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The role of quantity and quality of linguistic exposure on language development during childhood

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PhD dissertation

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List of abbreviations

ADS. Adult-directed speech.

AM. Amplitude modulation.

AoA. Age of acquisition.

AoE. Amount of (linguistic) exposure.

CBPT. Cluster-based permutation test.

CDS. Child-directed speech.

CTS. Cortical tracking of speech.

IDS. Infant-directed speech.

L1. First language.

L2. Second language.

LME. Linear mixed effects model.

mTRF. Multivariate temporal response function.

PSI. Phase-synchronization index.

S-AMPH. Spectral-amplitude-modulation-phase-hierarchy model.

Resumen de la tesis doctoral

El objetivo general de esta tesis doctoral es estudiar el impacto que factores del contexto lingüístico en el que crecen niñas y niños tienen en su desarrollo del lenguaje. Para ahondar en dicho objetivo, nos centramos en la cantidad y la calidad del input lingüístico que reciben dichas personas entre los 4 y los 7 años, y en cómo se desarrollan sus habilidades del lenguaje a distintos niveles como consecuencia de dicho input.

En concreto, la *cantidad de input lingüístico* está operacionalizada en esta tesis como la proporción de exposición a cada idioma en niños que se desarrollan en un idioma bilingüe euskera-castellano. Respecto a la *calidad del estímulo lingüístico*, nos centramos en estudiar el habla dirigida a niñas/os (*child-directed speech*), con el objetivo de estimar si está caracterizada por unas propiedades temporales que puedan facilitar el desarrollo de un sistema fonológico. Tanto la cantidad como la calidad de la exposición lingüística juegan aquí un rol de predictores del desarrollo de distintas áreas del lenguaje, que dividimos de manera amplia en habilidades fonológicas (memoria fonológica a corto plazo y conciencia fonológica) y habilidades no fonológicas, en las que circunscribimos las capacidades léxico-semánticas y sintácticas.

En el Estudio 1, evaluamos cómo el desarrollo del lenguaje en dos idiomas distintos está influenciado por la cantidad respectiva de exposición a cada uno de ellos. Para ello, seguimos a 74 niñas y niños bilingües de euskera-castellano en tres etapas longitudinales. En concreto, examinamos si diferentes proporciones de exposición a una lengua modulan el desarrollo y uso del lenguaje a distintos niveles: fonológico, léxico-semántico y sintáctico. Entre los resultados del Estudio 1, observamos un impacto directo de la cantidad de exposición a un idioma en el crecimiento longitudinal del conocimiento de distintos subdominios (especialmente el léxico-semántico y el sintáctico) en dicho idioma. Mientras que las habilidades fonológicas no estaban directamente moduladas por la cantidad de exposición, observamos que estaban más desarrolladas en el idioma más dominante a nivel de grupo (el euskera). Además, el uso de producciones espontáneas del lenguaje, en cuanto a un léxico rico y una sintaxis compleja, se desarrolló de manera directamente relacionada con la cantidad de input lingüístico. El hecho de que dicho uso espontáneo del lenguaje se desarrollara de una manera más robusta en el idioma más dominante, nos hace interpretar que depende de la acumulación de aprendizaje previo en otros dominios del lenguaje, posiblemente a través de la exposición. Contextualizamos nuestros resultados dentro de una perspectiva bilingüe del desarrollo del lenguaje, ofreciendo evidencia del impacto que tiene la exposición a cada una de las lenguas en el desarrollo de distintos dominios fundamentales para el conocimiento lingüístico de niños bilingües.

En el Estudio 2, examinamos si la exposición relativa a cada una de estas lenguas (euskera y castellano) da forma a una habilidad neurocognitiva relevante para la comprensión del habla, llamada "seguimiento cortical del habla" (o *cortical tracking of speech*). Con este fin seguimos a 35 niñas y niños bilingües del Estudio 1, en concreto aquellos que mostraron una mayor exposición al euskera (L1 o primer idioma) y menor al castellano (L2, su segundo idioma). A través de la técnica neurofisiológica de la electroencefalografía, intentamos determinar si dicho patrón desequilibrado de exposición a cada idioma jugaba un papel relevante en el seguimiento cortical del habla (tanto a nivel fonológico como no-fonológico). No encontramos evidencia a favor del impacto de la cantidad de la exposición a un idioma en el seguimiento cortical del habla. Sin embargo, sí que observamos relaciones específicas entre medidas comportamentales del lenguaje y el seguimiento cortical del lenguaje, tanto a nivel fonológico como a nivel no fonológico, y circunscritas únicamente al L1 (euskera). Estos resultados podrían informar futura investigación sobre el desarrollo de las habilidades neurocognitivas para el procesamiento del habla, aportando evidencia sobre su relevancia a nivel comportamental.

En el Estudio 3, nos trasladamos del análisis de la cantidad de la exposición lingüística hacia la calidad del habla que reciben los niños. Para ello, analizamos a 18 mujeres, hablantes nativas de castellano, mientras hablaban de manera espontánea a sus niñas o niños (habla dirigida a niños o *child-directed speech*) y a adultos (habla dirigida a adultos o *adult-directed speech*). Usamos un modelo espectro-temporal para estimamos tres factores: la tasa silábica, la prominencia prosódica del habla, así como la regularidad con la que las sílabas estaban acentuadas en el habla dirigida a niños en comparación a cuando los oyentes eran adultos. Observamos que, comparada con el habla dirigida a adultos, el habla dirigida a niños estaba caracterizada por una menor tasa silábica, mayor prominencia prosódica, y un mayor alineamiento entre las modulaciones de amplitud prosódicas y silábicas. Los resultados de este estudio son acordes con teorías vigentes sobre la emergencia de las habilidades fonológicas, las cuales subrayan que las regularidades temporales del habla dirigida a niños podrían ser más fácilmente explotadas por un sistema fonológico en desarrollo. Estas observaciones también pueden ser relacionadas con el Estudio 2, mostrando que el habla dirigida a niños podría ser más fácilmente seguida por la actividad oscilatoria cerebral durante el seguimiento cortical del habla.

En resumen, los tres estudios que forman la presente tesis pueden ser entendidos en una lógica interrelacionada, en la que la cantidad y la calidad de la exposición lingüística juegan un papel crucial en el desarrollo del lenguaje en edades en las que el input oral es crucial, en concreto de 4 a 7 años de edad.

Thesis summary

The empirical work that forms this thesis is formed by three interrelated experiments (Studies 1, 2, and 3) about the role of linguistic exposure on language development during childhood. Such shared overarching question is addressed from different empirical perspectives and methodological approaches, and therefore each study is backed by specific bodies of theoretical and empirical research. For this reason, the General Introduction offers an overview of the common aspects to the three studies, while the specific literature that contextualizes each study is present in their respective Introductions.

In Study 1, we evaluated how language development is influenced by the amount of exposure to two languages concurrently between four and six years of age, by following 74 Basque-Spanish bilingual children in three longitudinal stages. More specifically, we examined whether different proportions of linguistic exposure to each language shape language knowledge and use at phonological and non-phonological (i.e., lexico-semantic and syntactic) levels.

We observed a direct impact of the amount of linguistic exposure on the longitudinal growth of both languages, especially circumscribed to lexico-semantic and syntactic abilities. While phonological skills were not directly impacted by exposure, they were more proficient in the language with overall more exposure. Regarding the development of the spontaneous use of lexically diverse and syntactically rich utterances by children, we observed that it was subtended by both the amount of exposure and also potentially by accumulated knowledge in related language domains impacted by it (i.e., lexical and syntactic knowledge). We contextualize our findings into a bilingual account of which language domains are more particularly impacted by linguistic input and how knowledge within such domains may shape the use of two languages during childhood.

In Study 2, we tested whether the relative amount of linguistic exposure to each of the languages of bilinguals (in our case, Basque and Spanish) shapes a neurocognitive ability relevant for speech comprehension, the cortical tracking of speech. To achieve this goal, we followed 35 children from Study 1, namely those who had the biggest exposure to Basque (L1) and smallest to Spanish (L2), in order to test whether such unbalanced accumulated input in each language played a role in the maturation of the cortical tracking of phonological and non-phonological distributional properties of speech, for each language separately. We did not find evidence for a direct influence of the amount of exposure to the maturation of cortical tracking of speech. However, we observed specific relationships between the cortical tracking of speech at phonological and non-phonological levels and behavioral performance in the respective domains, although this finding was circumscribed to the dominant language of children (L1, Basque). We expect our findings to inform future developmental research about the factors influencing the development of the cortical tracking of speech, as well as how this neural mechanism contributes to speech abilities measured in children.

In Study 3, we shifted the focus of our investigation from quantitative (amount of exposure) to qualitative aspects of the linguistic input that children are exposed to. We tested 18 women, native speakers of Spanish, while spontaneously addressing their children (child-directed speech), or some adults (adult-directed speech). We used a spectro-temporal model and estimated the syllable rate, the prosodic prominence, and the regularity with which syllables are stressed in child-directed speech in comparison to adult-directed speech. We observed that child-directed speech was characterized by a slower syllable rate, more prosodic salience, as well as more regular alignment between prosodic and syllabic amplitude modulations than adult-directed speech. Our findings are in line with current theories about the emergence of phonological abilities, by highlighting temporal regularities in child-directed speech that could be exploited by a developing phonological system. These observations are also related to our findings in Study 2 about the cortical tracking of speech, and can serve a multilevel perspective of phonological development.

General introduction

The role of oral linguistic exposure on language development during childhood

In everyday life, we encounter speech in different forms and in a vast number of contexts, what makes individuals become proficient in their languages with an apparent ease throughout development. Nonetheless, a great amount of internal and environmental factors will modulate the rate and ease with which individuals achieve such proficiency. Among individual-level determinants of language acquisition (also relevant for broader cognitive development), chronological age and “sensitive periods” (Werker & Hensch, 2015) are crucial for attaining language milestones, such as the consolidation of language-specific phonemic categories (e.g., Burns et al., 2007) and the production of first words (see Kuhl, 2004). A delay in reaching such milestones might hamper the development of various linguistic processing skills (i.e., phonological, lexical, syntactic; e.g., Banai & Ahissar, 2018; Bishop & Snowling, 2004; Nittrouer & Burton, 2005), resulting in performance lags with respect to typically developing peers, such as what is seen in neurodevelopmental language disorders (e.g., developmental dyslexia, developmental language disorder).

Parallel to individual-level aspects, contextual (or environmental) factors will either positively or negatively influence language development depending on the richness of the inputs to which young learners are exposed. The main question of the present thesis is specifically aimed at exploring the role of the richness of oral linguistic input on language development during childhood, through the study of the quantity and the quality of exposure to a language.

A crucial source of inter-individual variations modulating language development trajectories is the amount of exposure to a language, reflecting quantitative aspects of the speech input (e.g., Pearson et al., 1997; Thordardottir, 2011). Bilingualism (as well as multilingualism) offers the opportunity to explore the role of the amount of exposure on language acquisition through the measurement of the relative input in each language. Studies 1 and 2 will focus on estimating the direct influence of the amount of linguistic exposure to languages on the development of knowledge of these languages in bilingual children, at both the behavioral and neurocognitive levels.

In addition to the amount of exposure to a language, the quality of the linguistic input impacts language development to a considerable extent. For example the socioeconomic status of the individual and their household is a sizable and pervasive contextual factor which has a strong impact on language acquisition (Dailey & Bergelson, 2022; Hart & Risley, 1995; Hoff, 2003a; Merz et al., 2020; Pace et al., 2017). Of particular relevance for this thesis, one of the most widely studied mediators between socioeconomic status and language development is the speech register used by adults to communicate with young children, known as child-directed speech (Cristia, 2022; Dailey & Bergelson, 2022; Marchman et al., 2017). Child-directed speech appears to boost language learning through the adaptation of spectral (e.g., pitch) and temporal features (e.g., speech rate), which engage and ease its processing (Fernald, 2000; Leong & Goswami, 2015). Therefore, the investigation of child-directed speech as a window into language development offers ways to determine the specific characteristics of the speech signal that may provide learning-facilitatory effects. For this reason, the study of child-directed speech will be the specific focus of Study 3.

Language knowledge across fundamental domains

With respect to the development of language abilities, several concepts will be tackled by the three studies of the thesis, and therefore we are defining them below.

Language knowledge (also referred to in some occasions as proficiency) is the general concept with which we approximate language development, and can be thought of as the capacity to comprehend and produce a given language. We will differentiate two broad categories of language knowledge: phonological and non-phonological abilities. **Phonological abilities** support the sensitivity, categorization, and manipulation of the sounds of a language, as well as the rules or distributional properties that govern those sounds. Consequently, non-phonological abilities are those language domains that do not directly relate to the categorization of speech sounds, but rather to the knowledge higher of higher-level linguistic units (i.e., words and sentences). In this thesis, we focus on two non-phonological domains: **lexico-semantic abilities**, that allow for the comprehension and use of vocabulary; and **syntactic skills**, which enable learners to extract the specific meaning of a linguistic structure (i.e., a sentence or a group of sentences), and through which we approximate broader grammatical knowledge.

Therefore, language knowledge within the mentioned domains will act as a dependent variable of the (quantity and quality of) linguistic exposure.

Quantity and quality of linguistic exposure on language development

Quantitative exposure to a language could be defined as the passive contact with linguistic inputs by the mere presence of the individual in the context in which it is used. Here, we conceptualize the amount of exposure to a language as a process through which the child is not only a passive listener, but also actively uses and produces this language. Such distinction is relevant because depending on whether the linguistic input, or the input and its use (as in our case), are assessed, different language outcomes can be observed (Bedore et al., 2012). Thus, the definition of ***amount of exposure* (AoE)** in the present thesis refers to the time spent within a context in which a given language is spoken. Such definition allows us to contextualize our investigation among research that used a similar term to explore the role of linguistic input in language development, including studies in bilingual and monolingual children, children with hearing impairments, and children growing in diverse socioeconomic and cultural contexts (e.g., Cristia et al., 2019; Nittrouer & Burton, 2005; Pearson et al., 1997). Here, we study bilingualism as a window into the impact of the amount of linguistic exposure on language development. Indeed, the quantification of AoE in each of the languages of bilinguals offers the opportunity of directly assessing the effect of different proportions of exposure to two languages within the same individuals.

In addition to AoE, several factors directly linked to bilingualism have been shown to play a role in language development such as the age of acquisition, contexts of language use (dual versus single-language contexts), socio-cultural factors of use (e.g., heritage languages, majority and minority languages), etc. Together, these different factors offer a faithful picture of the context and history of language learning that can explain the level of proficiency in different linguistic domains. Importantly, a recent Delphi consensus of researchers, teachers, and speech and language therapists agreed that a comprehensive study of bilingualism should include measures of "language exposure and use as well as the assessment of language impairments, proficiency levels, education and literacy history, the quality of the input, language mixing practices, and attitudes towards languages and language mixing" (Cat et al., 2022). Such subfactors of bilingualism offer a comprehensive account of the context in which bilingual development takes place. Among those factors, we focus on how AoE to two languages shapes their development.

More specifically, we quantify individual AoE to the two languages of bilingual children as a continuous variable, to explore its direct impact on the development of language knowledge. Such continuous AoE index allows us to overcome some of the disadvantages linked to the study of exposure through less direct measures based on between-groups comparisons (bilinguals versus monolinguals) or other bilingual-specific features (e.g., L1 vs. L2). Importantly, our exposure measure allows us to explore the effect of very limited amounts of exposure (e.g., less than 30% of the time in the case of L2) on language development in children "becoming bilinguals". In addition, it has been recently validated by methodological investigations that show that a multifactorial and continuous characterizations of bilingual exposure accurately predicts language performance (Gullifer et al., 2020; Gullifer & Titone, 2019).

In the first two studies, we capitalized on such continuous measure to explore the role of quantity of exposure on bilingual language development. In the third study, we explored linguistic exposure from a complementary perspective, namely looking at the quality of the input to which the children are exposed to.

Here we define ***quality of exposure*** as the availability or enhancement of a set of speech features that facilitates its efficient analysis by a language-learning individual. One example of the relevance of the quality of exposure for language acquisition and development is portrayed by studies in children with hearing impairments, whose impoverished perception of acoustic stimuli results in delays across different linguistic domains (Nittrouer, 1996; Nittrouer & Burton, 2005). In addition, it has been shown that the quality of the speech used by parents to communicate to their children, i.e., adapted, diverse, and increasingly complex in terms lexical and syntactic productions, positively influences language development (Furrow et al., 1979; Hoff-Ginsberg, 1986; Huttenlocher et al., 2002, 2010). And the last example, of particular relevance for this thesis, is the adaptation of spectral (i.e., pitch, tone) and temporal (e.g., speech rate) features of speech that adults produce when speaking to infants and children. Infant-directed speech registers have distinctive acoustic characteristics from adult-directed speech, which could make them especially suitable for learners for whom language processing is still a complex and demanding task (Fernald, 2000; Leong et al., 2017). Thus, the purpose of Study 3 is to assess whether, beyond infant-directed speech, child-directed speech also provides children with enhanced temporal statistics that might support phonological development.

In summary, we operationalize quantity (proportional amount of bilingual exposure, or AoE) and quality (temporal characteristics of child-directed speech) of oral linguistic input in order to estimate their impact on the language development of children that, while having already acquired a considerable amount of knowledge, are not yet proficient language users.

Oral linguistic exposure in children's language development

Our variables of interest to study the role of quantitative and qualitative richness of the speech input in language development are defined based on the oral nature of the speech inputs. The developmental time span (4 to 7 years old) on which the present thesis focuses has been typically examined with regard to the influence of quantity and quality of exposure on language development. Importantly, we know that during this period, bilingual children (the populations assessed in Studies 1 and 2) are still developing each of their languages (Xue et al., 2021) while being efficient language users of their phonological (Anthony & Lonigan, 2004), lexico-semantic (e.g., Altman et al., 2018), and morphosyntactic (Frizelle et al., 2018) abilities.

Although we acknowledge that infancy would also be an informative and appropriate period to explore the influence of linguistic exposure on language abilities (Bosch & Sebastián-Gallés, 1997, 2001; Carbajal & Peperkamp, 2020; Garcia-Sierra et al., 2016; Kuhl et al., 2003), we chose to test young children as we wanted to evaluate a broad array of language skills including speech production (e.g., lexical diversity of spontaneous speech productions, production of complex utterances such as multi-clause sentences, repetition of nonwords). Therefore, the three doctoral studies are centered around the investigation of language development when oral input is still the predominant source of linguistic exposure. Noteworthy, from 6 to 7 years of age, formal reading instruction starts, and written language exposure becomes an increasingly relevant source for building further language knowledge such as vocabulary size. Reading also enables children to learn from a new language register (e.g., more abstract and less frequent words, and more complex sentences, Nation et al., 2022) that predicts variance in language knowledge at the lexical and syntactic levels above and beyond what is explained by the oral input. Thus, we decided to circumscribe our age range of interest to developmental stages prior to the point where the influence of reading proficiency on language development becomes significant.

General aims and specific hypotheses: A multi-level approach to linguistic exposure

In order to offer a comprehensive account of the role of linguistic exposure on language development during childhood, the three studies of this thesis are presented following a common logic.

The aim of Study 1 was to determine the impact of AoE on the development of phonology, lexico-semantics, and syntax during early childhood. To achieve this, we assessed longitudinally both AoE and the language knowledge of 74 Spanish-Basque bilingual children in their two languages from 4 to 6 years old. Importantly, as a group, the amount of exposure was higher in Basque than in Spanish. To obtain an evaluation of the language performance of these children that was as broad as possible (i.e., receptive and productive abilities in the phonological, lexico-

semantic and syntactic domains), children were administered a battery of computerized and controlled tasks (e.g., picture naming, nonword repetition) as well as a "spontaneous speech production task" in their two languages.

The objective of Study 2 was to determine whether the amount of linguistic exposure (and its consequential language knowledge) could modulate a neurocognitive mechanism relevant for speech comprehension and more generally language development (Goswami, 2011), the so-called cortical tracking of speech (Giraud & Poeppel, 2012; also termed "speech-brain entrainment" in the literature). The cortical tracking of speech corresponds to the alignment of cortical oscillatory activity to the temporal distributional properties of phonological (speech envelope) or non-phonological (lexical frequency, sentence-level semantic relation between words) speech features. To achieve this aim, we measured the cortical tracking of speech and the language performance in both of the languages of 35 unbalanced bilingual children from Study 1 who had a significantly higher exposure to Basque than Spanish.

Lastly, Study 3 focused on analyzing whether child-directed speech was characterized by qualitatively richer speech productions (i.e., more regular temporal statistics that could drive the cortical tracking of speech) than adult-direct speech. In this case, we performed an acoustic analysis of the spontaneous and read speech productions of 18 adult native speakers of Spanish while addressing their children (child-directed speech) and adults (adult-directed speech).

All three studies were designed with the aim to study language processes as they occur in everyday life (e.g., receptive and productive abilities of spontaneous and natural speech). Importantly, while they go beyond classical analytic approaches (e.g., presenting highly experimentally-constrained stimuli) the three studies of this doctoral work acknowledge the complexity of the mechanisms involved in language learning. The motivation for following this ecological approach was to offer evidence generalizable to the natural complexity of language learning rather than being constrained to specific experimental paradigms (Alexandrou et al., 2018; Cantlon, 2020; Hamilton & Huth, 2020).

The specific research questions and hypotheses of each study could be summarized as follows and will be motivated and justified in the Introduction of each study.

Study 1. What is the role of AoE in the developmental trajectory of language knowledge?

- There will be a direct and continuous impact of AoE on language abilities across linguistic domains. We expect non-phonological (i.e., lexico-semantic and syntactic) abilities to be more strongly influenced by the amount of exposure than phonological abilities.
- The relative AoE to each of the languages of unbalanced bilingual children will determine the course of acquisition of knowledge in language-specific domains. The impact of differences in AoE between languages should be weaker for phonological than non-phonological skills development.

Study 2. What is the contribution of AoE (and related language knowledge) to the cortical tracking of speech?

- The cortical tracking of speech of bilingual children should be more precise for the language with the highest levels of AoE.
- Individual differences in language knowledge in various linguistic domains at behavioral level will be tied to the efficiency of the cortical tracking of the distributional properties of domain-specific speech features.

Study 3. Is child-directed speech associated with temporal characteristics that could facilitate speech comprehension and bootstrap language development?

- Child-directed speech register will convey more salient and exploitable temporal distributional properties than adult-directed speech.

1. Study 1. The contribution of the amount of linguistic exposure to bilingual language development: Longitudinal evidence from preschool years

1.1. Introduction

The influence of oral linguistic exposure on language acquisition is straightforward: the more instances of a language we encounter, the richer the knowledge about it we can attain. Thus, it is not surprising that the quality and quantity of oral linguistic exposure during the early years of life determines the general proficiency achieved in a given language (Gathercole & Thomas, 2005; Oller & Eilers, 2002; Paradis & Jia, 2016). The characteristics of oral linguistic inputs to which children are exposed should be particularly relevant during the early stages of language acquisition prior to reading acquisition, since they are the major language source (Hoff et al., 2012; Werker & Byers-Heinlein, 2008). Accordingly, variations in amount of exposure (AoE) to a language are linearly linked to its acquisition at multiple levels such as vocabulary (Carbajal & Peperkamp, 2020; Pearson et al., 1997; Thordardottir, 2011; Thordardottir et al., 2006), morphology (Gathercole & Thomas, 2005; Paradis et al., 2016), and general grammatical knowledge (Anderson et al., 2018; Gámez et al., 2019; Paradis & Jia, 2016). However, while the development of abilities in phonology or broader syntactic or grammatical knowledge have been extensively studied (e.g., Anthony & Lonigan, 2004; Carroll et al., 2003; Frizelle et al., 2018; Nippold et al., 2005, 2007), what specific effect AoE may have on their developmental trajectory is still unclear.

In previous research, it was common to explore the role of limited inputs on language development by operationalizing such input through cutoff measures (e.g., bilinguals vs. monolinguals, categorizing individuals by their age of language acquisition). In this study, we capitalize on bilingual language acquisition to directly evaluate the proportional AoE to two languages (Basque and Spanish) within the same participants, and quantify its impact on the development of fundamental linguistic abilities, including phonology, lexico-semantics, and syntax. While the development of such fundamental language domains is interrelated to a considerable extent (S. E. Gathercole et al., 1992; Marchman et al., 2004), there is evidence hinting at differential dependencies from AoE among lexical, phonological and syntactic abilities.

Regarding lexical abilities, the relationship between AoE and its development has been widely explored through measures of vocabulary knowledge, which has been shown to clearly benefit from an item-based (i.e., learning specific words from input) acquisition from oral exposure. The paradigmatic example of such relationship is lexical growth, which is easily observable after repeated encounters with a given word (Carbajal & Peperkamp, 2020; Pearson et al., 1997; Thordardottir, 2011; Thordardottir et al., 2006). Thus, children growing in a bilingual context rely on the quantitative and qualitative characteristics of linguistic input in each language to develop their bilingual lexicon. Such relationship between linguistic input and lexical development is observed in infancy (Carbajal & Peperkamp, 2020; Hoff et al., 2012) and spreads through childhood (Bowers & Vasilyeva, 2011; Lauro et al., 2020) and adolescence (Huang et al., 2020; Kuo et al., 2020). While productive and receptive lexical abilities develop at different rates, with receptive vocabulary being slightly ahead of its productive counterpart (the so-called receptive-expressive gap), such gap is larger and more persistent when the input is limited, as in bilingual development (Gibson et al., 2012; Oller et al., 2007; Windsor & Kohnert, 2004). Such receptive-expressive difference points at a potentially stronger relationship between AoE and receptive than productive vocabulary. Coherent with the "receptive-expressive gap" hypothesis, Giguere and Hoff (2022) found that initial differences in receptive vocabulary between L1 and L2 diminished between 4.5 and 10 years of age, while the L1-L2 gap was persistent in expressive vocabulary. Together, the former studies show that children even could still benefit from scant AoE to develop their vocabulary comprehension abilities in their non-dominant language. In summary, vocabulary learning could be thought of as a "data-hungry" process (Cristia, 2020) which feeds from all the —even limited— input available, but leading to bigger gains in the receptive than the productive subdomain.

While the relationship between AoE and lexical development is straightforward as it takes place on an item-based fashion, the influence of AoE on syntactic development is not as directly observable. The fact that syntactic structures are combinatorial makes them less readily repeated in the linguistic input than words, which appears to limit the direct role of AoE on their development when compared to lexical abilities (Oller et al., 2007; Paradis & Genesee, 1996). Still, it has also been observed that bilingual children can show reduced levels of both lexical and syntactic knowledge compared to monolinguals (Chondrogianni & Marinis, 2011; Thordardottir et al., 2006). Therefore, it is still needed to determine whether and to what extent language-specific AoE constrains bilingual syntactic knowledge development. In favor of the relevance of AoE for syntactic knowledge development, De Houwer (2005) showed that such development in bilinguals might occur independently for each language —hence depending on language-specific factors such as AoE— and follow a trajectory similar to what is observed in monolinguals. In monolinguals, it has been consistently shown that caregivers' use of increasingly complex syntactic structures predicts their children's syntactic development (Furrow et al., 1979; Hoff-Ginsberg, 1986; Huttenlocher et al., 2002, 2010). In bilinguals, Yip and Matthews (2006) found that the growth of the mean length of utterance (MLU), a classical proxy for syntactic development, strongly depends on language dominance: while L1 and L2 MLU grew steadily between 2 and 3 years of age in their study, L1 MLU was consistently bigger than in L2. However, to the best of our knowledge, the role of AoE on language-specific bilingual syntactic development is still an open question that the present study will directly address.

Unlike in lexical and syntactic development, AoE could play a minor role in phonological development (see Cristia, 2020 for an overview). This seems due to the fact that the acquisition of phonological abilities relies more on heritable factors than the former domains (Bishop, 2002; Kovas et al., 2005), which could make its typical development detached from exposure to a considerable extent. Indeed, because lexico-semantics, syntax and phonology might play different roles during language acquisition, some authors have proposed to divide the related skills in "phonological" and "non-phonological" (i.e., lexico-semantic and syntactic skills) abilities (Bishop & Snowling, 2004). This division has proven useful to differentiate the potential causes of language-related developmental disorders such as developmental dyslexia (that might occur because of phonological deficits) and developmental language disorder (that might result from both phonological and non-phonological deficits). Nonetheless, linguistic input characteristics should influence at least to some extent, the development of language-specific phonological abilities. Such influence is illustrated by the broadly studied impact of bilingualism (as opposed to monolingualism) on the development of phonemic categories in infancy and early childhood, showing a similar (although slightly delayed in some cases) development of phonemic boundaries in each language (Bosch & Sebastián-Gallés, 2003; Burns et al., 2007; Kuhl et al., 1997; Ruiz-Felter et al., 2016). However, fewer studies hint at the potential role of AoE on the development of phonological capacities during childhood (e.g., Gutiérrez-Clellen & Simon-Cereijido, 2010; Messer et al., 2010; Summers et al., 2010). Interestingly, Parra, Hoff, and Core (2011) found that, in 2- to 3-year-old children, AoE to L1 and L2 predicted the repetition of nonwords with phonemic and syllabic phonotactic properties of each language respectively. In the same study, it was found that nonword repetition performance was positively correlated between both languages, which points at both input-dependent and input-independent factors in phonological development. In addition, Parra et al. (2011) reported that AoE predicted vocabulary more than phonology, suggesting a potential greater role of AoE for the development of non-phonological compared to phonological abilities. However, this hypothesis must also account for findings showing that phonological abilities are relevant predictors of non-phonological language abilities such as vocabulary knowledge (Anthony et al., 2003; Carroll et al., 2003; Kehoe et al., 2020; Vaahtoranta et al., 2020). In fact, it is reasonable to assume that more efficient and precise coding, storage, and retrieval processes of speech sounds (i.e., phonological processing) should contribute to build up stable lexical representations.

Overall, previous studies have offered multiple snapshots of the influence of language use and AoE on the developmental trajectory of different language domains during early childhood. They suggest that AoE might play a stronger role in the development of non-phonological (lexico-semantics and syntax) compared to phonological abilities. In the present study, we aim to assess the role of AoE on both phonological (phonological awareness and phonological short-term memory) and non-phonological (lexico-semantic and syntactic) development in children at three stages spanning over preschool years and the first year of primary school (4 to 6 years of age). Importantly, we capitalize on AoE variations between the two languages of early Basque-Spanish bilingual children to explore these effects in a novel way. By testing AoE and language knowledge and use longitudinally for each language through a within-subject design, we plan to draw a comprehensive picture of the role of AoE in (bilingual) language development. The more specific aim of this study was twofold.

