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Within- and Cross-Language Relations Between Phonological Memory, Vocabulary, and Grammar in Bilingual Children

Margaret Kehoe,[a] **Diane Poulin-Dubois,**[b] **and Margaret Friend**[c]

[a] Department of Speech Therapy and Psycholinguistics, Faculty of Psychology and Educational Sciences, University of Geneva, Switzerland [b] Developmental Cybernetics, Department of Psychology, Concordia University, Montréal, Quebec, Canada [c] Center for Clinical and Cognitive Neuroscience, Department of Psychology, San Diego State University, CA

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ABSTRACT

Purpose: This study investigated within-language and between-language associations between phonological memory, vocabulary, and grammar in French–English (n = 43) and Spanish–English (n = 25) bilingual children at 30, 36, and 48 months. It was predicted that phonological memory would display both within-language and between-language relations to language development and that these relations would be stronger at the youngest age.

Method: Bilingual children participated in free-play sessions in both of their languages at each age, from which vocabulary and grammatical information (number of different words and mean length of utterance) was extracted. Vocabulary information was also obtained from parent inventories completed when the children were 30 months and a standardized receptive vocabulary test administered at 36 and 48 months. The children were also administered nonword repetition tests in both of their languages at each age.

Results: Mixed logistic regression indicated that phonological memory was associated with vocabulary and grammar within the same language and phonological memory in the other language. In two of the four statistical models, phonological memory exhibited positive between-language relations, and in one model, it exhibited negative between-language relations to language development. Results also indicated that within-language and between-languages effects remained constant, or between-language associations decreased during the age range studied.

Conclusion: Overall, the findings provide some support for cross-language associations between phonological memory and lexical and grammatical skills.

Phonological memory, the capacity to recall sequences of sounds, is highly correlated with vocabulary and grammatical development. Relations between phonological memory and language have been found in both monolingual (Edwards et al., 2004; Gathercole & Baddeley, 1989; Hoff et al., 2008) and bilingual children (Parra et al., 2011; Windsor et al., 2010). In particular, studies with bilingual children have documented strong within-language correlations between phonological memory and language (Core et al., 2017; Lee & Gorman, 2012; Parra et al., 2011). That is, phonological memory is related to language development in the same language. Several studies have also documented between-language (also referred to as cross-language) relations. Phonological memory in one language is related to phonological memory, vocabulary, and grammatical development in the other (Core et al., 2017; Masoura & Gathercole, 2005; Parra et al., 2011).

This study examines within- and cross-language relations between phonology, vocabulary, and grammatical development in bilingual children. The point of departure is the well-established finding that relations between

Correspondence to Margaret Kehoe: Margaret.Winkler-Kehoe@unige.ch. ***Disclosure:*** *The authors have declared that no competing financial or nonfinancial interests existed at the time of publication.*

vocabulary and grammar are essentially language specific in bilingual children (Conboy & Thal, 2006; Marchman et al., 2004). This study aims to widen out the investigation of cross-domain and cross-language relations to include phonology (specifically phonological memory) to determine whether the pattern of relations among language domains is similar or different when phonology is involved. Documenting the nature and direction of cross-domain and cross-linguistic relations is essential to understanding how bilinguals acquire language and has important repercussions for remediation in the case of language disorders. We begin by reviewing studies that investigate the link between phonological memory and language in monolingual children. We then examine within-language and between-language relations in bilingual children.

Relations Between Phonological Memory and Language in Monolingual Children

Phonological memory is most often measured via a nonword repetition (NWR) test in which children recall phonological sequences of increasing length and complexity conforming to the phonotactic constraints of the target language. Immediate recall of nonwords taps many phonological skills apart from phonological memory, including the ability to perceive, represent, and accurately produce sequences of sounds and syllables (Coady & Evans, 2008). However, the central underlying mechanism required to perform well in an NWR task is considered to be phonological memory, the focus of this study.

A widely used model of phonological memory described by Gathercole (2006) is based on Baddeley's (1986) notion of phonological short-term store or the phonological loop. "Auditory linguistic inputs are automatically represented in the store, where they are subject to rapid time-based decay" (Gathercole, 2006, p. 519). Gathercole emphasizes that the phonological loop does not operate in isolation from permanent knowledge representations. It may be influenced by the lexical characteristics of the memory stimuli and by phonological storage capacity. NWR provides a sensitive measure of the quality of phonological storage, which in turn may be influenced by perceptual analysis, individual variation in the endurance of the representations, and other storage factors.

Numerous studies show that the ability to recall meaningless phonological sequences is highly correlated to vocabulary development. According to Gathercole (2006), the link between NWR and vocabulary development was first established in a longitudinal study of children, aged 4–8 years, in which moderate correlations were documented between NWR and receptive vocabulary scores at 4, 5, and 6 years of age, whereas weak but significant correlations were obtained at 8 years of age (Gathercole & Baddeley, 1989). The association between NWR and vocabulary has been demonstrated in younger children, as well. In a small sample of 2-year-olds, Hoff et al. (2008) found that NWR accuracy was significantly correlated with vocabulary size, and Stokes and Klee (2009a) found that NWR performance was the strongest predictor of vocabulary scores among a variety of other demographic and behavioral variables in a much larger sample of 2-year-olds.

Other studies report a relation between NWR and grammatical development (Adams & Gathercole, 1995, 1996; Archibald et al., 2008; Girbau & Schwartz, 2008). Adams and Gathercole (1995) examined the link between NWR and spoken language output. They found that 3-year-old children with good NWR skills produced language that was grammatically more complex with longer utterances than children with poor NWR skills. In a later study with 4- to 5-year-olds, they found that NWR was correlated with utterance length and the amount of detail in narratives (Adams & Gathercole, 1996). In summary, learning a word or a morphosyntactic rule depends on accurate sequencing of phonemes or morphemes, processed in phonological short-term memory, thus explaining the robust correlations between vocabulary, grammatical ability, and NWR (French & O'Brien, 2008).

Following Gathercole's (2006) model, we assume that phonological memory supports vocabulary and grammatical development. However, this view is not shared by all authors. Some authors suggest that NWR supports vocabulary acquisition before the age of 5 years whereas vocabulary supports NWR after the age of 5 years (Gathercole et al., 1992). Others show that the relation may be bidirectional throughout childhood (Lauro et al., 2020; Verhagen et al., 2019). There is also evidence that young children may represent words in a holistic manner, possibly in terms of associated articulatory patterns (Ferguson & Farwell, 1975; Nittrouer et al., 1989; Vihman & Croft, 2007). As vocabulary size increases, children's lexical representations become more segmental, suggesting that vocabulary supports phonological memory even at young ages (Edwards et al., 2004). Given these different views and the fact that many studies include correlational analyses in which it is difficult to determine causality, we employ neutral terms to describe the relation between phonological memory and language.

Within-Language and Between-Language Associations in Bilingual Children

The focus of this study is on within- and cross-language relations involving phonological memory and language in bilingual children. Within- and cross-language relations have already been the subject of some attention in the lexical and grammatical domains. Marchman et al. (2004) contrasted two possibilities when examining relations between vocabulary and grammar in bilingual children: The first was that lexical–grammatical associations reflect general cognitive or language-learning abilities; the second was that lexical–grammatical associations are based on lexical and grammatical knowledge in each language. The first pattern is consistent with a language-general component underlying cross-domain relations, whereas the second is consistent with the contribution of language-specific influences. Marchman et al.'s study, which included analyses of lexical and grammatical information extracted from parent report and spontaneous language samples in bilingual Spanish–English children, aged 24–27 months, revealed that within-language associations were stronger than cross-language associations, providing support for language-specific over language-general accounts of language learning. This finding has been replicated over the years by several authors also testing English–Spanish bilinguals (Conboy & Thal, 2006; Hoff et al., 2018; Kohnert et al., 2010; Simon-Cereijido & Gutiérrez-Clellen, 2009).

Kehoe et al. (2021) posited that the relation between phonology and other language domains is different from the one between vocabulary and grammar, namely, the relation may be subject to both within- and cross-language relations. They conceptualized phonological development as comprising (a) a biologically based component related to the development of speech motor and articulatory skills and (b) a cognitive–linguistic component related to acquiring the phonological system of the ambient language (Stoel-Gammon, 2011). They argued that the speech motor skills underlying phonology may be constant across languages due to a shared oral mechanism, resulting in strong similarities between the two phonological systems of the bilingual. This is suggested by studies on bilinguals with motor speech impairment (Preston & Seki, 2011) and by studies on the speech motor abilities of adult bilinguals (Chakraborty et al., 2008), where similar speech patterns are observed across languages. The cognitive–linguistic (phonological) component should be language specific; however, "language-general-like" effects may arise due to the many shared segmental and phonotactic structures (Keffala et al., 2020; Parra et al., 2011), although this will depend upon the phonological properties of the individual languages. As support for this notion, Kehoe et al. refer to bilingual profile effects (Oller et al., 2007), whereby monolingual–bilingual differences are more extreme in certain language domains than others because of the distributed nature of bilingual knowledge. Distributed knowledge is particularly evident in vocabulary acquisition whereby the form-meaning relation is essentially arbitrary and must be learned on a language-specific basis. It is less evident in phonics (knowing letters "p", "b," and "s") due to the strong commonalities in letter-to-sound correspondence across languages (Oller et al., 2007). We posit that phonological production may operate in a similar fashion to phonics. Indeed, studies report differences between typically developing monolingual and bilingual children in the areas of lexical and morphosyntactic development (Hoff et al., 2012) but few differences in the area of speech sound development (Hambly et al., 2013). There is also evidence that phonological skills in one language predict phonological skills (Cooperson et al., 2013; Keffala et al., 2020; Montanari et al., 2018; Scarpino et al., 2019), vocabulary (Kehoe & Havy, 2019), and grammar (Cooperson et al., 2013) in the other language of the bilingual.

Kehoe et al. (2021) set out to investigate whether the relation between phonology and other language domains differs from the one reported between vocabulary and grammar. They measured phonology, vocabulary, and grammar in French–English bilingual children, aged 31 months. They found that English percent consonants correct (PCC) was related to vocabulary diversity (number of different words [NDW]) in both French and English whereas French PCC was related to mean length of utterance (MLU) in both French and English, supporting the hypothesis that language-general phonological skills are associated with vocabulary and grammar across languages.

This study extends Kehoe et al.'s (2021) findings by examining language-specific and language-general relations linking phonological memory and language in bilingual children. We posit that the language-general component may be as strong for phonological memory as it is for phonological production. Apart from the articulatory component already mentioned, the ability to repeat sequences of phonemes is dependent on general auditory memory capacity that is not specific to a particular knowledge base (Parra et al., 2011). Although NWR has often been heralded as a way to tap general phonological processing independent of language knowledge, there is a large body of literature that now shows that the word likeness of the nonword and language experience influence performance on an NWR test (Gathercole, 2006). Specifically, with respect to language experience, studies show that monolingual children obtain higher NWR scores than bilinguals in the same language (Kohnert et al., 2006); bilingual children obtain higher NWR accuracy in their first language (L1) or dominant language compared to their second language (L2) or less dominant language (Gibson et al., 2015; Masoura & Gathercole, 1999; Thorn & Gathercole, 1999), and NWR scores are correlated with language exposure rates (Parra et al., 2011). According to Thorn and Gathercole (1999), phonological properties of the dominant language may dominate connections within the phonological loop, leading to weaker connections for the nondominant language.

Thus, the claim that only language-general processes underlie cross-domain relations between phonological memory and language cannot be supported. Rather, our claim is that both language-general and language-specific processes underlie cross-domain relations involving phonological memory and language, highlighting the different role that phonology may play in cross-domain relations. If the claim is not upheld, this would suggest that phonology operates in a similar way to the lexicon and grammar, engendering language-specific but not language-general influences.

