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Compensation for Phonological Assimilation in Bilingual Children

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ABSTRACT

We investigate bilingual children's perception of assimilations, i.e. phonological rules by which a consonant at a word edge adopts a phonological feature of a neighboring consonant. For instance, English has place assimilation (e.g., *green* is pronounced with a final [m] in *green pen*), while French has voicing assimilation (e.g., *sac* is pronounced with a final [g] in *sac vert* "green bag"). Previous research has shown that French and English monolingual toddlers compensate for the assimilation rule of their language, correctly recovering the intended words, but not for a rule that does not exist in their language. Using a word recognition videogame with French sentences, we show that French-English bilingual 6-year-olds perform exactly like French monolinguals of the same age: they compensate for voicing but not for place assimilation. Thus, despite their dual language input they have acquired French voicing assimilation and show no interference from English place assimilation.

Introduction

Bilingual children need to acquire two distinct phonological systems, each composed of a variety of aspects, such as sound categories, syllable structure, and phonological rules. As in monolinguals, phonological acquisition begins very early, but does not necessarily proceed at the same speed. For instance, depending on the language pair and the overlap between their sound categories, the acquisition of these categories and the ability to use them for word learning can take longer to develop when infants are exposed to a dual language input (Fennell, Byers-Heinlein, & Werker, 2007; Havy, Bouchon, & Nazzi, 2016; Liu & Kager, 2015; Ramon-Casas, Swingley, Sebastián-Gallés, & Bosch, 2009; Sundara, Polka, & Genesee, 2006). This delay can be due both to the reduced exposure to each of the languages compared to the exposure of monolingual children, and to exposure to foreign-accented speech by one or both of their parents (Ramon-Casas, Fennell, & Bosch, 2017; Ramon-Casas et al., 2009). Bilingual acquisition might even lead to a different end state than that of monolinguals in the phonological processing of one or both of their languages (Cutler, Mehler, Norris, & Segui, 1989; Dupoux, Peperkamp, & Sebastián-Gallés, 2010; Sebastián-Gallés, Echeverría, & Bosch, 2005). For instance, contrary to 18–24 months-old Catalan monolinguals, 3- to 4½-year-old Spanish-Catalan bilinguals who are Spanish-dominant still fail to differentiate the vowels /e/ and /ɛ/ in Catalan word recognition (Ramon-Casas et al., 2009), and this failure has in fact been observed even in adult simultaneous (but Spanish-dominant) bilinguals (Sebastián-Gallés et al., 2005).

As to the way in which individual sounds combine and interact within words and phrases, children exposed to a dual speech input are faced with the task of disentangling and learning two sets of language-specific phonological rules and constraints. This challenging task may produce different patterns of acquisition compared to what has been documented for monolingual children.

Research on phonological development in young bilinguals beyond the acquisition of sound categories, however, remains scarce, and has so far focused on children's productions (Fabiano-Smith, Oglivie, Maiefski, & Schertz, 2015; MacLeod & Fabiano-Smith, 2015; Nicoladis & Paradis, 2011; Paradis, 2001). For instance, in a study using a non-word repetition task, Paradis (2001) investigated French-English bilingual toddlers' truncations in nonce words. Truncations (e.g., *nana* for *banana*) are typical of toddlers' productions and are known to be influenced by language-specific word-prosodic properties (Allen & Hawkins, 1980). While the truncation patterns of the bilingual toddlers in each of their languages were found to generally match those of the corresponding monolingual French and English toddlers, there was also some evidence of cross-linguistic transfer. Thus, their phonological systems appeared to be differentiated, yet not fully independent. In another study using a picture naming task, Nicoladis and Paradis (2011) explored French-English bilingual children's production of liaison, a complex phonological rule in French that causes word-final silent consonants to be pronounced before a vowel-initial word (e.g., *petit* [pəti] "small" is pronounced as [pətit] in *petit ours* "small bear"). They found that, in general, 3- to 5-year-old children's French vocabulary – but not their age – correlated positively with their production of liaison. Interestingly, when matched by vocabulary, bilinguals applied liaison less often than their monolingual peers, but only in low-frequency collocation frames, suggesting that their acquisition of liaison lagged behind that of monolinguals. However, the sample size of this matched comparison was very small (6 monolinguals and 6 bilinguals), making it difficult to draw conclusions.