First, we wanted to determine whether AoE has an impact on the developmental trajectory of the classical gap observed between performance in the first and the second language of bilinguals (e.g., Giguere & Hoff, 2022; Haman et al., 2017; Paradis et al., 2016). As AoE was dominant in Basque over Spanish in our group of participants[1], we expected an initially better group-level performance in Basque than Spanish across language domains. We expected different developmental trajectories between both languages, dependent also on the linguistic domain studied (i.e., lexico-semantics, syntax, and phonology). In particular, we expected non-phonological abilities to show a significant gap between Basque and Spanish, especially in the case of lexical abilities as they have been shown to be more influenced by input than syntactic abilities (Oller et al., 2007; Paradis & Genesee, 1996). On the other hand, we did not expect significant

[1] Since participants with different proportions of exposure to Basque and Spanish were included, we cannot term these languages as L1 and L2 respectively because both languages were learned simultaneously since early in life and a small group of participants had more relative exposure to Spanish than Basque.

differences in phonological abilities between Basque and Spanish at the starting point of the study nor in their developmental trajectories.

Second, we aimed to shed light onto whether the influence of AoE throughout the developmental time span of the study (i.e., taking into account the three longitudinal time points altogether) is specific to non-phonological skills, i.e., lexico-semantics and syntax, or whether it is stable across language domains including phonological skills, too. We predicted that the influence of AoE on language performance would be positive for lexical and syntactic abilities, but not (or less so) for phonological skills. However, we did not have a clear prediction about changes affecting the relationship between AoE and language performance within each developmental stage (i.e., each longitudinal testing point).

1.2. Method

1.2.1. Participants

Seventy-four children (36 females) that grew up in a Basque-Spanish bilingual context were recruited to take part in a longitudinal assessment. They were tested three times (T1, T2 and T3) spanning over the last year of preschool and the first year of primary school: T1 – 4.01 years old (*SD* = .07), T2 – 4.71 y.o. (*SD* = .11), and T3 – 6.4 y.o. (*SD* = .1). More detailed information about how participant's amount of exposure was assessed and about linguistic exposure patterns is described below (subsections *Amount of exposure* and *Group characteristics of bilingual exposure*). Children's participation was rewarded with an educational gift, and their parents were informed about the research aims and outcomes once at the end of the study. Participant recruitment procedure and data collection paradigms were approved by the BCBL Ethics Committee and complied with the Declaration of Helsinki. Three children were excluded from the longitudinal testing as their exposure to Basque was minimum (i.e., virtually none) and thus were not able to complete the tasks with the minimum performance required in each language for our goals.

1.2.2. Longitudinal assessment

At each stage, the assessment included (i) the administration of a questionnaire to the parents/legal tutors of participants that was aimed at characterizing the linguistic background of their child, and (ii) an in-lab evaluation. Within this in-lab evaluation, we assessed children's performance in lexico-semantics, syntactic and phonological abilities in Basque and Spanish. It was composed of a series of computerized "controlled" tasks (for which the stimuli selection and presentation were controlled and balanced between the Basque and Spanish versions), and of a task created to elicit a spontaneous conversation between the child and one of their parents. The objective of this last task was to assess children's language production skills in each language in an ecologically valid context similar to their everyday life. In addition to the language measures, we assessed children's non-linguistic cognitive abilities with the matrices subtest of Kaufman Brief Intelligence Test (KBIT-2, Kaufman & Kaufman, 2014). However, the vast majority of participants performed at ceiling level relative to their age standards and thus KBIT-2 measures did not offer enough variability to be included in the statistical models.

Amount of linguistic exposure - AoE

We estimated the amount of exposure (AoE) to each language through a multifactorial index previously validated by other studies of bilingual language development (Gullifer et al., 2020; Thordardottir, 2011; Thordardottir et al., 2006). The parents of the children participants provided information on their children's language exposure and use since birth through an extensive online questionnaire (*Amount of exposure questionnaire*, available at the Open Science Framework repository of the project). We used this information to build composite indexes of AoE to both Basque and Spanish. The composite AoE indexes comprised the age of acquisition of each language, the percentage of waking hours that a child had been exposed to each language between birth and each longitudinal stage, as well as a detailed current AoE to their languages at school, home, and leisure contexts. An AoE index of 100 % in a language would indicate exposure to a unique language since birth, while 0 % would indicate no contact with that language whatsoever. The specific operationalization of the AoE indexes can be found in the Supplementary Materials (Supplemental Formulas 1.1, 1.2, and 1.3). Our AoE metric can be conceptualized as a measure that puts together the "day-in-the-life" interview (e.g., Restrepo, 1998) and the cumulative life history of language exposure since birth (e.g., Thordardottir et al., 2006), which have proven effective methods for capturing early bilingual experience and are related to language knowledge across the domains of interest (phonology, lexico-semantics, and syntax) for the present study (e.g., Gámez et al., 2019; Thordardottir, 2011; Thordardottir et al., 2006). Moreover, all the observations taken into consideration to build our AoE scores comply with the recent recommendations of the Delphi consensus of researchers and therapists on protocols to characterize children's bilingual exposure (Cat et al., 2022).

Group characteristics of bilingual exposure

Most participants (and therefore the group as a whole) were simultaneous Basque-Spanish bilinguals, as they had started acquiring both languages at roughly the same time, as well as Basque-dominant, given that they were significantly more exposed to Basque than Spanish (see *Age of acquisition* in Table 1.1., and *% of exposure* in the last panel of Figure 1.1). In the Basque country, such exposure profile is typical as the sociocultural and educational policies promote the early acquisition of Basque which is a minority language now in active recovery (see Zalbide & Cenoz, 2008). In our group, Spanish (the majority language in the Basque Country) was typically acquired as a second language. Such differences in exposure between Basque and Spanish, in addition to a continuous range of AoE to each language respectively, were key for addressing our research questions about the role that AoE, and specific sustained AoE differences, play on (bilingual) language development across fundamental language domains.

Stage	Sample	Age	% AoE Basque	% AoE Spanish	AoA Basque	AoA Spanish
1	**71** (35 fem.)	**4.01** (.07)	**66.81** (22.69)	**25.17** (22.11)		
2	**65** (30 fem.)	**4.71** (.11)	**71.53** (20.06)	**23.92** (22.37)	**0.22** (.67)	**0.74** (1.11)
3	**63** (30 fem.)	**6.4** (.1)	**71.08** (21.77)	**26.14** (22.36)		

Table 1.1. General information about sample size and average age (in years), percentage of exposure (% AoE) and age of acquisition (AoA, in years) in each language. Standard deviation of each measure is represented between parentheses.

Lexico-semantics

Lexico-semantics was assessed by means of three measures: a **productive** and a **receptive vocabulary measure** via, respectively, a computerized picture-naming and a word-comprehension task in each language, as well as a **lexical diversity** index extracted from the spontaneous speech productions of children when talking with their parents.

Productive and the receptive vocabulary tasks

For both tasks, the number and difficulty of items increased along the three longitudinal stages. Thus, picture-naming task consisted of 23 items in the 1st stage of the study, and of 45 items in the 2nd and 3rd stages; in word-comprehension task, participants were presented with 19 items in the 1st stage, and 25 in the 2nd and 3rd stages. Regarding the difficulty of the items, we selected target words with decreasing lexical Zipf frequency (a proxy for word difficulty, see van Heuven et al., 2014) along the stages of the study for productive (Basque: *stage 1 mean Zipf frequency* = 3.90 (*SD* = 0.62), *stage 2* = 3.65 (*SD* = 0.59), *stage 3* = 3.62 (*SD* = 0.54); Spanish: *stage 1* = 4.25 (*SD* = 0.47), *stage 2* = 4.04 (*SD* = 0.44), *stage 3* = 3.94 (*SD* = 0.57)) and receptive vocabulary (Basque: *stage 1 mean Zipf frequency* = 3.64 (*SD* = 0.71), *stage 2* = 3.58 (*SD* = 0.49), *stage 3* = 2.97 (*SD* = .57); Spanish: *stage 1* = 4.17 (*SD* = .65), *stage 2* = 3.94 (*SD* = .37), *stage 3* = 3.32 (*SD* = .33)) respectively. In the picture-naming task, participants were required to name the pictures that appeared on screen in a randomized order, without any time constraint. In word-comprehension task, participants were presented with an auditory word over speakers, and presented with four pictures on screen at the same time. They were asked to point at the picture corresponding to the word that they heard. The three other pictures corresponded to distractors that presented either phonological, visual, or semantic similarities with the target word. The researcher coded each trial as either correct or incorrect upon response. The order of presentation of the two languages in both of the vocabulary tasks was counterbalanced across participants. In order to harmonize participants' performance in vocabulary tasks across languages and stages, we weighted performance in the different items (1, correct; 0, incorrect) by the inverse of their Zipf lexical frequency (extracted from EHME database for Basque words, Acha et al., 2014; and from EsPal database in the case of Spanish, Duchon et al., 2013). Therefore, more frequent (and easier) words had a smaller weight on participants' overall performance than less frequent ones that were less likely to be known by children (see Supplemental Formula 1.4). Thus, our measure of performance in picture-naming and word-comprehension tasks was Zipf-frequency-weighted accuracy.

Lexical diversity

The third of our lexico-semantic measures, lexical diversity, was extracted from a conversational **corpus of spontaneous speech productions**, that also served for estimating naturalistic indexes of syntactic abilities (namely, clausal density and mean length of utterance, described below within the syntactic abilities subsection). The setting of that task was aimed to be similar to the home environment, so that the child and their parent could interact freely, like they would do if they were playing with picture books, toys, or games at home. We informed parents of the purpose of the task, and provided them with the following simple instructions: "please, interact with your child as you would do at home, while allowing her/him to talk as much and as naturally as possible in their preferred language(s)." Previous studies reported that 7–10 minute-long recordings are sufficient to obtain reliable estimates of language proficiency in young children (Guo & Eisenberg, 2015). Nonetheless, we recorded child-parent speech interactions for 30 minutes, in order to generate robust estimates of language production development minimizing individual differences on loquacity and familiarity with each of the two languages.

A trained native speaker of Basque and Spanish transcribed the audios into text to build a longitudinal conversational speech corpus. The transcription followed the following procedure. First, and following widely used criteria (Miller, 1981), the audios were segmented into utterances either based on terminal intonation contour, or at the start of pauses longer than 2 seconds. Utterances with more than two coordinate clauses were segmented before the second conjunction (i.e., "*and*") to avoid their spurious lengthening due to clausal chaining through conjunctions (Rice et al., 2006). After a review searching for transcription errors, utterance-segmented transcripts were submitted to an automatic language detection algorithm (based on Google Translate databases, in Google Cloud Computing Services) to identify the language of each utterance (Spanish or Basque). Utterances that were not detected as belonging to either language were further identified manually by a native speaker of both languages. And utterances that remained unidentified (0.92% of all utterances, the majority containing only proper nouns or interjections) were discarded from further lexical and syntactic analyses.

Given the bilingual nature of the longitudinal conversational speech corpus, we applied natural language processing (NLP) models that took into consideration the syntactic differences between Basque and Spanish and allowed us harmonize the lexical and syntactic metrics across languages. Specifically, we used UD Pipe 2.0 NLP pipeline

(Straka, 2018) in both Basque (model *basque-bdt-ud-2.5-191206.udpipe*) and Spanish (model *spanish-gsd-ud-2.5-191206.udpipe*), which allowed us to annotate the utterances through lemmatization and dependency parsing in order to obtain our lexical and syntactic measures respectively.

Because the majority of lexical diversity estimation tools from texts and speech corpora (e.g., type-token ratio, Guiraud index, number of different types of lemmas) suffer from the issue of using overall ratios (i.e., average) that do not take into consideration individual differences in the number of tokens an individual produces (which could be greatly influenced by individual differences in loquacity or in AoE and proficiency, Vermeer, 2000), the moving-average type-token ratio (MATTR) was chosen (Covington & McFall, 2010). This method consists in computing the type-token ratio, which corresponds to the number of types (i.e., different lemmas produced) divided by the total number of lemmas, within windows of a specified number of lemmas across the transcript. The MATTR alleviates the issue of more loquacious participants being penalized in their lexical diversity metrics, since the probability of repeating a lemma increases with the total number of produced words (as it occurs in simple type-token ratio). A MATTR window of 40 lemmas was chosen (see Supplemental Formula 1.5) which did not penalize loquacious participants (see Supplemental Figure 1.1) nor inflated the lexical diversity estimates of children producing only 40 lemmas in a given language (our inclusion threshold for MATTR).

Syntactic abilities

Syntactic abilities were assessed through three measures. First, we extracted two measures from children's spontaneous speech productions, namely mean length of utterance and clausal density. A third syntactic measure, the repetition of sentences of increasing length, was used as a computerized measure indexing the receptive syntactic span of children in both languages.

Mean length of utterance

Different variants of mean length of utterance (MLU) have been widely used in developmental research to study syntactic and general grammatical development (e.g., Brown, 2013; Ezeizabarrena & Garcia Fernandez, 2018; Hoff-Ginsberg, 1986; Rice et al., 2006; Simon-Cereijido & Gutiérrez-Clellen, 2009). We employed MLU-15, the mean length in words of the 15 longest utterances per participant, longitudinal stage (1,2,3), and language (Basque, Spanish). The reason behind estimating MLU only for the 15 longest utterances was to reflect more faithfully syntactic proficiency by avoiding a bias towards very short utterances. Indeed, while some participants might produce utterances of relatively steady word counts, others may use short and long utterances interchangeably. It is worth noting that cross-linguistic comparison of MLU has limitations, especially when comparing languages differing in morphosyntactic structure (Döpke, 1998), since it tends to be higher for the language with less agglutinative morphology (Spanish in our case). While a former study attested the high correlation between MLU in words (MLU-w) and MLU in morphemes (MLU-m) in Basque, as well as the link between both and other lexical and morphological proxies for language development (Ezeizabarrena & Garcia Fernandez, 2018), to our knowledge there has not been a direct comparison between MLU in words and MLU in morphemes in Basque and Spanish or other bilingual combination of similar language types. Nonetheless, we expected a higher between-language comparability for the case of MLU in words, as it limits to an extent the impact of different morphologies in Basque and Spanish.

Clausal density

Clausal density has been less widely assessed than MLU, although it is being increasingly used (e.g., Guo et al., 2021; Nippold, 2009; Nippold et al., 2009; Weiler et al., 2021). However, it offers two potential advantages over MLU. First, it taps directly into syntactic complexity, as it takes into consideration the number of clauses per utterance. Second, it might offer a reliable estimate for syntactic development beyond age 4 (Frizelle et al., 2018), which has been classically considered the age at which MLU stops being sensitive to syntactic development (Huttenlocher et al., 2002). Nonetheless, MLU and clausal density showed strong correlations in the few studies that have explored them together in the past (Nippold, 2009; Nippold et al., 2005, 2007), and one of the mentioned studies found growth in both MLU and clausal density between 4 and 17 years of age (Frizelle et al., 2018). In our study, we estimated clausal density as the total number of clauses divided by the total number of utterances with clauses. We excluded utterances without clauses from clausal density analyses in order to remove too short or simple utterances that would bias our estimates towards smaller densities for children that produced multiple utterances without clauses. Our inclusion threshold for MLU and clausal estimates were 15 utterances per participant, longitudinal stage (1,2,3), and language (Basque, Spanish).

Receptive syntactic span

Our third syntactic index tapped into the receptive syntactic span measured through a sentence repetition task. The purpose of sentence repetition was to assess syntactic abilities in a more controlled manner than MLU-15 and clausal density, while being related to the previous measures. Given that this task is composed of full sentences rather than words (like the previously described lexico-semantic tasks), it taps into phonological, lexico-semantics, and syntactic abilities. Each language version of sentence repetition comprised 28 sentences, presented in blocks of increasing number of words (3 to 9 words). In each trial, participants first heard an auditory cue (50 ms) and then the auditory presentation of a sentence which they had to repeat. The order of presentation of the sentences was randomized within length blocks (4 sentences per block), and the order of presentation of each language was counterbalanced across participants. We included a termination criterion consisting in ending the task if a participant did not repeat correctly any of the sentences of a length block. Thus, our measure of receptive syntactic span was the total number of correctly repeated sentences.

Phonology

Phonological short-term memory and phonological awareness were assessed. To do so, we used a nonword repetition and a rhyme detection task, respectively. Both tasks have been previously reported as robust markers of phonological development during childhood (Anthony & Lonigan, 2004; S. E. Gathercole, 2006; Thordardottir & Brandeker, 2013), as well as predictors of oral language outcomes (in the case of phonological short-term memory; S. E. Gathercole & Baddeley, 1989; Jackson et al., 2019) and reading acquisition (more associated to phonological awareness; Fraser et al., 2010; Muter et al., 1998; Nation & Hulme, 1997; Vanvooren et al., 2017).

Nonword repetition

Nonword repetition is typically used as an index of phonological short-term memory (S. E. Gathercole et al., 1991), and its performance can be modulated by phonological proximity to the languages that participants know (S. E. Gathercole et al., 1997). Therefore, we manipulated the “lexical” stress and syllabic phonotactics of the nonwords to match the constraints of Basque and Spanish. The purpose of including nonwords was to observe the influence of AoE on phonological short-term memory while limiting the use of lexical knowledge. Each language variant of the nonword repetition task included 24 nonwords in total, composed of four blocks increasing in syllabic length (from 2 to 5 syllables), each of which included six trials. In each trial, participants heard an acoustic cue (50 ms) followed by the presentation of a nonword which they had to repeat. The order of presentation of nonwords was randomized within blocks of each syllabic length. The researcher coded each repetition as either correct or incorrect upon participant response. The average of fully correctly repeated nonwords per language was used as measure of performance in this task.

Rhyme detection

Rhyme detection in Basque and Spanish variants was assessed, by manipulating the same syllabic and lexical stress phonotactic constraints than in nonword repetition. In each version of the task, participants heard 24 couples of nonwords, and had to judge whether they rhymed or not (i.e., whether their vowels matched between the stressed vowel and the end of the nonwords). The average of correctly detected rhymes per language version was used as proxy for performance in rhyme detection, excluding from further analyses participants that performed below chance level (i.e., .5, or 50% of accuracy).

1.2.3. Data analysis

Prior to modeling the influence of AoE on the longitudinal trajectory of bilingual language outcomes, we detected and removed outliers based on the interquartile range (IQR) criterion. This way, we removed from each of the variables of interest datapoints that were over 1.5 times the interquartile range above the 75th percentile or under 1.5 times the interquartile range below the 25th percentile.

The main goal of our longitudinal study was to estimate bilingual language development across the three language domains as a function of AoE and time (i.e., longitudinal stage). In particular two questions were investigated related to: (i) the differences in longitudinal growth trajectories of unbalanced bilinguals between their two languages, taken as a "group-level" proxy of AoE; (ii) the longitudinal influence of AoE on language performance, through the study of child-specific continuous indexes of AoE. To address each question comprehensively, two sets of analyses were performed (see below). Conducting these two analyses on the same data was to simplify the interpretation of our results, by not having multiple interactions between categorical (i.e., language) and continuous factors (i.e., AoE).

In order capture the multilevel structure of our data, consisting of repeated within-participant observations across different domains, languages, and longitudinal stages, we used *participants* as random intercepts throughout all LME models, which allowed us to account for baseline individual differences (i.e., one intercept per participant and model) in the different languages and language domains.

We used *lmer* formula from *lme4* package (Bates et al., 2015) in R (version 4.2.1, R Core Team, 2022) to fit the different LMEs. In order to test for omnibus main effects and interactions of the predictors, we used the *anova* function of base R; and between-language and between-longitudinal stage differences in the each model were evaluated with *difflsmeans* from the *lmerTest* package (Kuznetsova et al., 2017).

1.2.3.1. Effect of language (Basque vs. Spanish) as a group-level proxy of AoE

Since the group-level AoE was significantly different between Basque and Spanish (i.e., Basque-dominant), we operationalized the factor "language" as a proxy of AoE (Basque AoE > Spanish AoE). It is relevant to note that language is only an approximation to language dominance at group level and, as such, is influenced by other factors in addition to AoE (such as age of acquisition). To assess the effect of language on longitudinal growth at each developmental stage, we fitted one linear mixed effect (LME) model for each collected measure of language performance as outcome variable, with stage (1, 2, 3) and language (Basque, Spanish), as well as their interaction, as fixed effects.

1.2.3.2. Direct effect of child-specific AoE indexes on each domain

Although testing the effect of language on the longitudinal trajectory of the different measures is useful to investigate language dominance-dependent differences in the developmental course of a language measure (the aforementioned first set of analyses), assessing how indexes directly measuring AoE influence performance is key to understand the direct impact of AoE on the development of each linguistic domain, in each language. For this second set of analyses, we built two additional subsets of LME models with the same structures for each language performance measure. The objective of the first subset of models was to assess the overall effect of AoE on language development and whether there were between-languages differences in the influence of AoE on language abilities *independently of developmental stage*. To achieve this, for each measure as the outcome variable, we fitted an LME model with the continuous child-specific AoE (in %), and the interaction between these individual AoE indexes and language (Basque, Spanish) as fixed effects. The aim of the second subset of models was to delve deeper into the specific relationship between individual AoE indexes and language performance *as a function of developmental stage*, within Basque and Spanish separately (the effect of language being assessed in the first set of models, i.e., 1.2.3.1). Thus, we fitted two LME models, one in Basque and one in Spanish, with the interaction between individual AoE indexes and stage as fixed effects.

1.3. Results

1.3.1. Longitudinal growth across domains in each language

Lexico-semantic abilities

First, we tested the longitudinal trajectory of lexico-semantic abilities. LME yielded a significant effect of language, $F(1, 327.39) = 60.65$, $p < .001$, and stage, $F(2, 334.37) = 83.77$, $p < .001$, on **productive vocabulary**, and no significant interaction between both factors, $F(2, 326.62) = 1.52$, $p > .05$. This is visible in Figure 1.1, which shows overall higher productive vocabulary in Basque than in Spanish across stages (stage 1: $t(326.8) = 6.06$, $p < .001$ ($\beta = .055$, $SE = .009$, CI [.037 .072]; stage 2: $t(326.5) = 3.47$, $p < .001$ ($\beta = 0.033$, $SE = .009$, CI [.014 0.051]); stage 3: $t(327.3) = 4.04$, $p < .001$ ($\beta = 0.039$, $SE = .010$, CI [.02 0.058])). There was also a parallel longitudinal growth of both languages with no significant increase between the 1st and 2nd stages in Basque, $t(330.3) = -0.28$, $p > .05$ ($\beta = -0.003$, $SE = .009$, CI [-0.021 0.015]), and only a small significant increase in Spanish, $t(332) = 2.1$, $p = .037$ ($\beta = .02$, $SE = .009$, CI [0.012 0.038]); while between the 2nd and 3rd stages there was a larger significant increase (of similar magnitude) in both languages (Basque: $t(328) = 7.75$, $p < .001$ ($\beta = .073$, $SE = .009$, CI [0.055 0.092]); Spanish: $t(327.3) = 7.07$, $p < .001$ ($\beta = .067$, $SE = .01$, CI [0.049 0.086])).

With respect to **receptive vocabulary**, there were significant main effects of language, $F(1, 327.3) = 77.23$, $p < .001$, stage, $F(2, 334.85) = 158.91$, $p < .001$, on word comprehension performance, as well as an interaction between language and stage, $F(2, 325.97) = 60.65$, $p < .001$. Such interaction was the product of Spanish receptive vocabulary growing at a steadier and faster rate than Basque, as visible in Figure 1.1. While the difference between the 1st and 2nd stages in Basque receptive vocabulary was not significant, $t(331.3) = -1.85$, $p > .05$ ($\beta = -0.073$, $SE = .006$, CI [-0.025 0.001]), the growth between the first two stages was evident in Spanish, $t(331.4) = 4.89$, $p < .001$ ($\beta = .031$, $SE = .006$, CI [0.019 0.044]). Between the 2nd and 3rd stages, there was a significant increase in both languages, but such increase was stronger in Spanish, $t(327.4) = 12.67$, $p < .001$ ($\beta = .083$, $SE = .007$, CI [0.07 0.096]), than in Basque, $t(328) = 7.75$, $p < .001$ ($\beta = .073$, $SE = .009$, CI [0.055 0.092]). Thus, the significant gap between both languages (i.e., Basque > Spanish) present in stage 1, $t(326.6) = 11.68$, $p < .001$ ($\beta = .073$, $SE = .006$, CI [0.061 0.086]), closed gradually (stage 2: $t(326.6) = 4.57$, $p < .001$ ($\beta = .03$, $SE = .007$, CI [0.017.043])), and receptive vocabulary performance was not significantly different between languages by stage 3, $t(326.1) = -0.66$, $p > .05$ ($\beta = -0.004$, $SE = .007$, CI [-0.017 0.009]).

The LME model for the third of our proxies for lexical abilities, **lexical diversity**, yielded that longitudinal stages were significant predictors of change $F(2, 193.54) = 13.15$, $p < .001$, while language did not predict significant differences, $F(1, 224.71) = 0.97$, $p > .05$. There was also a significant interaction between language and stage, $F(2, 194.9) = 7.33$, $p = .001$, reflecting different longitudinal trajectories of lexical diversity measures for Basque and Spanish (Figure 1.1). In the case of Basque, there was not a significant growth between the 1st and 2nd stages, $t(182.2) = .62$, $p > .05$ ($\beta = .005$, $SE = .008$, CI [-0.011 .02]) whereas between stages 2 and 3, lexical diversity increased, $t(179.5) = 6.11$, $p < .001$ ($\beta = .05$, $SE = .008$, CI [.033 .064]). In Spanish, there was no significant growth in lexical diversity during the timespan of the longitudinal study (difference between the 1st and 3rd stages: $t(207.4) = 1.33$, $p > .05$ ($\beta = .016$, $SE = .012$, CI [-0.023 .021])). Such growth in Basque lexical diversity between the 2nd and 3rd stages, in contrast to Spanish non-significant growth, produced a significant between-languages difference in the 3rd stage of the study. Thus, lexical diversity was higher in Basque than in Spanish by the last stage of the study, $t(212) = 3.73$, $p < .001$ ($\beta = .035$, $SE = .009$, CI [.016 .053]).

Syntactic abilities

Next, we fitted one LME for each of our three syntactic metrics. Within **receptive syntactic span** abilities, we observed that the performance in sentence repetition was significantly modulated by language, $F(1, 313.66) = 19.62$, $p < .001$, and stage, $F(2, 320.09) = 151.54$, $p < .001$, as well as by the interaction of both factors, $F(2, 312.14) = 20.46$, $p < .001$. The interaction between language and stage was driven by the fact that Spanish sentence repetition grew at a faster rate than Basque during the timespan of our study (Figure 1.1). Thus, while sentence repetition performance was not significantly different between Basque and Spanish in the 1st, $t(312.2) = .12$, $p > .05$ (β = .098, SE = .805, CI [-1.485 1.681]), nor the 2nd stage, $t(312.9) = .05$, $p > .05$ (β = .041, SE = .846, CI [-1.624 1.705]), by the 3rd stage, sentence repetition in Spanish was already significantly higher than in Basque, $t(312.8) = 7.64$, $p < .001$ (β = 6.57, SE = .86, CI [4.88 8.266]).

Regarding syntactic complexity measures, it is worth noting that, in line with previous studies (Nippold, 2009; Nippold et al., 2005, 2007), we found strong correlations between MLU and clausal density (Supplemental Figure 1.2). **MLU-15** was significantly modulated by language, $F(1, 245.85) = 11.43$, $p = .001$, and longitudinal stage, $F(2, 195.46) = 12.16$, $p < .001$, and that there was no interaction between both factors, $F(2, 193.78) = 2.4$, $p > .05$. Thus, MLU-15 was overall higher in Basque than in Spanish, $t(245.8) = 3.38$, $p <.001$ (β = 1.067, SE = .315, CI [.445 1.687]). Overall, longitudinal growth in MLU-15 was only observed between the 2nd and 3rd stages, $t(185) = 3.9$, $p < .001$ (β = 1.39, SE = .355, CI [.684 2.087]). Nonetheless, Basque MLU-15 grew between the 1st and 2nd stages, $t(178.9) = 2.17$, $p = .031$ (β = .898, SE = .414, CI [.081 1.715]), while Spanish MLU-15 did not show significant growth in the same time window, $t(206.7) = 1$, $p > .05$ (β = .246, SE = .634, CI [-1.496 1.005]), as visible in Figure 1.1.

The LME model for **clausal density** a significant effect of stage, $F(2, 157.76)$ = 4.47, $p = .013$, no significant overall difference between languages, $F(1, 169.9) = 2.19$, p > .05, and a marginal interaction between language and stage, $F(2, 160.96) = 3.04$, $p = .05$. Since this interaction was marginal, it was further explored. Unlike in MLU-15, CD growth in Basque did not take place between the 1st and 2nd stages, $t(150.3) = 1.88$, p > .05 (β = .033, SE = .018, CI [-0.002 .069]). However, there was a significant increase between the 2nd and 3rd stages, $t(146) = 2.69$, $p = .008$ ($\beta = .047$, $SE = .018$, CI [.013 .082]), such longitudinal growth was not statistically significant in Spanish (difference between the 1st and 3rd stages: $t(164.9) = .2$, $p > .05$ ($\beta = .006$, $SE = .03$, CI [-0.053 .065])). Such differing growth patterns between Basque and Spanish CD are visible in figure 1.1.

Phonological abilities

We had to discard **rhyme detection** from the analyses because it turned out to be a too difficult task for our participants, as the vast majority did not understand the instructions (i.e., the rhyme concept) or performed below chance level (50% of correct responses). Regarding the remaining **nonword repetition** task, LME model yielded significant main effects of language, $F(1, 325.4) = 28.11$, $p < .001$, stage, $F(2, 330.36) = 48.65$, $p < .001$, and no significant interaction between language and stage, $F(2, 325.44) = 1.63$, $p > .05$. Such longitudinal pattern, representative of an overall growth in nonword repetition that was parallel between Basque and Spanish, is visible in the Figure 1.1. Thus, nonword repetition performance in Basque was significantly higher in Basque than in Spanish across the study, $t(325.4) = 5.3$, $p < .001$ ($\beta = .053$, $SE = .010$, CI [.033 .073]), and there were significant increases in both languages between the 1st and 2nd stages, $t(332.1) = 2.94$, $p = .004$ ($\beta = .036$, $SE = .012$, CI [.012 .06]), and the 2nd and 3rd stages respectively, $t(326.1) = 6.69$, $p < .001$ ($\beta = .084$, $SE = .012$, CI [.059 .108]).