Relations Between Phonological Memory and Language in Bilingual Children

What is the evidence for within-language and between-languages relations between phonological memory and language in bilingual children? In some studies, only within-language correlations have been examined. For example, Lee and Gorman (2012) reported significant correlations between English NWR accuracy and English vocabulary in two groups of bilinguals (Spanish–English and Chinese–English), aged 7 years. Summers et al. (2010) also found that NWR was significantly related to morphosyntax on a language-specific basis in Spanish–English bilinguals, aged 4;6–6;5 (years;months).

In other studies, both within-language and between-languages correlations were tested but only within-language correlations surfaced as significant. For example, Thordardottir and Brandeker (2013) reported significant correlations between English NWR and English but not French vocabulary and between French NWR and French but not English vocabulary in 5-year-old French–English bilinguals. Windsor et al. (2010) found correlations between English NWR and English but not Spanish language test scores in Spanish–English bilinguals, aged 6–11 years. Similarly, Girbau and Schwartz (2008) reported high correlations between Spanish NWR and scores on Spanish but not English language tests in Spanish–English bilinguals, aged 7–10 years.

Other studies, in contrast, have reported cross-language relations between NWR and vocabulary or grammar. Masoura and Gathercole (1999) reported that, in Greek children learning English as an L2, NWR accuracy in English and Greek was correlated with vocabulary scores in English and Greek. French and O'Brien (2008) reported that NWR in English or in an unfamiliar language, Arabic, predicted grammatical development in French children acquiring English as an L2. Another set of studies has investigated within-language and between-language correlations in young simultaneous bilinguals (Core et al., 2017; Lauro et al., 2020; Parra et al., 2011). Although the focus of these studies has been on demonstrating the language-specific nature of the phonological memory–language connection, they have all demonstrated significant cross-language relations between phonological memory in one language and vocabulary and grammar in the other using correlational analyses. Parra et al. (2011) reported both within- and cross-language relations between phonological memory, assessed at 22 months, and language development (vocabulary and grammatical complexity scores based on parental report), assessed at 25 months, in bilingual Spanish–English children. Core et al. (2017) also reported between-language effects in Spanish–English bilinguals, aged 30 months, although the findings were not symmetrical across languages. English NWR ability was correlated with English vocabulary scores, whereas Spanish NWR was correlated with both Spanish and English vocabulary scores. Recently, Lauro et al. (2020) found significant within-language and between-language correlations between NWR and vocabulary in Spanish–English bilingual children, aged 2;6–5;0, although within-language correlations were stronger. Finally, one clear finding in many studies is that phonological memory scores in the two languages are correlated (Core et al., 2017; Parra et al., 2011; Windsor et al., 2010).

In summary, a number of studies have documented cross-language relations between phonological memory and language in bilingual children, although not all studies have found them. As for why cross-language effects between phonological memory and language have not been more frequently reported, age may be a contributing factor. As noted above, Core et al. (2017) and Parra et al. (2011) reported between-language effects with very young bilingual children, whereas many of the studies that have not obtained significant between-language correlations have been with older children. Phonological memory may exert language-general effects on vocabulary and morphosyntactic acquisition only at younger ages.

Keren-Portnoy et al. (2010) provide strong evidence for the influence of speech production experience on NWR performance, which may be more pronounced at earlier than later stages of development. The young bilingual child's sound inventory may consist of "early sounds," which are shared across their two phonetic inventories, thus leading to the recruitment of more general articulatory and phonological abilities. The older child's sound inventory may consist of language-specific sounds, which will depend upon lexical knowledge of the individual languages. The influence of speech production on NWR performance may explain, in part, the stronger presence of language-general effects at younger ages.

Apart from changing patterns of between-language effects across age, several studies point to the fact that the relation between phonological memory and language diminishes over time. Gathercole et al. (1992) found strong correlations between phonological memory and vocabulary development at 4 and 5 years of age, but no longer at 8 years of age. Verhagen et al. (2019) found evidence for a reciprocal relation between NWR and vocabulary from ages 2 through 5 years in Dutch monolingual children, with this relation becoming weaker over time. Masoura and Gathercole (2005) posit that phonological memory plays an important role in early vocabulary development but a reduced role later, possibly due to the influence of other factors such as long-term phonological knowledge. Another possibility is that children reach a ceiling on the NWR task. As children become highly accurate and less variable as a group, NWR performance may no longer correlate with language variability in other domains. Few studies have examined the relation between phonological memory and language over time in young bilingual children, with the exception of a recent study by Lauro et al. (2020), which found that language-specific phonological memory was a significant predictor of English and Spanish vocabulary during the period 2;6–5;0. In the statistical model, phonological memory emerged as a main effect and not as part of an interaction term with age, indicating that it did not predict growth during this period. Their findings are consistent with others in suggesting that the relation between phonological memory and vocabulary is strongest at younger ages. One of the aims of this study is to examine the relation between phonological memory and language over time.

Summary of Study and Research Predictions

This study examines within-language and between-language relations between phonological memory and language development in two populations of bilingual children (French–English and Spanish–English) at 30, 36, and 48 months. Our central premise is that cross-language relations between phonological memory and language are to be expected because of the language-general aspect of both the auditory memory and articulatory/phonological components in phonological memory, which should exert an influence on language development in both languages.

The inclusion of two populations of bilinguals is motivated by the fact that the presence of similar effects in the two bilingual groups should strengthen the findings of within-language or between-language effects. Furthermore, the two sets of language pairs (English–French and English–Spanish) differ on similar phonological dimensions. English is characterized by stress-timed rhythm in which stressed and unstressed syllables are produced with unequal prominence, whereas Spanish and French are characterized by syllable-timed rhythm in which stressed and unstressed syllables are produced with more equal prominence (Ramus et al., 1999). French and Spanish contain a greater number of long words than English (Lleó & Demuth, 1999; MacLeod et al., 2011). English, however, has more complex syllable structure than French and Spanish (Delattre & Olsen, 1969). We have no reason to believe that the phonological characteristics of these three languages should exert different influences on language development. Nevertheless, to ensure that the NWR tests in English, Spanish, and French are of similar phonological difficulty, we coded the phonetic complexity of the nonwords by employing a quantitative measure of phonetic complexity, Jakielski's (2000) Index of Phonetic Complexity (IPC). This index assigns complexity points for parameters known to pose difficulty for children in phonological production. In addition, we controlled for the number of syllables since the length effect (NWR accuracy decreases with increasing number of syllables) may be stronger in English than in French or Spanish, because English has fewer long words than the other two languages (Gibson et al., 2015).

Based on the literature, we predict both within-language and between-language relations between phonological memory and language as previously reported for young bilingual children (Core et al., 2017; Parra et al., 2011). Furthermore, we expect the phonological memory–language relations to be stronger at the youngest age and become weaker over time. Conversely, because we test relatively young children (i.e., through to 4 years), the influence of phonological memory on language may remain strong throughout this period and only diminish after this age, that is, after 5 years as suggested by Gathercole et al. (1992).

Method

This study is part of a larger project in which 65 bilingual French–English children in Montréal, Canada, and 67 bilingual Spanish–English children in San Diego, California, were tested longitudinally from 1;4 through to 5;0. In this study, we focus on subsamples of these children tested at three waves, which correspond approximately to 30, 36, and 48 months. These ages were selected because they correspond to rapid development in different language domains: 30 months correspond to well-developed vocabulary and word combinations, whereas 36 and 48 months correspond to sentence production and major cognitive milestones.

Participants

From the data pool, we selected all bilingual children who had completed tests in phonological memory, vocabulary, and grammar across their two languages. Data were complete for some children at each age, some at two ages, and some at only one age. We retained data for all children since it improved statistical power and our statistical models were able to account for dependencies in the data for children seen on multiple occasions (see

Gonzalez-Barrero et al., 2020, for a similar design). Thus, all children were part of a longitudinal research study, although we do not have data on all children at all waves. In the French–English sample, 43 children were selected: 14 children had complete data at a single age, 18 children had complete data at two ages, and 12 children had complete data at the three ages. In the Spanish–English sample, 25 children took part in the study: Three children had complete data at a single age, 10 children had complete data at two ages, and 12 children had complete data at all ages. Tables A1 and A2 in Appendix A present more detailed information on the number of children tested at each age range. The high exclusion rate was due to missing data for the NWR task. This may reflect child noncompliance, verbal reticence, fatigue, or heritage language attrition. A high degree of missing data on NWR tests is common in young children (Hoff et al., 2008; Stokes & Klee, 2009b).

Children were exposed to English and French (Montréal) or English and Spanish (San Diego) from birth. We included children who were exposed to their less dominant language at least 20% of the time at the first age. Nevertheless, we made an exception for three children (425 and 442 in Montréal and 827 in San Diego) who had exposure rates of nearly 20% (i.e., 18%–19%) to maximize sample sizes. It was the case, however, that exposure rates changed over time and some children at later ages had exposure rates as low as 12%. There were not many of these children, and they were retained if they fulfilled the criterion of having at least 20% exposure rate at an earlier time period (i.e., at 30 months). In the Montréal sample, many of the children received input in both French and English from bilingual French–English parents, whereas in the San Diego sample, the input patterns were more varied. Only four of the 25 children received input in Spanish and English from both parents. Among the Montréal children, there were four trilinguals who were minimally exposed to a third language (i.e., less than 10%). Most children were first born (70% in the French–English sample and 84% in the Spanish–English sample). They were all typically developing with normal hearing and vision. This information was established via a telephone interview with the parents prior to the scheduling of a recording session. Tables 1 and 2 summarize the demographic characteristics of the participants in the French–English and Spanish–English samples, including age, gender, dominance, maternal education (in years), and relative language exposure. The dominant language was the language in which the children received the greatest percentage input based on the Language Exposure Assessment Tool (LEAT; see below). Although the Spanish–English sample was older, on average, than the target ages, for simplicity's sake, we refer to ages 30, 36, and 48 months throughout the article for both groups.

General Procedure

At each age, children attended two sessions of 60-min duration (one in English and one in French or Spanish) in the Cognitive and Language Development Laboratory of Concordia University in Montréal or in the Infant and Child Development Laboratory at San Diego State University scheduled 1 week apart. The language of testing was counterbalanced across participants. In each session, children participated in a free-play language sample from which vocabulary (NDW) and morphosyntactic (MLU) information was extracted. At 30 months, parents completed the MacArthur–Bates Communicative Development Inventories (CDI) in the children's respective languages (English, Spanish, and French versions), and at 36 and 48 months, children were administered receptive vocabulary tests (English, Spanish, and French versions of the Peabody Picture Vocabulary Test [PPVT]). At all ages, children were administered an NWR test in both of their languages.

Materials

LEAT

Language exposure was estimated by using the LEAT, which is an Excel-based parent interview (DeAnda et al., 2016) administered over the phone prior to the child's visit. The LEAT obtains information on the languages spoken by the interlocutors who interact regularly with the child, whether the interlocutors are native speakers, and the number of hours of talking or being overheard by the child in each language. The program yields estimates of the relative exposure to each language in hours per day, hours per week, and proportion exposure. We used proportion exposure to each language as the estimate of relative exposure. The LEAT was administered at each age range as exposure rates changed over time for some children.

CDI

The American English CDI Words and Sentences (Fenson et al., 1993) and its Canadian French (L'Inventaire MacArthur de Développement de la Communication: Mots et Phrases [IMDC]; Trudeau et al., 1999) and Mexican Spanish (Inventarios del Desarrollo de Habilidades Comunicativas Palabras y Enunciados [IDHC]; Jackson-Maldonado et al., 2003) adaptations were completed by the parents at the first age, 30 months. The CDI (referred to as the English CDI) contains a parent report checklist of 680 words, in which caregivers indicate the words their children say. The CDI has high internal consistency (Cronbach's α = .96) and strong test–retest reliability. The IMDC (referred to as the French CDI) was normed on children acquiring Québécois French and has strong

Table 1. Descriptive statistics for demographic variables in French–English bilinguals.