Here, we investigate the perception of a phonological process that alters the surface form of words in specific contexts. *Assimilations* are phonological rules that cause certain sounds to adopt specific features from adjacent sounds. While common across the world's languages, the sounds that undergo a change, the specific features that change, and the contexts that trigger them vary from one language to the other. For example, in English, the word-final alveolar consonants /t/, /d/, and /n/ can adopt the place of articulation of a following labial (/b/, /m/, /p/) or velar (/g/, /k/) consonant. Thus, a word like *green* [ɡri:n] may be produced as *greem* [ɡri:m] if followed by a word beginning with a labial sound, such as the consonant /b/ in the phrase *green ball* [ɡri:m bɔ:l]. While *place* assimilation rules are present in many languages, assimilation may also involve other features. This is the case in French, which has no phonological place assimilation rule; instead, it is the *voicing* feature (i.e., the vibration of the vocal folds) of certain consonants that may spread to neighboring sounds. More specifically, voiceless obstruents (/p/, /t/, /k/, /f/, /s/, /ʃ/) may adopt the voicing value of a following voiced obstruent (/b/, /d/, /g/, /v/, /z/, /ʒ/), and, vice versa, voiced obstruents may turn into their voiceless counterparts if followed by a voiceless obstruent. For instance, due to voicing assimilation the French word *robe* [ʁɔb] "dress" may be pronounced as [ʁɔp] if followed by a word beginning with a voiceless obstruent, as in the phrase *robe sale* [ʁɔpsal] "dirty dress". The application of assimilation rules is context-specific, such that, for instance, the word *robe* does not undergo assimilation if followed by a consonant other than a voiceless obstruent, as in the phrase *robe noire* [ʁɔbnwaʁ] "black dress".

There is ample evidence that listeners have detailed knowledge of language-specific assimilation, and compensate for its effect in order to retrieve the intended word (Coenen, Zwitserlood, & Bölte, 2001; Darcy, Ramus, Christophe, Kinzler, & Dupoux, 2009; Gaskell & Marslen-Wilson, 1996; Gaskell & Snoeren, 2008; Mitterer & Blomert, 2003). For instance, using a word detection task, Darcy et al. (2009) showed that French listeners tend to recognize the word *robe* [ʁɔb] when it is pronounced with a final [p] in a sentence containing *robe sale*, where voicing assimilation is viable, but not in a sentence containing *robe noire*, where it is unviable. Thus, they compensate for their native rule of voicing assimilation in a context-sensitive manner. By contrast, they hardly compensate for a hypothetical rule of place assimilation; that is, they generally fail to recognize the word *lune* [lyn] "moon" when it is pronounced with final [m] in a sentence containing *lune pale* "pale moon", even though it presents a viable context for place assimilation (the place of articulation of both [m] and [p] is labial).¹ English

¹They recognize it even less when it is pronounced with final [m] in an unviable context for place assimilation, such as *lune rousse* "red moon" (*rousse* starts with a uvular, not a labial, consonant), suggesting a small language-independent compensation effect.

listeners who were tested on English sentences showed the reverse pattern; that is, they compensated more for their native rule of place assimilation than for a hypothetical rule of voicing assimilation.