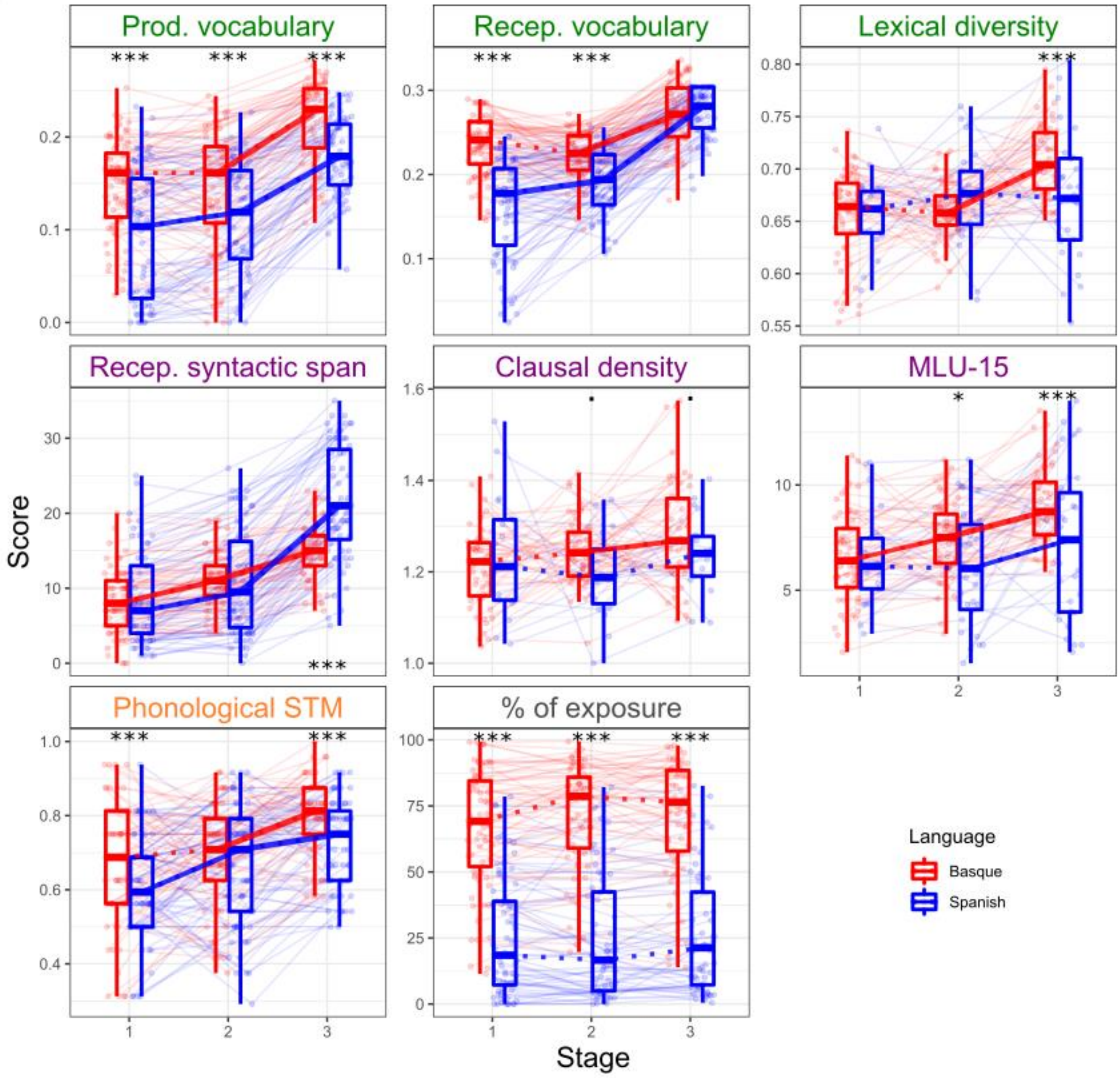

Figure 1.1. Longitudinal trajectory of the different language measures of the study, grouped by lexico-semantic (green), syntactic (purple), phonological (orange), and AoE measures (dark grey). Points represent each participant's score in each measure, language, and stage. Boxplots represent group estimates, with horizontal lines within each box marking the median score. Upper and lower hinges mark the first and third quartile, and whiskers show 1.5 * inter-quartile range. The connecting lines represent longitudinal trajectories between two consecutive stages: continuous and dotted lines mark significant and non-significant growth, respectively. Significant between-languages differences within each stage are marked with *, **, and *** for $p < .05$, 01, and .001 respectively. The symbol • marks marginally significant differences (i.e., $p = .05$).

Overall, there was growth across the different language domains during the timespan of our longitudinal study in Basque and Spanish. Nonetheless, there were differential rates of growth between languages for most of the linguistic domains, which could be attributed to the marked differences in AoE that are present in our sample. Therefore, the aim of our second set of analyses was to assess whether sustained languages differences in AoE have a direct influence on language performance across the 3 longitudinal stages was the specific aim of our second set of analyses. The lack of significant changes in AoE across the longitudinal stages (see last panel of Figure 1.1) was an important assumption to reach this objective, assumption which was respected by our data.

1.3.2. Direct Influence of amount of exposure to Basque and Spanish across domains

1.3.2.1. First subset of models: The effect of AoE on each measure across languages

Lexico-semantic abilities

AoE was positively related to **productive vocabulary** in both languages throughout the whole longitudinal study, $t(327.7) = 13.07$, $p < .001$ ($\beta = .039$, $SE = .003$). Its influence on picture-naming task was not significantly different between languages, $t(95.6) = 1.01$, $p > .05$ ($\beta = .007$, $SE = .007$).

Similarly, **receptive vocabulary** was greatly modulated by AoE in both languages, $t(381) = 7.17$, $p < .001$ ($\beta = .02$, $SE = .003$), with no significant between-languages difference in the influence of AoE on word comprehension, $t(381) = 1.65$, $p > .05$ ($\beta = .009$, $SE = .006$).

For the **lexical diversity** indexes, we did not observe an overall influence of AoE, $t(228) = 78$, $p > .05$ ($\beta = .003$, $SE = .004$), nor a different influence of AoE between Basque and Spanish, $t(382) = -1.9$, $p > .05$ ($\beta = -0.012$, $SE = .006$).

Syntactic abilities

Overall, AoE was a relevant predictor of **receptive syntactic span**, $t(310.94) = 9.11$, $p < .001$ ($\beta = 2.971$, $SE = .326$), with no significant difference in its influence between Basque and Spanish on the repetition of sentences, $t(98.19) = 1.27$, $p > .05$ ($\beta = 1.12$, $SE = .882$).

MLU-15 measured during spontaneous speech production was significantly predicted by AoE in both languages, $t(228.98) = 6.3$, $p < .001$ ($\beta = 1.119$, $SE = .177$), with no significant interaction of AoE and language, $t(85.06) = -0.96$, $p > .05$ ($\beta = -0.318$, $SE = .332$). However, AoE was not an overall significant predictor of the **clausal density** of the spontaneous speech productions of children, $t(146.69) = .47$, $p > .05$ ($\beta = .004$, $SE = .01$), and there was no significant difference in the influence of AoE on this measure between languages, $t(91.05) = -0.75$, $p > .05$ ($\beta = -0.012$, $SE = .016$).

Phonological abilities

AoE was not directly related to **phonological short-term memory abilities** as it did not predict nonword repetition performance significantly, $t(146.69) = .47$, $p > .05$ ($\beta = .004$, $SE = .01$). In addition, there was no significant difference of the influence of AoE on this measure between languages, $t(91.05) = -0.75$, $p > .05$ ($\beta = -0.012$, $SE = .016$).

1.3.2.2. Second subset of models: Specific relationship between AoE and each measure within each language and stage

The specific weights of AoE on each language measure for each stage and language are presented in Table 1.2. In this table, we can observe the widespread and cross-linguistic influence of linguistic input on productive and receptive vocabulary knowledge. Such AoE influence was more limited in the case of lexical diversity, which we observed to be significantly modulated by AoE only in the 3rd stage and in Basque.

Regarding syntactic abilities, the results of clausal density were similar to lexical diversity, as clausal density was also positively influence by AoE in Basque and in the last stage of the study only. However, clausal density also negatively correlated with AoE in the 1st stage of the study in Basque. The influence of AoE on MLU-15 in Basque was widespread across the three stages of the study, while in Spanish it was observed in stages 2 and 3. Receptive syntactic span was tied to exposure in both languages and across all stages.

Regarding phonological abilities, there was no direct relationship between AoE and nonword repetition in any language nor stage.

Influence of Amount of exposure on each measure						
Language	Basque			Spanish		
Stage	1	2	3	1	2	3
Prod. vocabulary	4.87 (<.001)	5.94 (<.001)	4.88 (<.001)	8.26 (<.001)	5.81 (<.001)	3.23 (.001)
Recep. vocabulary	4.13 (<.001)	2.03 (.04)	2.91 (.004)	5.34 (<.001)	2.26 (.025)	2.1 (.037)

Lexical diversity	.37 (>.05)	-1.21 (>.05)	4.17 (<.001)	-0.62 (>.05)	.41 (>.05)	.02 (>.05)
Recep. syntactic span	4.22 (<.001)	3.4 (<.001)	3.97 (<.001)	2.78 (.006)	3.77 (<.001)	2.92 (.003)
Clausal density	-2.42 (.017)	.49 (>.05)	2.82 (.005)	.48 (>.05)	1.19 (>.05)	1.35 (>.05)
MLU-15	2 (.048)	2.73 (.007)	4.06 (<.001)	1.59 (>.05)	3.84 (<.001)	5.72 (<.001)
Phonological STM	1.69 (>.05)	-0.45 (>.05)	.73 (>.05)	-0.07 (>.05)	.26 (>.05)	-0.52 (>.05)

Table 1.2. The effect of AoE on each measure for each language separately. Each cell represents the strength of the relationship (t-value, and p-value between parentheses) between AoE and the specific language measure within each stage, language, and language domain. Significant positive and negative relationships are marked with green and red shading respectively, and non-significant relationships with grey.

1.4. Discussion

The main goal of Study 1 was to offer a snapshot of the developmental trajectory of bilingual development as a function of the amount of linguistic input during childhood. To achieve this, we tested longitudinally children growing in a Basque-Spanish simultaneous and unbalanced bilingual context and quantified the impact of AoE on performance depending on language dominance, developmental stage, and linguistic domain (i.e., lexico-semantics, phonology, and syntax). We found relevant differences in the rates of growth of lexical and syntactic abilities between Basque and Spanish, as well as a direct influence of AoE on them. Regarding phonological abilities, we found significant between-languages differences, but not a direct influence of AoE. Our findings, that are discussed below, inform the role of AoE in bilingual language development during preschool years, and shed light on language acquisition in monolinguals with limited linguistic inputs.

First, our analyses revealed significant effects of language dominance (reflecting group-level AoE variations, with overall higher AoE in Basque than Spanish) on the longitudinal growth of language abilities across the different domains. Within lexico-semantic abilities, there was robust evidence in favor of the parallel longitudinal growth of productive vocabulary in Basque and Spanish. Thus, while children longitudinally similarly improved on their productive vocabulary knowledge in both languages, the language gap at the onset of the study remained intact by the end of the study, with performance being better in their most dominant language (Basque). In contrast, there was a relevant language effect on the developmental growth of receptive vocabulary. Whereas Basque receptive vocabulary performance only increased between the 2nd and 3rd stages, Spanish receptive vocabulary growth was steadier and larger throughout the three longitudinal stages. As a consequence, the initial language gap (at 4 y.o.) receptive lexical abilities closed by the end of the study (6 y.o.). While previous research attested the persistence of a receptive-productive gaps during bilingual language development, as children are often more proficient in receptive vocabulary (e.g., Gibson et al., 2012; Giguere & Hoff, 2022), our results point at a "gap-closing" pattern in receptive but not expressive lexical abilities between the most dominant (Basque) and the less dominant (Spanish) language at around 6 years of age. These results are in line with Thordardottir (2011), who also did not find significant differences between the receptive abilities between L1 and L2 in French-English children by age 5, coinciding with the timing at which the receptive vocabulary gap between Basque and Spanish closed in our study. From our results, it is apparent that when AoE reaches a sufficient threshold, the receptive lexical abilities of bilingual children in their less dominant language can catch up with those of the dominant language, and this seems to happen earlier than for productive vocabulary abilities.

Counterintuitively, the receptive measure of the syntactic domain (sentence repetition) showed a better performance in the less dominant language of children (Spanish) at the end of the longitudinal assessment. It is noteworthy that when designing this task, we controlled for several aspects if the stimuli. For example, the length of sentences (number of words) was similar in Basque and Spanish and this could have led to detrimental effects on performance in Basque: Basque has an agglutinative morphology, which usually reduces the number of words than comparably complex sentences in Spanish. Thus, equal word counts between these two languages could result in overall more difficult sentences in Basque than Spanish, which could bias our estimates towards higher receptive syntactic scores in Spanish than in Basque. Keeping this possibility in mind, we still found that the longitudinal trajectories for receptive syntactic abilities differed between languages. In Basque, growth was steady but smaller than in Spanish, for which receptive syntactic knowledge increased between the 1st and the 2nd stages, and specially between the 2nd and the 3rd stages. This pattern was highly similar to the one observed for the development of receptive vocabulary. We propose that, when proficiency and AoE is relatively low, i.e., the non-dominant Spanish language here, receptive abilities will strongly benefit from every (although limited) input instance in order to bootstrap language acquisition to eventually end up catching up first on receptive abilities. In addition, our results suggest that such benefits should take more time to appear for productive abilities (Giguere & Hoff, 2022). Interestingly, the amount of *oral* language exposure might become less relevant as soon as children can also exploit *written* inputs, especially for learning less frequent lexical and syntactic structures (Nation et al., 2022).

We found robust between-languages differences, together with between-measures similarities, on the children's use of language in unconstrained settings. In Basque, children increased the productive lexical diversity at the end of the study (between the 2nd and the 3rd stages). This was not observed in Spanish, for which lexical diversity did not change across stages. In addition, we did not observe a direct influence of AoE on lexical diversity in any language. To our knowledge, there is only one study that explored lexical diversity in bilingual language development in a similar way to ours (Simon-Cereijido & Gutiérrez-Clellen, 2009). However, neither the effects of exposure nor development on lexical diversity were assessed. In monolinguals though, parental linguistic input have been shown not only to play a role in the growth of vocabulary knowledge but also to modulate productive lexical diversity (Hoff, 2003b, 2003a; Hoff-Ginsberg, 1986; Huttenlocher et al., 1991). Our results add to this body of evidence by showing that increases in lexical diversity are observed in the language with higher AoE (Basque) and that individual AoE indexes in this language significantly predict lexical diversity at the latest stages of development (3rd stage here). These findings suggest that a considerable amount of language knowledge has to be amassed (at around 6 years of age in our case) before children can exploit exposure as a way to support the use of a richer vocabulary.

Similar to the naturalistic metric of lexical diversity, there was more consistent longitudinal growth in Basque than Spanish regarding the syntactic complexity of the spontaneous productions of children (MLU and clausal density). This similar pattern between lexical and syntactic skills was also found by Simon-Cereijido and Gutiérrez-Clellen (2009), who reported a strong within-language interdependence between the productive lexical diversity and MLU of bilingual children around 6 years of age. Such age corresponds to the 3rd stage of our study, for which we showed a concurrent the only timepoint in which there was a concurrent increase (with respect to the 2nd stage) in lexical diversity and syntactic complexity (in both MLU and clausal density) in Basque, the dominant language of children. In addition, Basque AoE significantly influenced both lexical diversity (in stages between which a significant growth was observed –stages 2 and 3), and syntactic complexity (in both MLU-15 and clausal density) longitudinal growth. Such findings echo the results of previous studies in monolingual children (Huttenlocher et al., 2002, 2010). Unlike Basque, significant longitudinal growth of syntactic was almost absent in Spanish, in which growth was only observed in MLU between the 2nd and 3rd stages. As both measures of MLU and clausal density have previously proven to be sensitive proxies of syntactic growth in monolinguals (Frizelle et al., 2018), it is likely that the syntactic complexity of the productions of bilingual children increased relatively more in their more dominant language, for which they also received sufficient exposure. In fact, exposure might be fundamental for syntactic development since the growth in MLU-15 and clausal density in both Basque and Spanish only took place when it was preceded or accompanied by a significant direct influence of AoE. While it was shown that early (2 to 3 years of age) MLU development was modulated by language dominance (L1 > L2) (Yip & Matthews, 2006), our results support a direct role of individual AoE experience on bilingual MLU growth during later stages of childhood (4 to 6 years of age).

The fact that the growth of productive lexical diversity and syntactic complexity and their link with AoE mainly take place at the last developmental stage of our study (around 6 years of age) contrasts with the sustained growth and influence of AoE on receptive and productive vocabulary knowledge, and receptive syntactic span. Exposure might therefore play a relevant role in explaining language performance but this may vary depending on the stage of development and the language domain and ability considered. At the beginning of the study, children relied on AoE to build their lexical receptive knowledge. In parallel with the developmental increase in vocabulary knowledge, we observed that more linguistic domains started to depend on exposure. This suggests that vocabulary knowledge might act as a building block for the development of broader arrays of language abilities (see also Simon-Cereijido & Gutiérrez-Clellen, 2009). Interestingly, a steadily diverse parental vocabulary input was shown to determine vocabulary knowledge of monolingual children early on (from 1 to 2.5 years of age; Silvey et al., 2021), in line with our finding that the strongest influence of AoE on receptive and productive vocabulary across languages was at the earliest point of our study (4 years of age). However, syntactic complexity measures might increasingly benefit from exposure throughout development (table 1.2) (see also Silvey et al., 2021).

Similar to productive vocabulary, there was a steady and parallel growth of phonological abilities across languages. Most interestingly, nonword repetition was not influenced by individual AoE indexes in neither language nor developmental stage (see table 1.2). The limited role of AoE on phonological compared to lexical and syntactic development (Cristia, 2020) might stem from the stronger dependence of phonological acquisition on heritable genetic factors compared to environmental factors such as AoE

(Bishop, 2002; Kovas et al., 2005). Nonetheless, phonological performance was overall better when children had to repeat nonwords with syllabic and stress phonotactics specific to their dominant language also associated with higher levels of exposure, despite the highly similar phonological Basque and Spanish systems (Ezeizabarrena & García, 2015). Altogether these findings support a relatively small and indirect role of AoE in the development of language-specific phonotactics sensitivity (Messer et al., 2010; Munson, 2001; Vitevitch & Luce, 2005) compared to other factors (e.g., language proficiency lexical knowledge, Gutiérrez-Clellen & Simon-Cereijido, 2010). It is noteworthy that because the nonwords of the repetition task followed language-specific lexical stress patterns, variations in lexical knowledge between languages might have directly contributed to performance on our phonological task.

Overall, the present study informs theoretical and empirical research that proposes that the role of input in language acquisition is modulated by language domains and developmental stages (e.g., Chondrogianni & Marinis, 2011).

More particularly, first, vocabulary learning appears as a 'data-hungry' process that benefits greatly from the available input even when it is limited (Cristia, 2020): vocabulary knowledge increased in both languages throughout the study and was greatly influenced by AoE. In addition, the relatively late growth of productive lexical diversity in the more dominant language of bilingual children seemed to directly depend on AoE, possibly reflecting a faster vocabulary development in this language.

Second, we observed a robust growth in the productive syntactic complexity of children in both languages. This syntactic growth depended tightly on child-specific AoE indexes as it occurred when AoE was a significant predictor of these abilities. We suggest that later stages of language development (as compared to vocabulary) could be especially sensitive to and determinant for syntactic development.

Last, we showed that the development of phonological abilities steadily took place in both languages and that AoE did not directly influence such acquisition as it was the case for the other language domains assessed. Nonetheless, it cannot be ruled out that AoE might influence the sensitivity to language-specific phonotactics that we know play a role in building-up phonological representations.

1.4.1. Conclusion

In summary, our findings highlight a developmental tight relationship between AoE and bilingual language development at different levels of linguistic granularity and domains (from sublexical phonological structure to lexical and syntactic constructions). Our results support the usage-based theories of language acquisition (Tomasello, 2005) and help extend such frameworks to bilingual language acquisition. Our findings contribute to the field by shedding new light on how child-specific language environments shape bilingual language developmental trajectories and the language "gap" that characterizes the performance of unbalanced bilinguals. Overall, we offer a developmental snapshot of the interplay between children intrinsic characteristics and environmental factors on the emergence of proficient language knowledge and use, paving the way for the design of more tailored and efficient programs for bilingual education and the assessment of language disorders in this group of children.

Study 1 attested the relevant influence of AoE on the development of fundamental language domains in two languages of bilingual children. While Study 1 focused on the developmental trajectory of different language domains from a behavioral perspective, the goal of Study 2 was to shed light on the role of AoE on the neurocognitive mechanisms which support language comprehension, such as the cortical tracking of speech.

2. Study 2. The contribution of early language exposure to the cortical tracking of speech: evidence from bilingual children

2.1. Introduction

Continuous exposure to spoken language in a wide variety of contexts makes its acquisition appear spontaneous and effortless. Nonetheless, highly complex brain mechanisms subtend the processes that allow us to understand and speak a language fluently. Language comprehension requires efficient analysis, segmentation and parsing of the rapidly unfolding linguistic structures that are embedded in continuous speech streams. Developmental evidence shows that the cortical mechanisms supporting language comprehension emerge and become language-specific essentially between birth and the start of primary school (for reviews see Kuhl, 2004; and Skeide & Friederici, 2016). However, little is known about whether and how these neurophysiological processes mature as a function of the *amount of exposure* (AoE) to a language during early childhood, despite AoE being a strong contributor to the development of language knowledge in these early stages (Study 1). In the present study, we investigated whether AoE and language knowledge influenced neural oscillatory activity in response to speech in bilingual children. Limitations in AoE could have downstream consequences for the development of such neurocognitive abilities during early childhood and affect children's future social and academic wellbeing. Additionally, the number of children who are exposed to several languages from an early age and thereby receive limited inputs in each of their languages, is rapidly increasing (Paradis et al., 2011). Thus, accurate multidimensional models about the development of language skills require understanding how different levels of language exposure and proficiency modulate fundamental brain mechanisms underlying speech comprehension.

We hypothesized that AoE and language proficiency shape the maturation of the *cortical tracking of speech* (CTS) —a neurocognitive process that has been shown critical for understanding continuous speech— of phonological, lexical and syntactic information. We propose that AoE is determining in building up speech temporal statistics that contribute to the efficient dynamic alignment of cortical oscillatory activity to relevant units in the speech signal (the so-called speech-brain entrainment; Giraud & Poeppel, 2012; Luo & Poeppel, 2007). Thus, greater AoE to a given language should be associated with more precise CTS. Additionally, richer language knowledge provided by AoE should support the tracking of linguistic information at different linguistic levels (i.e., phonological, lexical and syntactic) to help the efficient and expert comprehension of continuous speech (Broderick et al., 2021; ten Oever & Martin, 2021).

Study 1 showed a clear contribution of AoE to language knowledge, which also depended on the language domain and the developmental stage considered (see also V. C. M. Gathercole & Thomas, 2005; Oller & Eilers, 2002; Paradis & Jia, 2016). In monolingual environments, the amount of child-directed input has been related to word processing speed (Hurtado et al., 2008; Weisleder & Fernald, 2013) that is a relevant index of the encoding of lexical information from a continuous speech input. Hurtado et al. (2014) found that, in bilingual environments, the relative AoE to two languages was positively correlated with word processing speed in each language separately. Therefore, AoE appears to provide children with language knowledge at different levels that, in turn, supports increasingly efficient processing and comprehension skills for continuous speech.

Importantly, exposure enhances certain aspects of phonological abilities (Nittrouer, 1996; Nittrouer & Burton, 2005; for a review, see Nittrouer, 2002), which have been proposed to be subtended by CTS (Goswami, 2011, 2017; as detailed below). More specifically, data has shown that the influence of AoE on language learning during childhood is mediated by the progressive tuning of phonological abilities, that facilitate the comprehension of speech as it unfolds over time (S. E. Gathercole, 2006; S. E. Gathercole et al., 1991; Parra et al., 2011). Although in Study 1 we did not find a direct relationship between AoE and phonological abilities, we did observe that the phonological abilities in the more dominant language developed earlier than in the less dominant language. Thus, it appears that sufficient language knowledge is required for phonological representations to emerge and gain language specificity. For example, AoE to the different languages of bilinguals benefits their performance when repeating language-specific nonwords (Messer et al., 2010; Parra et al., 2011). In addition, research in children with hearing difficulties show that reductions in the quality and quantity of speech input delay the development of both phonological and broader speech comprehension skills (Briscoe et al., 2001; Nittrouer & Burton, 2001, 2005). Overall, the aforementioned studies strongly suggest that an efficient CTS determines adequate phonological development.

Goswami (2011, 2017) proposed that the cortical tracking of amplitude modulations (AMs) —temporal fluctuations in the speech signal— at delta (0.5 – 4 Hz) and theta (4 – 8 Hz) frequency bands, aligning closely with the occurrence of stress/prosodic patterns and syllables respectively, subserves the temporal sampling of phrases, words, and syllables during phonological development. Accordingly, the accurate processing of AMs contributes to the emergence of phonological representations (Goswami & Leong, 2013; Leong & Goswami, 2014). In adults, CTS at the delta and theta frequency bands has been shown to support speech comprehension (e.g., Ding & Simon, 2012; Gross et al., 2013; Luo & Poeppel, 2007; Molinaro & Lizarazu, 2018; Peelle et al., 2013), and a growing number of studies have shown that CTS is in place and developing in infancy and childhood (e.g., Attaheri et al., 2022; K. H. Menn, Ward, et al., 2022; Ríos-López et al., 2020).

The contribution of input to phonological development through CTS is hinted by several pieces of evidence. Kalashnikova et al. (2020) showed that, when addressing children at risk of developmental dyslexia (characterized typically by phonological deficits), adults' use of hyperarticulated vowels was reduced, which could have an impact when accessing phonological information from the speech signal. Also relevant in this regard, several studies showed that phonological deficits in dyslexic children are tightly linked to atypical CTS within the delta and theta bands (Destoky et al., 2020; Di Liberto et al., 2018; Granados Barbero et al., 2022; Molinaro et al., 2016; Power et al., 2016) in comparison to both chronological-age-matched and reading-age-matched peers (Di Liberto et al., 2018; Power et al., 2016), which suggests that CTS could be causally related to phonological development. However, Destoky et al. (2020) reported poorer CTS in dyslexic children only when compared to chronological and not to reading age-matched controls. Given these somewhat divergent findings, the contribution of accumulated linguistic experience to the maturation of CTS during phonological development remains an unanswered question that deserves exploration.

Our study enables addressing whether linguistic input contributes to phonological CTS, by exploiting the non-trivially different AoEs of unbalanced bilinguals and testing concurrently CTS and phonological abilities in each of their languages.

In addition to phonology, there is also evidence suggesting that lexical and syntactic knowledge (whose acquisition is tightly linked to AoE, as we showed in Study 1) might be also linked to the efficiency of speech tracking neurocognitive mechanisms. CTS has been shown to be modulated by knowledge about both context-driven word predictability (Broderick et al., 2021; Klimovich-Gray et al., 2021; Koskinen et al., 2020; Molinaro et al., 2021) and speech syntactic structures (Kaufeld et al., 2020; Meyer et al., 2017; Meyer & Gumbert, 2018). In addition, Panda et al. (2020) showed that vocabulary knowledge was linked to the synchronization between language-related cortical areas through neural oscillatory activity – although not specifically CTS - during continuous speech listening.

Taken together, the aforementioned evidence points to the role of acquired language knowledge across various linguistic domains on CTS tuning. However, no study directly addressed the impact of language knowledge on CTS during early language learning, nor whether AoE could shape CTS. Shedding light on these questions could help understand the role of CTS during development, which to date, has been essentially focused on the acquisition of phonology, and not on broader non-phonological language skills that are strongly influenced by AoE.

The aim of the present study was to explore the role of AoE and language proficiency on the cortical tracking of phonological and non-phonological speech features to answer the following questions:

1) Is there a direct influence of AoE on the cortical tracking of speech distributional properties coding for (i) phonological (i.e., the speech envelope) and (ii) non-phonological (i.e., lexical and syntactic structures) information?
2) Does the cortical tracking of speech features coding for phonological, lexico-semantic and syntactic information predict behavioral language performance in these linguistic domains respectively?

2.2. Method

2.2.1. Participants

Participants were 35 (18 females) Basque-Spanish bilinguals between 6 and 7 years of age (*Mean age* = 6.92; *SD* = .11). They were the children from Study 1 who showed the most exposure to Basque (> 70% of their waking hours) and the least to Spanish (< 30%) when they were 6 years old (at the last stage of Study 1). Such selection criteria were aimed to enable us to investigate the influence of AoE (low in Spanish vs. high in Basque) on CTS in two different languages within *the same* participants.

Since the participants had started formal reading instruction only a few months before the start of the study, the amount of written input was not sufficient to be considered a main source of language input at the time of testing. Thus, the potential influence of written language exposure on the contribution of AoE to CTS in our study was considered to be minimal (Dehaene et al., 2015; Goswami & Bryant, 1990; Morais et al., 1979).

Participants had normal hearing, no history of neurological disorders, nor familial risk of developmental language disorder or any other cognitive-related genetic pathology. The study was approved by the BCBL Ethics Committee and complied with the Declaration of Helsinki.

2.2.2. Behavioral session

The relative **AoE** to each language was assessed, as in Study 1, through sociolinguistic questionnaires filled by the children's parents. As in the first study, the composite index of AoE to each language that we used to select children (Figure 2.2), was computed through the formulas presented in supplementary materials (Supplemental Formulas 1.1 to 1.3).

Lexical and phonological abilities were assessed in both Basque and Spanish following the procedures of Study 1. Because of the tight relationship between CTS and phonology as well as between phonology and reading (e.g., Di Liberto et al., 2018; Gooch & Snowling, 2018; Ríos-López et al., 2021), we also assessed participants' reading abilities. Importantly, all our tasks were previously validated as being sensitive to bilingual language exposure (Gámez et al., 2019; Paradis et al., 2016; Thordardottir et al., 2006).

For lexical abilities, we assessed **vocabulary knowledge** through a picture-naming task consisting of 45 items for each language. Participants were asked to name the pictures that appeared on the screen in random order, without any time constraints. The experimenter coded each trial as either correct or incorrect after the child responded. The order of presentation of the two languages was counterbalanced across participants. As in Study 1, performance in the picture-naming task was scored as Zipf-frequency-weighted mean accuracy.

Phonological abilities were evaluated with a nonword repetition task consisting of 18 items in each language. In this task, participants were randomly presented with nonwords with phonotactic features of Basque and Spanish. Participants had to repeat each nonword. The experimenter coded each repetition as either correct or incorrect upon response. Mean accuracy for each language was taken as a measure of language-specific phonological abilities.