Variable	*M* (*SD*)	Minimum	Maximum
30 months (*n* = 34; 14 females, 17 English dominant)			
Age (months)	30.55 (1.13)	28	33
Mother education (years)	15.85 (2.38)	11	20
Exposure English (%)	49.50 (18.44)	19	82
Exposure French (%)	49.44 (18.55)	18	81
36 months (*n* = 30; 12 females, 15 English dominant)			
Age (months)	36.32 (1.01)	34.7	38.5
Mother education (years)	15.97 (2.54)	11	20
Exposure English (%)	50.47 (19.77)	14	80
Exposure French (%)	47.73 (19.49)	22	81
48 months (*n* = 20; 7 females, 10 English dominant)			
Age (months)	48.59 (.94)	46.9	50.5
Mother education (years)	17 (1.84)	13	20
Exposure English (%)	46.35 (19.04)	22	87
Exposure French (%)	50.45 (18.77)	13	78

test–retest reliability. It contains 688 words. The IDHC (referred to as the Spanish CDI) contains a checklist of 680 words and presents with moderate test–retest reliability (Jackson-Maldonado et al., 1993). Expressive vocabulary in each language was estimated as the number of words parents reported that children produce.

The PPVT

The PPVT-III (Dunn & Dunn, 1997) and its Canadian French (Echelle de vocabulaire en images Peabody [EVIP]; Dunn et al., 1993) and Spanish (Test de Vocabulario en Imagenes Peabody [TVIP]; Dunn et al., 1997) adaptations were administered to the children at 36 and 48 months. The PPVT, the EVIP, and the TVIP are standardized tests of receptive vocabulary. The child is instructed to point to one picture out of four that best matches a word given by the examiner. The vocabulary score is the number of items to reach the ceiling minus the number of errors. Internal consistency and test–retest reliability of the PPVT are strong, with reliability coefficients in the .90s. The PPVT (referred to as the English PPVT) also has moderate-to-strong construct validity with other vocabulary assessments (Dunn et al., 1997). The EVIP (referred to as the French PPVT) has good test–retest reliability (r = .72) and internal consistency (α = .81). It has high correlations with other vocabulary tests (r = .86) and with IQ (r = .62–.72; Dunn et al., 1993). The TVIP (referred to as the Spanish PPVT) has good reliability and construct validity (Dunn et al., 1986). We employed raw rather than standardized scores given that children were all tested at similar ages.

NWR Test

The NWR tests employed in this study are based on the ones developed by Parra et al. (2011) for young English- and Spanish-speaking children. Nonwords were constructed from real words taken from the English and Spanish versions of the CDI such that the sounds that occur in the real words also occur in the nonwords in the same word positions. In addition, the nonwords contain the same phonotactic frames and stress patterns as the real words from which they are derived. Parra et al. developed

Table 2. Descriptive statistics for demographic variables in Spanish–English bilinguals.

Variable	*M* (*SD*)	Minimum	Maximum
30 months (*n* = 34; 14 females, 17 English dominant)			
Age (months)	32 (1.65)	29	34.5
Mother education (years)	15.5 (2.12)	12	18
Exposure English (%)	43.15 (15.98)	19	73
Exposure French (%)	56.85 (15.98)	27	81
36 months (*n* = 30; 12 females, 15 English dominant)			
Age (months)	39.6 (2.0)	35.2	42.6
Mother education (years)	15.47 (1.93)	13	18
Exposure English (%)	56.37 (13.96)	31	88
Exposure French (%)	43.63 (19.49)	12	69
48 months (*n* = 20; 7 females, 10 English dominant)			
Age (months)	52.09 (.94)	47.7	56.2
Mother education (years)	15.4 (2.01)	12	18
Exposure English (%)	54.55 (20.63)	12	84
Exposure French (%)	45.45 (20.63)	16	88

12-item English and Spanish tests containing one-, two-, and three-syllable nonwords for children, aged 22 months. We employed the same stimuli as they did but, in addition, created a 12-item French version (Patrucco-Nanchen et al., 2019) and added four- and five-syllable words to create 16-item and 20-item versions for all three languages. We did not use an existing French NWR test because it was important that all tests had a similar design across languages. The 12-item version was administered at 30 months, the 16-item version was administered at 36 months, and the 20-item version was administered at 48 months.

The nonwords were presented orally by an examiner who was a native speaker of the language of testing. Each test included two training trials with monosyllabic nonwords. The nonwords were accompanied by toys representing people and animals. During the test, the examiner showed a toy, used a nonword to name the toy, and asked the child to repeat it (e.g., "This guy is named Kog. Can you say Kog?"). If the child did not repeat the nonword, the examiner repeated it up to 3 times. Only the first repetition produced by the child was scored, regardless of its accuracy. If a child failed to repeat the nonwords for six consecutive trials, the test was ended. Only children who attempted to repeat at least three nonwords were included in the analyses.

Free-Play Spontaneous Language Sample

Children interacted with their parents in one free-play session in each language at each age. Parents were told to play as they would at home and to speak to their child in either English, French, or Spanish, depending on the target language for the session. The duration of the free-play session was 20 min at 30 months, 15 min at 36 months, and 10 min at 48 months. During the session, dyads played with a complex toy, either a farm or a house. The toy set used for each language was counterbalanced across participants. The language samples were recorded using a portable digital tape recorder (Montréal: Marantz PMD620 and San Diego: Samson Tech Zoom H2n).

Data Coding and Analyses

Semantic and Grammatical Analysis

Language samples were transcribed using the Systematic Analysis of Language Transcripts (SALT) software (Miller & Iglesias, 2012). Eight transcribers completed three to eight transcriptions each. Transcribers were fluent in both languages of the bilingual children Prior to starting work on the study, transcribers completed online training provided by the SALT software. They performed practice transcriptions and were required to meet a minimum interrater agreement of .8. A research assistant performed reliability transcription/coding for approximately 15%–20% of the transcripts. Word-level agreement ranged from .89 to .95 across the French, Spanish, and English transcripts.

Using the SALT software, MLU calculated in words and NDW were automatically generated for each child. Many children displayed code switching, defined as the presence of nontarget words and phrases (i.e., the presence of English words and phrases in a French or Spanish free-play session). MLU and NDW were calculated only for noncode-switched words and phrases. Calculations of NDW and MLU were based on complete and intelligible utterances, generally more than 100 utterances per child.

Phonological Coding of Nonwords

Each target nonword was coded in terms of syllable number and its phonetic complexity using the IPC (Jakielski, 2000). In terms of phonetic complexity, a point was assigned to each nonword if it contained a dorsal consonant (e.g., dook [duk]); a fricative or liquid (e.g., <u>buice</u> [bus], <u>challoon</u> [ʧəˈlun]); a final consonant (e.g., jat [ʤæt]); three or more syllables (e.g., <u>lolemas</u> [ˈlɔləmʌs]); two or more consonants with different places of articulation (PoAs; e.g., <u>dook</u> [duk], which has coronal and dorsal PoAs vs. kog [kɔg], which has only dorsal POA); a tautosyllabic cluster, which is a cluster that occurs within a syllable (e.g., "pl" in <u>wanutsoplen</u> [ˈwanʌtˌsoplən]); or a heterosyllabic cluster, which is a cluster that is split across two syllables (e.g., "ts" in <u>wanutsoplen</u> [ˈwanʌtˌsoplən]). Appendix B lists the English, French, and Spanish nonwords and their complexity points. A series of one-way analyses of variance did not indicate any difference between the phonetic complexity scores of the English, French, and Spanish nonwords neither for the 12-item test administered to children aged 30 months, $F(2, 33) = 1.36$, $p = .27$; the 16-item test administered to children aged 36 months, $F(2, 45) = 0.27$, $p = .77$; nor the 20-item test administered to children aged 48 months, $F(2, 57) = 0.28$, $p = .76$. Thus, the phonetic complexity of the nonwords is similar across languages.

Phonological Transcription of Nonwords

We employed PCC as the measure of NWR accuracy. We did not include percent vowels correct due to the difficulties of achieving good interrater reliability for vowels in young children. Following Hoff et al. (2008), we calculated PCC on the basis of words attempted and not on the basis of the total number of words, since we were unable to determine whether a nonproduced word was due to lack of attention, verbal reticence, or poor phonological memory.

Graduate students with experience in phonetic transcription and who were native speakers of the respective languages transcribed the nonwords. We considered all consonant substitutions, omissions, and additions as errors since they reflect difficulty in the ability to accurately recall phoneme sequences. We did not count, however, potential substitutions due to cross-linguistic interaction as errors; for example, a French or Spanish /r/ produced as an English /r/ was counted as correct. We also did not make adjustments for age-appropriate phonological errors since we assume, as many, that an NWR task is not a pure test of phonological memory but also taps other phonological capacities such as discrimination and production.[1] Keren-Portnoy et al. (2010) distinguish between whole-word versus segmental errors, the former reflecting changes in sequential order (metathesis) and additions and omissions of syllables. Although whole-word errors were observed, they were not frequent. Thus, our coding system does not distinguish between these two types of errors.

Interrater reliability was determined on the phonetic transcriptions of the NWR tests. Repetition accuracy was scored by native speakers of the respective languages. Ten children (across ages) representing 12% of the data in the Montréal group and 17% in the San Diego group were transcribed for reliability. Consonant-by-consonant analysis yielded interrater agreement of .93 for English and .89 for French in the Montréal group and .88 for English and .97 for Spanish in the San Diego group.

Statistical Analyses

Data were analyzed using mixed-effects logistic regression, which allowed us to model production accuracy on the basis of binomial data. The analyses were performed using R statistical software (R Development Core Team, 2020) and the lme4 package (Bates et al., 2015) for mixed-effects models. To evaluate the contribution of each predictor in the model, we performed pairwise model comparisons between a saturated model and a more restricted model. The saturated model included all main effects and interactions, whereas the restricted model omitted the predictor under consideration. Comparisons were made using likelihood ratio tests, which yield a chi-square statistic. Multilevel variables were further analyzed using Wald z statistics.

The dependent variable, PCC, is a proportion (i.e., number of consonants correct/number of total consonants) for each individual nonword production. For example, challoon /ʧəˈlun/ produced as [ʧəˈjun] was coded as 2/3 because two of the three target consonants were produced correctly. We also included a "weights" argument set to the number of total consonants to take into account that a proportion (e.g., 0.5) could refer to different numerators and denominators (1/2, 2/4, 3/6, etc.). Because NWR proportion scores yield a limited number of response alternatives, they are appropriate to logistic regression rather than to a model that assumes continuous data.

To examine between-language and within-language effects across age, we constructed four models: the first and second models to determine the relation between English NWR and language, and French NWR and language in English–French bilinguals and the third and fourth models to determine the relation between English NWR and language, and Spanish NWR and language in English–Spanish bilinguals. Four separate databases were prepared, in which each child's individual phonological memory, vocabulary, and grammatical measures (NWR, CDI or PPVT, NDW, and MLU) were converted into z scores at each age range. These, along with control and phonological structure variables, were then inserted into a larger database, which included the individually coded values of each nonword production under consideration across the three ages. It should be noted that the vocabulary measure includes results from the CDI at the youngest age and from the PPVT, a receptive vocabulary test, at the oldest ages. NDW is a separate vocabulary measure, which was extracted from spontaneous language samples at all ages.

The control variables were relative exposure (to English, French, or Spanish also converted into z scores), gender, maternal education (in years), and age range (30, 36, and 48 months). The phonological structure variables were syllable length (range of two to five syllables) and phonetic complexity (range of two to eight based on the IPC) coded for each nonword.