Compensation for assimilation has also been found in children. For instance, Marshall, Ramus, and van der Lely (2010) adapted the word detection task of Darcy et al. (2009) and observed compensation for English place assimilation both in normally developing children aged between 9 and 12 years, and in children with dyslexia and/or SLI. More recently, different paradigms have been used to study compensation for assimilation in younger children (Skoruppa, Mani, & Peperkamp, 2013; Skoruppa, Mani, Plunkett, Cabrol, & Peperkamp, 2013). For instance, Skoruppa, Mani and Peperkamp (2013) developed a picture-pointing task for French and English 2½- to 3-year-old toddlers. French toddlers were tested on both their native voicing assimilation and the non-native place assimilation rule. In each trial, they were first presented with two pictures, one of a familiar and one of an unknown object. Each picture was presented with a short labeling sentence, where the label for the unknown object differed from that of the familiar one only in either the place or the voicing feature of the final consonant. For instance, the familiar object chair – in French: *chaise* [ʃɛz] – would be paired with an unknown object called [ʃɛs]. Both pictures then reappeared on screen side by side, accompanied by a phrase containing the novel word embedded in one of two possible phonological contexts: either followed by a consonant that allows for the corresponding assimilation (*viable* condition), such as the voiceless obstruent /p/ in *Montre la [ʃɛs] par ici!* “Show the [ʃɛs] over here!”, or followed by a context that does not license the respective assimilation (*unviable* condition), such as the liquid consonant /l/ in *Montre la [ʃɛs] là-bas!* “Show the [ʃɛs] over there!”. In voicing assimilation trials, French toddlers pointed at the familiar object more often upon hearing the altered word form in a viable than in an unviable context for assimilation. Furthermore, when tested on non-native place assimilation, they failed to recognize the familiar words independently of the context. Additionally, English toddlers were tested, but only on their native place assimilation rule, for which they showed context-sensitive compensation. In a second study, however, Skoruppa, Mani, Plunkett, et al. (2013) showed that like French toddlers, English toddlers fail to compensate for a non-native assimilation rule. Here, 24-month-olds were tested in an intermodal preferential looking paradigm. The design of the experiments was similar to the one for the picture pointing task. In particular, pictures of familiar objects were paired with pictures of unfamiliar objects whose label differed from that of the familiar one only in the last consonant. Following the presentation of the two pictures and their labels, the pictures were shown side by side and toddlers were asked to look at one of them. Both French and English toddlers were tested on voicing assimilation. French toddlers increased their looks to the familiar object in the post-naming phase when they heard an assimilated form in a viable but not in an unviable context. English toddlers, by contrast, showed no such increase, regardless of the context in which the assimilated form occurred.

Taken together, these studies thus show that like adults, French and English toddlers show language-specific knowledge of assimilation: they compensate for their native but not for a non-native assimilation rule. This is quite remarkable, since the frequency with which assimilation applies in spontaneous speech tends to be low. For instance, Dilley and Pitt (2007) found that in an English corpus of spontaneous speech, 3.2% of words ended in a consonant that can undergo place assimilation given its following context, of which 9% were effectively assimilated. Note, though, that a higher assimilation rate, 22%, has been reported for English infant-directed speech (Buckler, Goy, & Johnson, 2018). For French, no systematic analysis of voicing assimilation rates in conversational speech has yet been conducted. However, in a corpus of journalistic speech, Adda-Decker and Hallé (2007) found that 1.8% of all word boundaries contained a viable context for voicing assimilation, and assimilation rates were slightly above 20%.

What makes these previous studies particularly interesting is that they examined compensation for complete assimilation. In fact, in the sentences that were read by the speaker who recorded the stimuli, the spelling of the assimilated forms reflected a complete change in voicing or place of articulation. For instance, the voicing-assimilated form of the word *chaise* [ʃɛz] was written as the non-word *chaisse*, corresponding to [ʃɛs]. There were thus no acoustic traces of the canonical form.

In spontaneous speech, assimilation is often partial, yielding a phonetically ambiguous sound (English place assimilation: Ellis & Hardcastle, 2002; Dillely & Pitt, 2007; Gaskell & Snoeren, 2008; French voicing assimilation: Snoeren, Hallé, & Segui, 2006; but cf. Hallé & Adda-Decker, 2007). Such partial assimilations are easier for the listener to compensate since they contain bottom-up cues to the target consonant (see, for instance, Snoeren, Segui, & Hallé, 2008), and indeed compensation in these cases does not rely primarily on experience with the rule in one's native language (e.g., Gow & Im, 2004; Mitterer, Csépe, & Blomert, 2006; Mitterer, Csépe, Honbolygo, & Blomert, 2006). By contrast, when assimilation is complete, listeners must rely on abstract, phonological, knowledge of the rule. Moreover, complete assimilation creates potential lexical ambiguities, and hence interferes with word recognition. This is especially challenging for young children, who are in the process of building a lexicon. Thus, they might hypothesize that, for instance, [ʒz]-[ʒs] represents a minimal pair rather than two surface forms of the word *chaise*, and hence look for two associated meanings rather than one.