Reading decoding skills were assessed with a nonword reading task, which consisted in reading two lists of 30 nonwords with phonotactic features of each language respectively (similarly to nonword repetition). For each language, stimuli were presented separately. The order of language presentation was counterbalanced across participants. Children had to read the list of nonwords from a sheet of paper, as correctly and fast as possible starting from the item on the top of the list. The experimenter coded each nonword as either correctly or incorrectly read upon participant's response. Then, the number of correctly read nonwords per minute was computed as a measure of reading decoding skills for each language separately.

2.2.3. Electroencephalography session (EEG)

2.2.3.1. EEG task: speech listening

Participants were presented with continuous streams of **natural speech in the form of storytelling**. We used two stories that were adaptations of two short books targeted to 6-year-old children, and followed a very similar narrative structure.

Importantly, the register used in books targeted to children offers a great variability of words and lexical frequency (Nation et al., 2022; see Supplementary Figure 2.1), which was relevant to explore the effect of AoE and language knowledge on the cortical tracking of lexical information.

The first story was about the history of outer space exploration, and the second one about the evolution of life on Earth. For each story, both a Basque and a Spanish version were created. Half of the participants heard both stories in one language combination (e.g., 'outer space' in Basque, and 'life on Earth' in Spanish), and vice versa for the other half of participants. The order of language presentation was counterbalanced across participants. Each story was narrated continuously by a female native speaker of both languages in a child-directed speech register. They lasted about 15 minutes, because this duration has proven to be sufficient to robustly estimate cortical tracking of speech (Destoky et al., 2019). Participants were asked to listen attentively to the stories that were presented to them over speakers. They were sitting in a comfortable upright position and asked to look at static images depicting the story narrative that were presented on the center of a computer screen positioned ~80 cm from their eyes. Every 5 minutes approximately, participants were asked three simple yes/no questions (9 per story) to check whether they were paying reasonable attention to speech and comprehending the stories.

2.2.3.2. EEG preprocessing

EEG data was recorded using a 64 Ag-AgCl electrodes standard setting (actiCAP, Brain Products GmbH, Germany). One electrode was placed over the outer canthus of each eye, and one below the left eye to monitor eye movements and blinks. Electrode impedance was always kept below 15 kΩ and remained below 10 kΩ in the vast majority of electrodes across participants. During data collection, raw EEG signal was amplified (BrainAmp DC, Brain Products GmbH, Germany), online high-pass filtered at 0.05 Hz, digitized using a sampling rate of 1000 Hz, and referenced to the midline central electrode (Cz).

To obtain the best possible temporal alignment between acoustic stimuli and EEG signal, we included an additional channel resulting from the digitization of the speakers' acoustic signal, with a sampling rate of 1000 Hz (Polybox, Brain Products GmbH, Germany). This allowed us to account for and compensate varying lags between the digitized trigger and the actual presentation of acoustic stimuli. We then cross-correlated the amplitude values of the speakers signal and its corresponding audio template every 30 seconds to ensure an optimal alignment. Thus, before EEG data preprocessing, triggers that marked the onset of each speech fragment were realigned to the time of maximum correlation with the actual presentation of the acoustic signal.

All **EEG data preprocessing** steps, and later data transformations were conducted at the sensor level in MATLAB (version R2014B, MathWorks, 2014), using both custom code and functions from FieldTrip toolbox (version 20180604, Oostenveld et al., 2011). First, we downsampled EEG and audio signals to 200 Hz. Second, we bandpass filtered the signal between 0.2 and 40 Hz with a zero-phase fourth-order finite impulse response filter, using the default transition bandwidth in the FieldTrip toolbox for bandpass filtering. Third, we detected and removed physiological artifacts through independent component analysis (ICA, runica method) to the filtered signal. After visual inspection of ICA, we subtracted independent components related to eye movements and blinks from the EEG signal (*mean number of rejected components per participant* = 2.06, *SD* = .5). Fourth, we divided the continuous EEG signal from each storytelling and condition into 2000-ms epochs (the inverse of our lowest frequency of interest and frequency resolution, 0.5 Hz) with a temporal overlap of 1000 ms. Epochs and channels which overall voltage departed more than 3 z-values from the average of all epochs and channels respectively, were discarded (*mean percentage of epochs removed per participant* = 1.14 %, *SD* =.66; *mean number of channels removed per participant* = 1 out of 64, *SD* = 1.93). Interpolation of bad channels was achieved using the weighted average of their neighbors. Our EEG data exclusion criteria was to not further analyze participant datasets for which more than 30% of the data was rejected. Although no participant exceeded such threshold, two participants were excluded (one of them did not want to remain seated while listening to the stories and the other one fell asleep during the recording). Thus, we ended up having a sample of 33 analyzable EEG and behavioral datasets for each language.

2.2.3.3. CTS indexes

In order to test CTS at phonological and non-phonological levels, we used two types of CTS metrics (Figure 2.1). The first CTS index used was *coherence* (Halliday et al., 1995) which measures the phase correlation between two signals (here the brain and the speech signals, thus termed *speech-brain coherence*), and that we used to extract the brain tracking of phonological speech information (i.e., the speech envelope). The second set of CTS indexes were *multivariate temporal response functions* (mTRFs, Crosse et al., 2016) of continuous brain oscillatory activity to phonological, lexical, and syntactic information. mTRF consist in the linear mapping of the values of a continuous vector (acting as regressor) on continuous brain activity (acting as response, EEG in our case).

Coherence

We computed **speech-brain coherence** as the phase correlation between EEG and speech envelope (i.e., the Hilbert transformed audio signal). To achieve this, we used custom functions in MATLAB by following the specifications described in Molinaro and Lizarazu (2018). We circumscribed speech-brain coherence analyses to the 0.5 – 10 Hz frequency range, which spans over the delta (0.5 – 4 Hz) and theta (4 – 7 Hz) frequency bands in which prosodic phrasing (~1000 ms) and syllables (~200 ms) respectively take place (as described in the *Introduction*). In order to test whether speech-brain coherence within theta band was specifically related to syllable tracking, we estimated the syllable rate of the stories (based on an automatic algorithm, de Jong & Wempe, 2009; in Praat, Boersma & Weenink, 2021). The overall average syllable rate was 5.63 Hz (*SD* = .33), roughly the same in Basque (5.7 Hz, *SD* = .28) and Spanish (5.56 Hz, *SD* = .36). Given that our speech-brain coherence analysis had a frequency resolution of 0.5 Hz, the frequency bin that aligned most closely to the syllable rate was 5.5 Hz.

Coherence values vary between 0 (no linear phase relation) and 1 (total linear phase relation). To find the moment of maximum speech-brain synchronicity, we computed coherence between both signals at 6 different time lags (ranging from 40 to 140 ms in steps of 20 ms) in two arrays of sensors that have previously shown speech-brain coherence effects, located symmetrically within the left (i.e., T7, C3, TP7, and CP3) and right (i.e., T8, C4, TP8, CP4) temporal hemispheres. These a priori selection of sensors was only used to determine the time of maximum coherence, and not for localizing coherence effects in our analyses (which were located through cluster-based permutation tests, see later). A 60 ms lag of the EEG with respect to the speech signal was the timepoint of maximum coherence across participants and conditions, to which we circumscribed our speech-brain coherence estimates for later statistical analyses.

mTRFs

Three **mTRF models** were computed, coding for distributional features of speech at three levels: envelope (phonology), lexical frequency (lexical), and sentence-level semantic distance (syntactic). Importantly, computing envelope mTRF was used to verify that it related to the envelope tracking measured with coherence and to establish a positive control for mTRF analyses of non-phonological features, which are less salient in the signal.

The speech envelope regressors have the same operationalization (i.e., the Hilbert transformed audio signal) as described in the speech-brain coherence analyses (also following the specifications in Molinaro & Lizarazu, 2018).

Lexical and syntactic regressors consisted of continuous vectors (one per linguistic feature and story) consisting of bursts at the onset of every content word in each story. The amplitude of such bursts corresponded to latent variables that were used as proxy for lexical and syntactic information respectively. For the lexical regressor, we used lexical frequency: the amplitude of each burst was the inverse of the Zipf lexical frequency of its corresponding word (similar to the operationalization of Zipf frequency in Study 1; see Supplemental Figure 2.1). For the syntactic regressor, we computed the sentence-level semantic distance vector (see Supplemental Figure 2.2): we first obtained the semantic representation of each story word in a 300-dimensional space through fasttext Python package for text representations (Joulin et al., 2016) and then, the amplitude of each burst was computed as 1 minus the Pearson correlation of the semantic dimensions of a word with the average of all its preceding words within a sentence. This way, lexical items with a bigger semantic correlation with their preceding words within a sentence were less salient, and less semantically related words stood out relative to their preceding context.

After obtaining all the regressors of interest, we used the mTRF toolbox (Crosse et al., 2016) in MATLAB to fit one mTRF encoding model with the EEG response for each feature (envelope, lexical frequency, and sentence-level semantic distance), and for each language and participant. Our mTRF analysis time window was 900 ms-long, spanning from 150 ms before to 750 ms after every value in each regressor. In order to train and test the encoding model, we split our continuous EEG signal and each corresponding feature vectors (~ 16 minutes) into 8 folds of equal length (~ 2 minutes). We trained the encoding model in 7 folds and tested its accuracy in the remaining one, repeating this process for 30 iterations per fold. In each iteration, we obtained a correlation coefficient (r-value) between each feature and the EEG response as well as between the EEG response and a randomly permuted version of the feature. Also, within each iteration, the correlation coefficients of each feature were contrasted against their permuted version, and the results were averaged across iterations. The resulting average value, the correlation coefficient between a feature and EEG above chance level, was used in further statistical analyses as proxy for the extent to which each feature linear mapped by EEG activity.

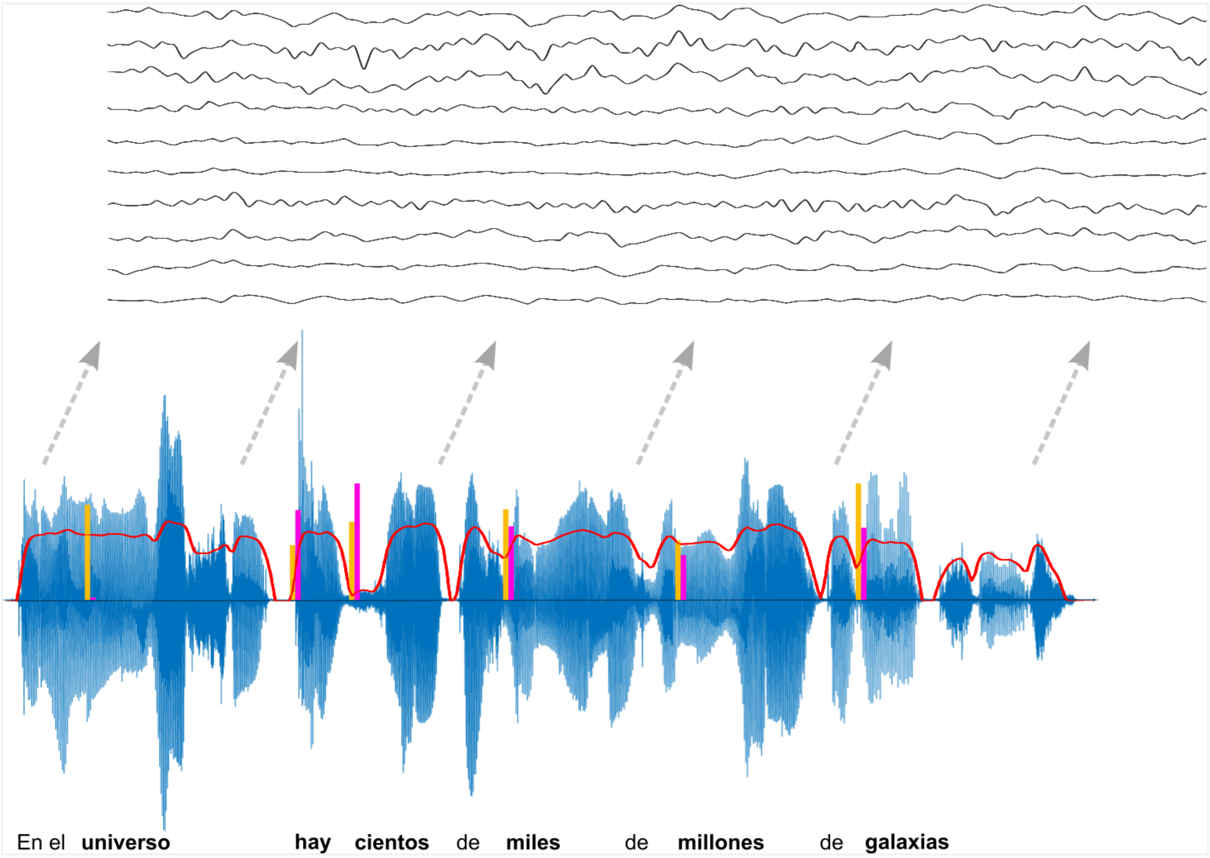

Figure 2.1. Graphical summary of the CTS analyses. In blue, the speech waveform of "*En el universo, hay cientos de miles de millones de galaxias*" ("*In the universe, there are hundreds of billions of galaxies*"). Speech-brain coherence and envelope-level mTRF models are based on the relationship between the speech envelope (in red) and EEG activity (top). Lexical frequency and sentence-level semantic distance mTRFs are obtained from the EEG response to bursts of different amplitude (lexical frequency, orange; sentence-level semantic distance, pink) at the onset of each content word.

2.2.4. Statistical analysis

2.2.4.1. Behavioral language measures

In order to assess between-languages differences in language performance, we fitted LME models with language as predictor of each dependent measure (AoE and scores on the picture naming, nonword repetition, and nonword reading tasks) and participants as random intercepts, to account for the within-individual design of our study. LME models were fitted using the same software specifications than in Study 1.

2.2.4.2. Speech-brain coherence

We used cluster-based permutation tests (CBPTs) to analyze whether there were significant speech-brain coherence effects in Basque and Spanish, as well as between-languages differences in such CTS metric. CBPT is an efficient way of estimating the presence of a statistical effect in a high dimensional space, as it allows to account for the spatial adjacency of electrodes and test for significant effects that are shared across a group of electrodes (a cluster) (Maris & Oostenveld, 2007). In our case, we run dependent-samples one-tailed CBPTs in FieldTrip with 1000 permutations. CBPTs allowed for a minimum of 2 electrodes as cluster as a way limit the possibility of single-electrode false-alarm effects, and we corrected for multiple comparisons based on the number of a-priori significant clusters. We first assessed whether there was above-chance speech-brain coherence by contrasting through CBPT the phase alignment of EEG and genuine speech envelope versus the phase alignment of EEG and a surrogate version of the envelope that did not follow the original speech order (i.e., flipped speech envelope surrogate). Then, we contrasted (also through CBPT) the speech-brain coherence values of Basque and Spanish to see whether there was a significant language effect in this CTS metric.

2.2.4.2. mTRFs

For between-languages comparisons of mTRFs, we used each participant's correlation coefficient (r-value) between the regressor (e.g., lexical frequency) and the

EEG response as individual estimate of how faithfully EEG mapped a given speech feature (e.g., lexical frequency). Thus, an r-value of 1 would be a perfect correspondence between mTRF feature and EEG signal, and an r-value of 0 would mean no correlation whatsoever. We selected the average r-value of the 5 electrodes that showed the biggest correlation with each regressor for statistical comparisons between languages. Speech-brain coherence yields estimates at sensor level, which can be submitted to CBPT to estimate the topographical location of the effect on the scalp. Given that our estimate of the mTRF model fit was a single r-value per participant, language and feature, we did not have the sensor-level resolution necessary for CBPT. Thus, instead of CBPTs, we used Bayesian t-tests (in JASP, version 0.16.4, JASP team, 2022) to contrast whether the mTRF models for envelope, lexical, and syntactic information differed or not between Basque and Spanish. Bayesian t-tests allow to assess not only whether there was evidence for the alternative hypothesis (in our case, between-languages difference in CTS), but also for the null hypothesis (between-languages similarity in CTS) (van Doorn et al., 2021).

2.2.4.3. Correlation analyses between CTS and behavioral language measures

In order to explore relationships between CTS of different linguistic features and language performance, linear regressions were conducted within each language, by correcting for family-wise type I error via false discovery rate (FDR).

2.3. Results

2.3.1. Language measures

In line with their significantly higher exposure to Basque than to Spanish, $t(63) = 35.13$, $p < .001$ ($\beta = 72.298$, $SE = 2.058$), participants showed significantly higher vocabulary knowledge, $t(32) = 13.18$, $p < .001$ ($\beta = 0.077$, $SE = .006$), and nonword reading decoding, $t(30.35) = 5.02$, $p < .001$ ($\beta = 3.263$, $SE = .651$), in Basque than in Spanish (see Figure 2.2). However, there was no language effect on nonword repetition, $t(30.1) = -0.84$, $p > .05$ ($\beta = -0.014$, $SE = .017$), nor on the comprehension of the stories that participants listened to during the EEG session, $t(28) = 0.12$, $p > .05$, ($\beta = 0.005$, $SE = .039$).

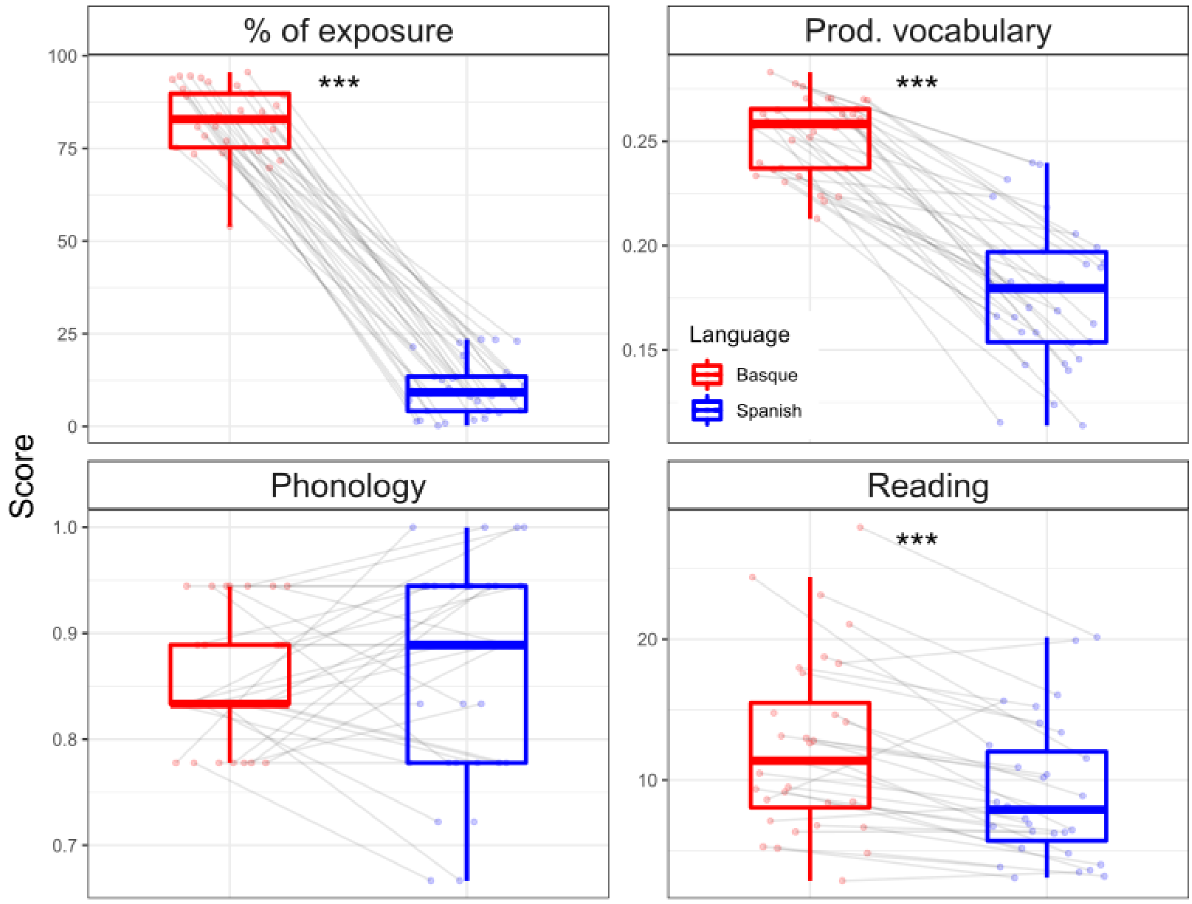

Figure 2.2. Amount of exposure and behavioral performance in vocabulary, phonology, and reading as a function of testing stage. Points represent each participant's score in the different measures, languages, and stages. Boxplots represent group estimates, with horizontal lines within each box marking the median score. Upper and lower hinges mark the first and third quartile, and whiskers show 1.5 * inter-quartile range. Lines connect the scores of each participant between languages.

2.3.2. Envelope CTS

Within the delta frequency band, speech-brain coherence was significant between 0.5 and 1.5 Hz in Basque, *cluster statistic* = 271.73, $p < .001$, ($SD = 0.001$), and Spanish, *cluster stat.* = 278.17, $p = .001$, ($SD = 0.001$) (Figure 2.3). In the theta range (4 – 7 Hz), we did not find significant speech-brain coherence in any of the languages (all corrected *p-values* > .05). We also did not observe significant coherence in the specific 5.5 Hz bin that aligned closely to the syllable rate of both languages ($p > .05$).

In addition, there was no language effect on coherence in the mentioned 0.5 – 1.5 Hz delta band, in which both languages showed significant CTS (see also Figure 2.3). Moreover, coherence in this delta range had considerably overlapping topographies in both languages (Figure 2.4).

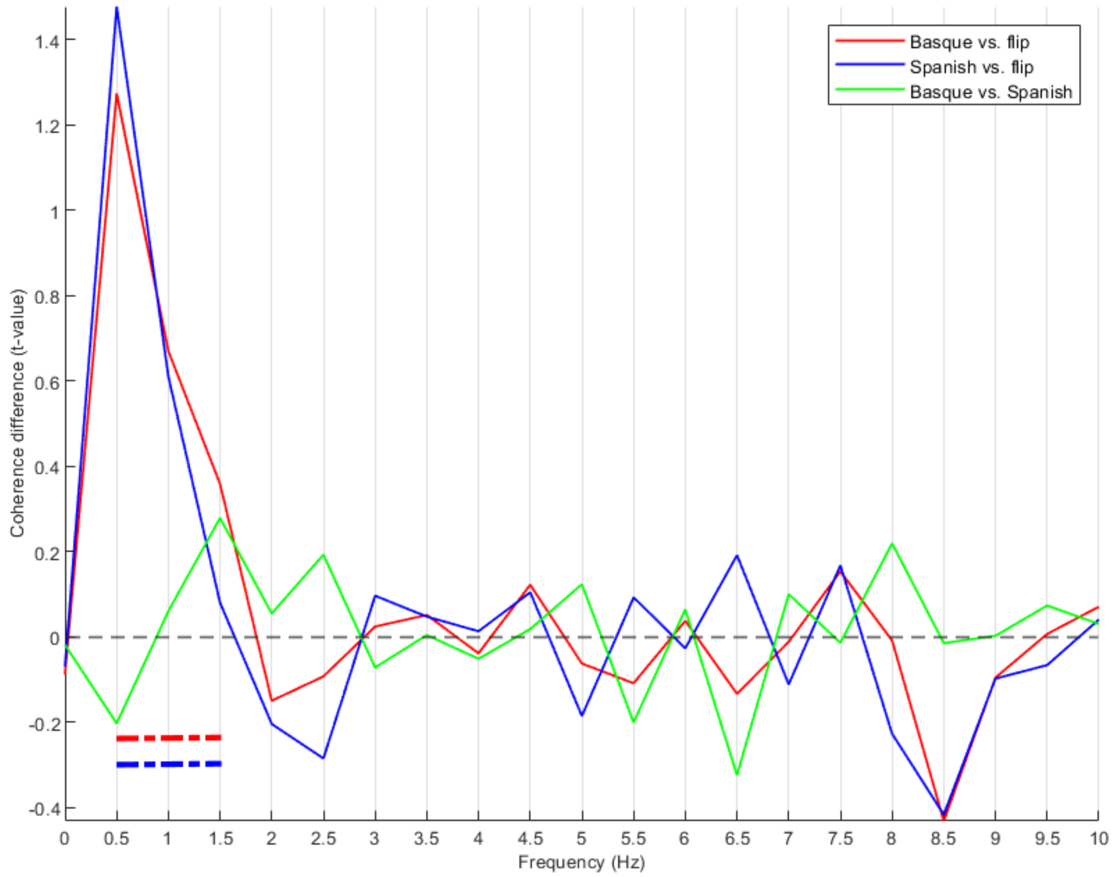

Figure 2.3. Speech-brain coherence across frequency bands for Basque (red), Spanish (blue) against their random surrogate (flipped version); and the contrast between Basque and Spanish (green). The discontinuous horizontal lines on the bottom mark the frequency range in which there was significant coherence for Basque (red), and Spanish (blue).

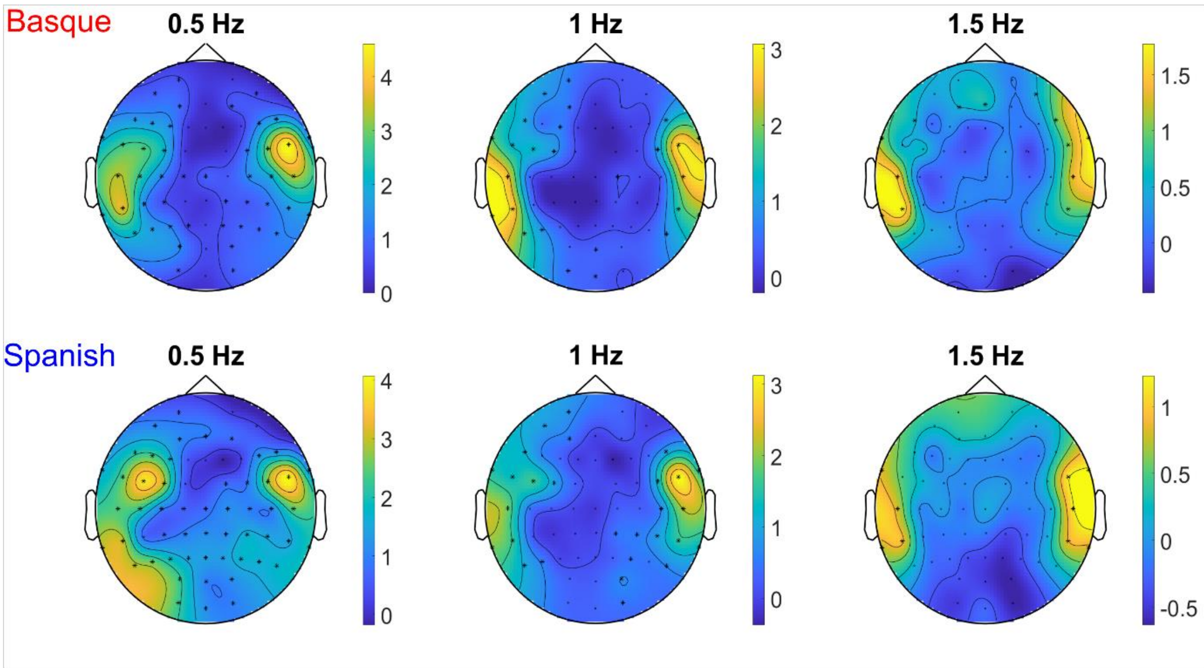

Figure 2.4. Topography of speech-brain coherence in the 3 significant frequencies in Basque (top) and Spanish (bottom). The colormap marks the size of the difference in coherence (normalized) between genuine speech and its flipped version (i.e., yellow, higher relative coherence; blue, lower). Bigger dots within each topographic map signal significant electrodes (in CBPT).

Similar to speech-brain coherence, we did not find significant differences in speech envelope mTRFs between Basque and Spanish. Indeed, there was weak evidence in favor of the lack of between-languages differences in the EEG responses to speech AMs, BF_{10} = .357, *error* = .034 %, *median difference* = -0.189, *CI* [-0.522 .138] (supplemental Figure 2.4).

2.3.3. Lexico-syntactic CTS: lexical frequency and sentence-level semantic distance

There was no language effect on lexical frequency mTRFs (Figure 2.5). In this case, there was moderate evidence for the lack of between-languages differences, BF_{10} =

.204, *error* = .037 %, *median difference* = -0.065, *CI* [-0.369 .264] (Figure 2.5, and supplemental Figure 2.5).

In addition, we found moderate evidence against a language difference on sentence-level semantic distance mTRF indexes, BF_{10} = .194, *error* = .037 %, *median difference* = -0.040, *CI* [-0.370 .289] (Figure 2.5, and supplemental Figure 2.6).

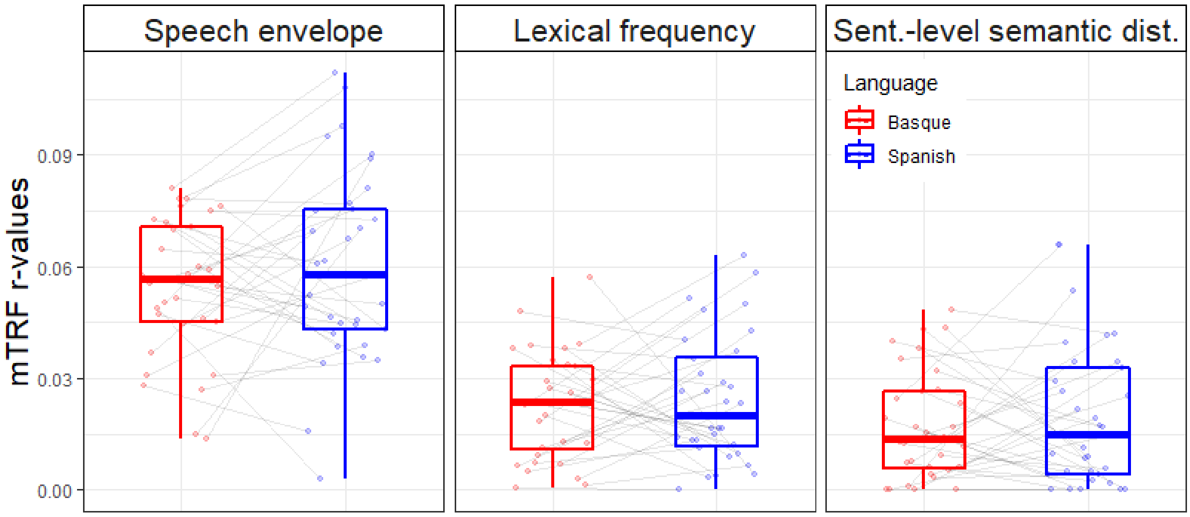

Figure 2.5. Language contrasts of the correlations between regressors and EEG signal for mTRFs of speech envelope, lexical Zipf frequency, and sentence-level semantic distances. Points represent each participant's r-value in the different mTRF models. Boxplots represent group estimates, with horizontal lines within each box marking the median score. Upper and lower hinges mark the first and third quartile, and whiskers show 1.5 * inter-quartile range. Lines connect each individual's r-values.