The language variables were NWR (of the other language), as well as within-language and between-language vocabulary (CDI at 30 months and PPVT at 36 and 48 months), NDW, and MLU scores. To establish the most parsimonious model, we first entered the control and phonological structure variables. We then entered between-languages variables (NWR, vocabulary, NDW, and MLU of the other language) and the interaction of these variables with age. Following that, we entered within-language variables (vocabulary, NDW, and MLU of the same language) and the interaction of these variables with age. Because of the large number of variables and the risk of overparameterization, we removed nonsignificant control and phonological structure variables, and nonsignificant language variables following the addition of the interaction effects. The final, optimal model was the one with best model fit and parsimony according to Akaike information criterion (AIC) and the Bayesian information criterion (BIC). Specifically, the final model had the most substantial improvement in AIC values from the control model (at least 10 units) combined with improvement (or no appreciable change) in BIC values. The model included random intercepts for

[1]Language-specific considerations included the following: (a) The Spanish lateral approximant /ʎ/ produced as a palatal approximant [j] was considered as correct as many Spanish dialects exhibit a merger of these two consonants. (b) Failure to use the Spanish spirantization process was not penalized since it may be a late-acquired process in bilingual children (Lleó & Cortés, 2013).

participants and items (i.e., words). The random factor for participants allowed us to account for dependencies across age since some children participated at multiple ages. The model was fitted using maximum likelihood estimation. We added between-language before within-language variables because they were the focus of the study; however, additional analyses indicated that the order of variable entry did not alter the final model.

Results

Tables 3 and 4 present descriptive statistics on the language measures across the three ages for the French–English and Spanish–English bilinguals. Figures 1 and 2 display the mean NWR accuracy for French–English and Spanish–English bilinguals, respectively. Results for French and English NWR tests are similar at ages 30 and 36 months but diverge in the oldest group of French–English bilinguals, with higher scores achieved in English. A similar trend is seen with the Spanish and English NWR tests in that results are the same at the first age range but diverge at the later ages, with higher scores achieved in English.

Table 3. Descriptive statistics for the nonword repetition test and language measures at the three different ages in the French–English bilinguals.

Variable	*n*	*M* (*SD*)	Minimum	Maximum
30 months				
EnNWR	33	78.06 (15.68)	33.33	96.97
FrNWR	33	78.72 (15.17)	36.67	96.88
EnCDI	33	348.50 (195.05)	44	680
FrCDI	33	294.97 (161.38)	7	571
EnNDW	33	88.85 (36.14)	8	148
FrNDW	33	81.59 (42.71)	4	172
EnMLU	33	2.00 (.59)	1.03	3.11
FrMLU	33	2.00 (.71)	1.0	4.34
36 months				
EnNWR	30	86.25 (8.06)	64.71	96.49
FrNWR	30	84.34 (6.85)	69.39	95.92
EnPPVT	30	31.43 (14.94)	7	62
FrPPVT	30	15.90 (11.60)	0	37
EnNDW	30	88.93 (34.65)	30	154
FrNDW	30	91.37 (46.60)	5	193
EnMLU	30	2.32 (.67)	1.32	3.60
FrMLU	30	2.20 (.79)	1.15	3.58
48 months				
EnNWR	20	93.80 (5.51)	81.01	100
FrNWR	20	86.25 (10.32)	63.38	98.59
EnPPVT	20	54.45 (18.61)	16	89
FrPPVT	20	32.15 (19.66)	4	72
EnNDW	20	111.2 (41.94)	7	196
FrNDW	20	93.5 (62.05)	14	240
EnMLU	20	3.11 (.80)	1.0	4.19
FrMLU	20	2.59 (1.10)	1.30	5.27

Note. EnNWR = English nonword repetition test; FrNWR = French nonword repetition test; EnCDI = English MacArthur–Bates Communicative Developmental Inventories; FrCDI = French MacArthur–Bates Communicative Developmental Inventories; EnNDW = English number of different words; FrNDW = French number of different words; EnMLU = English mean length of utterance; FrMLU = French mean length of utterance; EnPPVT = English Peabody Picture Vocabulary Test; FrPPVT = French Peabody Picture Vocabulary Test.

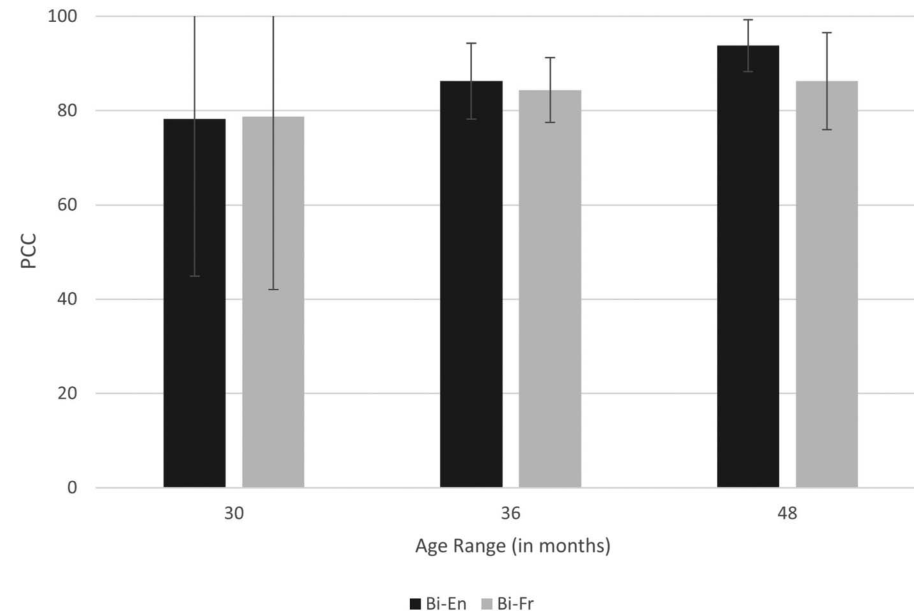
Table 4. Descriptive statistics for the nonword repetition test and language measures at the three different ages in the Spanish–English bilinguals.

Variables	*n*	*M* (*SD*)	Minimum	Maximum
30 months				
EnNWR	20	66.47 (10.26)	50	84.85
SpNWR	20	63.70 (12.73)	38.46	82.76
EnCDI	20	270.05 (137.16)	69	569
SpCDI	20	261.95 (128.53)	56	549
EnNDW	20	90.75 (35.81)	32	167
SpNDW	20	70.85 (32.13)	26	155
EnMLU	20	1.73 (.38)	1.12	2.62
SpMLU	20	1.57 (.34)	1.12	2.43
36 months				
EnNWR	19	76.10 (13.64)	33.33	94.64
SpNWR	19	68.15 (15.5)	28.57	93.18
EnPPVT	19	38.79 (18.72)	13	81
SpPPVT	19	8.47 (6.22)	2	21
EnNDW	19	121.32 (36.50)	50	201
SpNDW	19	90.89 (40.41)	18	162
EnMLU	19	2.45 (.60)	1.51	3.57
SpMLU	19	2.11 (.55)	1.19	3.20
48 months				
EnNWR	20	82.83 (9.09)	65.82	98.72
SpNWR	20	76.35 (11.87)	42.03	94.20
EnPPVT	20	59.2 (20.72)	20	94
SpPPVT	20	18.05 (10.45)	1	35
EnNDW	20	109.95 (36.33)	44	184
SpNDW	20	71.45 (43.49)	16	184
EnMLU	20	2.97 (.60)	1.59	3.86
SpMLU	20	1.97 (.64)	1.21	3.78

Note. EnNWR = English nonword repetition test; SpNWR = Spanish nonword repetition test; EnCDI = English MacArthur–Bates Communicative Developmental Inventories; SpCDI = Spanish MacArthur–Bates Communicative Developmental Inventories; EnNDW = English number of different words; SpNDW = Spanish number of different words; EnMLU = English mean length of utterance; SpMLU = Spanish mean length of utterance; EnPPVT = English Peabody Picture Vocabulary Test; SpPPVT = Spanish Peabody Picture Vocabulary Test.

Tables C1–C3 in Appendix C present the correlation coefficients between proportion language exposure, NWR, and language measures at the three different ages in the French–English bilinguals. Tables C4–C6 in Appendix C present the same for the Spanish–English bilinguals. Correlations that remained significant after applying Benjamini–Hochberg corrections to adjust for false positive error rate are highlighted in gray in the tables. Although there are no significant correlations between language exposure and NWR scores at any age in either of the bilingual groups, there are moderately high significant correlations between NWR accuracy in the two languages of the bilinguals at 30 months in the French–English bilinguals and at 36 months in the Spanish–English bilinguals and correlations between NDW and MLU at all age ranges in both groups of

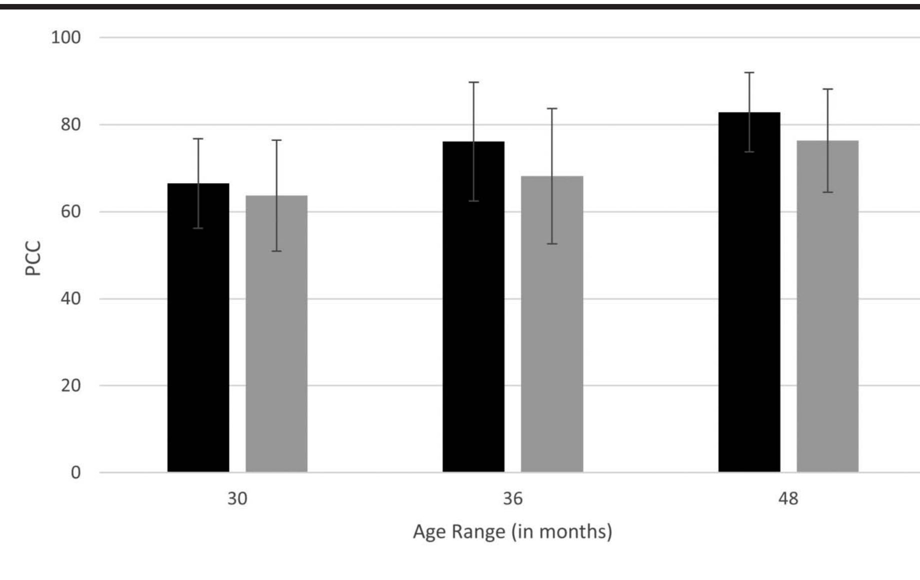
Figure 1. Mean nonword repetition accuracy (percent consonants correct [PCC]) across age range in English (En) and French (Fr) for the French–English bilinguals (Bi).



bilinguals. Furthermore, there are significant correlations between language exposure and vocabulary/grammar at 30 and 36 months in the French–English bilinguals and at 30 months in the Spanish–English bilinguals.

To determine whether there were within-language and between-language relations between NWR and language measures, we ran four mixed logistic regression models with PCC (for each nonword) as the dependent variable and within- and between-language measures as the independent variables. To determine whether the relation between NWR and language changed over time, we included the interaction of age with language measures. Control variables, language exposure, years of mother's education, and gender did not improve model fit in any

Figure 2. Mean nonword repetition accuracy (percent consonants correct [PCC]) across age range in English (En) and Spanish (Sp) for the Spanish–English bilinguals (Bi).



model and were subsequently removed. In all models, age was significant, indicating that NWR accuracy improved with age. This finding is expected and will not be commented on further. When entered together, the phonological structure variables, complexity, and number of syllables did not emerge as significant, suggesting that these variables shared variance. When entered separately, complexity emerged as the better predictor of NWR scores than syllable length in three of the four models. In Model 3 (the relation between English NWR and language in the English–Spanish bilinguals), both complexity and syllable length were significant predictors; however, syllable length was a slightly (but not significantly) better predictor of NWR scores than complexity. To maintain symmetry across the different models, however, complexity was retained as the phonological structure variable for this model. The influence of complexity and syllable length on NWR accuracy across age is displayed in Tables D1–D4 in Appendix D.

In the first model, we examined the relation between English NWR and language measures in the French–English data set. There were 1,253 separate items included in the model across the 43 participants and three ages. French and English vocabulary, $\chi^2(1) = 6.07$, $p = .01$, and French NWR, $\chi^2(1) = 14.75$, $p < .001$, emerged as significant predictors. Furthermore, there was a significant interaction between age and French vocabulary, $\chi^2(2) = 12.14$, $p = .002$, indicating that the relation between English NWR and French vocabulary declined with age. To determine which ages differed significantly, we reran the model recoding the age variable. There was a significant difference between 30 and 36 months ($z = -2.73$, $p = .006$) and between 30 and 48 months ($z = -3.39$, $p < .001$), but not between 36 and 48 months ($z = -1.27$, $p = .20$). There was no significant interaction between English vocabulary and French NWR and age. The influence of complexity in the model was marginally significant, $\chi^2(1) = 3.70$, $p = .054$.