The aim of the present study is to examine how the presence of a second language during early childhood affects the acquisition of assimilation rules. Would bilingual children perform like two monolinguals in one, hence showing evidence of language-specific phonological processing in both of their languages? To start investigating this question, we examine how French-English bilingual children who have heard both languages regularly from their first year of life perceive complete voicing and place assimilation when listening to French. While place assimilation is not part of French phonology, French-English bilinguals may be familiar with this rule from their English input. Moreover, depending on their parents' language background and use, they might be exposed to English-accented French (as well as to French-accented English). Obligatory native phonological rules have been shown to transfer to L2 speech; for instance, many native Polish speakers apply their rule of final obstruent devoicing in their L2 English (Flege & Dravidian, 1984). Research on the production of cross-word assimilation rules in adult L2 speech appears to be nearly inexistent, but we are aware of one piece of evidence: Altenberg and Vago (1983) examined the L2 English of two native Hungarian speakers and found that one of them tended to apply the Hungarian rule of regressive voicing assimilation that does not exist in English. Thus, bilingual children might be exposed to some L2 French containing place assimilations, which might interfere with their acquisition of voicing assimilation.²

Two constraints weigh heavily on the choice of experimental design and the age at which we can test children in the present study. First, in order to directly compare children's processing of voicing vs place assimilation, we need to test each child on both rules in a single experiment. Even more so, for the experiment to be interesting to do with bilingual children, the monolingual children should show a significant interaction between rule (voicing vs. place assimilation) and context (viable vs. unviable). In other words, they should show a strong context effect for voicing assimilation and no such effect (or a much weaker one) for place assimilation, thus providing clear-cut evidence for language-specific knowledge of assimilation. In the studies with monolingual toddlers mentioned above (Skoruppa, Mani, & Peperkamp, 2013; Skoruppa, Mani, Plunkett, et al., 2013), native and non-native rules were tested in separate groups of participants and the interaction was not tested. By contrast, the monolingual adults in Darcy et al. (2009) were tested on both rules and did show the crucial interaction. Second, we need a sufficient number of monosyllabic nouns that are both imageable and assimilable, and that are known by both mono- and bilingual children. This is not an easy feat, most importantly because the lexicons of bilingual children in each of their two languages are known to be smaller than that of the unique language of monolinguals of the same age, due to their reduced exposure to each language (Bialystok, Luk, Peets, & Yang, 2010; Hoff et al., 2012; Marchman, Fernald, & Hurtado, 2010). In addition, given the within-participant design, the items for voicing assimilation and those for place assimilation need to constitute different sets. Finally, none of the items should have an assimilated form that corresponds to a real word known by children, and French-English cognates should be avoided.

²Although we are not aware of any research showing the mere absence of the application of L2 assimilation rules, we conjecture that bilingual children might also be exposed to L2 French in which neither voicing nor place assimilation applies.

In light of these constraints, we decided to test 6-year-old children, to select 12 items for each of the rules plus a few extra for training, and to implement the study as a child-friendly touchpad videogame that would keep them engaged. In this game, children are presented with pictures of familiar objects. For each item they hear a phrase containing the object's name, always pronounced with either a place or a voicing change in its final consonant in either a viable or an unviable context for the corresponding assimilation rule. If children recognize the altered word form as a good pronunciation of the familiar object, they are to touch its picture, shown on one side of the screen, while if they reject it as a valid pronunciation of the target word, they are instructed to touch a red cross, shown on the other side. How often children touch the picture of the familiar object – that is, how often they accept the altered word form as a good pronunciation – in the viable and unviable contexts for each assimilation rule is thus informative of their ability to compensate for assimilation. The sentences for voicing assimilation and those for place assimilation are intermingled, such as to avoid order effects.

In Experiment 1, we test French monolingual 6-year-olds. Based on previous results with monolingual adults (Darcy et al., 2009) and toddlers (Skoruppa, Mani & Peperkamp, 2013; Skoruppa, Mani, Plunkett, et al., 2013), we expect them to show compensation for voicing (native) assimilation but little or no compensation for place (non-native) assimilation. Crucially, we also expect to observe a significant difference in their response patterns for these two rules, thus providing clear evidence that native and non-native assimilation are treated differently.

In Experiment 2, we test French-English bilingual children of the same age, for whom there are several plausible outcomes. On the one hand, 6-year-old bilinguals may have already acquired French voicing assimilation, with no interference from English. If this is the case, then we should observe the same response pattern as that in their monolingual peers in Experiment 1, i.e. compensation for voicing but not or only a little for place assimilation. On the other hand, it is possible that bilinguals show signs of delay and/or cross-linguistic influence in their compensation patterns. For instance, a substantial delay might lead them to show a lack of compensation by rejecting all assimilated forms, even those representing valid voicing assimilations. Alternatively, due to their familiarity with place assimilation in their English input and/or the presence of some place assimilation in English-accented French input, they may show context-specific compensation for both voicing and place assimilation in French. Or, they may be confused about the precise nature of the two rules in their two languages; they could thus be more flexible regarding mispronunciations and accept all word alterations as valid, regardless of context. Other outcomes, however, are unexpected in any plausible developmental trajectory. For instance, we do not expect to observe compensation for place but not for voicing assimilation, or acceptance of place but not of voicing changes regardless of context.