2.3.4. Relationship between CTS and behavioral language measures

An envelope CTS and a lexico-syntactic CTS composite scores were computed to aggregate EEG metrics for a more robust estimate of CTS-behavior relationships, while limiting the possibility of spuriously significant findings. These composite scores were validated by the positive correlations found between (i) coherence to the speech envelope at delta and theta, and the envelope mTRF (average Pearson's r coefficient =

.59; Basque: .6; Spanish: .57; all *p-values* < .01) and (ii) lexical frequency and sentence-level semantic distance mTRFs (average Pearson's r = .79; Basque: .81; Spanish: .78; all *p-values* < .01).

There was a significant and positive relationship between nonword repetition and **envelope CTS** in Basque, $t(29) = 2.43$, $p = .022$ ($\beta = .01$, $SE = .001$) (Figure 2.6), but not in Spanish, $t(31) = .2$, $p > .05$ ($\beta = .036$, $SE = .18$). There was no significant relationship between envelope-CTS and picture-naming or nonword reading in any of the two languages (all *p-values* > .05).

Performance in the picture-naming task was positively related to lexico-syntactic CTS in Basque, $t(30) = 2.39$, $p = .023$ ($\beta = .003$, $SE = .001$) but not in Spanish, $t(30) = .07$, $p > .05$ ($\beta = .348$, $SE = .133$) (Figure 2.6). There was no significant relationship between lexico-syntactic CTS and nonword repetition or nonword reading neither in Basque nor in Spanish (all *p-values* > .05).

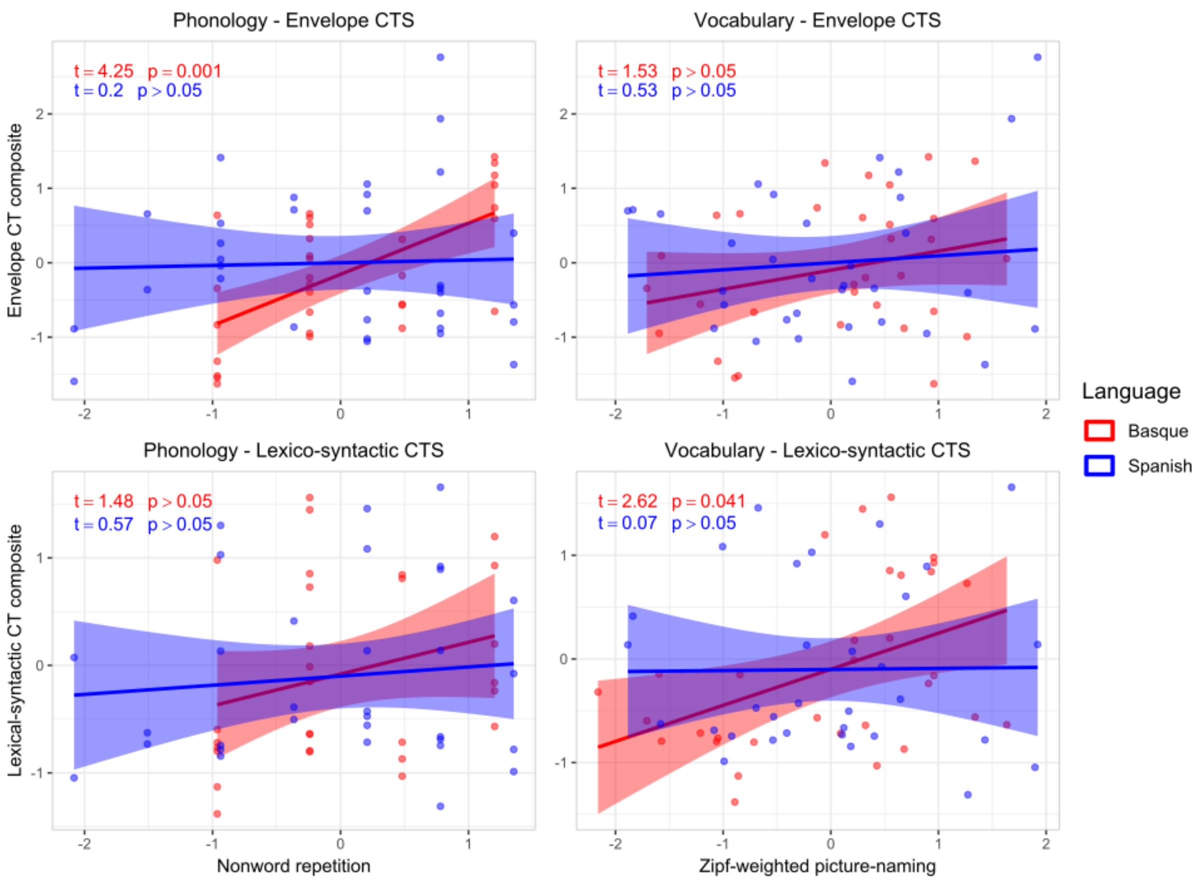

Figure 2.6. Relationship between CTS and behavioral metrics (picture-naming and nonword repetition tasks). Lines represent the slopes of linear regressions between CTS and behavioral metrics in each language respectively, with shadowed areas around the lines marking 95% confidence intervals. Estimates in top left corners represent the t- and p-values (FDR corrected).

2.4. Discussion

The main goal of the present study was to estimate the impact of amount of exposure (AoE) to a language and of abilities in this language on the cortical tracking of speech (CTS). We found that, in 6-year-old bilingual children, the cortical tracking of phonological (speech envelope) and non-phonological (lexical frequency or sentence-level semantic distance) distributional properties of speech did not differ between languages despite the unbalanced bilingual profile of our participants (i.e., Basque, L1, high AoE; Spanish, L2, low AoE). Therefore, our results suggest that CTS was independent from AoE. Nonetheless, specific relationships between language performance and the cortical tracking of phonological and non-phonological speech features were reported, a finding which, we will discuss, can be relevant for developmental research on CTS.

Our results provide evidence that the cortical tracking of the speech envelope is an important neural mechanism at play in early childhood (see K. H. Menn, Michel, et al., 2022 for evidence in infants and Ríos-López et al., 2020 for evidence in early childhood). Moreover, the present study is to our knowledge the first assessing the cortical tracking of two languages within the same group of bilingual children. We report a robust cortical tracking of the speech envelope of both of the languages of bilinguals through two different metrics. Regarding speech-brain coherence, significant CTS was found within the 0.5 to 1.5 Hz delta range, the timescale of prosodic stress occurrences, whose tracking has been proven relevant for efficient lexical segmentation (Kooijman et al., 2009). In line with previous research (Ríos-López et al., 2020), we did not find significant theta-band speech-brain coherence in our group of children, which has been related to the tracking of syllabic speech units and might be more relevant at later stages of development (Doelling et al., 2014; Peelle et al., 2013). It is possible that the developing language system of children is more sensitive to the slower delta frequency timescales for tracking continuous speech, and only starts exploiting faster syllabic AMs once their phonological representations are more developed. Indeed, a recent cross-linguistic study points shows that language-specific knowledge shapes the cortical tracking of syllabic information in adults (Peter et al., 2022). They demonstrated that adult native speakers of French (a syllable-timed language) showed enhanced cortical tracking of the syllable rate (~5 Hz) above English and Japanese listeners (stress- and mora-time languages respectively), for whom syllable-timing is less relevant. Nonetheless, Menn et al. (2022) showed significant cortical tracking of the syllable rate in infants listening to adult- and infant-directed speech. Task requirement differences could explain such divergent findings between Menn et al. (2022) and our study at the theta-rate. In Menn's study, infants' CTS was measured while they were listening to their mothers in relatively short (40 seconds) live interactions (audiovisual stimuli), whereas in our study, children's tracking abilities were assessed while they were listening to 15-minute-long stories (audio and static images). It is therefore possible that the length of the tasks and the use (or lack thereof) of additional visual cues modulated CTS differently between studies, in line with the attested supportive effect of visual information within theta-band cortical encoding of speech (Lakatos et al., 2008; Power et al., 2013).

Looking at topographical patterns of speech-brain coherence, we observed a clear spatial overlap between the two languages of our bilingual participants, showing no between-languages differences in the location of significant electrode clusters, and the presence of a wide bilateral distribution over the scalp (Figure 2.4). Because estimating the location of sensor-level EEG effects can only be done coarsely, we did not have a specific prediction beyond this bilateral temporal response that is typically shown in response to auditory stimulation. Nonetheless, such widely distributed speech-brain coherence topography was to an extent predicted by Sánchez-Alonso and Aslin (2022), who suggested that the use of naturalistic stimuli in developmental research (the case of our study) would result in more widespread and less left-lateralized brain responses to speech than what is usually shown in more constrained settings (e.g., Hamilton et al., 2018; Huth et al., 2016).

While we showed for the first time that speech-brain coherence analyses and envelope-level mTRF models provided converging evidence that our young participants robustly tracked the speech envelope of both their dominant (Basque) and non-dominant (Spanish) language, no language effect was found despite significantly higher Basque AoE and proficiency. This was also the case for the cortical tracking of lexico-syntactic information, indexed by the EEG responses to lexical frequency and sentence-level semantic distance. One explanation could be that, at the time of testing, children had developed similar receptive language abilities in both their languages, illustrated by their similar performance across languages on the comprehension abilities of the stories. This absence of a language gap in receptive performance was further supported by a similar pattern observed around five months earlier (6.4 y.o., last stage of Study 1), as well as by the fact that, at the time of testing, there was no longer a language effect on their phonological abilities (6.9 y.o., Supplementary Figure 2.3). Another possibility is that the influence of AoE and language knowledge on CTS is subtle and dependent on individual capacities, and thus cannot be observed at the group level. Previous studies have proposed that, rather than uniform categories (e.g., bilingual vs. monolingual, L1 vs. L2), specific continuous factors linked to individual experiences with one language (e.g., AoE, age of acquisition, amount of code switching) should explain better the impact of bilingualism on the structure and function of the brain (e.g., DeLuca et al., 2019; Hosoda et al., 2013; Mårtensson et al., 2012; Sulpizio et al., 2020). However, such continuous approach to bilingualism would not be informative here, given that participants were selected based on their exposure (considerably larger in Basque than Spanish), limiting individual variability in AoE (see % of exposure in Figure 2.2).

Still, the present study enables us to explore such individual differences in language proficiency and knowledge linked to bilingualism. Without limiting ourselves to L1-L2 categorical distinctions, we analyzed for both the languages of bilinguals whether individual language knowledge in specific domains was associated with individual CTS at the related levels (i.e., phonological abilities with envelope CTS, and lexical abilities with lexico-syntactic CTS).

First, we reported a significant relation between envelope CTS and phonological abilities, only in Basque. Namely, the cortical tracking of the speech envelope at multiple levels (delta and theta speech-brain coherence, and envelope-level mTRFs) was linked to nonword repetition performance, but not to productive vocabulary knowledge or nonword reading abilities. This finding is in line with Di Liberto et al. (2018)'s study which reported that the cortical tracking of phonetic features was related to phonological abilities in dyslexic children. Moreover, our finding is coherent with the hypothesis that sensitivity to prosodic and syllabic speech AMs (the ones that we specifically target in our study) subserves the temporal sampling of phonological units within such timescale (phrases, words, and syllables) during phonological development (Goswami, 2011, 2017; Goswami & Leong, 2013; Leong & Goswami, 2014). Accordingly, bilingual participants who exhibited higher CTS to such speech AMs were those who showed more developed phonological processing abilities. Thus, our results help confirm that phonological abilities and neurocognitive abilities for tracking speech AMs develop hand in hand (Boets et al., 2007; Di Liberto et al., 2018; Lundberg et al., 1988; Power et al., 2016; Vanvooren et al., 2017). In the same vein, Ríos-López et al. (2021) found that, in pre-readers, envelope CTS (in delta) predicted later reading outcomes. It is relevant to note that, while tracking speech AMs contributes to the development of phonological skills (Leong & Goswami, 2014, 2017; Molinaro et al., 2016), studies in adults highlight that CTS might be more reliant on speech rate rather than on the speech envelope modulations, at least in quiet listening environments (Hauswald et al., 2022; Schmidt et al., 2021). Therefore, the role of envelope CTS for early language development might decrease as soon as individuals can rely on sufficient lexico-semantic and syntactic knowledge to track continuous speech (e.g., Kaufeld et al., 2020; Molinaro et al., 2021).

While the role of language knowledge on the cortical tracking of speech features beyond the pure acoustic envelope is being increasingly studied in adults (e.g., Broderick et al., 2021; Kaufeld et al., 2020), we report initial evidence in children. We observed a significant positive relationship between lexical abilities and the cortical tracking of lexico-syntactic features conveyed by the speech signal, circumscribed to the most dominant language of the bilingual children. These findings are in line with Hurtado et al. (2014)'s results showing that, in infants growing in bilingual environments, the relative AoE to their languages was positively correlated with speech processing efficiency and vocabulary knowledge in each language. Our results add to this purely behavioral evidence showing that lexical knowledge abilities are tied to the precise temporal mapping of lexico-syntactic conveyed in connected speech by continuous EEG activity, but only when sustainedly high AoE is provided.

CTS predicted both phonological and lexical performance only in Basque, the L1 of participants with the highest AoE and proficiency (Figure 2.6). We interpret this as reflecting that the more stable language representations and processes in Basque might more consistently and faithfully map onto individual differences in CTS. On the contrary, weaker L2 Spanish knowledge might not map as readily onto neural resources engaged in CTS. Accordingly, the behavioral performance of children in the Spanish tasks was overall more variable than their performance in the Basque tasks (in phonological and lexical abilities particularly, see Figure 2.2). It is also possible that a larger sample could have revealed the significant behavioral-CTS relationships in Spanish, by coping with this greater L2 performance variability.

Overall, the present findings inform the theoretical, empirical, and computational accounts that suggest that proficient language models play an important role when extracting linguistic information from continuous speech. Namely, "adult" (or "dominant and proficient") language models can help exploiting syntactic structures to organize linguistic meaning (Martin, 2020; Martin & Doumas, 2017), grouping words within or between phrases (Meyer et al., 2017), and predicting upcoming linguistic information (Molinaro et al., 2021; ten Oever & Martin, 2021). Specially relevant to our findings is the study by Kaufeld et al. (2020), which aimed to disentangle the role of prosody from the role of linguistic structure and meaning for delta-band CTS in adults. They found that linguistic content modulated delta neural oscillatory activity beyond stimulus-driven prosodic timing. It is therefore possible that, during language development, delta CTS helps map the acoustically driven prosodic timing while individuals learn a language and also accumulate linguistic knowledge present in similar acoustic timescales such as syntactic information. Interestingly, Menn, Ward, et al. (2022) reported that 10 months-old infants could track stressed syllables within delta frequency band and that these skills predicted vocabulary knowledge at 24 months. Future longitudinal studies assessing the different reliance on temporal or linguistic features for tracking the speech signal as a function of age and language knowledge, will help clarify whether and when this potential developmental shift takes place.

In summary, our findings shed new light on the role of AoE and language knowledge on neurocognitive mechanisms supporting speech comprehension such as CTS. For the first time, we show that the cortical tracking of the temporal speech envelope and lexico-syntactic speech features does not depend on levels of exposure, at least in our group of bilingual children. We also highlight that individual differences in specific language abilities depend on the cortical tracking of related linguistic features conveyed by continuous speech. In general, our findings can inform future research about the role of linguistic input on CTS, as well as a developmental account of which linguistic features are tracked by a developing neurocognitve language model.

Study 2 focused on investigating the influence of AoE on CTS. As stated in the General Introduction, there is a field of research that focuses on whether infant- and child-directed speech registers could be potentially beneficial for engaging efficient CTS mechanisms in a developing language system. Therefore, Study 3 explored the temporal regularities of child-directed speech in order to determine whether the "quality" of speech could be exploited by children while developing their language-specific phonology.

3. Study 3. Local temporal regularities in child-directed speech[2]

3.1. Introduction

Under typical listening conditions, humans effortlessly process and comprehend speech as it unfolds over time. Several theories suggest that cortical oscillations (the relatively regular synchronous firing of neuronal populations) in the auditory and broader language regions synchronize to the speech signal at several timescales (Ghitza, 2011; Giraud & Poeppel, 2012). Such synchronization mechanisms allow the temporal processing of speech and facilitate its comprehension. Neurophysiological research corroborates this view by showing cortical tracking of speech acoustic cues that map onto linguistic syllables and prosodic patterns (e.g., Ding & Simon, 2012; Doelling et al., 2014; Molinaro & Lizarazu, 2018; Peelle et al., 2013). Moreover, there is direct evidence that links an efficient cortical tracking of prosodic (Rimmele et al., 2021; delta band oscillations, 0.5 – 4 Hz) and syllabic (Doelling et al., 2014; theta band oscillations, 4 – 8 Hz) acoustic cues in the speech signal with speech comprehension. While most of the evidence about the oscillatory mechanisms for tracking acoustic regularities in speech comes from proficient adult populations, infants' and children's abilities to track the temporal cues of speech have also been studied (e.g. Attaheri et al., 2022; Gervain & Werker, 2013; Ríos-López et al., 2017; Tallal, 1980). However, there is currently little

[2] A similar version of this study is published as: Pérez-Navarro, J., Lallier, M., Clark, C., Flanagan, S., & Goswami, U. (2022). Local Temporal Regularities in Child-Directed Speech in Spanish. Journal of Speech, Language, and Hearing Research, 65(10), 3776–3788. https://doi.org/10.1044/2022_JSLHR-22-00111

evidence concerning whether the temporal regularities of child-directed speech (CDS) are enhanced (as compared to adult-directed speech, ADS) in order to support and guide the emergence of a phonological system. There is also little evidence concerning which statistical forms this temporal enhancement may take. Answering this question is crucial for a comprehensive developmental framework that considers how the brains of infants and children exploit the temporal regularities of the speech they are typically addressed with to achieve proficient language comprehension.

Several studies have highlighted the presence of temporal regularities within the prosodic and syllabic timescales, which inform the aims of the present study. At the syllabic level, the rate of approximately 5 syllables per second (5 Hz) is common across languages (Ding et al., 2017; Greenberg et al., 2003). At the prosodic stress level, Tilsen and Arvaniti (2013) showed that amplitude envelope-based methods (similar to those used in the present study) could capture stress regularities in spontaneous utterances. In the same vein, Inbar et al., (2020) found that prosodic units (termed 'intonation units' in their study) produced by adult speakers appear at a roughly constant rate of ~1 Hz. Interestingly, Stehwien and Meyer (2021) analyzed an annotated corpus of radio newscasts in German to show that the prosody of intonational phrases (mapping onto utterances) determined the periodicity of their nested subordinate phrases, suggesting that prosody could have a determining role in shaping the local temporal regularities of adult-directed speech. Overall, the evidence suggests that there is a close overlap between the rhythms of quasi-regular speech units such as stressed syllables and syllables and the timescales at which neurophysiological mechanisms operate to subserve their processing (see Poeppel & Assaneo, 2020 for a comprehensive review on the rhythms of speech production and perception).

While it is well established that human neurocognitive abilities subtending the extraction and segmentation of phonological units in speech fine-tune and gain language specificity during the early years of life (for reviews see Kuhl, 2004; Skeide & Friederici, 2016; Werker & Hensch, 2015), it is still unclear how the speech inputs directed to infants and children provide them with robust temporal statistics that can support this phonological tuning. Of particular interest for the present study are the low-frequency temporal statistics present in the amplitude envelope of the speech signal, governed by amplitude modulations (AMs) centered at different temporal rates. AMs are systematic intensity changes in the speech signal, mainly taking place at the delta (~2 Hz) and theta (~5 Hz) rate bands of AM, that help to signal the occurrence of linguistic units like prosodic phrasing (~1000 ms) and syllables (~200 ms) respectively (Ding, Patel, et al., 2017; Greenberg, 2006; Greenberg et al., 2003). Such temporal fluctuations in the amplitude envelope of the speech signal, particularly the AM rise times (rates of change for these AM bands), provide salient acoustic markers relevant to extracting prosodic and syllabic phonological units, while faster modulations (~35 Hz) are thought to contribute to the extraction of phonemic information (Poeppel et al., 2008). The identification of phonological units in the speech signal is crucial for phonological and reading development (Ziegler & Goswami, 2005). Behavioral evidence, in line with the evidence on the cortical tracking of speech (e.g., Doelling et al., 2014; Rimmele et al., 2021), highlights the functional role of tracking delta and theta AMs in sentence segmentation and syllabic parsing respectively (Ghitza, 2012, 2017). A key functional role for delta and theta AMs is also in line with the temporal sampling theory (Goswami, 2011), a developmental framework for language acquisition centered on phonology. The temporal sampling theory proposes that the automatic alignment of endogenous brain rhythms with AM-governed rhythm patterns in speech is critical for linguistic and phonological development, and that this unconscious neural alignment (or sampling) process may be atypical in developmental dyslexia, which is characterized by both phonological and amplitude rise time difficulties.

Coherent with the temporal sampling hypothesis, two bodies of evidence attest the key role of tracking low frequency speech AMs for phonological development. Firstly, multiple studies across languages have shown that impairments in AM sensitivity accompany the atypical phonological development characteristic of developmental dyslexia (e.g., Goswami et al., 2002, 2010; Leong & Goswami, 2014; Surányi et al., 2009; see Hämäläinen et al., 2012 for a systematic review). Secondly, sensitivity to AMs during the first years of life is a predictor of outcomes in fundamental language domains, such as phonological awareness (Goswami, Wang, et al., 2010; Vanvooren et al., 2017), vocabulary (Kalashnikova et al., 2019), and reading abilities (Vanvooren et al., 2017). In addition, recent longitudinal studies show that cortical oscillatory tracking of prosodic information is present in infants from 4 months, and increases during early childhood (Ríos-López et al., 2020; Attaheri et al., 2022), suggestive of the relevance of delta-band speech tracking for language development. Ríos-López et al., (2021) showed that a bigger delta-band cortical tracking of speech in pre-reading children indeed predicts better reading skills one year later, after the beginning of formal reading instruction.

Previous evidence shows that adults adapt their speech complexity to children's linguistic abilities and communicative feedback, in order to facilitate comprehension (Huttenlocher et al., 2010; Kalashnikova et al., 2020; Lam & Kitamura, 2012; Smith &

Trainor, 2008). There is abundant evidence concerning the spectral (pitch) characteristics of infant-directed speech (IDS), which are exaggerated to make it a phonetically-salient and engaging register to address language-learning individuals (Dilley et al., 2020; Fernald, 1985; Kuhl et al., 1997; Trainor & Desjardins, 2002; Werker et al., 2007; Werker & McLeod, 1989; see Fernald, 2000 for a review). The enhanced spectral characteristics of IDS are well-established, however less is known regarding potential temporal adaptations that may take place when addressing infants and children. Two well-known temporal features of IDS are a slower speech rate and shorter utterances (Fernald et al., 1989; Fernald & Simon, 1984; Leong et al., 2017). It may be the case that CDS could also provide especially regular temporal statistics to facilitate identification of and access to phonological units in speech and thereby to facilitating the emergence of a proficient phonological system. Such a hypothesis was initially explored by Leong and Goswami (2015) in relation to the AM organization of CDS in English, typically regarded as a stress-timed language (i.e., a language characterized by certain regularity in the timing of stressed syllables); and further tested by contrasting IDS and ADS in English (Leong et al., 2017). In the latter study, Leong et al. (2017) showed that IDS differed from ADS in its temporal organization, especially regarding two critical aspects. One was the higher prominence of delta band modulation energy in IDS compared to ADS: the modulation spectrum revealed relatively more power in the delta band for IDS than for ADS. This feature is likely linked to enhanced prosody in IDS, providing more salient temporal information relevant to extracting phonological information at slower timescales (e.g., intonation phrases, words, and stressed syllables) to a learning individual. The second feature was that stressed syllables were more regularly spaced in IDS than ADS, shown by significantly greater phase synchronization (rhythmic alignment) of delta-rate and theta-rate AMs (~2Hz and ~5 Hz respectively) in IDS. This was interpreted as providing a predictable temporal skeleton to facilitate the infant's attentional and perceptual access to syllables during early stages of language learning.

However, to date, there is no study concerning the potential benefit that the temporal organization of CDS (in contrast to ADS) could provide during pre-school years, nor to what extent such temporal organization is present in non-stress timed languages like Spanish. Languages like Spanish are characterized by salient syllabic timing, and thus have been traditionally categorized as syllable-timed languages, (see Ramus et al., 1999, and Varnet et al., 2017, for instances of supporting evidence; but also Arvaniti, 2009; Turk & Shattuck-Hufnagel, 2013 for opposing views). Here we focus on kindergarten, a stage in which phonological abilities (e.g., phonological awareness and phonological short-term memory) are explicitly taught, as they will support later reading acquisition (e.g., Caravolas et al., 2001; Muter et al., 2004). We investigated whether the temporal regularities of CDS differed from those of ADS in Spanish, by directly contrasting the temporal statistics of the two speech registers within the same study for the first time. If CDS shows similar salient temporal features to English, in principle this could signal the presence of language-universal temporal statistics that may facilitate learning, particularly regarding an emergent phonological system. To this purpose, we focused on three temporal features of speech: the modulation spectrum, the temporal regularity of the placement of stressed syllables and syllable rate. We studied the two features —modulation spectrum and the temporal regularity of the placement of stressed syllables—that Leong et al., (2017) already found distinctive in IDS in English, a stress-timed language. The modulation spectrum for each speech register was computed and the area under the curve (AUC) was compared in delta versus theta bands for CDS and ADS respectively. Our aim was to discern whether in Spanish, the two speech registers can be differently categorized as more prosody-salient (greater AUC in the delta-rate AM band) or syllable-salient (greater AUC in the theta-rate AM band). To characterize the regularity with which syllables were stressed in CDS in contrast to ADS, we analyzed the temporal alignment between delta and theta AM bands in terms of AM phase alignment (rhythmic synchronicity). To this purpose, we used the spectral-amplitude modulation phase hierarchy (S-AMPH) model developed by Leong and Goswami (2015). The S-AMPH model allows us to decompose the amplitude envelope of the speech signal and measure the temporal alignment between different AM bands nested within the signal in different words and phrases in terms of their phase synchronization (see Figure 3.1 for a phrasal example). Of particular interest for our study, delta-theta phase alignment plays a crucial role in the perception of prosodic patterns in English and has been proposed as a novel statistic for the language-learning brain (Leong & Goswami, 2015). Greater delta-rate to theta-rate AM phase synchronization is thought to help to identify prosodic patterning by specifying strong versus weak syllables (Leong et al., 2014). When both AM bands peak together, a strong syllable is heard. When a trough in the slower delta-rate AM band (centered on ~2 Hz in the speech materials used by Leong et al., 2014) coincides with a peak in the faster theta-rate AM band (centered on ~4 Hz in Leong et al., 2014), a weak syllable is heard. Whether the same is true in Spanish is currently unknown. Finally, we analyzed syllable rate. Our goal was to extend previous findings of CDS being more slowly paced than ADS (Biersack et al., 2005; Sjons et al., 2017), and to investigate the potential links between a putative slower speech rate in CDS and its expected enhanced temporal regularities. In summary, the role of sensitivity to AM information for efficient speech processing and language development is well supported. In the present study, we take a step further and explore whether specific AM regularities in the acoustic signal of CDS in Spanish (AUC in delta versus theta AM bands, delta-rate to theta-rate AM phase synchronization, and speech rate) are enhanced in comparison to ADS, with the assumption that developing an emergent phonological system should benefit from the presence of salient temporal statistics in the input. By testing Spanish, classically considered to be a syllable-timed language, our results should provide developmental evidence regarding the possibly universal relevance of AM phase relations to extracting phonological grain sizes in language learning. Further, our data can offer a comprehensive link between the cumulative knowledge from the cognitive neuroscience of language about cortical tracking of speech and universal processes in language acquisition.

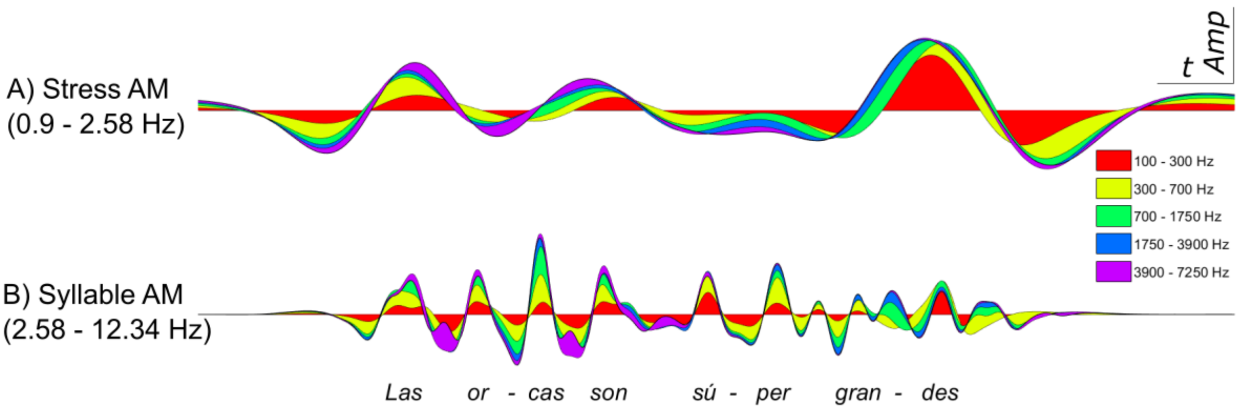

Figure 3.1. Example of S-AMPH model's spectro-temporal decomposition of an utterance ("*Las orcas son súper grandes*", *Whales are super big*). **A**) Stress AM band (delta range, 0.9 – 2.58 Hz). **B**) Syllable AM band (theta range, 2.58 – 12.34 Hz). To estimate prosodic and syllabic salience, amplitude modulation is extracted from Stress (A) and Syllable (B) bands respectively. To estimate the regularity of stressed syllables, we calculated the phase alignment between 1 cycle of Stress (A) and 2 cycles of Syllable (B) AMs.