In the second model, we examined the relation between French NWR and language measures in the French–English data set. There were 1,200 separate items included in the model across the 43 participants and three ages. French vocabulary and French MLU, $\chi^2(1) = 8.59$, $p = .003$, as well as English NWR, $\chi^2(1) = 12.96$, $p < .001$, and English MLU were significant predictors in the model. In addition, there were significant interactions between age and French vocabulary, $\chi^2(2) = 25.72$, $p < .001$, and age and English MLU, $\chi^2(2) = 9.36$, $p = .009$. We again recoded the age variable in order to determine which ages differed significantly. The relation between NWR and French vocabulary increased from 30 to 48 months ($z = 3.56$, $p < .001$) and from 36 to 48 months ($z = 4.88$, $p < .001$), but not from 30 to 36 months ($z = -1.19$, $p = .24$). The relation between NWR and English MLU declined from 30 to 36 months ($z = -3.02$, $p = .003$) and marginally declined from 30 to 48 months ($z = -1.93$, $p = .054$), but there was no change from 36 to 48 months ($z = 0.35$, $p = .73$). There was no significant interaction of age with French MLU and English NWR, suggesting similar effects across age. The influence of complexity in the model was significant, $\chi^2(1) = 11.03$, $p < .001$. A summary of Models 1 and 2 are provided in Tables 5 and 6.

In the third model, we examined the relation between English NWR and language measures in the San Diego data set. There were 921 separate items included in the model across 25 participants and three age ranges. Results indicated that English vocabulary, $\chi^2(1) = 6.50$, $p = .01$; English MLU, $\chi^2(1) = 7.97$, $p = .005$; and Spanish NWR were significant predictors in the model. In addition, there was a significant interaction between age and Spanish NWR, $\chi^2(2) = 16.55$, $p < .001$. We recoded age in order to determine which ages differed significantly. The relation between English NWR and Spanish NWR increased from 30 to 36 months ($z = 2.74$, $p = .006$) but declined from 36 to 48 months ($z = -3.85$, $p < .001$). There was no change between 30 and 48 months ($z = -0.47$, $p = .64$). There were no significant interactions between age and English vocabulary and MLU. The influence of complexity in the model was significant, $\chi^2(1) = 6.87$, $p = .009$.

In the fourth model, we examined the relation between Spanish NWR and language measures in the San Diego data set. There were 904 separate items included in the model across 25 participants and three ages. Spanish vocabulary, $\chi^2(1) = 10.26$, $p = .001$; English NWR, $\chi^2(1) = 8.45$, $p = .004$; and English MLU, $\chi^2(1) = 7.81$, $p = .005$, were significant predictors in the model. However, the relation between Spanish NWR and English

Table 5. Model 1. Influence of the English nonword repetition test on language measures in the French–English bilinguals.

Fixed effects	**Estimate**	***SE***	***z***	**Pr(>|z|)**
(Intercept)	1.41614	0.15448	9.167	< 2e–16***
EnVoc	0.19941	0.07675	2.598	0.009372**
FrVoc	0.21251	0.10787	1.970	0.048842*
FrNWR	0.32108	0.07963	4.032	5.52e–05***
Complexity	−0.22083	0.10978	−2.012	0.044262*
Age range 36	0.73303	0.13385	5.476	4.34e–08***
Age range 48	1.67485	0.17197	9.739	< 2e–16***
FrVoc × Age range 36	−0.35952	0.13192	−2.725	0.0006424**
FrVoc × Age range 48	−0.53434	0.15770	−3.388	0.000703***
Random effects				
Groups name	**Variance**	***SD***		
ID (intercept)	0.1845	0.4296		
Word (intercept)	0.1938	0.4402		

Note. EnVoc = English vocabulary; FrVoc = French vocabulary; FrNWR = French nonword repetition test.

*$p < .05$. **$p < .01$. ***$p < .001$.

Table 6. Model 2. Influence of the French nonword repetition test on language measures in the French–English bilinguals.

Fixed effects	Estimate	*SE*	*z*	Pr(>|z|)
(Intercept)	1.33546	0.16378	8.154	3.52e–16***
FrVoc	0.24041	0.10973	2.191	0.028456*
FrMLU	0.24464	0.07963	3.072	0.002126**
EnNWR	0.24768	0.06761	3.663	0.000249***
EnMLU	0.41814	0.13105	3.191	0.001419**
Complexity	−0.46772	0.12634	−3.702	0.000214***
Age range 36	0.48156	0.13260	3.632	0.000282***
Age range 48	1.28387	0.16822	7.632	2.31e–14***
FrVoc × Age range 36	−0.16138	0.13624	−1.185	0.236204
FrVoc × Age range 48	0.57744	0.16228	3.558	0.000373***
EnMLU × Age range 36	−0.44797	0.14856	−3.015	0.002566***
EnMLU × Age range 48	−0.38241	0.19953	−1.926	0.054162
Random effects				
Groups name	**Variance**	***SD***		
ID (Intercept)	0.08331	0.2886		
Word (Intercept)	0.27697	0.5263		

Note. FrVoc = French vocabulary; FrMLU = French mean length of utterance; EnNWR = English nonword repetition test; EnMLU = English mean length of utterance.

*p < .05. **p < .01. ***p < .001.

MLU was negative, meaning higher Spanish NWR scores were associated with lower English MLU scores. There were no significant age interactions suggesting that all language measures exerted a similar effect across age. The influence of complexity in the model was significant, $\chi^2(1) = 16.09$, $p < .001$. A summary of Models 3 and 4 are provided in Tables 7 and 8. Appendix E provides metrics for each step of the four models, including AIC and BIC values. These results are summarized in Table 9 in terms of within-language and between-language effects and age interactions.

Discussion

This study examined the relation between phonological memory and language skills in young French–English and Spanish–English simultaneous bilinguals. Of interest was whether phonological memory was related to language skills within and between language and whether this relation changed from 30 to 48 months. Our results offer some support for between-language effects. In all analyses, NWR in one language was related to NWR in the other language. Furthermore, English NWR skills were positively related to vocabulary in English and French, and French NWR skills were positively related to MLU in French and English in the Montréal bilinguals; the relation of NWR to language skills was primarily within language in the San Diego bilinguals. In the following sections, we consider what our findings reveal about the relation between NWR and language.

Table 7. Model 3. Influence of the English nonword repetition test on language measures in the Spanish–English bilinguals.

Fixed effects	Estimate	*SE*	*z*	Pr(>|z|)
(Intercept)	0.61385	0.18474	3.323	0.000891***
EnVoc	0.19657	0.07323	2.684	0.007266**
EnMLU	0.18463	0.006523	2.830	0.004650**
SpNWR	0.23585	0.10147	2.324	0.020104*
Complexity	−0.42157	0.14945	−2.821	0.004789**
Age range 36	0.79807	0.13671	5.837	5.3e–09**
Age range 48	1.46100	0.14285	10.228	< 2e–16***
SpNWR × Age range 36	0.36981	0.13528	2.734	0.006265**
SpNWR × Age range 48	−0.06221	0.13180	−0.472	0.636953
Random effects				
Groups name	**Variance**	***SD***		
ID (Intercept)	0.07344	0.2710		
Word (Intercept)	0.40806	0.6388		

Note. EnVoc = English vocabulary; EnMLU = English mean length of utterance; SpNWR = Spanish nonword repetition test.

*p < .05. **p < .01. ***p < .001.

Within-Language and Between-Language Associations of Phonological Memory and Language

We begin by considering the within-language effects. Our results are consistent with numerous studies showing a robust association between NWR and vocabulary development (Gathercole, 2006; Hoff et al., 2008; Lauro et al.,

Table 8. Model 4. Influence of the Spanish nonword repetition test on language measures in the Spanish–English bilinguals.

Fixed effects	Estimate	*SE*	*z*	Pr(>|z|)
(Intercept)	0.51876	0.18752	2.766	0.00567**
SpVoc	0.24404	0.07518	3.204	0.00136**
EnNWR	0.24913	0.08293	3.004	0.00266**
EnMLU	−0.21636	0.07773	−2.784	0.00537**
Complexity	−0.54864	0.11343	−4.837	1.32e–06***
Age range 36	0.47729	0.14571	3.276	0.00105**
Age range 48	1.28819	0.15100	8.531	< 2e–16***
Random effects				
Groups name	**Variance**	***SD***		
ID (Intercept)	0.2352	0.4850		
Word (Intercept)	0.2732	0.5226		

Note. SpVoc = Spanish vocabulary; EnNWR = English nonword repetition test; EnMLU = English mean length of utterance.

**p < .01. ***p < .001.

Table 9. Summary of within-language, between-language, and age-related effects in statistical models.

Dependent variable	Within language	Interaction with age	Between languages	Interaction with age
French–English bilinguals				
EnNWR	EnVoc		FrVoc (pos) FrNWR	FrVoc ↓
FrNWR	FrVoc	FrVoc ↑	EnMLU (pos)	EnMLU ↓
	FrMLU		EnNWR	
Spanish–English bilinguals				
EnNWR	EnVoc		SpNWR	SpNWR ↑ ↓
	EnMLU			
SpNWR	SpVoc		EnMLU (neg) EnNWR	

Note. EnNWR = English nonword repetition test; EnVoc = English vocabulary; FrVoc = French vocabulary; pos = positive influence; FrNWR = French nonword repetition test; FrMLU = French mean length of utterance; EnMLU = English mean length of utterance; SpNWR = Spanish nonword repetition test; SpVoc = Spanish vocabulary; neg = negative influence.

2020). Being able to temporarily store sound sequences is important to word learning. The association between NWR and vocabulary is noteworthy in this study given that vocabulary was assessed by two different measures. At 30 months, children's productive vocabulary was measured by parental report, whereas at 36 and 48 months, children's receptive vocabulary was measured by a standardized vocabulary test. Despite the potential "noise" introduced by different administration methods, vocabulary was associated with NWR in both languages of both groups of bilinguals and remained so throughout the age range studied. Our results also indicated a significant relation between NWR and MLU, over and above that of vocabulary, in two of the four statistical models: French NWR scores were related to MLU in the French–English bilinguals, and English NWR scores were related to MLU in the Spanish–English bilinguals. These results are in agreement with many studies showing associations between children's phonological memory and morphosyntactic development (Adams & Gathercole, 1995, 1996; Archibald et al., 2008; Girbau & Schwartz, 2008). Children's ability to recall unknown phonological sequences is related to their ability to enlarge their sentences by adding morphemes. Our choice of MLU as grammatical measure was guided by early studies showing a relation between phonological memory and utterance length (Adams & Gathercole, 1995); however, more fine-grained measures of grammatical morpheme use may reveal even stronger relations between phonological memory and grammar (Cooperson et al., 2013). We did not observe any significant relations between NWR and NDW, an alternate measure of vocabulary development. NDW and MLU were highly correlated in many cases, and it seems that MLU was a better variable than NDW to capture the variance associated with NWR.

The central prediction of this study, however, was that there should be both within- and cross-language relations between phonological memory and language. We conceptualized phonological memory as comprising an auditory memory and an articulatory/phonological component, which, due to shared knowledge, exerts language-general effects on language development in the bilingual. The cross-language effect most consistently documented in this study was the one between the two NWR scores. NWR in one language was related to NWR in the other language. Such a result has been reported previously in both younger and older bilingual children (Masoura & Gathercole, 1999; Parra et al., 2011; Windsor et al., 2010). This finding is consistent with the more general finding that phonological production in one language is associated with phonological production in the other language of the bilingual (Cooperson et al., 2013; Keffala et al., 2020; Scarpino et al., 2019). These findings are suggestive of language-general effects implicating both memory and phonological capacities that were the impetus behind this study. Similar between-language relations for vocabulary and morphosyntax (i.e., vocabulary in one language influencing vocabulary in the other language) have not been reported (Conboy & Thal, 2006; Marchman et al., 2004) or only in isolated studies (Dixon, 2011; Kohnert et al., 2010). In this study, we documented correlations between NWR in the two languages of the bilinguals; however, in none of the comparisons did vocabulary or grammar in the two languages correlate.