In line with current standards for transparency in research, we have made all materials, data, and analysis scripts available in a dedicated project page hosted by the Open Science Framework platform: <https://osf.io/52z9g/>.

Experiment 1: monolinguals

Methods

Participants

Twenty-one French monolingual 6-year-olds (13 girls, 8 boys, mean age: 70.01 months, age range: 64.73–75.33 months) participated. An additional two children were tested but not included in the analysis due to failure to pass the training criteria (see *Exclusion criteria* section below). Written consent was obtained from the parents of all participating children prior to testing.

Materials

A set of twenty-four monosyllabic French nouns and matching color pictures were selected as test items. Some of the pictures were taken from Rossion and Pourtois' (2004) color version of the Snodgrass pictures set; the others were drawn by the first author. All items were judged to be known by French 6-year-old children based on vocabulary questionnaires collected during a pilot study. Several of the nouns had an English cognate that differed, however, in at least one phoneme.

Half of the nouns were selected to test voicing assimilation, the other half to test place assimilation (see Appendix). The nouns for voicing assimilation ended in either a voiced or a voiceless obstruent, e.g., *robe* [ʁɔb] “dress”, *tasse* [tas] “cup”. From each of these nouns, an assimilated form was constructed by changing the voicing value of the final consonant, thus transforming voiced obstruents into their voiceless counterparts, and vice-versa (e.g., [ʁɔb] → [ʁɔp], [tas] → [taz]). The nouns for place assimilation ended in one of the alveolar consonants [t, d, n], e.g., *botte* [bɔt] “boot”, *viande* [vjɑ̃d] “meat”, *lune* [lyn] “moon”. From each of these nouns, an assimilated form was constructed by changing the place of articulation of the final consonant to bilabial (e.g. [bɔt] → [bɔp], [vjɑ̃d] → [vjɑ̃b], [lyn] → [lym]). Most assimilated forms were non-words; four of them were infrequent real words not known to 6-year-old children.

Each of the 24 assimilated forms was embedded in two short sentences with a touching request. One of the sentences provided a *viable* context for assimilation, and one an *unviable* context. Examples are shown in Table 1. Thus, for voicing assimilation, the final obstruent of the assimilated form was followed by an obstruent with the same voicing value (viable context), or by any other consonant (i.e., an obstruent with the opposite voicing value, or a liquid or nasal consonant; unviable context). Similarly, for place assimilation, the final, labial, consonant of the assimilated form was followed by a labial consonant (viable context), or by a consonant with another place of articulation (unviable context). Note that for this rule, the terms *viable* and *unviable* refer to the context's status according to the place assimilation rule in English.

Nine additional color pictures denoting familiar nouns were selected for pre-training ($n = 3$) and training ($n = 6$). The items for pre-training were a ball, a heart, and a hen. The ball was only matched with its correct name (in French, *balle* [bal]), and the other two items were only matched with a non-word, differing from the object's name on either the entire rhyme (**kime* [kim] for *coeur* [kœʁ] “heart”) or on its final consonant (**pouke* [puk] for *poule* [pul] “hen”). The items for training were – like the test items – each matched with both its correct pronunciation and a non-word, differing only in either voicing ($n = 4$) or place of articulation ($n = 2$) of the final consonant (e.g., *glace* [glas] “ice cream” – **glaze* [glaz]). All pre-training and training items, as well as the matched non-words, were embedded in the final position of a short sentence of the form *Touche le/la # !* “Touch the #”.

All sentences were recorded by a phonetically-trained female native French speaker. They were presented to her with the assimilated forms spelled as non-words, for instance *Touche la taze devant toi* and *Touche la taze maintenant* for the assimilated form [taz] of the target word *tasse* [tas] “cup” in the viable and unviable voicing conditions, respectively, and *Touche la bope maintenant* and *Touche la bope devant toi* for the assimilated form [bɔp] of the target word *botte* [bɔt] “boot” in the viable and unviable place assimilation conditions, respectively. She was instructed to read each sentence in child-directed speech, without pauses and without releasing the final consonant of the target word. Minor editing and intensity normalization (70 dB) were done using the software *Praat* (Boersma & Weenink, 2015).

