, we 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). We then computed corresponding effect sizes ($\hat{\eta}_p^2$). When the F test was not significant, we followed up with a conditional equivalence testing (CET) as described in Study 1a. Both the original and adjusted p-values using the method described in Benjamini and Hochberg (1995) were reported.

Results

Recall that the LMS primarily measures parents' language mixing behaviour during the 1:1 interactions with their child. We first investigated the additional contribution of parent-reported mixing beyond the total 1:1 input observed in day-long recordings. After introducing the total 1:1 input, the estimate of the parent-reported mixing's contribution to infant overall volubility decreased (Estimate = −305.7, 95% CI [−709.1, 129.0]). Model comparison yielded an inconclusive result (F (1, 29.9) = 1.96, $\hat{\eta}_p^2$= .06, p_1 = .172, p_2 = .482).

Next, we explored the additional contribution of the proportion of 1:1 mixing to infant overall volubility beyond control variables (Table 4). After controlling for the 1:1 input (Model 1b) or global input (Model 2b), the estimate of 1:1 mixing proportion's contribution to volubility remained negative and did not change remarkably. Model comparison between Model 1a and 1b as well as between Model 2a and 2b further indicated that the proportion of 1:1 mixing made a significant negative contribution to infant overall volubility beyond the total 1:1 input (F (1, 74.1) = 6.86, $\hat{\eta}_p^2$ = .08, p_1 = .011) and the total global input (F (1, 73.7) = 4.50, $\hat{\eta}_p^2$ = .06, p_1 = .037). The p-values remained significant or marginally significant after correcting for multiple NHSTs. When we additionally included infants' sex, age, and language balance into the models on top of the global input (3a & 3b), the estimate of 1:1 mixing proportion's relation to volubility attenuated (Estimate = −263.6, 95% CI [−583.0, 53.9]), but the significance tests suggested an inconclusive result (F (1, 73.0) = 2.36, $\hat{\eta}_p^2$= .03, p_1 = .129, p_2 = .257).

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Table 4. Unique contribution of the proportion of 1:1 mixing to infant overall volubility ($N = 21$, Study 1b).

	Infant Overall Volubility (*obs.* = 79, $N = 21$)[1]					
Variables	Model 1a	Model 1b	Model 2a	Model 2b	Model 3a	Model 3b
(Intercept)	1671.5	1739.0	1769.2	1835.0	1305.5	1347.5
Infant Sex					330.2	264.1
					[−52.3, 711.5]	[−117.7, 645.5]
Infant Age (day)					770.7	885.0
					[514.9, 1023.2]	[597.9, 1167.9]
Language Balance					269.4	220.5
					[−94.2, 642.6]	[−138.9, 587.8]
Global Input			368.8	348.3	343.1	326.9
			[66.7, 695.6]	[48.6, 674.3]	[68.9, 661.2]	[55.4, 647.6]
1:1 Input	879.9	865.0				
	[627.4, 1157.7][2]	[622.3, 1127.1]				
% 1:1 Mixing		−365.1		−364.6		−263.6
		[−620.1, −83.5]		[−676.1, −21.7]		[−583.0, 53.9]
Additional Contribution from Proportion of 1:1 Mixing						
Model Comparison (*F*)	6.86		4.50		2.36	
df	(1, 74.1)		(1, 73.7)		(1, 73.0)	
$\hat{\eta}_p^2$	.08		.06		.03	
NHST[3] p_1	.011*[4]		.037*		.129	
CET[3] p_2	–		–		.257	

Notes:
[1]Model 1a & b and 2a & b: *Overall Volubility* ∼ *Variables* + (1|*Infant*) + (1|*Time Point*); Model 3a & b: *Overall Volubility* ∼ *Variables* + (1|*Infant*). 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.
[2]95% Confidence Intervals.
[3]NHST: Null-hypothesis Significance Test (H_0: $P^2 = 0$). CET: Conditional Equivalence Testing (H_0:$1 > P^2 > .06$).
[4]Original *p*-values. The two significant results remained significant or marginally significant ($p < .10$) after correcting for multiple NHSTs.
Obs. – Observations; 1:1 – One-on-one social contexts; % – Proportions.