We observed a positive cross-language relation between NWR and language in two of the four statistical models. Superior English NWR abilities were associated with superior vocabulary skills in English and French, and superior French NWR abilities were associated with superior morphosyntactic skills in French and English, providing support for the language-general nature of phonological memory. It is interesting that vocabulary was the best predictor of English NWR and that grammar was the best predictor of French NWR. We do not think this reflects any important differences in cross-domain relations between English and French phonology. In statistical models, same-language vocabulary and grammar measures were significant predictors of NWR when entered separately but not when entered together, probably due to the shared variance between language measures. We retained in the statistical models those variables that were the best predictors of NWR in each language. Findings vary across studies as to whether vocabulary or grammatical scores are best related to phonology (Cooperson et al., 2013). We found a similar type of variability in this study.

In contrast to the French findings, superior Spanish NWR abilities were associated with poorer morphosyntactic abilities in English. It is telling that the facilitative effects emerged in French–English bilinguals growing up in Montréal, an "additive" bilingual environment, and the nonfacilitative effect emerged in Spanish–English bilinguals growing up in San Diego, a more "subtractive" bilingual environment. It is tempting to relate the nature of the cross-language effects to the bilingual language context, which would suggest that sociocultural factors play a role in whether facilitative between-language effects emerge. Admittedly, this possibility is not necessarily consistent with the claim that cross-language relations reflect language-general effects implicating phonological memory. Nevertheless, researchers examining within- and cross-language relations in the lexical and grammatical domains have observed similar facilitative and nonfacilitative effects. Kohnert et al. (2010), for example, attributed positive cross-language associations in productive vocabulary to the additive environment in which Hmong–English bilinguals were acquiring their two languages (e.g., a bilingual preschool in which the L1 was maintained). They contrasted their findings to those of Tabors et al. (2003), who reported negative correlations between vocabulary scores in the L1 and L2 of 4-year-old Spanish–English bilinguals. The bilingual children in Tabors et al.'s (2003) study received more heterogeneous input in English and Spanish. Similarly, parent reports indicated that the San Diego bilinguals received language input from more varied sources than the Montréal bilinguals and received reduced input over time to Spanish, whereas language input over time in Montréal remained relatively balanced. Hoff et al. (2018) argue that these negative cross-language effects do not reflect cross-language influences in mental processes but, rather, social influences.

Still, we wonder why between-language effects did not emerge in all analyses. One possible reason is lack of statistical power. Cooperson et al. (2013) documented significant between-language relations between phonological production in one language and language measures in the other in bilingual children. However, Cooperson et al. tested 186 Spanish–English bilinguals, whereas this study tested a smaller number of children. In addition, the number of children in the San Diego sample was smaller than in the Montréal sample. The use of a larger bilingual population may have improved statistical power and allowed significant effects to emerge across all analyses.

A second possibility concerns the phonological properties of the NWR tests, which were characterized by phonemes and structures common to both languages of the bilingual and ones that were specific. Several authors have observed the language-specific way in which the phonological short-term memory system functions. Lauro et al. (2020) point out the relation between phonological memory and language is stronger when the stimuli to be remembered share phonological properties with the language measures. Our claims of cross-language and cross-domain effects were made irrespective of the word likeness of the nonwords since the task draws upon shared memory and articulatory/phonological components even when using word-like nonwords; however, the extent to which language general skills are recruited may depend upon the phonological properties of the NWR test (Hüls, 2017).

In summary, the findings provide moderate support for our hypothesis that the phonological memory–language connection differs from the lexical–grammatical one. Recently, Simon-Cereijido and Méndez (2018, 2020) sought to find cross-language relations in the lexical and grammatical domains using language-general measures that tap semantic knowledge and conceptual vocabulary in preschool-age Spanish–English bilinguals. They found that conceptual semantics accounted for a small percentage of unique variance in the final model for Spanish grammar; however, the effect of conceptual vocabulary on English grammar disappeared once language-specific vocabulary measures were entered into the model. In this study, between-language measures accounted for variance over and above within-language measures in three of the four statistical models, although admittedly, in one of the models, its influence was negative. We acknowledge that differences in methods, particularly differences in language measures, between studies involving phonology and those focusing on vocabulary and morphosyntax may account for some of the differences observed.

Within-Language and Between-Language Associations Over Time

A second aspect of the study was to examine whether within- and cross-language relations between phonological memory and language change over time. Longitudinal studies of NWR performance are not numerous, but a clear finding stemming from a handful of studies is that the association between NWR and vocabulary knowledge becomes weaker with increasing age (Gathercole, 2006; Masoura & Gathercole, 2005; Verhagen et al., 2019). Gathercole et al. (1992) suggest that the association may stay strong through 4 to 5 years but decline after that age. Our findings were consistent with those of Gathercole et al.'s study (1992). There was no evidence that the association between NWR and vocabulary declined during the period 30–48 months. The main generalization of the age-related analyses was that within-language and between-language effects stayed constant across age. An additional generalization was that when age interactions were present, within-language effects became stronger and between-language relations became weaker. Overall, the findings suggest that between-language effects become less robust with advancing age.

Influence of Phonological Structure on NWR

Finally, we investigated the influence of two phonological structure variables, phonetic complexity and syllable length, on NWR performance. Our findings revealed that phonetic complexity influences NWR accuracy. As phonetic complexity increased, NWR accuracy decreased. This was particularly the case for French and Spanish. In the case of English, there was only a marginal effect of complexity on English NWR accuracy in the French–English group, and both syllable number and complexity predicted English NWR accuracy in the Spanish–English group.

That phonetic complexity was generally superior to syllable length in predicting NWR accuracy is not unexpected given that the children were very young and may have been still subject to phonological production errors to which the IPC (Jakielski, 2000) would have been sensitive. As for the reduced phonetic complexity effect in English, we hypothesize that there may have been features of the English NWR test not measured by the complexity measure, which rendered it easier than the other NWR tests. One possibility is the presence of compound-like forms in English (e.g., hetterbetter and peterkiter), which allowed for chunking of phonological sequences and could explain why children obtained superior results on the English NWR test compared to the French and Spanish ones.

Conclusions

This study investigated whether there are within- and cross-language relations between phonological memory, vocabulary, and grammar in two populations of bilinguals, French–English and Spanish–English, from 30 to 48 months of age. Previous studies have put emphasis on the language-specific properties of NWR, whereas we explored its language-general potential and its ability to bootstrap language skills in the bilingual's other language. We found that phonological memory was associated across languages and exhibited within-language relations with vocabulary and grammar. It exhibited cross-language relations with vocabulary and grammar in two of the four models tested. These findings have clinical implications for language remediation since they reveal that strong phonology in one language has the potential to bootstrap phonology, vocabulary, and grammar in the other language. Nevertheless, facilitative cross-language effects were not documented in all statistical models, and the strength of the cross-language effect tended to decrease over time, suggesting that cross-language effects, when present, are relatively transitory. There was also some indication that these effects were moderated by sociocultural context. Future studies should examine cross-language relations between language domains, contrasting the different role that phonology may play in these relations, to further understand under what conditions cross-language effects emerge.

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Numbers of Bilingual Participants Across Age

Table A1. Details on the number of French–English bilinguals tested at the different age ranges.

No.	30 months	36 months	48 months
1	401	401	401
2	404	404	404
3	405	405	405
4		406	406
5	408		
6	411	411	411
7	412	412	412
8	413	413	
9	416	416	
10		418	418
11		421	421
12		422	422
13	423	423	423
14	424	424	
15	425	425	425
16	426	426	426
17		428	428
18	432		
19		433	433
20	434		
21	437	437	437
22		438	438
23	439	439	439
24	441	441	441
25	442		
26	445		
27	447	447	447
28	448		
29		453	453
30	454		
31	455		
32		456	
33	458	458	
34	459		
35	461	461	
36	463	463	
37	464	464	
38	465		
39	466	466	
40	467		
41	468	468	
42	470		
43	471		

Note. "401, 404, 405…" refer to the identity of the participant.

Appendix A (p. 2 of 2)

Numbers of Bilingual Participants Across Age

Table A2. Details on the number of Spanish–English bilinguals tested at the different age ranges.

No.	30 months	36 months	48 months
1	801		801
2	804		
3	808	808	
4	819	819	819
5	824	824	824
6	827		
7	841	841	841
8	842	842	842
9	845	845	845
10		847	847
11	850	850	850
12	852	852	852
13		854	854
14		859	859
15		866	866
16	867		867
17	870	870	870
18	871	871	871
19	872	872	
20		878	878
21	881	881	881
22	883	883	883
23	884		
24	885	885	885
25	890		890

Note. "801, 804, 808…" refer to the identity of the participant.

Appendix B (p. 1 of 2)

List of Nonwords for Each Language Including Information on Number of Syllables and Phonological Complexity

No.	Nonword	IPA	No. of syllable	Complexity	Complexity per list		
English nonwords							
1	Kog[a]	kɔg	1	3	Nonwords 1–12	Nonwords 1–16	Nonwords 1–20
2	Buice	bus	1	3	Total complexity = 37	Total complexity = 59	Total complexity = 78
3	Jat	ʤæt	1	2			
4	Dook	duk	1	3			
5	Challoon	ʧə'lun	2	3			
6	Pookie	ˈpuki	2	2			
7	Kuppy	ˈkʌpi	2	2			
8	Bicken	ˈbɪkən	2	3			
9	Bajapop	ˈbæʤəˌpɔp	3	4			
10	Telina	tə'linə	3	2			
11	Lolemas	ˈlɔləmʌs	3	6			
12	Panaphone	ˈpænəˌfon	3	4			
13	Hetterbetter	ˈhɛɾɚˌbɛɾɚ	4	4			
14	Mole-muckle	ˌmolə'mʌkəl	4	6			
15	Peterkiter	ˈpiɾɚˌkaɪɾɚ	4	5			
16	Wanutsoplen	'wanʌtˌsoplən	4	7			
17	Pamuburako	ˈpæməbʊ'rako	5	4			
18	Barootupole	ˌbærʊtə'polə	5	4			
19	Birlemacota	ˌbiɹləmə'kotə	5	6			
20	Tenorapoken	ˌtɛnɔɹə'pokən	5	5			
French nonwords							
1	Dulle[b]	dyl	1	2	Nonwords 1–12	Nonwords 1–16	Nonwords 1–20
2	Bame	bam	1	1	Total complexity = 42	Total complexity = 60	Total complexity = 85
3	Roupe	ʁup	1	4			
4	Sobe	sɔb	1	3			
5	Mallon	malɔ̃	2	2			
6	Gabou	gabu	2	2			
7	Souteur	sutœʁ	2	5			
8	Fonette	fɔnɛt	2	3			
9	Voupireuil	vupiʁœj	3	6			
10	Pylécot	pileko	3	4			
11	Tefilon	tefilɔ̃	3	4			
12	Cicomal	sikɔmal	3	6			
13	Libogapé	libogape	4	4			
14	Chopicanant	ʃɔpikanɑ̃	4	4			
15	Télancabo	telɑ̃kabo	4	4			
16	Désimenture	dezimɑ̃tyʁ	4	6			
17	Kakolinaté	kakolinate	5	5			
18	Mitouralosé	mituʁalose	5	6			
19	Porlokatemi	poʁlokatemi	5	7			
20	Doulokaditur	dulokadituʁ	5	7			

(*table continues*)

Appendix B (p. 2 of 2)

List of Nonwords for Each Language Including Information on Number of Syllables and Phonological Complexity

No.	Nonword	IPA	No. of syllable	Complexity	Complexity per list		
Spanish nonwords							
1	Lan[c]	lan	1	2	Nonwords 1–12	Nonwords 1–16	Nonwords 1–20
2	Trus	trus	1	4	Total complexity = 32	Total complexity = 54	Total complexity = 78
3	Sen	sen	1	2			
4	Pol	pol	1	3			
5	Fato	fato	2	2			
6	Neca	'neka	2	2			
7	Lesa	'lesa	2	2			
8	Gache	'gaʧe	2	3			
9	Gañeca	ga'ɲeka	3	3			
10	Mullina	mu'ʎina	3	2			
11	Peballo	pe'βaʎo	3	3			
12	Calota	ka'lota	3	4			
13	Makodrisa	mako'dɾisa	4	6			
14	Choriklete	ʧoɾi'klete	4	7			
15	Bikolata	biko'lata	4	4			
16	Kosipolo	kosi'polo	4	5			
17	Debevaláca	deβeva'laka	5	6			
18	Tolepemáso	tolepe'maso	5	4			
19	Tornalumédo	toɾnalu'meðo	5	6			
20	Lujamicégan	luxami'seɣan	5	8			

Note. IPA = International Phonetic Alphabet.