3.2. Method

3.2.1. Participants and conditions

We recorded the CDS and ADS speech productions of 18 female Spanish-speaking adults (*mean age* = 39.06 y.o.; *SD* = 5.39). All participants had attained higher education and lived in urban areas of the Basque Country. 16 participants could be considered monolinguals (exposed to Spanish more than 70% of their time) and two participants could be considered Spanish-Basque bilinguals (exposed to their second language, Basque, at least 30% of their time). We selected them based on Spanish being the language they used to address others in the vast majority of interactions (*mean use of Spanish* = 87.5 %; *SD* = 9.20). For CDS productions, participants were accompanied by their 4 year-old children (*N* = 18, 6 females, *mean age* = 4.1 y.o.; *SD* = .35), with the aim of generating as ecologically valid CDS productions as possible, like those that could happen in everyday life (Lam & Kitamura, 2012; Smith & Trainor, 2008). The purpose of having 4-year-old children as addressees of CDS was to ensure that children were mature enough to understand the purpose and, therefore, be attentive and quiet during the CDS recordings (~20 minutes). In the ADS productions, participants addressed one of the experimenters (*N* = 2, 1 female, mean age = 28.1 y.o.; SD = .4). For each speech register, participants were asked to (i) address their child or the adult interlocutor in spontaneous speech monologues—the critical spontaneous CDS and ADS conditions—, and (ii) read to their interlocutors—baseline reading CDS and ADS conditions. Although our main purpose was to study spontaneous speech, we added baseline reading conditions to control for potential participant variability in their spontaneous productions (see Hirose & Kawanami, 2002), as well as for discerning whether CDS shows boosted temporal regularities regardless of its production context. Each participant thus took part in four speaking conditions: spontaneous CDS, read CDS, spontaneous ADS, and read ADS. Participants were provided with several topics to facilitate their spontaneous productions to children (e.g., animals and pets, family trips, anecdotes that their children liked, etc.) and adults (e.g., participant's studies, working life, how they spent their leisure and family time, etc.). Elicitation instructions were minimal in order to generate speech productions as ecologically valid as possible, and were the following: "please, talk/read to the child/adult about any of the mentioned topics in an engaging way. Let us know if you run out of ideas, and we will suggest a few new topics." We recorded each participant during between 9 and 10 minutes per speaking condition, to get at least 8 minutes of analyzable continuous speech signal (i.e., after removing noisy and silent segments) per condition.

3.2.2. Speech recordings

Speech was recorded in a soundproof room while participants and addressees were seated in front of each other, with a cardioid microphone (Sennheiser e 840) at approximately 10 centimeters from the speakers' head. Continuous speech (single channel, 44.1 kHz, 16-bit PCM) was segmented into utterances based on their terminal intonation contour, and at the start of pauses longer than 2 seconds between productions, according to the same standard criteria (Miller, 1981) that were employed in Study 1. Additionally, utterances with more than two coordinate clauses were segmented before the second conjunction (i.e., "*and*"), to avoid spuriously lengthening due to clausal chaining (Rice et al., 2006). Utterances containing false starts, repetitions and reformulations were either excluded or trimmed to their correct formulation to limit the impact of those factors in our temporal metrics (Tree, 1995). In total, participants provided 5070 utterances. We excluded from further analyses 645 utterances shorter than 2 seconds (12.72 % of the data set), as they did not provide enough information for reliable low-frequency (~1 Hz) AM estimations. Thus, the final dataset was composed of 1084 spontaneous CDS, 1400 read CDS, 1067 spontaneous ADS, and 874 read ADS utterances. After segmentation, the volume levels of each utterance were z-scored prior to our temporal analyses.

3.2.3. Temporal analyses

We used a spectro-temporal acoustic model (S-AMPH, Leong & Goswami, 2015) that allowed us to characterize the multiscale temporal hierarchy of amplitude modulation information in speech. To achieve this, the S-AMPH model reduces the dimensions of the speech signal into three AM bands in two main steps. First, band-pass filtering the z-scored utterances into 5 spectral bands (band edge frequencies: 100, 300, 700, 1,750, 3,900, and 7,250 Hz) through a series of adjacent zero-phase finite impulse response (FIR) filters. Second, each spectral band signal was Hilbert filtered, and subsequently band-pass filtered through an additional series of 3 AM bands: delta (0.9 – 2.58 Hz), theta (2.58 – 12.34 Hz) and beta/low-gamma (12.34 – 40 Hz). The ranges of our AM bands, determined by the signal-driven model construction of S-AMPH for English, map closely onto the frequency bands typically linked with prosodic (delta, 0.5 – 4 Hz), syllabic (theta, 4 – 7 Hz) and phonemic (beta/low gamma, 12 – 50 Hz) timescales respectively (e.g., Giraud & Poeppel, 2012). These timescales were mapped for each of the 5 different spectral bands, which are color coded in Figure 3.1. This figure depicts the output of the model for the delta and theta bands for a single phrase. Visual inspection of Figure 3.1 shows that some peaks in the delta band correspond to peaks in the theta band. In these cases, phase synchronization indices (PSI values) would be larger, indicating the likely presence of a stressed syllable. The figure also shows that typically the S-AMPH modeling produces one theta band peak per syllable in a given utterance.

We estimated both the amplitude-modulation spectrum and the phase synchronization between AM bands to test whether CDS and ADS differed in the distribution of their modulation rates and in their phase relations regarding delta-rate and theta-rate AMs. The modulation spectrum analysis approximately indicates whether we can categorize each register as more prosody-prominent versus syllable-prominent respectively. Since utterances that were too long, too short, or that contained long pauses could bias modulation rate estimates, we limited the modulation spectrum analyses to utterances in the range of 2 to 6 seconds and excluded utterances with silences longer than 1 second. To characterize the modulation spectra of our speech materials, we Hilbert filtered each utterance's 5 bands resulting from the first S-AMPH step and passed them through a FIR filterbank with 24 log-spaced channels ranging from 0.9 to 40 Hz. We then computed mean power across modulation channels for each frequency band, followed by the power difference from the mean (in dB) for each modulation channel. We used the average power difference from the mean of the 5 spectral bands for further statistical analyses of the modulation spectrum.

The phase synchronization index (PSI) estimates the rhythmic relations between the adjacent delta-rate and theta-rate AM bands (A and B respectively in Figure 3.1). Cross-frequency PSI quantifies phase alignment between two oscillators of different frequencies (Tass et al., 1999; see Supplemental Formula 3.1). This is achieved by adjusting the *n:m* ratio, in which *n* and *m* are the number of cycles of the lower (delta in this study) and higher (theta) frequency oscillators, respectively. PSI values range between 0 (no phase synchronization) and 1 (perfect phase synchronization). The n:m ratio that best accommodated delta-theta PSI for our Spanish materials was 1:2 (see S2). Therefore, PSI results are computed using the 1:2 ratio. S-AMPH model also extracts a beta/low gamma (12.34 – 40 Hz) AM band, mapping onto phonemes/onset-rime units. Given that the hypotheses of the present study address low frequency (< 12 Hz) modulations, we did not further analyze such higher frequency beta/low gamma AM band. However, it is noteworthy that 1:2 was also the ratio that best suited theta-beta/low gamma phase alignment, which is in line with a previous S-AMPH analysis of IDS and ADS in English (Leong et al., 2017). Since we obtained 5 delta-theta PSIs per utterance (one per spectral band), we averaged them and conducted our statistical analyses on mean PSI.

We computed syllable rate to assess whether CDS is slower paced than ADS, as well as whether the speed at which utterances are produced contributes to their temporal regularity. Syllable rate was semiautomatically computed in Praat (Boersma & Weenink, 2021), based on the acoustic algorithm developed by de Jong and Wempe (2009). Volume parameters were adapted to the decibel (dB) levels of each participant's recording to obtain reliable syllable rate estimates regardless of between-participant loudness and pitch differences. We validated a subset of 1584 (38 % of all utterances) of automatic syllable rate metrics with their corresponding manually annotated syllable rate indexes, estimated by trained native speakers, showing indeed a high correlation between manually annotated and automatically detected syllable rate ($r(1582) = .95$, $p < .001$; Supplemental figure 3.2).

3.3. Results

In order to assess the influence of speech register (CDS, ADS), and speaking condition (spontaneous speech, read speech) on each of our temporal measures (distribution of modulation energy, phase synchronization, and syllable rate), we used linear mixed effect (LME) models. Given the within-participant structure of our study, we included each participant as a random intercept in the model. We used the *lmer* function of lme4 package (v.1.1.28, Bates et al., 2015) as well as *anova* function to test the omnibus main effects and interactions of our predictors.

3.3.1. Modulation Spectrum (Prosodic salience)

To operationalize our planned analyses concerning the peak locations of the modulation spectra (Figure 3.2, panel A), we calculated the area under the curve (AUC), defined as the linear transformation of each frequency band's difference in dBs from mean power. Delta and theta segments of the modulation spectrum differed greatly in their AUC (Figure 3.2, panel A), as previously shown by other studies (e.g., Ding, Patel, et al., 2017). Overall (i.e., across registers and conditions), AUC was significantly bigger in theta than in delta, $t(36) = 25.62$, $p < 0.001$ ($\beta = 0.260$, $SE = 0.010$, CI [0.240 0.280]). Therefore, we circumscribed our planned analyses to each of the AM bands separately. LME showed that, within **delta**, there were significant effects of speaking register, F(1,

54) = 11.45, p = 0.001, condition, $F(1, 54) = 51.43$, $p < .001$, and an interaction between register and condition, $F(1, 54) = 23.39$, $p < 0.001$. This pattern of results reveals a bigger delta AUC in CDS than in ADS, $t(54) = 5.81$, $p < 0.001$ ($\beta = 0.066$, $SE = 0.011$, CI [0.043 0.089]), as well as in spontaneous than in read speech, $t(54) = 8.49$, $p < 0.001$ ($\beta = 0.097$, $SE = 0.011$, CI [0.074 0.120]). In the **theta** segment of the modulation spectrum, LME also yielded a significant effect of speaking register, $F(1, 54) = 20.51$, $p < 0.001$, condition, $F(1, 54) = 98.07$, $p < 0.001$, as well as an interaction between both factors, $F(1, 54) = 18.79$, $p < 0.001$. However, the theta segment of the modulation spectrum was characterized by the inverse pattern relative to delta, namely ADS showing a bigger theta AUC than CDS, $t(54) = 6.27$, $p < 0.001$ ($\beta = 0.027$, $SE = 0.004$, CI [0.019 0.036]), as well as read speech showing a bigger theta AUC than spontaneous speech, $t(54) = 10.07$, $p < 0.001$ ($\beta = 0.044$, $SE = 0.004$, CI [0.035 0.052]). Indeed, for theta, the modulation spectrum of all conditions peaked at around 5 – 6 Hz, corresponding to the syllable rate (as previously shown across languages; Ding, Patel, et al., 2017; Greenberg et al., 2003).

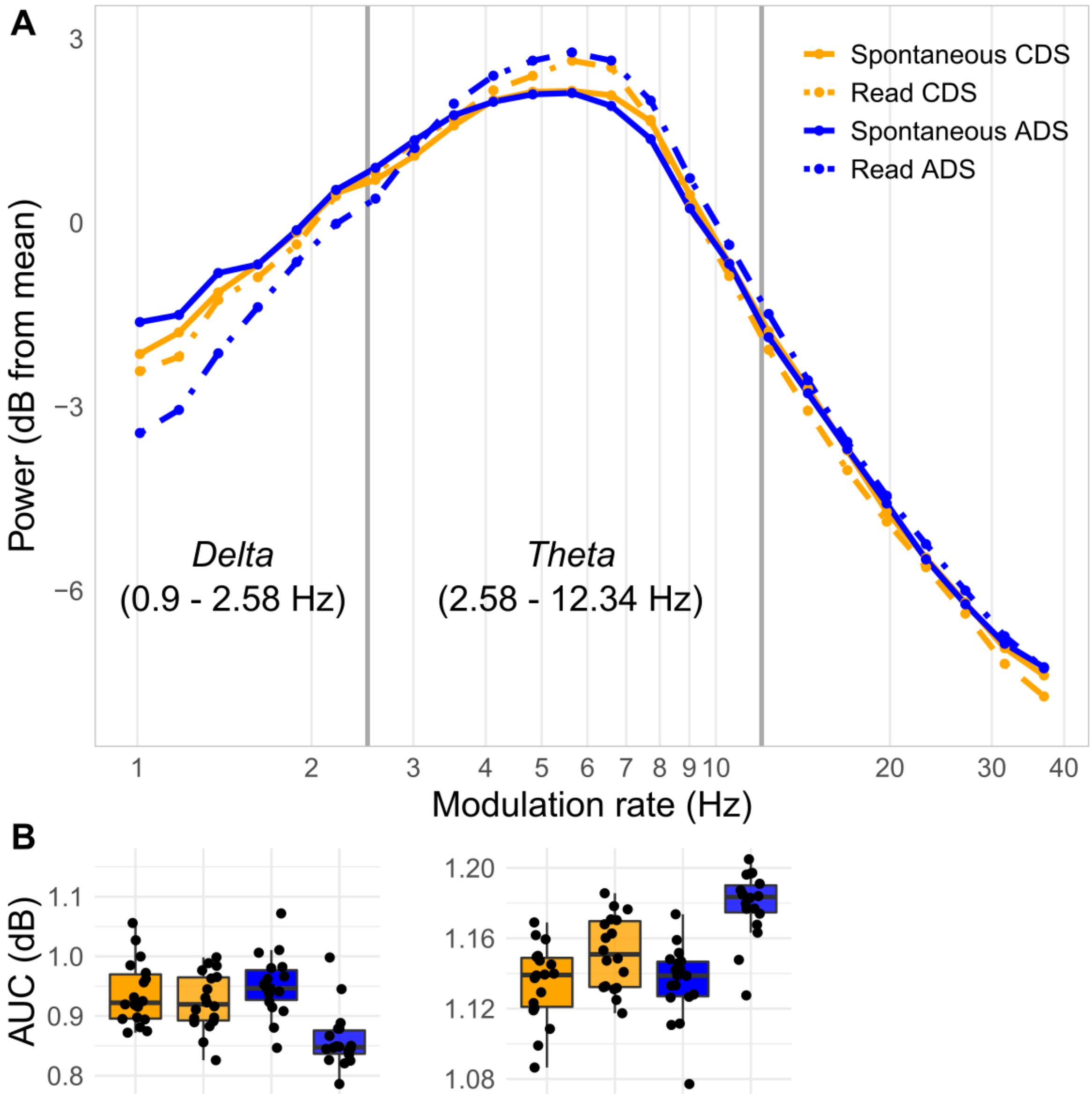

Figure 3.2. A) Modulation spectra of the four speaking conditions. The vertical grey lines divide the signal-derived modulation rates of the S-AMPH model that we used to define delta and theta bands, to which we subset our PSI and AM spectrum analyses. **B**) Area under the curve (AUC) of the delta (left) and theta (right) bands of spontaneous CDS, read CDS, spontaneous ADS, and read ADS respectively from left to right. The horizontal lines between conditions represent significant differences in AUC, adjusted for multiple comparisons (** $p < .01$; **** $p < .0001$). **C**) AUC of canonical theta band (4 - 7 Hz). Significant differences between speaking conditions are represented as in section B. Dots in Panels B and C represent mean AUC values per participant.

Thus, spontaneous and read CDS had significantly greater modulation energy (i.e., bigger delta AUC) than spontaneous and read ADS respectively, suggestive of more salient prosodic structure in CDS. The results for spontaneous speech are in line with the IDS-ADS prosodic differences in IDS in English demonstrated by Leong et al. (2017). The data for read CDS are completely novel. Moreover, and in line with the differences between read and spontaneous materials that have been reported with respect to prosody (e.g., Hirose & Kawanami, 2002; Howell & Kadi-Hanifi, 1991), our results suggest that when reading to or spontaneously addressing adults in a syllable-timed language, a greater syllabic salience takes place (i.e., bigger theta AUC).

3.3.2. Regularity of stressed syllables (delta-theta phase synchronization, PSI)

Delta-theta PSI values in the different spectral bands demonstrated a similar pattern across speech registers (Supplemental Figure 3.3). Therefore, we first computed an LME model with mean PSI values as the dependent variable. The LME yielded a significant effect of speaking register, $F(1, 54) = 26.82$, $p < .001$, showing that CDS is characterized by higher delta-theta phase synchronization than ADS, $t(54) = 2.49$, $p = 0.016$ ($\beta = 0.011$, $SE = 0.004$, CI [0.002 0.020]) (Figure 3.3). There was no significant effect of speaking condition (spontaneous vs. read) nor interaction between register and condition ($p > .05$).

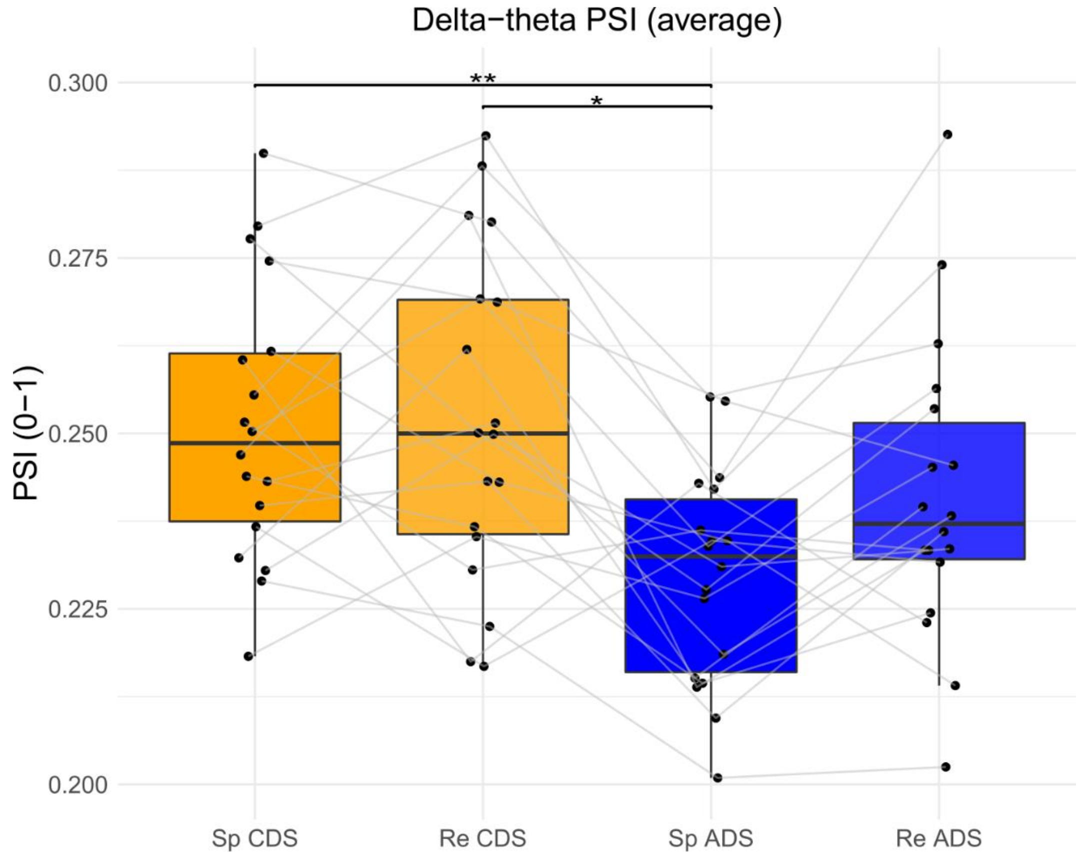

Figure 3.3. Mean delta-theta PSI. Gray lines connect participants' mean PSI across conditions. Horizontal lines within each box represent median PSI. Upper and lower hinges mark the first and third quartile, and whiskers show 1.5 * inter-quartile range. Bonferroni-corrected significant differences are represented with * ($p < .05$) and ** ($p < .01$).

3.3.3. Syllable rate

The LME model on syllable rate yielded significant effects of speech register, $F(1, 54) = 8.32$, $p = .006$, and condition, $F(1, 54) = 7.93$, $p = .007$, but no interaction between these factors ($p > 0.05$). These main effects are visible in Figure 3.4, which shows the higher syllable rate of ADS relative to CDS, $t(54) = 2.203$, $p = 0.032$ ($\beta = 0.262$, $SE = 0.119$, *CI* [0.025 0.499]), and of read speech relative to spontaneous speech, $t(54) = 2.155$, $p = 0.036$ ($\beta = 0.256$, $SE = 0.119$, *CI* [0.019 0.493]). Figure 3.4 also shows that there is much less variability in the speech rate of read speech, and interestingly, particularly of speech read to children (CDS). This suggests that readers spontaneously adapt their speech when reading to children to make it highly predictable. It should be noted that the method we used to calculate syllable rate yields slightly smaller values than manual annotation or other typically used calculations. Accordingly, we multiplied our syllable rate values by 1.28 as stated in the method's manuscript (de Jong & Wempe, 2009). This confirmed an overlap with the peak of the modulation spectrum in the theta band for each register and condition (Figure 3.2).

Next, we analyzed the relationship between syllable rate and the temporal regularity of the utterances. The negative correlations between syllable rate and delta-theta PSI were significant (Figure 3.5). This shows that the slower paced utterances were the most temporally organized utterances in our dataset.

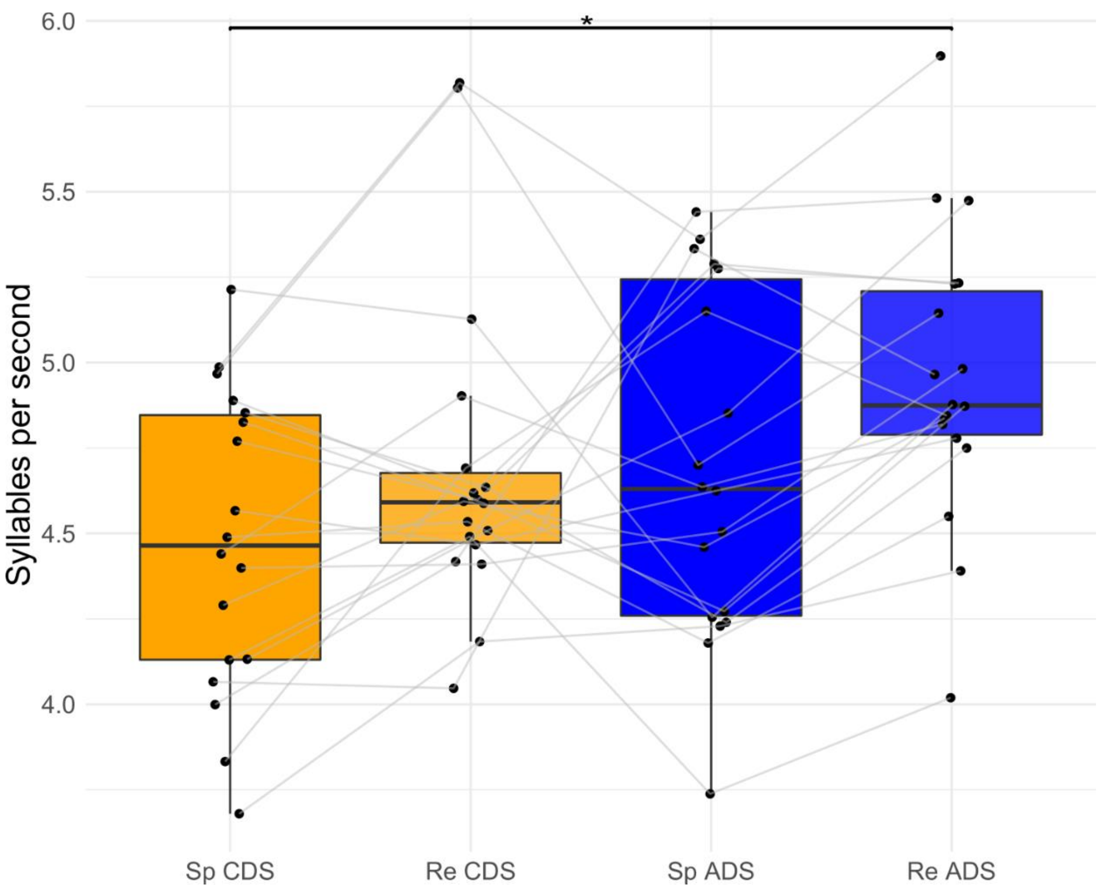

Figure 3.4. Syllable rate across speaking conditions. Gray lines connect participants' mean syllable rates across conditions. Horizontal lines within each box represent median syllable rate. Upper and lower hinges mark the first and third quartile, and whiskers show 1.5 * inter-quartile range. Bonferroni-corrected significant differences are represented with * ($p < .05$).

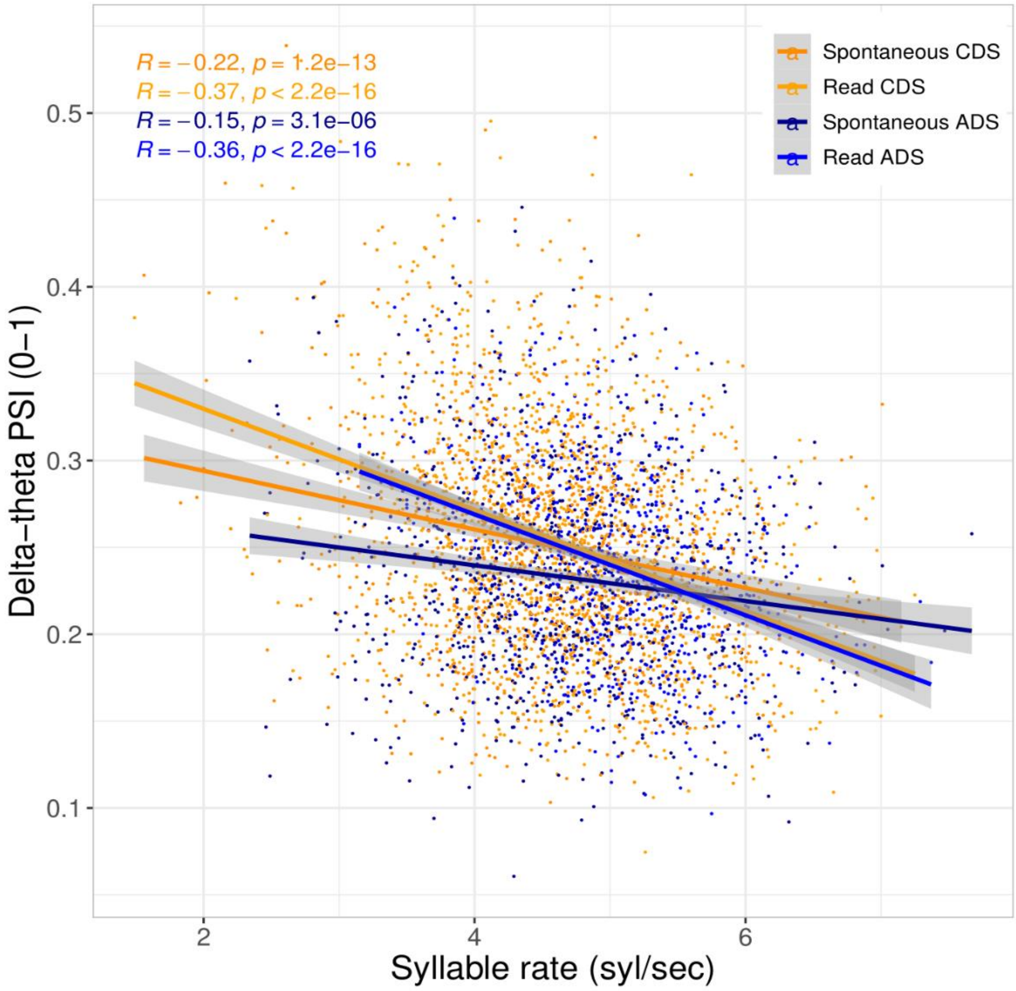

Figure 3.5. Correlation between syllable rate and delta-theta PSI. The four lines indicate the slopes of fitted linear models for each speaking condition. Top left: Pearson correlation coefficients and p-values for each speaking condition.

3.4. Discussion

In the present study, we investigated both spontaneous and read CDS and ADS in Spanish with the objective of contrasting them in terms of temporal regularities. Our within-participant design allowed us to investigate whether adults flexibly adapt their spontaneous speech productions to boost speech temporal regularities when addressing 4-year-old children rather than other adults. Using three temporal metrics, we found that CDS in Spanish carries more regular temporal statistics than ADS. First, CDS has significantly more modulation energy in the delta band than ADS, whether it is spoken spontaneously or whether the adult is reading to the child. Second, CDS contains more regularly stressed syllables than ADS, as shown by the greater phase alignment of the delta-rate and theta-rate AM bands in the CDS registers. Third, CDS shows a slower syllable rate relative to ADS. Adults slow down when speaking to children, as might be expected when addressing language-learning individuals. Additionally, read CDS also showed a notably narrower range than the other registers regarding syllable rate, suggesting that when reading to young children, temporal information becomes highly predictable. This may help to explain why early story reading is such an important contributor to language development (Attig & Weinert, 2020).

The amplitude modulation spectrum of CDS suggested that it has significantly more modulation energy in the delta band than ADS (Figure 3.2). This is in line with prior IDS data in English (Leong et al., 2017), classically considered a stress-timed language. The fact that we also found enhanced prosodic salience in CDS in Spanish, typically termed a syllable-timed language, is consistent with the idea that IDS and CDS boost relatively slow suprasegmental information to aid the mapping of phonological units by language-learning individuals (Fernald, 2000). Neurophysiological studies (including Study 2) show that infants and children rely on suprasegmental/prosodic than syllabic information for tracking and segmenting continuous speech (Attaheri et al., 2022; Ríos-López et al., 2020), which may help to explain the enhanced delta band modulation energy in Spanish CDS. Despite this enhancement of delta-band modulations, and as expected, the modulation spectrum for this syllable-timed language peaked in the theta band for both Spanish CDS and ADS, as has previously been reported across languages for ADS (e.g., Ding, Patel, et al., 2017; Greenberg et al., 2003). However, ADS showed significantly more modulation energy in the theta band compared to CDS. This might indicate that the temporal regularities of ADS are more systematic at the syllabic timescale, coherent with the evidence of syllables being a fundamental temporal landmark for adult neurocognitive speech processing abilities (Doelling et al., 2014; Ghitza, 2012).