Table 1. Sample sentences with viable and unviable contexts for voicing and place assimilation.

rule	target word	context	example	translation
voicing	<i>tasse</i> [tas] “cup”	viable	<i>Touche la [taz] devant toi !</i>	“Touch the # in front of you.”
		unviable	<i>Touche la [taz] maintenant !</i>	“Touch the # now.”
place	<i>lune</i> [lyn] “moon”	viable	<i>Touche la [lym] par ici.</i>	“Touch the # over here.”
		unviable	<i>Touche la [lym] là-devant.</i>	“Touch the # there up front.”

To verify that the target consonants in the test sentences were always produced in their fully assimilated form, we asked 12 adult monolingual French speakers to listen to the final V(C)C segments of each assimilated word (e.g., [az] from *Touche la taze maintenant*) in both viable and unviable conditions, and to categorize the final consonant. In each trial, they were given two options to choose from: either the assimilated form (in this example, [z]) or the unassimilated form (here, [s]). To avoid a bias for the assimilated form, control samples extracted from sentences in which the target words were produced without assimilation (always in an unviable context, e.g., [as] from *Touche la tasse maintenant*) were included as distractors.³ The order of presentation of the two rules (place, voicing) was alternating, while items and contexts (viable, unviable) were fully randomized. Consonants from voicing items were correctly identified in 97.9% of the cases in the viable condition and 95.8% in the unviable condition. A paired-samples t-test revealed no significant difference in voicing classification accuracy between conditions ($t(11) = 0.67, p = .52$). Consonants from place items were correctly identified in 98.6% of the cases in the viable condition and 92.4% in the unviable condition. No significant difference in place classification accuracy was found between conditions ($t(11) = -1.62, p = .13$). Finally, a two-way ANOVA on samples' accuracy revealed no main effects of rule or condition nor an interaction between them (rule: $F(1,44) = 0.31, p > .1$; condition: $F(1,44) = 0.69, p > .1$, interaction: $F(1,44) = 2.76, p > .1$).

Procedure

The experiment was implemented as a videogame app for tablets. Specifically, we used a modified version of the app of Cristia (2016); this app has an animated cartoon character that interacts with the child. It was installed on an iPad Air 2 (model A1566) with a 9.7-inch screen and running on iOS 9. The study took place either in a quiet room at a kindergarten school in Paris ($n = 13$), or in our babylab ($n = 8$). During the experiment, children sat down at a low table accompanied by the experimenter. Parents of children tested in the babylab were allowed to observe the experimental session through a monitor in a separated room, or by staying in the same room in silence and out of the child's sight.

Before the game began, the experimenter explained the task and motivated the child to play. Children were told that during the game, they would see an object on one side of the screen and a red cross on the opposite side (Figure 1), and that a cartoon girl would appear and ask them to touch the object. Children were then told that the girl sometimes made mistakes while saying the name of the object, and if she did, they should touch the red cross instead of the object. The exact sequence of events in each trial was as follows: first, the picture of the object and the red cross appeared each on one side of the screen. Following a 3 second pause, the girl appeared in the middle of the screen and waited until the child touched her. This second pause, controlled by the children, gave them sufficient time to look at the picture and recognize the object before hearing the phrase. Once they had touched the girl, the touch response became blocked while the girl produced the request phrase. The touch response then reactivated, allowing the child to give an answer by touching either the picture of the object or the red cross. No time limit was given to produce an answer, however, if the child took more than 6 seconds to respond, the girl would make a sound to remind the child to make a choice.

The experiment lasted approximately 10 minutes and was composed of three stages:

Pre-training. The game began with three trials of low difficulty that allowed the child to get familiarized with the game and the touchpad. In all three trials, the target word or non-word appeared sentence-finally (e.g., *Touche la balle !* "Touch the ball!"). The order of pre-training trials was identical for all children, always beginning with a ball paired with its correct pronunciation, and continuing with a heart and then a hen, for which only non-words were used (the first one differing on the entire rhyme, the second one only on the last consonant). During this

³These sentences had been recorded by the same speaker concurrently with the sentences used in the experiment.