Interim discussion

The results from Study 1b extended findings from Study 1a by showing that the proportion of 1:1 mixing made a unique negative contribution to infant volubility beyond the total amount of 1:1 or global input. Moreover, throughout Study 1a & b, the effect size of mixed-language input's contribution to infant volubility was not negligible. It is consistent with what we have found for input in children's non-dominant language: despite accounting for a relatively smaller proportion in children's total input, it still makes a unique contribution to infant volubility (Ruan, 2022; Ruan et al., 2020). Similarly, even while it might be rare, mixed-language input is associated with infant volubility.

So far, we examined the relation between mixed-language input and infant overall volubility, which is the number of infant vocalizations produced in a day across all language contexts. The negative relation might be driven by two mechanisms: (1) infants who receive a higher proportion of 1:1 mixing might expend more cognitive effort in processing mixed input hence vocalize less; (2) caregivers of children who are less vocally active may wish to stimulate their child and/or to teach vocabularies and hence switch languages more frequently during dyadic interaction. In Study 2, we examined whether lower infant vocalization rates are related to more mixed input within the segments where language mixing occurred. If infants do vocalize less when parents increase the use of language mixing (as suggested in the first mechanism), we should observe a negative correlation.

Study 2. Language mixing and infant local volubility

Methods

Participants and procedures were identical to Study 1a.

Measures

Infant Local Volubility

We summed the number of child vocalizations (CVCs) only from the mixed segments and named it infant *local* volubility. Infant local volubility was computed by day for each infant at each age.

AWCs of Mixed-Language Input

Global mixing measures were indexed by LENA-derived adult word counts (AWCs) in the mixed segments. These measures were computed by day for each infant at each age.

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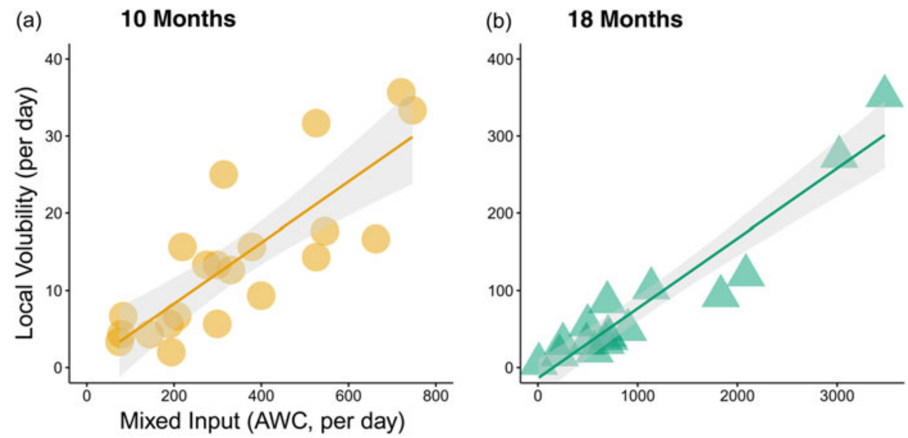

Figure 3. The relation between infant local volubility and mixed input indexed by adult word counts (AWCs) in function of time point (a: 10 months; b: 18 months). Orange dots and green triangles represent infants when they were at 10 and 18 months respectively.

Statistical analysis

We performed our analyses at the same platform using the same packages as Study 1a. Due to the small variation in local volubility, we could not fit our data from two ages into a linear mixed-effect model without overfitting the model. Therefore, we 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, we averaged CVCs and AWCs in mixed segments at each age for each infant. Both the original and adjusted *p*-values using method described in Benjamini and Hochberg (1995) were reported.

Results

Our results showed a strong and positive correlation between the number of infants and caregivers' vocalizations within mixed segments at both 10 months (Estimate = 47.9, 95% CI [31.5, 64.2], F (1, 19) = 37.6, $\hat{\eta}_p^2 = .66$, $p < .001$, Figure 3a) and 18 months (Estimate = 109.7, 95% CI [89.1, 130.3], F (1, 14) = 130.5, $\hat{\eta}_p^2 = .90$, $p < .001$, Figure 3b). Both *p*-values remained significant after correcting for multiple NHSTs.

Interim discussion

Our results suggest a robust and positive relation between the number of infants' and caregivers' vocalizations within the contexts involving language mixing at both ages. Unlike overall volubility (the number of vocalizations produced throughout a day), local volubility in this study specifically refers to the number of infant vocalizations produced IN THE PRESENCE OF MIXED INPUT. Therefore, this positive association between local volubility and input within mixed segments indicates that infants vocalized more in contexts where they heard more adult words containing language mixing. In other words, contexts involving language mixing still create a stimulating environment for vocalizations from both caregivers and infants. This strong volubility-input association found locally in mixed segments also corroborates our previous findings with English- or French-only input (Ruan, 2022; Ruan et al., 2020). It is also consistent with the positive relation between the frequency of parental intra-sentential language mixing and infants' vocabulary size found in Bail and colleagues' study (2015).