[a]Specific coding criteria for each language included the following: (a) [ʁ] was coded as a fricative in French; (b) the Spanish lateral approximant [ʎ] in Peballo and Mullina was not coded as a lateral since it is mostly realized as a palatal approximant [j] particularly in the speech of young children; and (c) word-medial and word-final /r/ in English nonwords Hetterbetter and Peterkiter was coded as a rhotic vowel (e.g., [ɚ]) rather than as syllabic /r/ since /r/ is generally vocalized in unstressed syllables. [b]Stress is not indicated in French because French has phrasal stress in which the last syllable of the phrase receives prominence (Dell, 1984). [c]Only primary stress is indicated in Spanish.

Appendix C (p. 1 of 3)

Correlation Coefficients Between Language Exposure and Language Measures in the French–English and Spanish–English Bilinguals at Ages 30, 36, and 48 Months

Table C1. Correlation coefficients between language exposure and language measures in French–English bilinguals at 30 months.

Variable	EnNWR	FrNWR	EnVoc	FrVoc	EnNDW	FrNDW	EnMLU	FrMLU
ExEn	.07	−.15	**.53***	**−.64*****	.23	**−.77*****	.36	−.49
EnNWR		**.66****	.43	.29	.29	−.20	.48	.18
FrNWR			.13	.40	.06	.01	.41	.46
EnVoc				−.07	.43	−.50	**.59***	−.23
FrVoc					−.21	**.53***	−.04	**.54***
EnNDW						−.41	**.67*****	−.18
FrNDW							−.41	**.61****
EnMLU								−.13
FrMLU								—

Note. Significant *p* values after Benjamini–Hochberg corrections have been applied are **in bold**. EnNWR = English nonword repetition test; FrNWR = French nonword repetition test; EnVoc = English vocabulary; FrVoc = French vocabulary; EnNDW = English number of different words; FrNDW = French number of different words; EnMLU = English mean length of utterance; FrMLU = French mean length of utterance; ExEn = proportion exposure to English.

*$p < .05$. **$p < .01$. ***$p < .001$.

Table C2. Correlation coefficients between language exposure and language measures in French–English bilinguals at 36 months.

Variable	EnNWR	FrNWR	EnVoc	FrVoc	EnNDW	FrNDW	EnMLU	FrMLU
ExEn	.04	−.39	.27	**−.61***	.17	**−.76*****	.14	**−.71*****
EnNWR		.41	.30	.20	.30	−.07	.35	.04
FrNWR			.15	.52	.06	.36	.09	.44
EnVoc				.22	.50	−.14	.43	−.19
FrVoc					−.13	.66**	−.15	**−.66*****
EnNDW						−.18	**.71****	−.18
FrNDW							−.19	**.85*****
EnMLU								−.04
FrMLU								—

Note. Significant *p* values after Benjamini–Hochberg corrections have been applied are **in bold**. EnNWR = English nonword repetition test; FrNWR = French nonword repetition test; EnVoc = English vocabulary; FrVoc = French vocabulary; EnNDW = English number of different words; FrNDW = French number of different words; EnMLU = English mean length of utterance; FrMLU = French mean length of utterance; ExEn = proportion exposure to English.

*$p < .05$. **$p < .01$. ***$p < .001$.

Appendix C (p. 2 of 3)

Correlation Coefficients Between Language Exposure and Language Measures in the French–English and Spanish–English Bilinguals at Ages 30, 36, and 48 Months

Table C3. Correlation coefficients between language exposure and language measures in French–English bilinguals at 48 months.

Variable	EnNWR	FrNWR	EnVoc	FrVoc	EnNDW	FrNDW	EnMLU	FrMLU
ExEn	.06	−.39	.28	−.44	.38	−.42	.31	−.46
EnNWR		.05	.34	−.19	.19	−.04	.004	.02
FrNWR			.12	**.78***	−.24	.53	−.31	.47
EnVoc				.05	.25	−.35	−.02	−.43
FrVoc					−.49	.50	−.48	−.41
EnNDW						−.33	**.77**	−.28
FrNDW							−.13	**.80***
EnMLU								−.004
FrMLU								—

Note. Significant *p* values after Benjamini–Hochberg corrections have been applied are **in bold**. EnNWR = English nonword repetition test; FrNWR = French nonword repetition test; EnVoc = English vocabulary; FrVoc = French vocabulary; EnNDW = English number of different words; FrNDW = French number of different words; EnMLU = English mean length of utterance; FrMLU = French mean length of utterance; ExEn = proportion exposure to English.

**$p < .01$. ***$p < .001$.

Table C4. Correlation coefficients between language exposure and language measures in Spanish–English bilinguals at 30 months.

Variable	EnNWR	SpNWR	EnVoc	SpVoc	EnNDW	SpNDW	EnMLU	SpMLU
ExEn	.42	0	**.72***	−.64	.40	−.07	.32	0
EnNWR		.36	.43	.08	.35	.09	.57	.01
SpNWR			−.11	.08	−.02	.17	−.03	.11
EnVoc				−.24	.51	.07	.41	.02
SpVoc					.04	.35	.19	.25
EnNDW						.18	.64	.19
SpNDW							−.04	**.77***
EnMLU								.06
SpMLU								—

Note. Significant *p* values after Benjamini–Hochberg corrections have been applied are **in bold**. EnNWR = English nonword repetition test; SpNWR = Spanish nonword repetition test; EnVoc = English vocabulary; SpVoc = Spanish vocabulary; EnNDW = English number of different words; SpNDW = Spanish number of different words; EnMLU = English mean length of utterance; SpMLU = Spanish mean length of utterance; ExEn = proportion exposure to English.

*$p < .05$. ***$p < .001$.

Appendix C (p. 3 of 3)

Correlation Coefficients Between Language Exposure and Language Measures in the French–English and Spanish–English Bilinguals at Ages 30, 36, and 48 Months

Table C5. Correlation coefficients between language exposure and language measures in Spanish–English bilinguals at 36 months.

Variable	EnNWR	SpNWR	EnVoc	SpVoc	SpNDW	SpNDW	EnMLU	SpMLU
ExEn	−.05	−.26	.52	−.36	.37	−.43	.46	−.40
EnNWR		**.81*** **	.24	.19	.27	.44	.40	.40
SpNWR			.01	.43	.03	.61	.00	.30
EnVoc				.14	.56	−.21	.55	−.13
SpVoc					.02	.16	−.16	.16
EnNDW						.01	**.70***	−.11
SpNDW							−.05	.55
EnMLU								−.00
SpMLU								—

Note. Significant p values after Benjamini–Hochberg corrections have been applied are **in bold**. EnNWR = English nonword repetition test; SpNWR = Spanish nonword repetition test; EnVoc = English vocabulary; SpVoc = Spanish vocabulary; EnNDW = English number of different words; SpNDW = Spanish number of different words; EnMLU = English mean length of utterance; SpMLU = Spanish mean length of utterance; ExEn = proportion exposure to English.

$^{*}p < .05$. $^{***}p < .001$.

Table C6. Correlation coefficients between language exposure and language measures in Spanish–English bilinguals at 48 months.

Variable	EnNWR	SpNWR	EnVoc	SpVoc	EnNDW	SpNDW	EnMLU	SpMLU
ExEn	−.02	−.40	.31	−.38	.38	−.41	.37	−.47
EnNWR		.37	.46	.30	−.38	.22	.15	.20
SpNWR			−.02	.41	−.42	.42	−.14	.43
EnVoc				.17	−.03	.05	.42	−.08
SpVoc					−.32	.14	.19	.31
EnNDW						.07	.56	.20
SpNDW							.29	**.85*** **
EnMLU								.24
SpMLU								—

Note. Significant p values after Benjamini–Hochberg corrections have been applied are **in bold**. EnNWR = English nonword repetition test; SpNWR = Spanish nonword repetition test; EnVoc = English vocabulary; SpVoc = Spanish vocabulary; EnNDW = English number of different words; SpNDW = Spanish number of different words; EnMLU = English mean length of utterance; SpMLU = Spanish mean length of utterance; ExEn = proportion exposure to English.

$^{***}p < .001$.

Appendix D (p. 1 of 2)

Influence of Complexity and Syllable Length on Nonword Repetition Accuracy Across Age Range for the Different Nonword Repetition Tests

Table D1. Influence of complexity and syllable length on English nonword repetition accuracy across age range (30, 36, and 48 months) in the French–English bilinguals.

	Age in months					
	30		36		48	
Variable	*M*	*SD*	*M*	*SD*	*M*	*SD*
Complexity[a]						
2	72.38	13.36	76.61	15.22	92.78	7.43
3	71.75	13.27	81.4	13.2	88.75	9.85
4	55.83	16.69	80.26	12.61	81.22	12.44
5			65.46	24.33	83.75	14.43
6					77.87	13.87
Syllable no.						
1	69.51	16.64	73.75	16.17	87.5	11.86
2	78.64	15.52	81.75	11.62	90.48	9.73
3	58.13	17.76	78	16.34	86.35	12.91
4			71.05	16.38	83.62	11.07
5					74.88	15.92

[a]Complexity levels were combined when a given complexity level was represented by a single nonword to avoid sampling across a minimal number of items. Thus, instead of six to seven complexity levels, consonant accuracy is shown for a maximum of five complexity levels.

Table D2. Influence of complexity and syllable length on French nonword repetition accuracy across age range (30, 36, and 48 months) in the French–English bilinguals.

	Age in months					
	30		36		48	
Variable	*M*	*SD*	*M*	*SD*	*M*	*SD*
Complexity						
2	71.54	17.31	80.81	14.49	91.47	9.3
3	59.07	15.58	66.47	25.89	82	17.95
4	58.33	17.52	64.71	19.57	79.17	16.18
5			61.34	18.57	67.46	14.93
6					65.33	20.24
Syllable no.						
1	63.89	17.61	63.45	17.1	76.67	16.08
2	71.25	21.11	79.61	25.76	91.25	10.81
3	59.86	14.49	72.81	20.06	86.33	12.8
4			64.71	16.54	75.9	13.68
5					64.74	18.02

Appendix D (p. 2 of 2)

Influence of Complexity and Syllable Length on Nonword Repetition Accuracy Across Age Range for the Different Nonword Repetition Tests

Table D3. Influence of complexity and syllable length on English nonword repetition accuracy across age range (30, 36, and 48 months) in the Spanish–English bilinguals.

	Age in months					
	30		36		48	
Variable	***M***	***SD***	***M***	***SD***	***M***	***SD***
Complexity						
2	72.38	13.36	76.61	15.22	92.78	7.43
3	71.75	13.27	81.4	13.2	88.75	9.85
4	55.83	16.69	80.26	12.61	81.22	12.44
5			65.46	24.33	83.75	14.43
6					77.87	13.87
Syllable no.						
1	69.51	16.64	73.75	16.17	87.5	11.86
2	78.64	15.52	81.75	11.62	90.48	9.73
3	58.13	17.76	78	16.34	86.35	12.91
4			71.05	16.38	83.62	11.07
5					74.88	15.92

Table D4. Influence of complexity and syllable length on Spanish nonword repetition accuracy across age range (30, 36, and 48 months) in the Spanish–English bilinguals.