Our findings of higher delta-theta PSIs in CDS suggest that its stressed syllables are temporally more regularly placed than in ADS. Indeed, prior speech modelling work has shown that delta-theta AM phase relationships underpin speech rhythm perception (Leong et al., 2014), with AM peak synchronization helping to determine the perceived metrical patterning of utterances such as trochaic versus iambic. Given the syllable-timed nature of Spanish, the greater predictability of stressed syllables may help the phonological mapping of Spanish by language-learning individuals. Our data thus contribute to the current evidence on continuous speech rhythmicity, by showing that, at utterance level, CDS is more rhythmic than ADS. These findings are also in line with previous adult studies that have contextualized the temporal regularities of speech within local (utterance level) stress patterns (Arvaniti, 2009; Nolan & Jeon, 2014; Tilsen & Arvaniti, 2013). Indeed, there is recent evidence for local prosodic stress regularities in ADS in different languages (e.g., Inbar et al., 2020; Stehwien & Meyer, 2021). The slower syllable rate in CDS relative to ADS is also of relevance when comparing temporal statistics. In summary, CDS appears to offer a continuous speech stream that is easier to segment via slower speech rate (fewer syllables per second), greater rhythmicity (predictability of occurrence of stressed syllables), and the enhancement of delta-band speech information (prosody-salient register). In line with this interpretation, previous evidence shows that while adult neurocognitive mechanisms adapt to different speech rates within the 4 – 7 Hz syllabic range (e.g., Foulke & Sticht, 1969; Ghitza, 2011; Lizarazu et al., 2019), children's comprehension abilities benefit from slower speech rates (Berry & Erickson, 1973; Haake et al., 2014; Montgomery, 2004; Riding & Vincent, 1980). The adapted temporal statistics in Spanish CDS demonstrated here could thus aid comprehension by children as well as facilitate the development of a phonological system. The enhanced local (utterance-level) temporal regularities of CDS, whether it is read or spoken, provide a set of temporal statistics that can be exploited by children's neurocognitive mechanisms for statistical (Romberg & Saffran, 2010) and distributional learning (see Banai & Ahissar, 2018 for a review). Sensitivity to these AM-related statistics would enable a child to build increasingly more robust phonological representations at word and syllable level. Indeed, the mapping of speech temporal statistics is known to be inefficient in individuals with phonological deficits such as dyslexia (Ahissar et al., 2006; Banai & Ahissar, 2018; Goswami, 2011; Leong & Goswami, 2017). Previous studies with adults have also shown prosodic (Inbar et al., 2020) and syllabic (Ding, Patel, et al., 2017) regularities across languages. However, our results highlight that greater temporal synchronization between delta-rate and theta-rate AMs may be a specific characteristic of CDS (in contrast to ADS). This finding is consistent with an 'acoustic-emergent' perspective regarding phonological development from infancy onwards (Leong & Goswami, 2015).

Regarding potential cross-language universality, it is notable that Leong et al., (2017) found the same enhanced delta-rate to theta-rate AM synchronization as found here in English IDS when compared to English ADS, hence in a stress-timed language. This may imply that there are certain key AM statistics that are universal concerning the temporal regularities present in the amplitude envelope of speech directed to young learners. As these two languages are typically grouped into two different rhythmic categories (i.e., English, stress-timed; and Spanish, syllable-timed), the current findings may point in principle towards an enhanced rhythmic organization of speech when addressing language learners, regardless of the rhythmic timing of a specific language. We propose that, at the very early stages of language development, infants are presented with speech inputs that contain higher pitch (Fernald, 2000), enhanced delta-band modulation energy and prominent rhythm (delta-theta AM phase synchronization), the latter providing temporal landmarks to begin the task of speech segmentation in the form of identifying and predicting the placement of stressed syllables (Leong et al., 2017; Cutler & Norris, 1988). Thus, infants can rely on salient spectro-temporal information that is boosted in IDS to orient their attention to acoustic cues relevant to extracting phonological information. As lexical knowledge develops and children progress in their word segmentation skills, the temporal regularity in CDS is exploited to parse the stress patterns characterizing whole-word phonological forms. This may be of particular relevance in languages that, like Spanish, have a greater proportion of multi-syllabic words than English. Once an efficient language processing system has developed, ADS can then contain less regular temporal statistics, as such regular statistics are not required to aid segmentation. Indeed, adults can adapt their linguistic processing via the over-learned temporal predictions of proficient language models (e.g., Molinaro et al., 2021; Ten Oever & Martin, 2020).

However, to test this cross-language developmental hypothesis, additional cross-linguistic evidence in languages belonging to other rhythmic categories (e.g., the mora-timed rhythms of Japanese), as well as in languages in which lexical stress is completely predictable (e.g., French), or has different degrees of predictability (e.g., Basque). Such studies could help to further our understanding of the possible enhancement of delta-theta phase synchronization in CDS and its potential role in phonological development. In addition to cross-linguistic evidence, cross-cultural investigations are needed to contextualize these findings regarding the temporal regularities of child-adapted speech, as there are also cultural and socioeconomic factors that shape the quantity and quality of IDS and CDS (Cristia et al., 2019; Schick et al., 2022; see Cristia, 2022 for a systematic review). Although there is evidence for the maturation of the cortical tracking of delta-rate versus theta-rate AMs in infants (Attaheri et al., 2021) and children (Ríos-López et al., 2020), as well as about the potential role that it has for phonological development and reading acquisition (Ríos-López et al., 2021), further studies are needed to fill the gap regarding the emergence of cortical tracking of syllables from infancy and during childhood, and how this may be aided by the temporal regularities of IDS and CDS.

In closing, our data are also relevant to evaluating the temporal sampling hypothesis of developmental dyslexia, which suggests that there is a specific link between delta- and theta-rate AM sensitivity and phonological development during the first years of life across languages (Goswami, 2011; Goswami et al., 2016; Goswami, Wang, et al., 2010; Vanvooren et al., 2017). Longitudinal neurophysiological evidence in Spanish shows that cortical tracking of speech in children relies mainly on prosodic (delta band) acoustic information (Ríos-López et al., 2020, 2021), and a similar pattern is found longitudinally for infants in English (Attaheri et al., 2022). Indeed, a recent study by Menn et al. (2022) in Dutch found that the cortical tracking of the delta AM rate in infants predicted their later vocabulary knowledge. Our findings are consistent with such evidence, showing that enhanced temporal regularities within the delta frequency band (0.5-2.5 Hz, the timescale of stressed syllables) occur more reliably in CDS (as previously shown in English IDS, Leong et al., 2017) than in ADS. Moreover, our results are broadly in line with the Temporal Sampling hypothesis from the perspective of the importance of temporal AM statistics <10 Hz for phonological development. Future studies that directly compare IDS, CDS and ADS could help to delineate the developmental sequence of the temporal regularities that an emerging phonological system needs to map in order to aid comprehension and language learning.

General discussion

In this section, we will revisit our main research goals and hypotheses in light of the evidence gathered from the three studies. We will discuss how the results of each study relate to one another and integrate them within an overarching framework of language development during childhood. More specifically, the aim of this section is to propose a joint empirical account of the role of the quantity and quality of linguistic exposure on language development from different methodological perspectives and levels of linguistic analysis. With this discussion, we hope to help outline an account of how input-level characteristics (i.e., quality and quantity) can influence the development of phonological, lexico-semantic, and syntactic abilities at the behavioral and neurocognitive levels.

One of our main predictions was that the amount of linguistic exposure (AoE) would have a stronger impact on the development of non-phonological (i.e., lexico-semantic and syntactic) than phonological abilities, given that the former needs a direct experience with specific linguistic instances (i.e., words and sentences) in order to develop, while the latter relies to a larger extent on exposure-independent neurocognitive abilities for sound processing (Bishop, 2002; Kovas et al., 2005). Accordingly, Study 1 showed that AoE had a greater impact on the performance in lexical and syntactic abilities than on phonological abilities, and that in fact the rate of longitudinal growth of lexical and syntactic abilities was directly mediated by AoE, which was not the case for phonological abilities. Given that we operationalized AoE as a continuous measure comparable in each language, we were able to assess the role played by a wide range of inputs on the development of language abilities in both languages concurrently. While the direct impact of bilingual exposure on lexical and syntactic knowledge was established by previous bilingual studies (e.g., Carbajal & Peperkamp, 2020; Gámez et al., 2019; Paradis & Jia, 2016; Pearson et al., 1997; Thordardottir, 2011; Thordardottir et al., 2006), our results add up to such evidence by offering an estimate of the role of AoE to two languages simultaneously on the growth of phonological, lexical, and syntactic abilities between 4 and 6 years of age. Two important additional findings from Studies 1 and 2 contribute to advancing our understanding of the role of AoE for language development.

First, we found that knowledge in the lexical, phonological and syntactic domains improved longitudinally and steadily in both the languages of bilingual children (Figure 1.1). Thus, despite between-languages variations in AoE, children kept accumulating and improving their knowledge in both languages. Because of this constant accumulation of knowledge, performance in the less dominant language caught up eventually (by age 6), in particular on language skills engaging receptive abilities (i.e., word comprehension and sentence repetition) but not for productive abilities (i.e., picture naming). Our findings thus help inform the question: "*When do bilingual children with a limited amount of exposure to a language catch up with their monolingual peers?*" Our results suggest that, at least for the developmental period of Study 1 (i.e., 4 to 6 years old), the answer to this question will depend on both the linguistic domain (non-phonological versus phonological domains) and the language process (receptive versus productive) assessed. In fact, lexical and syntactic abilities were more impacted by the input than phonological skills, and receptive abilities in the less dominant language seemed to reach similar levels to the more dominant language faster than productive abilities. It could be the case that the impact of AoE on phonological abilities took place earlier in development, and thus it is not observable in the study. This is suggested by the fact that Basque and Spanish have largely overlapping phonologies (Ezeizabarrena & García, 2015); and thus, if AoE impacted their learning, it is likely that by the time of Study 1 such accumulated phonological learning from AoE would have been equated between languages. Nonetheless, it is important to acknowledge that our longitudinal study might have overlooked some interaction effects of AoE with potentially important other factors, such as task difficulty, age of language acquisition, or the amount of overlap between specific language pairs (Paradis & Jia, 2016), that future studies should try to quantify.

Interestingly, the steady longitudinal growth observed for lexical and syntactic knowledge across the languages of bilinguals was not replicated when the spontaneous use of language at the lexical and syntactic levels was considered. In this case, the longitudinal growth in the lexical diversity and syntactic complexity of the utterances produced spontaneously by children were observed in the more dominant language almost only. Namely, there were several longitudinal steps in which the use of lexically diverse and syntactically complex utterances increased in Basque (MLU between stages 1 and 2, and MLU, clausal density and lexical diversity between stages 2 and 3), as compared to only one instance of growth in Spanish (MLU between stages 2 and 3). Therefore, the growth in the spontaneous use of lexical and syntactic knowledge may be dependent on accumulated knowledge in the corresponding domains, and therefore start only after reaching certain levels of proficiency. It could also be possible that parents talked to their children more frequently in their dominant language, in response to their children's higher proficiency and use of this language. Such increase in the diversity of the lexical items and the complexity of the utterances in children's input has been repeatedly linked to lexical and syntactic development above and beyond the mere repeated exposure to a language (Furrow et al., 1979; Hoff-Ginsberg, 1986; Huttenlocher et al., 2002, 2010).

Second, another set of findings supports the role of AoE on language development showing that phonological and non-phonological abilities different rely on exposure in order to develop. Overall, we could not highlight any direct influence of AoE on phonological abilities (phonological short-term memory) in any of the languages of the bilinguals, although we did report a language effect on performance: throughout the longitudinal assessment, children repeated nonwords that contained lexical stress and syllabic phonotactic characteristics of Basque, their dominant language, compared to Spanish. These findings point at an indirect effect of AoE (i.e., mediated by language dominance) on the development of word-level phonotactics (Messer et al., 2010; Munson, 2001; Vitevitch & Luce, 2005). Such indirect effect might possibly be mediated by enhanced lexical knowledge in the dominant language, which we showed was itself directly influenced by AoE. Interestingly, the language effect on phonological abilities was not found in Study 2 (unlike productive vocabulary and reading proficiency), when the children were around 7 years of age, and had a highly unbalanced profile in terms of AoE to their languages. The lack of language differences on phonological performance might reflect the gap between languages closing at this developmental stage (see *Phonology* in Supplementary Figure 2.3). Importantly, at this stage, children were also starting to acquire reading skills, which we know exerts an influence on phonological development (Castles and Coltheart, 2004). Thus, acquiring reading may have triggered a boost in the development of the phonological skills of the children of Study 2. In support of this hypothesis, CTS at the envelope level, that is thought to strongly relate to phonological abilities (see also Di Liberto et al., 2018), was not significantly different between Basque and Spanish. Therefore, there is the possibility that, around 6-7 years of age, phonological abilities in bilinguals are similarly developed in both languages, with the less dominant language reaching native-like levels despite considerably limited input. These findings inform on how an L2 might develop, given the relevance of phonological abilities for extracting linguistic information from the speech signal at relatively earlier stages of language learning (S. E. Gathercole, 2006). Given the attested bootstrapping of phonological abilities to develop broader language abilities during childhood (Anthony et al., 2003; Carroll et al., 2003; Kehoe et al., 2020; Vaahtoranta et al., 2020), native-like developed phonological skills could support the growth of L2 abilities that are not yet at the same stage as in L1 (e.g., lexical and syntactic abilities in Study 1, and lexical and reading abilities in Study 2).

Unlike phonological skills, lexical (receptive vocabulary) and syntactic (sentence repetition) receptive abilities greatly relied on quantitative characteristics of the speech input. This was especially noticeable in the less dominant language of bilinguals (Spanish) for which children improved these abilities at a faster rate than in Basque. By the end of Study 1 (6 years old), children's performance in receptive vocabulary was similar in both languages, and for sentence repetition, performance was even higher in Spanish than Basque. As mentioned above, the development of receptive abilities may be highly sensitive to any presented linguistic inputs to help bootstrapping the development of other language abilities when AoE is very limited. Findings from Study 2 support this view. We included children who were very unbalanced bilinguals in terms of AoE (more dominant in Basque than Spanish) and productive vocabulary (higher in Basque than in Spanish). Yet, the neurocognitive abilities that we know support speech comprehension, and indexed by CTS metrics, were highly similar across the two languages. Like language receptive abilities, CTS in bilingual learners might support language acquisition when the input is limited by acting as an "input-hungry" continuous speech tracking device operating independently of language dominance and proficiency.

Indeed, our hypothesis that larger language exposure and knowledge would result in more efficient neural tracking at the envelope and linguistic levels was not supported by our findings, at least when measured at this stage of development. This could be the result of an interplay between exposure and brain maturational factors in bilinguals. Linguistic exposure in the context of bilingual language acquisition seems to leverage on neuroplasticity to extend the critical periods in which languages are learnt at native-like levels (Werker & Hensch, 2015; Xue et al., 2021). In the case of Study 2, as children had started acquiring both of their languages from early in life, there is the possibility that they were still within a sensitive period for developing their neurocognitive abilities for language comprehension in both of their languages with native proficiency (as it is the typical bilingual learning profile in the Basque Country). Coherent with this interpretation, rather than AoE, the age of acquisition of a language (< 3 y.o. for both languages) might act as a pervasive determinant of the structural and functional effects of bilingualism on the neuroplasticity of language-related brain areas (Berken, Chai, et al., 2016; Berken, Gracco, et al., 2016; Claussenius-Kalman et al., 2020; Gullifer et al., 2018; Klein et al., 2014; see Claussenius-Kalman et al., 2020 for an overview of significant and null effects of age of acquisition on brain structure).

Although AoE did not modulate the efficiency of the cortical tracking of the distributional properties of acoustic and linguistic speech features, we showed that individual variations in language performance were specifically tied to the neural tracking of the corresponding speech features in continuous speech: in other words, phonological abilities were positively related to the tracking of amplitude modulation changes in the speech signal (envelope tracking), and lexical abilities were associated to the cortical tracking of (lexical and syntactic) linguistic information. The relationship between phonological abilities and the tracking of the speech envelope is broadly in line with the temporal sampling hypothesis (Goswami, 2011, 2017), that proposes a causal pathway between an efficient cortical tracking of the amplitude modulations of speech and phonological (as well as reading) development. While previous studies have shown that CTS is a relevant predictor of vocabulary during infancy (K. Menn, Ward, et al., 2022), we now show that CTS and phonological abilities are positively related at age 7, corresponding to the early stages of reading acquisition. This is coherent with a recent study showing that CTS in pre-readers predicted their reading abilities at 7 years of age, at the end of their first year of formal reading acquisition (Ríos-López et al., 2021). It is worth noting that such phonology-envelope CTS relationship was only present in Basque (L1), result that we did not predict. Further research is therefore needed to help elucidate the developmental range at which CTS is crucial for phonological and reading abilities.

In relation to the temporal sampling framework for phonological development, Study 3 showed that CDS was characterized by enhanced and more salient temporal distributional properties of speech, as opposed to ADS. In addition to conveying a relatively slower speech rate than ADS, we observed that CDS was characterized by enhanced temporal regularities at both the prosodic (modulations at the delta frequency range) and syllabic (theta frequency range) levels. Interestingly, Study 2 showed that the speech-brain at both delta and theta frequencies (as well as envelope-level mTRF) was positively related to phonological abilities. Altogether, these findings bring converging evidence for the role of slow speech temporal timescales for the tracking of prosodic and syllabic information and the build-up of refined phonological representations. It is worth noting that syllabic tracking might play a more important role for phonological acquisition later in development as our 7-year-old participants only showed significant delta (and not theta) speech-brain coherence at the group level (see also Ríos-López et al., 2021). Importantly, Study 3 shows that adults adapt the temporal distributional statistics of their speech utterances when addressing language-learning individuals, to match the capacity of their developing neurocognitive processing system for speech. Ideally, future developmental research going beyond the age range of our study could help delineating whether CDS is less produced by adults as children become more proficient in their language(s).

Importantly, our results from Study 2 show that children with a reasonably high language expertise (7 years old) might extract meaning from speech through the tracking of temporal distributional properties of speech that go beyond purely acoustic features. In fact, Study 2 shows a robust relationship between the cortical tracking of "linguistic" (lexical and syntactic) distributional speech properties and vocabulary knowledge. Study 2 is to our knowledge the first evidence of the occurrence of such linguistic neural tracking in a child population. While many studies in infants and children (including Study 2) highlight the relevance of envelope-level (acoustic) CTS for developing phonological and broader language abilities (e.g., vocabulary, reading; e.g., Attaheri et al., 2022; K. Menn, Ward, et al., 2022; Ríos-López et al., 2020, 2021), only adult studies had highlighted so far that CTS goes beyond tracking the pure acoustics of the signal (Broderick et al., 2021; Klimovich-Gray et al., 2021; Meyer et al., 2017; Molinaro et al., 2021). The "cost-minimization" argument proposes that once individuals reach enough language knowledge, their proficient neurocognitive language models do not need to actively extract linguistic information from the speech signal by relying on phonological abilities. Instead, proficient language users can exploit their language knowledge to predict upcoming information based on their lexico-semantic and syntactic knowledge (Martin & Doumas, 2017; ten Oever & Martin, 2021). This observation could be the first documentation hinting at a developmental shift affecting CTS: from the tracking of purely acoustic information to match the requirements of an immature language system, to the tracking of higher order linguistic information when the system has reached sufficient language knowledge. Nonetheless, such developmental shift might start much earlier than around 7 y.o. (i.e., when children can comprehend the vast majority of the words in the speech they are exposed to, around 3-4 years of age), which is an interesting question to be addressed by future developmental research.

Limitations

Several limitations of this doctoral work have to be raised. The first one is related to sample size. Our studies could be seen as "medium sample size" (N = 74, 35, and 18 for Study 1, 2, and 3 respectively). These sample sizes were constrained by methodological and feasibility factors, as Study 1 was longitudinal and included speech corpora analyses, in Study 2 combined EEG and behavioral assessments, and Study included speech manual transcriptions and analyses. Future studies could rely on more broadly automatized protocols for assessing language performance in spontaneous productions (e.g., automatic transcriptions, natural language processing tools for language detection and analysis). This will enable researchers to include larger samples for a more robust estimation and analyses of developmental data, which is prone to be influenced by numerous sources of heterogeneity. Another limitation to the generalizability of our findings is the fact that we did not include standardized nor composite scores for several of the language measures (e.g., phonological abilities), which limits the robustness with which they are estimated. This issue arises from including a wide set of measures in both languages, which limits the use of a common standardized battery as well as of several measures of the different domains to create composite scores. Nevertheless, future research could focus on specific relationships revealed by this thesis and test the reliability of our findings with more robust estimates. Another limitation is the fact that we did not include a control condition in Study 2, which could consist in testing the cortical tracking of an unknown language or of amplitude-modulated noise in order to contrast the impact of intelligibility (or lack thereof) on CTS. Another specific limitation of Study 3 is the fact that we tested the spontaneous productions of participants when addressing their children (CDS) and unknown adults (ADS). Such difference in familiarity with the addressees might have contributed to a more engaging CDS (in contrast to ADS) and possibly boost the CDS-ADS differences.

Conclusion

The overarching question of the present thesis was whether the quantity and quality of linguistic input play a relevant role in language development during childhood. We showed that the development of specific non-phonological language domains, such as lexico-semantics and syntax, are directly impacted by the amount of linguistic exposure. On the opposite, phonological abilities as well as the cortical tracking of speech were not shown to depend on AoE. Importantly, we demonstrate that, when assessing exposure factors modulating language growth, the study of language dominance and proficiency is complementary to the investigation of more direct continuous measures of percentage of AoE.

With respect to the quality of linguistic exposure, we showed that, when talking to their children, adults adapt their speech register to boost speech temporal regularities, as a potential strategy to meet the neurocognitive requirements of the immature language processing system of young learners.

In closing, we trust that the evidence gathered from the present doctoral work can be useful for future theoretical proposals that take into consideration the multilevel structure (i.e., neurocognitive, behavioral, contextual) of language development. We hope that our findings can inform teaching and clinical practices for children growing in bilingual environments, by highlighting specific environmental factors that, like the amount of linguistic exposure, shape language knowledge and proficiency to a great extent and should be taken into account when assessing typical and atypical language development.

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CRediT authorship contribution statement

Study 1

Jose Pérez-Navarro: Conceptualization, Formal Analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Marie Lallier:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision.

Study 2

Jose Pérez-Navarro: Conceptualization, Methodology, Formal analysis, Writing – Original draft, Writing – Review & Editing Investigation, Data curation, Visualization, Funding acquisition; **Nicola Molinaro**: Conceptualization, Writing – Review & Editing, Supervision; **Giorgio Piazza**: Data collection, Data curation; **Anastasia Klimovich-Gray**: Methodology, Formal analysis, Writing – Review & Editing, Data Curation, Resources, Visualization; **Mikel Lizarazu**: Methodology, Formal analysis, Writing – Review & Editing, Data Curation, Resources, Visualization; **Marie Lallier**: Conceptualization, Writing – Original draft, Writing – Review & Editing, Supervision.

Study 3

Jose Pérez-Navarro: Conceptualization, Formal Analysis, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing. **Marie Lallier:** Conceptualization, Writing – original draft, Writing – review & editing. **Catherine Clark:** Investigation. **Sheila Flanagan:** Formal Analysis, Methodology, Software, Visualization, Writing – review & editing. **Usha Goswami:** Conceptualization, Writing – original draft, Writing – review & editing.

Data availability

The code used for preprocessing, analysis and visualization in the different projects is available at their respective Open Science Framework (OSF) repositories: Study 1, Study 2, and Study 3. Only the data for Study 3 is available currently given that the other two studies are pending submission to a scientific journal.

Supplemental materials

Study 1

Supplemental Formula 1.1. Formula and rationale of the AoE to a language composite index (*AoE_L*). The *$CurrentHomeAoE_L$* and *$CurrentSchoolAoE_L$* values are themselves composite indexes (*SF2* and *SF3* respectively):

$$AoE_L = \frac{(Age - AgeofAcquisition_L) \times BirthToAgeAoE_L + \left((CurrentHomeAoE_L \times .75) + (CurrentSchoolAoE_L \times .25)\right)}{2}$$

The rationale behind the multipliers of the different indexes that build the composite measure is weighing the contexts in which participants are exposed to a given language by the relative number of waking hours that they represent in an everyday life situation. We took into consideration the relative amount of waking hours that children spend at home (~3147 h; 75% of the total of waking hours) and at school (~1050 h; 25% of waking hours), as well as the relative amount of school hours that children spend in classes (~875 h; 83%) and leisure time (~175 h; 17%) according to their schooling system (Official Gazette of the Basque Country, April 25th, 2008).

Supplemental Formula 1.2. Formula of the *$CurrentHomeAoE_L$* composite index:

$$CurrentHomeAoE_L = (Mother_L \times .5) + (Father_L \times .35) + (NuclearFamily_L \times .08) + (MaternalExtendedFamily_L \times .035) + (PaternalExtendedFamily_L \times .035)$$

In SF2, we took into consideration the proportion of waking hours that children spend in contact with the different members of their familial environment (Leaper et al., 1998; Pancsofar & Vernon-Feagans, 2006). In the case of one-parent families, we adapted the above formula to *$CurrentHomeAoE_L$**, which aggregates the input from both parents into a single value (*$Parent_L$*), as well as the ones from the maternal and paternal extended family (*$Extended\ Family_L$*), as follows:

$$CurrentHomeAoE_L * = (Parent_L \times .85) + (NuclearFamily_L \times .08) + (ExtendedFamily_L \times .07)$$

Supplemental Formula 1.3. Formula of the *$CurrentSchoolAoE_L$* composite index:

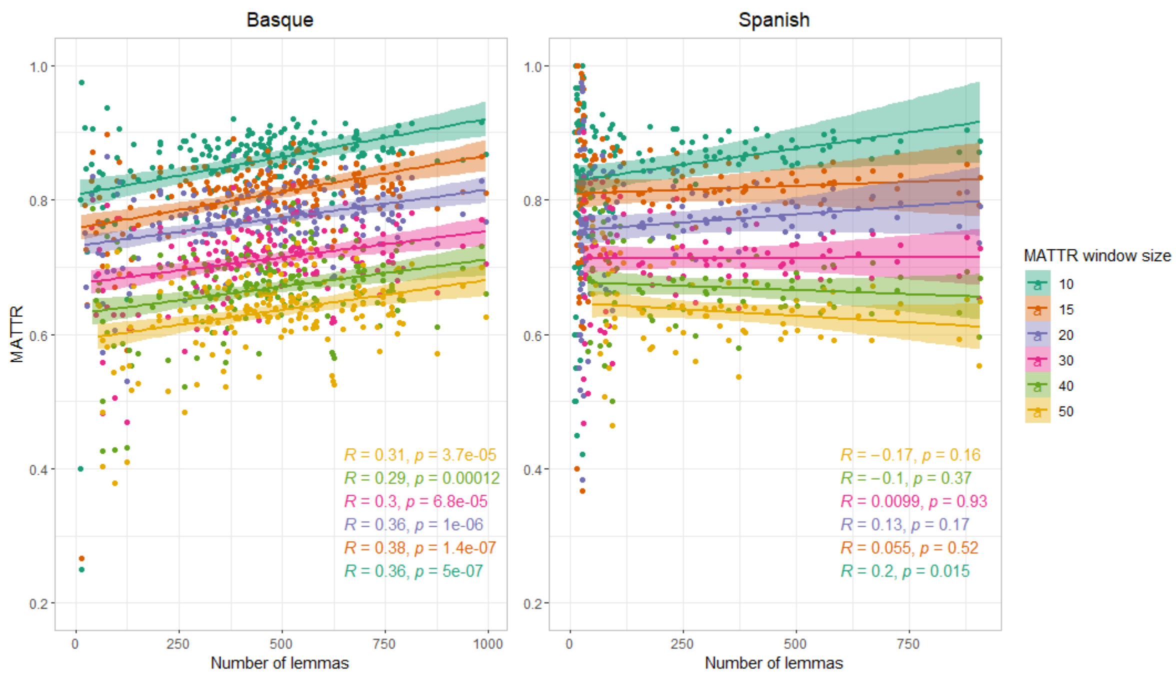
$$CurrentSchoolAoE_L = (SchoolLearningContent_L \times .83) + (SchoolLeisureTime_L \times .17)$$

Supplemental Formula 1.4. Zipf lexical frequency-weighted correctness for vocabulary tasks:

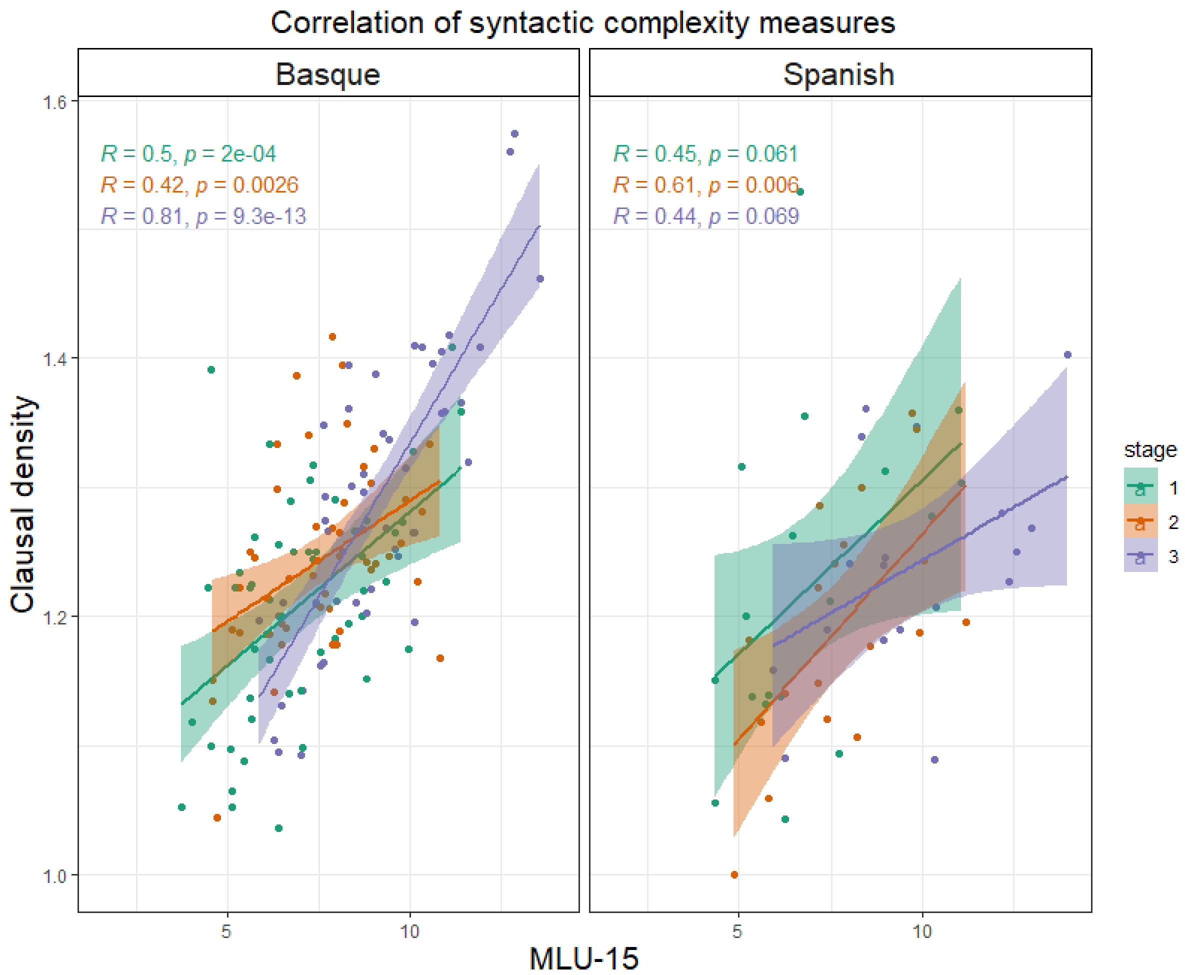
$$word\ correctness \times (1/(word\ Zipf\ frequency))$$