General discussion

In summary, we investigated the relation between infant volubility and mixed-language input estimated by parent reports (scores) and by direct observation from day-long recordings (proportions and counts). First, we found that infants who had higher Language Mixing Scores, or heard a greater proportion of 1:1 mixing, produced fewer vocalizations in a day. The proportion of 1:1 mixing made a unique contribution to infants' overall volubility beyond the total amount of 1:1 or global input. However, within the mixed segments, more adult words were accompanied with more infant vocalizations.

In previous studies, a negative relation was observed between mixed input and infants' 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 including vocabulary size (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 dots between more parental language mixing and smaller vocabulary size. We propose two potential pathways. First, empirical evidence suggests that language mixing sometimes introduces a processing cost (Byers-Heinlein et al., 2017, 2022b; Gross et al., 2019; Morini & Newman, 2019; Potter et al., 2019), due to higher cognitive demands (Byers-Heinlein et al., 2017) and/or statistic regularity violations (Potter et al., 2019). Therefore, infants who hear a higher proportion of language mixing during 1:1 interactions might expend more cognitive effort in processing language mixing and vocalize less. This might result in a slower rate of vocabulary growth. A second pathway could involve an impact in the reversed direction: caregivers of children who have a smaller vocabulary size or produce fewer vocalizations may switch languages more frequently during dyadic interaction. We know that parents adjust their language usage according to their child's developmental status and behaviour (Saint-Georges et al., 2013). Parents with a quieter child might mix languages more often to provide novel stimuli in an effort to gain their child's attention and to elicit 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 to teach words (Kremin et al., 2022a).

Results from Study 2 seem to disfavor the first pathway. Within segments involving language mixing, infants produced more utterances in contexts where they received more words from their caregivers. Thus, processing input containing language mixing does not seem to impede infants from vocalizing. Worth noting, infants and caregivers' vocalizations within mixed segments were correlated as strongly as within segments involving input in children's dominant and non-dominant language found in our previous study (Ruan, 2022; Ruan et al., 2020). This finding supports views of everyday language mixing comprehension that downplay processing costs (Kohnert et al., 1999; Kohnert & Bates, 2002; Valdés Kroff et al., 2018). Kremin and colleagues found in the same corpus used for the current study that most language mixing happened between sentences (Kremin et al., 2022a). It is crucial because empirical evidence suggests no processing cost for comprehending inter-sentential code-switching among infants (Byers-Heinlein et al., 2017; Gullifer et al., 2013). Therefore, bilingual caregivers, at least those who participated in our study, avoid the use of cognitively-demanding forms of language mixing with their child. Furthermore, 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 increased 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), in addition to the strategies summarized in PRIMIR model (compare-contrast, statistical learning, and co-occurrence patterns etc., Curtin et al., 2011). Meanwhile, we cannot rule out the possibility that there is a delay between receiving mixed input and its 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 observed within mixed segments (Ramírez-Esparza et al., 2014, 2017; Ruan, 2022; Ruan et al., 2020).

To test the hypothesis that children's low vocal activeness drives caregivers to switch languages, as suggested in the second pathway, we need more direct evidence. Existing findings show that language mixing can sometimes help infants process bilingual information, especially information in the non-dominant language (Gross et al., 2019; Kremin et al., 2022b; Orena & Polka, 2019; Read et al., 2021; Schott et al., 2021). Language mixing in various forms can also facilitate learning novel words among pre-schoolers (Brouillard et al., 2020; Kaushanskaya et al., 2022; Read et al., 2021; Tsui et al., 2022). 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 infant volubility might not necessarily indicate that mixed input is detrimental to children's vocal development; instead, bilingual caregivers might switch languages to help their children successfully acquire both languages (Byers-Heinlein et al., 2017; Kremin et al., 2022a).