	Age in months					
	30		36		48	
Variable	***M***	***SD***	***M***	***SD***	***M***	***SD***
Complexity						
2	71.54	17.31	80.81	14.49	91.47	9.3
3	59.07	15.58	66.47	25.89	82	17.95
4	58.33	17.52	64.71	19.57	79.17	16.18
5			61.34	18.57	67.46	14.93
6					65.33	20.24
Syllable no.						
1	63.89	17.61	63.45	17.1	76.67	16.08
2	71.25	21.11	79.61	25.76	91.25	10.81
3	59.86	14.49	72.81	20.06	86.33	12.8
4			64.71	16.54	75.9	13.68
5					64.74	18.02

Appendix E (p. 1 of 4)

Step-by-Step Outline of Statistical Models

Model 1. Influence of the English nonword repetition test on language measures in the French–English bilinguals.

Variable	Estimate	*SE*	*z*	Pr(>|z|)	
Control				AIC: 1934.5	BIC: 1965.3
(Intercept)	1.3397	0.1671	8.018	1.08e−15***	
Complexity	−0.2203	0.1095	−2.012	0.0442*	
Age range 36	0.9091	0.1347	6.750	1.48e−11***	
Age range 48	1.8805	0.1731	10.862	< 2e−16***	
Control + Between				AIC: 1925.0	BIC: 1966.1
(Intercept)	1.35952	0.16039	8.476	< 2e−16***	
FrVoc	0.01145	0.08653	0.132	0.89471	
FrNWR	0.25952	0.07873	3.296	0.00098***	
Complexity	−0.22290	0.10978	−2.030	0.04232*	
Age range 36	0.85232	0.13401	6.360	2.01e−10***	
Age range 48	1.77017	0.17312	10.225	< 2e−16***	
Control + Between + Interactions				AIC: 1918.4	BIC: 1969.8
(Intercept)	1.39926	0.15973	8.760	< 2e−16***	
FrVoc	0.23011	0.11221	2.051	0.04029*	
FrNWR	0.33648	0.08165	4.121	3.77e−15***	
Complexity	−0.22338	0.11012	−2.029	0.04251*	
Age range 36	0.76983	0.13541	5.685	1.31e−18***	
Age range 48	1.69991	0.17424	9.756	< 2e−16***	
FrVoc × Age range 36	−0.32757	0.13419	−2.441	0.01465*	
FrVoc × Age range 48	−0.51550	0.16102	−3.201	0.00137**	
Control + Between + Interactions + Within (final model)				AIC: 1914.4	BIC: 1970.8
(Intercept)	1.41613	0.15448	9.167	< 2e−16***	
EnVoc	0.19941	0.07675	2.598	0.009372**	
FrVoc	0.21251	0.10787	1.970	0.048841*	
FrNWR	0.32108	0.07963	4.032	5.52e−05***	
Complexity	−0.22083	0.10978	−2.012	0.044262*	
Age range 36	0.73303	0.13385	5.476	4.34e−08***	
Age range 48	1.67485	0.17197	9.739	< 2e−16***	
FrVoc × Age range 36	−0.35952	0.13192	−2.725	0.006424**	
FrVoc × Age range 48	−0.53433	0.15770	−3.388	0.000703***	

Note. AIC = Akaike information criterion; BIC = Bayesian information criterion; FrVoc = French vocabulary; FrNWR = French nonword repetition test; EnVoc = English vocabulary.

**p* < .05. ***p* < .01. ****p* < .001.

Appendix E (p. 2 of 4)

Step-by-Step Outline of Statistical Models

Model 2. Influence of the French nonword repetition test on language measures in the French–English bilinguals.

Variable	Estimate	*SE*	*z*	Pr(>|z|)	
Control				AIC:1965.8	BIC: 1996.3
(Intercept)	1.3062	0.1891	6.908	4.90e–12***	
Complexity	–0.4408	0.1246	–3.537	0.000405***	
Age range 36	0.7006	0.1401	5.002	5.69e–07***	
Age range 48	1.3002	0.1666	7.806	5.88e–15***	
Control + Between				AIC: 1952.1	BIC: 1992.8
(Intercept)	1.33531	0.18387	7.262	3.80e–13***	
EnMLU	0.01301	0.07411	0.176	0.860670	
EnNWR	0.35192	0.08428	4.176	2.97e–05***	
Complexity	–0.44859	0.12483	–3.593	0.000326***	
Age range 36	0.61894	0.13969	4.431	9.38e–06***	
Age range 48	1.24381	0.16598	7.494	6.69e–14***	
Control + Between + Interactions				AIC: 1939.2	BIC: 2000.3
(Intercept)	1.3711	0.1831	7.489	6.94e–14***	
EnMLU	0.2289	0.1630	1.405	0.160102	
EnNWR	0.5529	0.1216	4.547	5.45e–06***	
Complexity	–0.4544	0.1257	–3.616	0.000299***	
Age range 36	0.5477	0.1417	3.866	0.000111***	
age range 48	1.1863	0.1709	6.942	3.86e–12***	
EnMLU × Age range 36	–0.1748	0.1773	–0.986	0.324190	
EnMLU × Age range 48	–0.4855	0.2120	–2.290	0.022012*	
EnNWR × Age range 36	–0.2350	0.1441	–1.631	0.102907	
EnNWR × Age range 48	–0.4772	0.1441	–3.310	0.000932***	
Control + Between + Interactions + Within				AIC: 1919.3	BIC: 1990.6
(Intercept)	1.35597	0.16377	8.280	< 2e–16***	
FrVoc	0.28206	0.08061	3.499	0.000467***	
FrMLU	0.22898	0.07932	2.887	0.003890**	
EnMLU	0.33616	0.14394	2.335	0.019518*	
EnNWR	0.38757	0.11096	3.493	0.000478***	
Complexity	–0.45670	0.12481	–3659	0.000253***	
Age range 36	0.50604	0.13355	3.789	0.000151***	
Age range 48	1.11492	0.16155	6.901	5.15e–12***	
EnMLU × Age range 36	–0.27966	0.16689	–1.676	0.093797	
EnMLU × Age range 48	–0.56585	0.19135	–2.957	0.003105**	
EnNWR × Age range 36	–0.15838	0.13690	–1.157	0.247269	
EnNWR × Age range 48	–0.29190	0.14303	–2.041	0.041269*	
Control + Between + Interactions + Within + Interactions (final model)				AIC: 1897.7	BIC: 1969.0
(Intercept)	1.33546	0.16378	8.154	3.52e–16***	
FrVoc	0.24041	0.10973	2.191	0.028455*	
FrMLU	0.24464	0.07963	3.072	0.002126**	
EnMLU	0.41814	0.13105	3.191	0.001419**	
EnNWR	0.24768	0.06761	3.663	0.000249***	
Complexity	–0.46772	0.12634	–3.702	0.000214***	
Age range 36	0.48156	0.13260	3.632	0.000282***	
Age range 48	1.28387	0.16822	7.632	2.31e–14***	
FrVoc × Age range 36	–0.16138	0.13624	–1.185	0.236201	
FrVoc × Age range 48	0.57744	0.16228	3.558	0.00373***	
EnMLU × Age range 36	–0.44797	0.14856	–3.015	0.002566**	
EnMLU × Age range 48	–0.38421	0.19953	–1.926	0.054160	

Note. AIC = Akaike information criterion; BIC = Bayesian information criterion; EnMLU = English mean length of utterance; EnNWR = English nonword repetition test; FrVoc = French vocabulary; FrMLU = French mean length of utterance.

**p* < .05. ***p* < .01. ****p* < .001.

Model 3. Influence of the English nonword repetition test on language measures in the Spanish–English bilinguals.

Variable	**Estimate**	***SE***	***z***	**Pr(>|z|)**	
Control				AIC: 1832.1	BIC: 1861.1
(Intercept)	0.5842	0.2067	2.826	0.00472**	
Complexity	−0.4211	0.1481	−2.843	0.00446**	
Age range 36	0.7754	0.1363	5.689	1.28e−08***	
Age range 48	1.5776	0.1450	10.883	< 2e−16***	
Control + Between				AIC: 1824.4	BIC: 1858.2
(Intercept)	0.6252	0.1953	3.201	0.001369**	
SpNWR	0.2587	0.0772	3.351	0.000806***	
Complexity	−0.4193	0.1480	−2.833	0.004617**	
Age range 36	0.7061	0.1361	5.188	2.13e−07***	
Age range 48	1.5029	0.1451	10.355	< 2e−16***	
Control + Between + Interactions				AIC: 1808.6	BIC: 1852.0
(Intercept)	0.6235	0.1951	3.196	0.00139**	
SpNWR	0.2408	0.1073	2.245	0.02477*	
Complexity	−0.4178	0.1490	−2.803	0.00506**	
Age range 36	0.7745	0.1382	5.603	2.11e−08***	
Age range 48	1.4689	0.1445	10.167	< 2e−16***	
SpNWR × Age range 36	0.3344	0.1413	2.367	0.01793*	
SpNWR × Age range 48	−0.1500	0.1369	−1.095	0.27333	
Control + Between + Interactions + Within (final model)				AIC: 1794.6	BIC: 1847.6
(Intercept)	0.61385	0.18474	3.323	0.000891***	
EnVoc	0.19657	0.07323	2.684	0.007266**	
EnMLU	0.18463	0.06523	2.830	0.004650**	
SpNWR	0.23585	0.10147	2.324	0.020104*	
Complexity	−0.42157	0.14945	−2.821	0.004789**	
Age range 36	0.79807	0.13671	5.837	5.3e−09***	
Age range 48	1.46100	0.14285	10.228	< 2e−16***	
SpNWR × Age range 36	0.36981	0.13528	2.734	0.006265**	
SpNWR × Age range 48	−0.06221	0.13180	−0.472	0.636953	

Note. AIC = Akaike information criterion; BIC = Bayesian information criterion; SpNWR = Spanish nonword repetition test; EnVoc = English vocabulary; EnMLU = English mean length of utterance.

**p* < .05. ***p* < .01. ****p* < .001.

Appendix E (p. 4 of 4)

Step-by-Step Outline of Statistical Models

Model 4. Influence of the Spanish nonword repetition test on language measures in the Spanish–English bilinguals.

Variable	Estimate	*SE*	*z*	Pr(>|z|)	
Control				AIC: 1760.1	BIC: 1789.0
(Intercept)	0.4208	0.2018	2.086	0.037*	
Complexity	−0.5367	0.1122	−4.784	1.72e−06***	
Age range 36	0.6312	0.1438	4.459	8.24e−06***	
Age range 48	1.4450	0.1507	9.589	< 2e−16***	
Control + Between				AIC: 1745.3	BIC: 1783.7
(Intercept)	0.48084	0.18905	2.543	0.010977*	
EnMLU	−0.22992	0.07868	−2.922	0.003473**	
EnNWR	0.32024	0.08007	3.999	6.35e−05***	
Complexity	−0.54349	0.11266	−4.824	1.40e−06***	
Age range 36	0.51963	0.14530	3.576	0.000349***	
Age range 48	1.33915	0.15074	8.884	< 2e−16***	
Control + Between + Within (final model)				AIC: 1737.0	BIC: 1780.3
(Intercept)	0.51876	0.18752	2.766	0.00567**	
SpVoc	0.24404	0.07618	3.204	0.00136**	
EnMLU	−0.21636	0.07773	−2.784	0.00537**	
EnNWR	0.24913	0.08293	3.004	0.00266**	
Complexity	−0.54864	0.11343	−4.837	1.32e−06***	
Age range 36	0.47729	0.14571	3.276	0.00105**	
Age range 48	1.28819	0.151000	8.531	< 2e−16***	

Note. AIC = Akaike information criterion; BIC = Bayesian information criterion; EnMLU = English mean length of utterance; EnNWR = English nonword repetition test; SpVoc = Spanish vocabulary.

*$p < .05$. **$p < .01$. ***$p < .001$.