Supplemental Formula 1.5. Moving-average type-token ratio (MATTR) used for lexical diversity metrics. Such formula is applied to each period of 40 lemmas (the moving-average window):

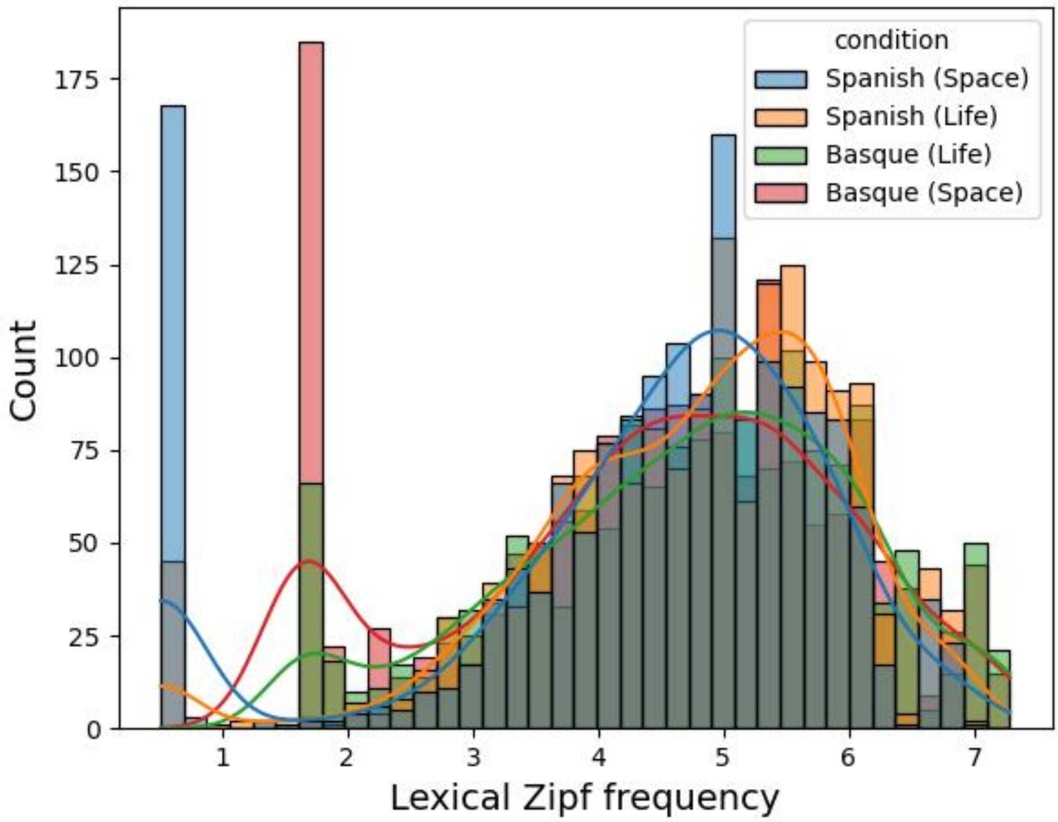
$$(L_1 + L_2 + \ldots + L_{40}) / 40$$



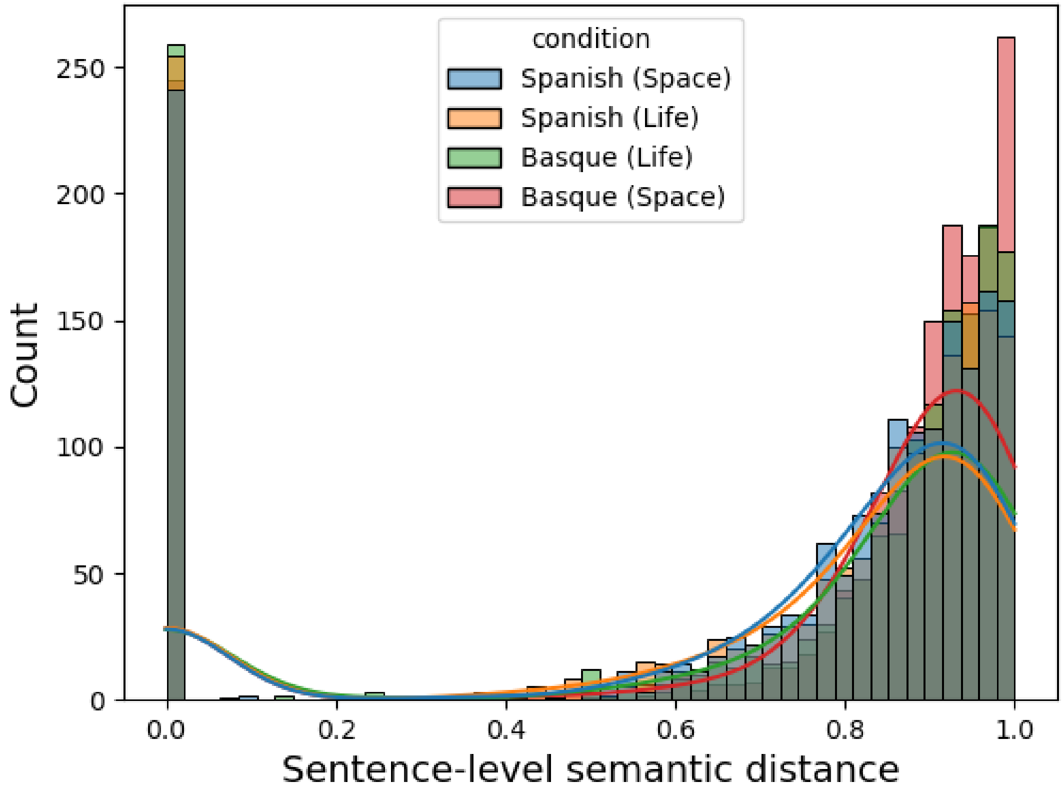
Supplemental Figure 1.1. MATTR as a function of the number of lemmas a participant produced in each language (left, Basque; right, Spanish). Each point is an individual MATTR value, with the lines and shadowed areas representing the fit of a linear model between number of lemmas and MATTR for the different window sizes (different colors). The estimates in the bottom right corner of each figure represent *Pearson's R* value and significance threshold (*p* < .05).



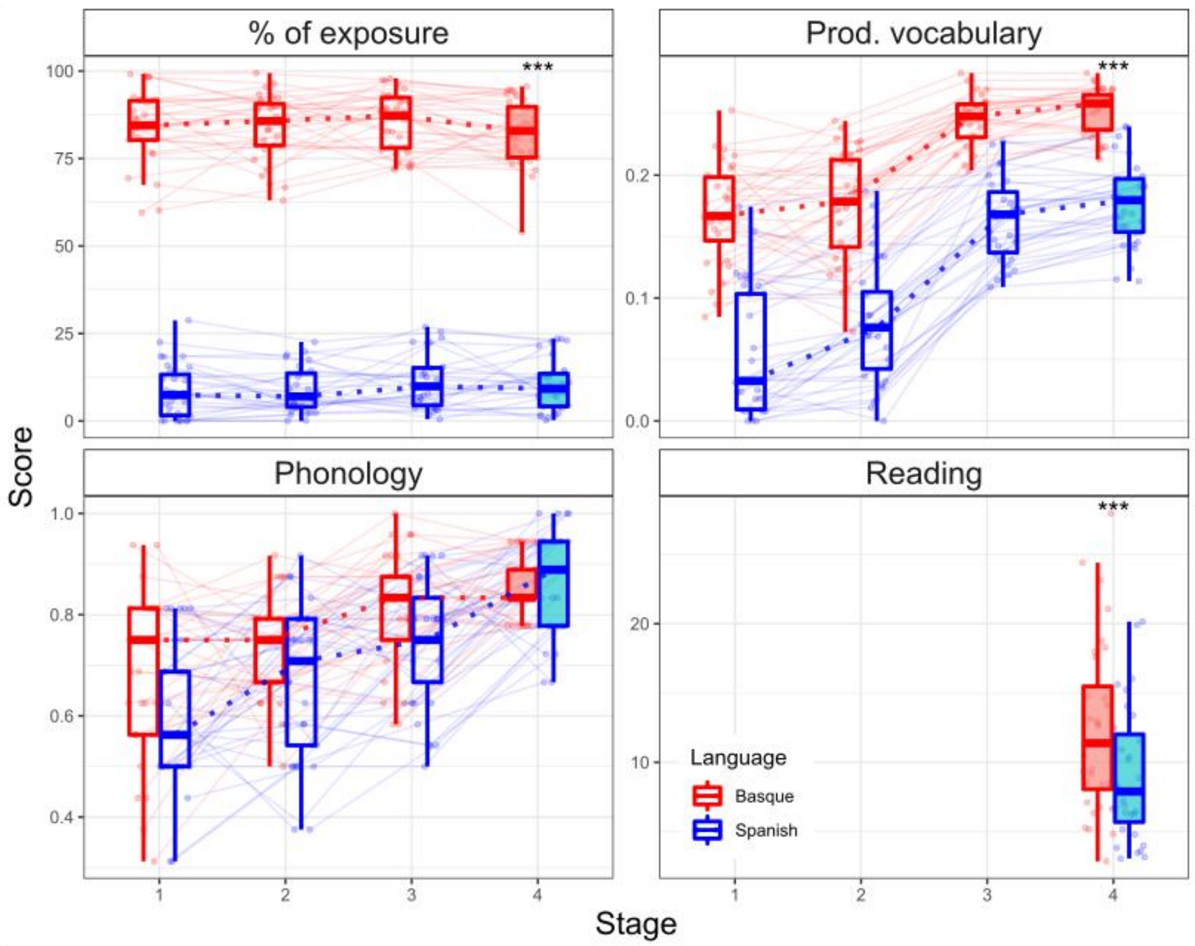
Supplemental Figure 1.2. Correlation between MLU-15 and clausal density. The estimates in the top left corner of each panel represent *Pearson's R* value and significance threshold ($p < .05$).



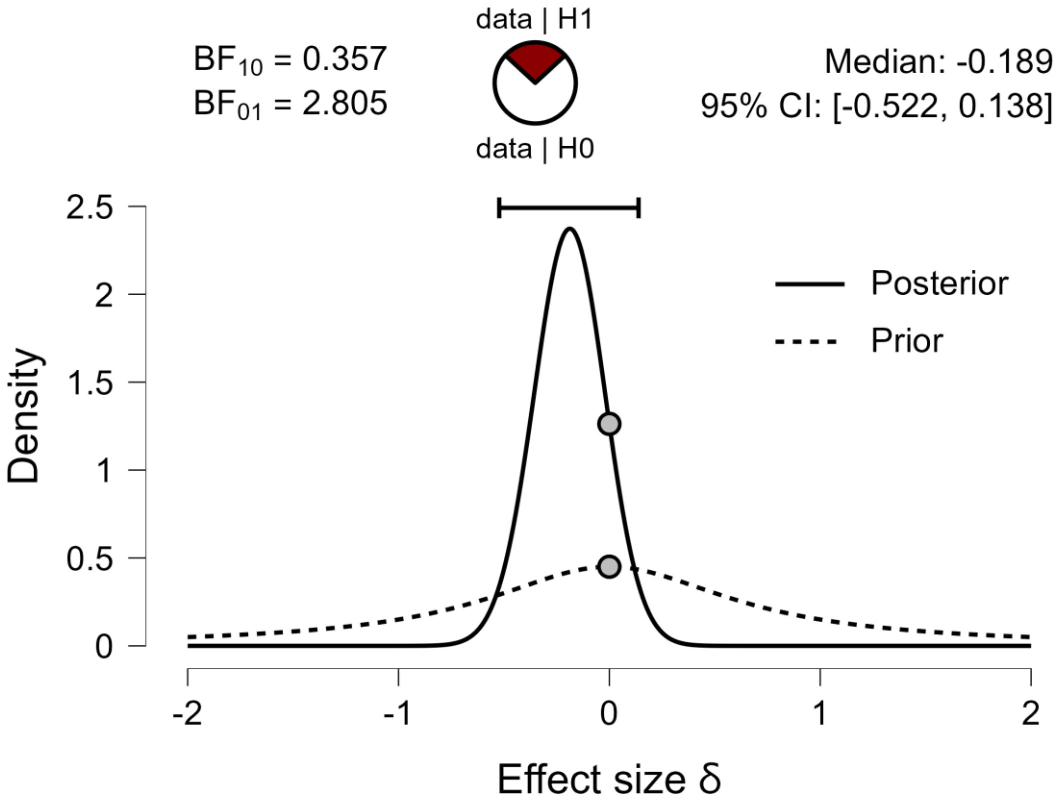
Supplemental Figure 2.1. Zipf frequency distributions of content words in Spanish (1st, blue; 2nd, yellow), and Basque (1st, green; 2nd, red) stories. Bars represent content word count per Zipf frequency bin and smooth lines mark its density distribution.



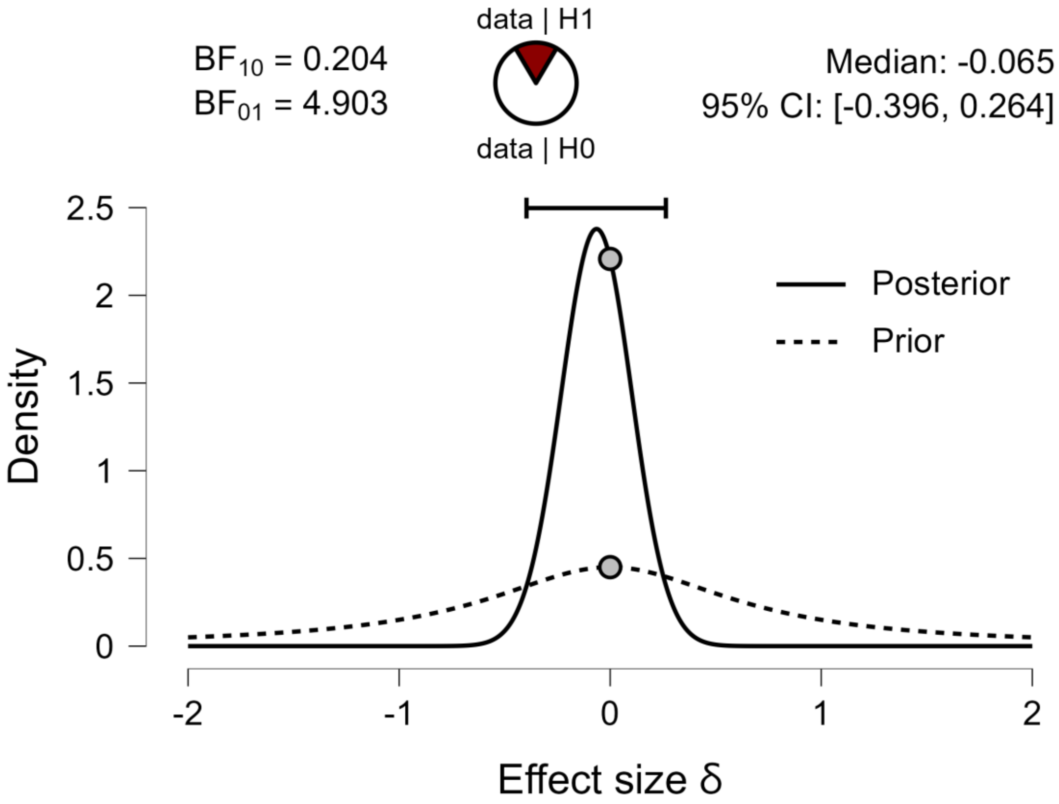
Supplemental Figure 2.2. Sentence-level semantic distance distributions of content words in Spanish (1st, blue; 2nd, yellow), and Basque (1st, green; 2nd, red) stories. Bars represent content word count per bin of sentence-level semantic distance and smooth lines mark its density distribution.



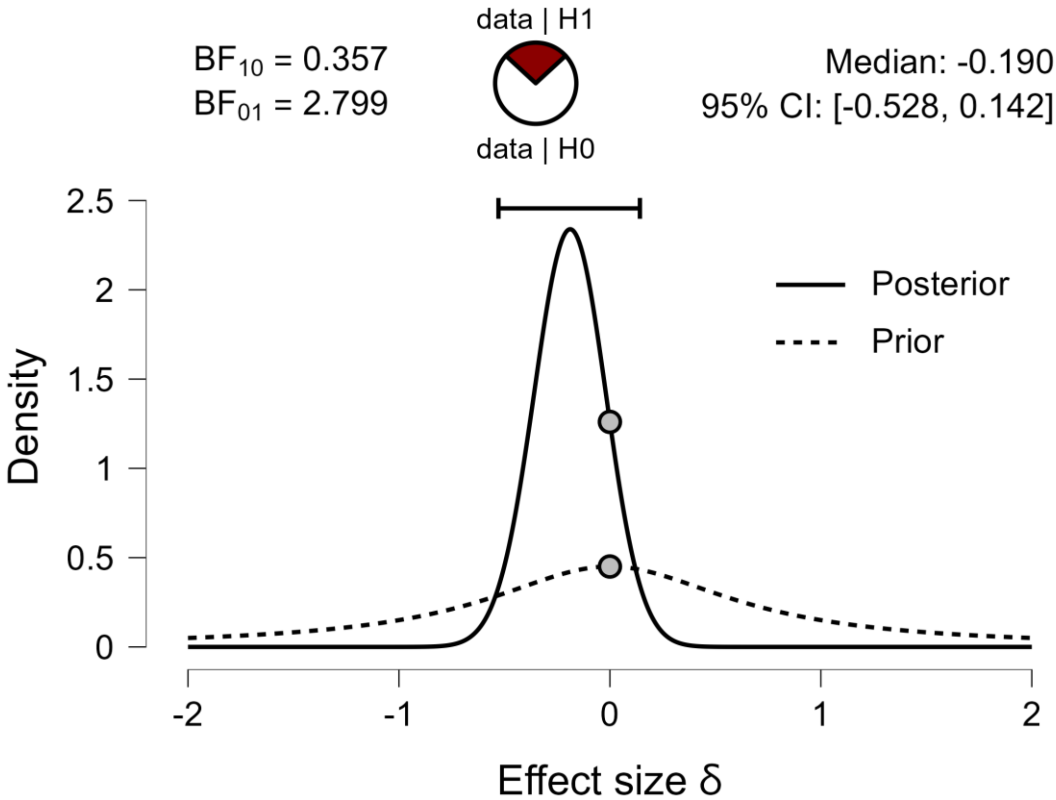
Supplemental Figure 2.3. Amount of exposure and behavioral performance in vocabulary, phonology, and reading as a function of testing stage. Empty boxplots mark the scores of participants of Study 2 in the three stages of Study 1; colored boxplots mark the "4th" follow-up EEG Study 2. Points represent each participant's score in the different measures, languages, and stages. Boxplots represent group estimates, with horizontal lines within each box marking the median score. Upper and lower hinges mark the first and third quartile, and whiskers show 1.5 * inter-quartile range. The connecting dotted lines represent the trend between adjacent stages.



Supplemental Figure 2.4. Prior and posterior probability of differences between Basque and Spanish speech envelope mTRFs. The density distributions represent the probability of difference (0 = lack of differences). The top pie chart shows the proportion of evidence for the alternative hypothesis (between-languages difference, dark red), and the null hypothesis (lack of between-languages difference, white) respectively.



Supplemental Figure 2.5. Prior and posterior probability of differences between Basque and Spanish lexical Zipf frequency mTRFs. The density distributions represent the probability of difference (0 = lack of differences). The top pie chart shows the proportion of evidence for the alternative hypothesis (between-languages difference, dark red), and the null hypothesis (lack of between-languages difference, white) respectively.

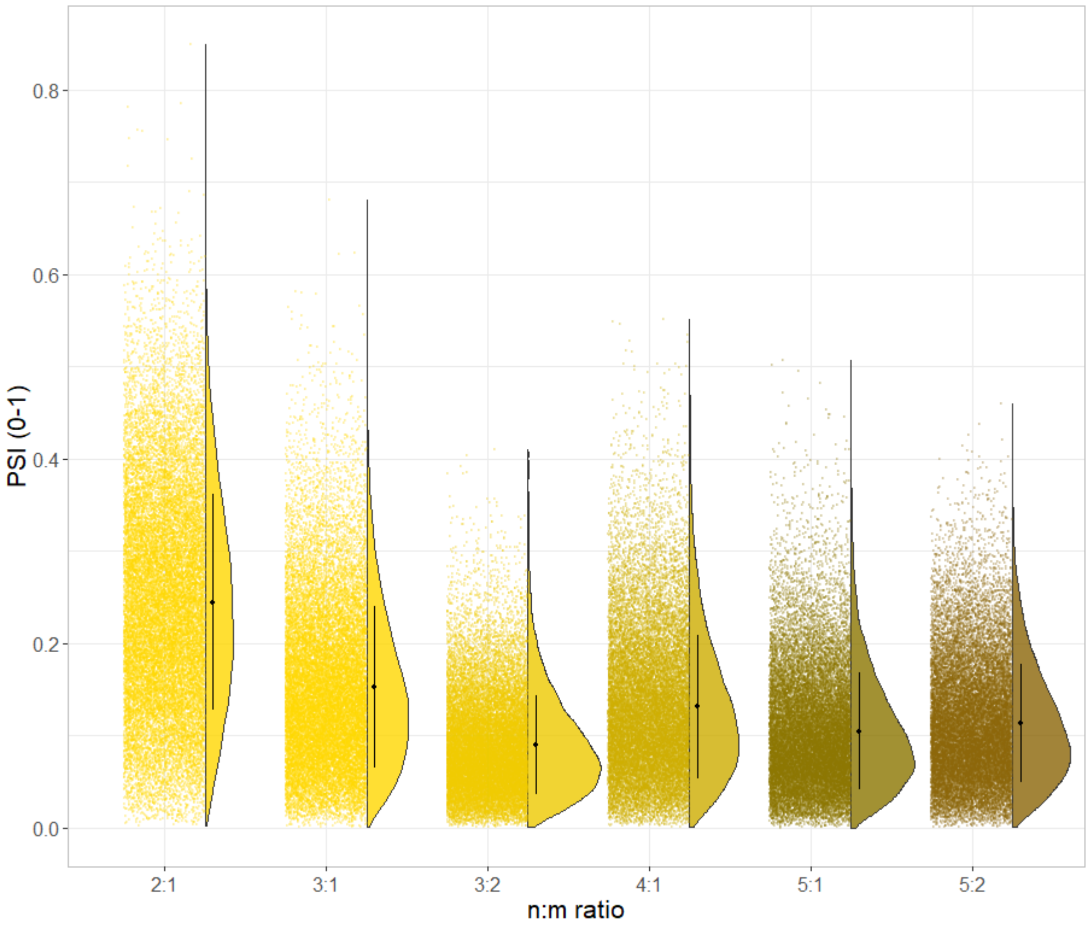


Supplemental Figure 2.6. Prior and posterior probability of differences between Basque and Spanish sentence-level semantic distance mTRFs. The density distributions represent the probability of difference (0 = lack of differences). The top pie chart shows the proportion of evidence for the alternative hypothesis (between-languages difference, dark red), and the null hypothesis (lack of between-languages difference, white) respectively.

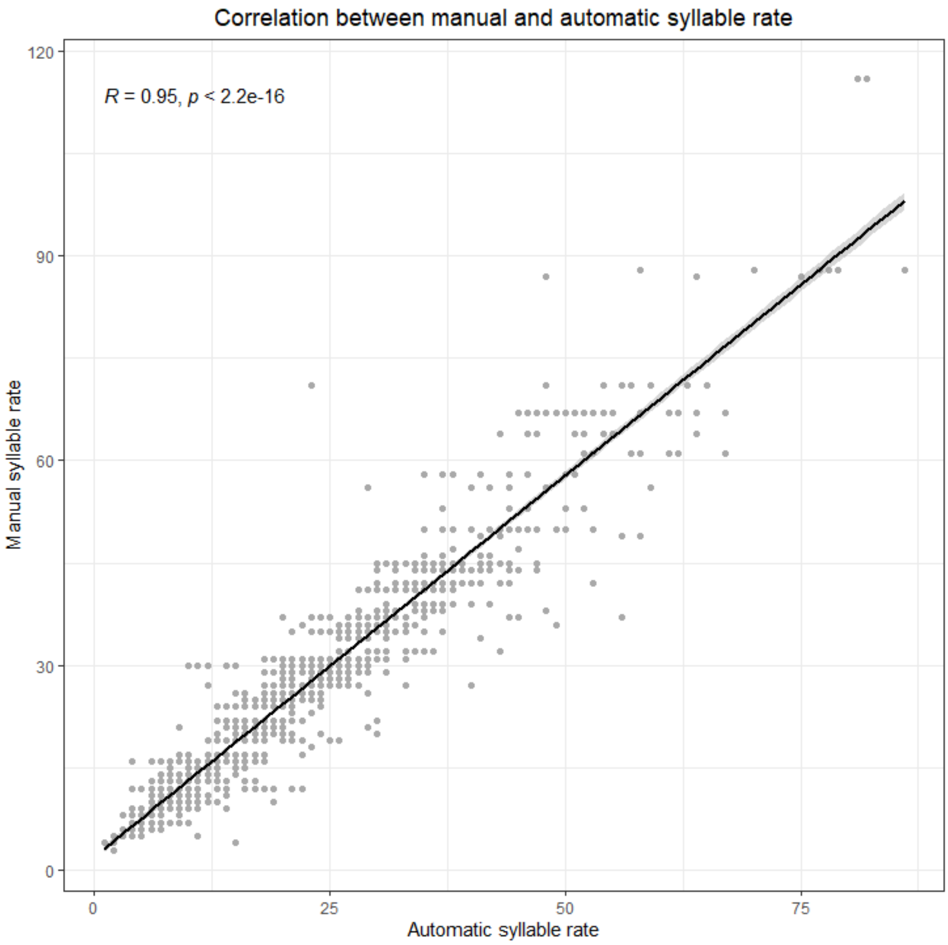
Study 3

$$\mathrm{PSI} = \left| \left\langle e^{1(n\theta_1 - m\theta_2)} \right\rangle \right|$$

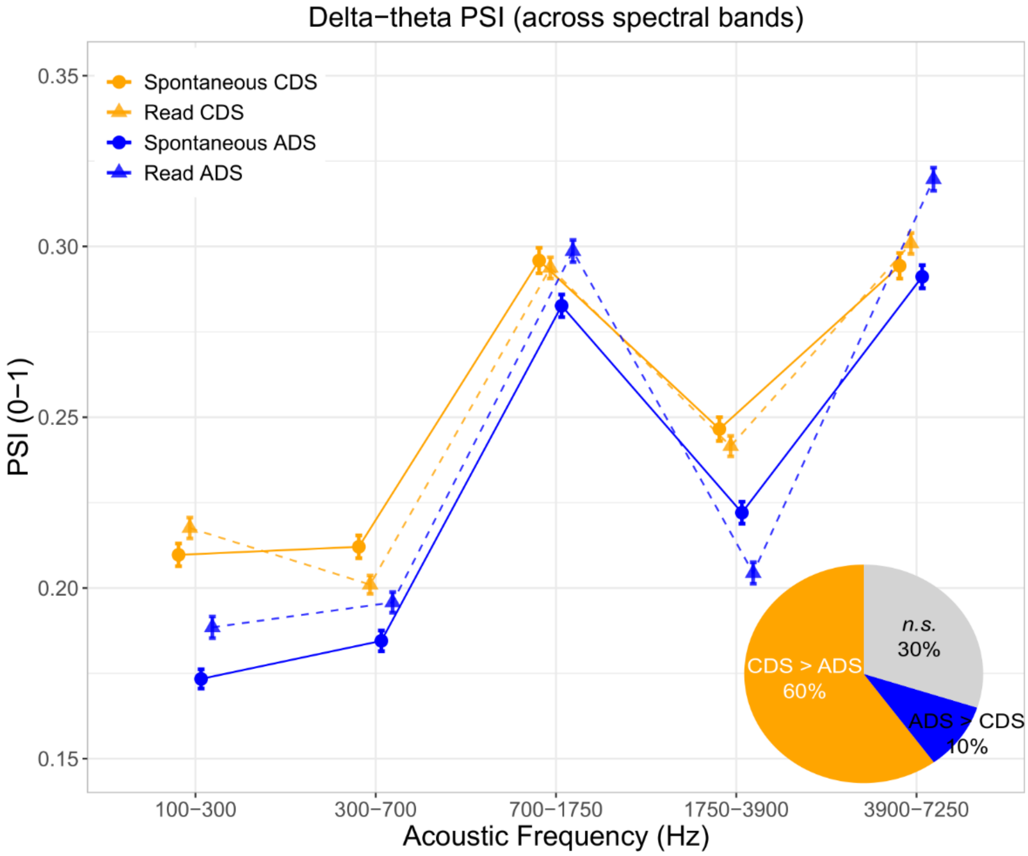
Supplemental Formula 3.1. Formula of cross-frequency phase synchronization index (PSI).



Supplemental Figure 3.1. Delta-theta PSI values across different n:m ratios. The point within each distribution represents the mean, and the bars represent standard deviations.



Supplemental Figure 3.2. Pearson's correlation between manual and automatic syllable counts. R- and p-values for the correlation index at the top left corner.



Supplemental Figure 3.3. Delta-theta PSI across speaking conditions and spectral bands. Error bars represent standard error of the mean. Pie plot in the bottom right corner represents the percentage of Tukey HSD contrasts for which PSI is higher for CDS (orange), ADS (blue), or resulted in a non-significant difference (gray, adjusted p-threshold = .05).