Furthermore, the relation between language mixing and infant volubility might also depend on the metric that we used to quantify mixed input. In our study, a negative relation was found when language mixing was indexed by scores and proportions, both of which are measures of mixed-language input relative to the total input. However, when language mixing was indexed by absolute measures such as raw segment counts (Study 1a) or adult word counts (Study 2), its relation with infant volubility tended to be positive. These findings together might suggest that children vocalized more when they received more mixed-language input if the mixed input did not account for a large proportion of their total input. In other words, generating more input might help dilute any effects of language mixing on infant volubility. Indeed, in Study 1b, the estimate for the effect of reported and observed 1:1 mixing decreased after we introduced the total (1:1 or global) input and was no longer significant for reported mixing. Therefore, the current study complements the findings from previous bilingual research on single-language input (Ramírez-Esparza et al., 2014, 2017; Ruan, 2022; Ruan et al., 2020) by showing that more input, no matter if it is single- or mixed-language, encourages infants to vocalize more; simultaneously, more infant vocalizations also encourage parents to produce different types of input.

The characteristic of our participants, specifically their language background, might also contribute to the results of the current study. The families who participated in this study lived in a homogeneous and balanced bilingual community (Montreal, Canada) where French and English are used equally in the society. Across families, parents also reported high proficiency in both languages. The uniqueness of their linguistic profile determines that we do not know whether our results would generalize. Language status in the community, parents' language proficiency, and their language strategy in childrearing (e.g., OPOL) can influence parental language mixing behaviour to varied extent (Quay & Chevalier, 2019), which in turn, changes mixed input's relation with infant volubility. Future studies should examine the same research questions in other bilingual communities (Byers-Heinlein et al., 2022b).

Some of our results were statistically inconclusive. There are two possible explanations. First, our sample size was relatively small, largely because the laborious work involved in manual coding limited the sample size. However, the corpus still consists of 1,264 hours of recordings. We also tried to increase the number of observations by performing the analyses based on days rather than infants and results from both analyses are consistent. Second, although the frequency of mixing varied greatly across families, on average, mixed input made up a relatively small proportion of children's input in our corpus (4% and 6% for global and 1:1 mixing respectively, Table 2), similar to what has been observed in other corpora (Benitez et al., 2022; see a higher proportion of mixing reported in Place & Hoff, 2011, 2016). This might restrain the extent to which we can observe relations between mixed input and infant volubility, compared to single-language input (Ruan, 2022; Ruan et al., 2020). However, it does not mean that mixed input is insignificant to child language development: overall, our results indicated that mixed input had a medium-sized relation to infant overall volubility.

Additionally, this study has the following limitations that can be addressed in future research. First, children's language environment outside the home was unknown, which was especially relevant for 18-month-olds as some of them went to daycares on weekdays. Children's attendance at daycares also resulted in only one day of recording being available at 18 months. Future studies should expand to settings outside home (Soderstrom et al. 2018). Second, details within mixed segments such as how many times caregivers code-switch and in which direction should be considered in future studies since they are relevant to how difficult they are for infants to process (Byers-Heinlein et al., 2017; Morini & Newman, 2019; Potter et al., 2019). In particular, the syntactic location of language mixing was only available for a portion of our data (Kremin et al., 2022a); otherwise, we could have explored our corpus in greater depth as to how the linguistic context in which language mixing happens and how it is related to infant volubility. Third, although we observed a robust and positive input-volubility correlation within mixed contexts, this study did not address whether infants vocalized more in mixed- or single-language contexts. Future studies could consider comparing infant volubility across different language contexts. Lastly,

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we explored the relation between mixed input and infant volubility at a relatively large timescale (a day), future studies could study caregiver-infant vocalization sequences to better understand how bilingual parents change their frequency of language mixing according to their child's vocal activeness (Lopez et al., 2020; Pretzer et al. 2019; Warlaumont et al., 2014).

Taken together, we observed that a greater relative, but not absolute, amount of parent-reported or observed mixed input in 1:1 social contexts was related to lower overall volubility in infancy and toddlerhood. Although it could be argued that processing language mixing hinders infant vocalizations, our data disfavor this argument since we also found that, within contexts involving language mixing, more adult words were related to more infant vocalizations. These findings together can be applied to foster a harmonious bilingual development (De Houwer, 2015), as they imply that parents and educators should be less concerned about mixing languages when talking to their children, and instead focus on creating a verbally stimulating environment regardless of how the two languages are used. Our study is an invitation for more research to understand language mixing in bilingual children's input and its relation to child bilingual development.

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Competing interests. The authors declare none.

Data availability statement. The data and code that support the findings of this study are available on https://osf.io/aq9n2/.

Supplementary Material. For supplementary material accompanying this paper, visit http://dx.doi.org/10.1017/S1366728923000287

Supplementary material Table S1.

Supplementary material Table S2.

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