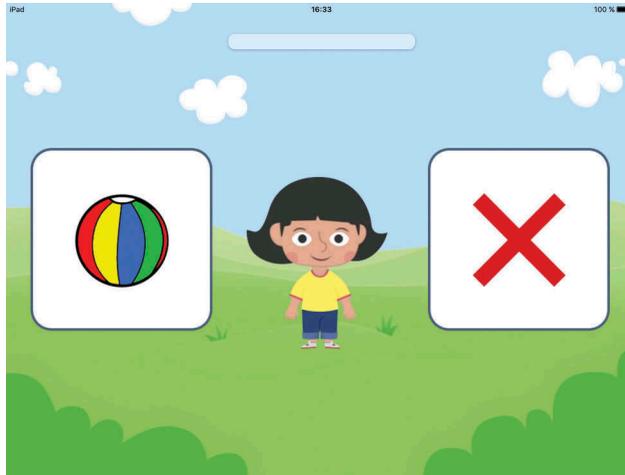


Figure 1. Screenshot of the game, showing the picture of a familiar object (here, a ball) on the left and a red cross on the right, with the cartoon character in the middle.

first stage, the experimenter offered help when necessary, and incorrect trials were repeated until the child answered correctly. Each time a correct answer was given, a cheerful chime played and a progress bar located at the top of the screen increased in size. After completion of pre-training, a star appeared on screen and the child was congratulated before moving on to the next stage.

Training. Children were presented with 6 training trials, half of which contained the correct pronunciation of the target word, and the other half a mispronunciation formed by a change in either voicing or place of articulation of the final consonant. As in pre-training, words appeared sentence-finally and trials were repeated until the correct answer was given, but the experimenter remained silent until the child made a choice. If the answer was correct, they heard a cheerful chime and the experimenter gave positive feedback, while if it was incorrect, the experimenter encouraged the child to try again without offering help. As a reward, a star appeared on screen after the third and sixth successful trial.

Test. Children were told that they had won the first part of the game and would play a second part without any help from the experimenter, who would stay in the room but turn her back and look away. To motivate them to keep playing, the experimenter explained that there were four stars to win, and that they would receive a sticker if they won them all. Unknowingly to them, trials were never repeated, and all children would get to see the four stars and win the sticker.

Children were presented with sentences containing the assimilated form of the target word in sentence-medial position, followed by either a viable or an unviable context for the corresponding assimilation rule. There were six trials of each of four experimental conditions (i.e., *voicing viable*, *voicing unviable*, *place viable*, *place unviable*), for a total of 24 trials. The context in which each test item appeared was counterbalanced across two lists, thus presenting each item only once to each child. Trials were divided into four blocks of six, containing equal numbers of voicing and place trials, as well as equal numbers of viable and unviable trials. Odd-numbered blocks contained two voicing viable trials and one place viable trial; in even-numbered blocks it was the opposite. All four test conditions were completely balanced every two blocks, and the side on which the picture of the target object appeared (left or right) was balanced within every block. No feedback was given during the test, except for the progress bar included in the game. At the end of each block, a star appeared.

Exclusion criteria

Although the game was expected to be easily learnt, a limit on the number of errors accepted in the training phase was imposed to make sure that all children included in the analysis had understood the task. Specifically, children were excluded from analysis if they *a*) made mistakes in more than two items, or *b*) made more than two mistakes on the same item. This resulted in two excluded participants.

Results and discussion

Children's responses were automatically collected by the app and coded as a binary dependent variable representing whether the child touched the picture or the cross in each trial. Figure 2 shows the proportion of trials where the picture of the familiar object was touched, split by condition.

Responses were analyzed with a generalized linear mixed model (GLMM) with binomial family and logit link using the package *lme4* (Bates, Maechler, Bolker, & Walker, 2015) in the *R* environment (R Core Team, 2017). The model included fixed effects of assimilation rule (*voicing*, *place*) and context (*viable*, *unviable*), as well as the interaction between them. A maximal random effects structure was used (Barr, Levy, Scheepers, & Tily, 2013), including an intercept as well as slopes for rule, context and their interaction by participant, and an intercept and slope for context by item. The variables *rule* and *context* were treatment-coded, with *rule* = *voicing* and *context* = *viable* as baseline levels.⁴ *P*-values were obtained for all fixed effects using the *car* package (Fox & Weisberg, 2011).⁵ A summary of the results is shown in Table 2.

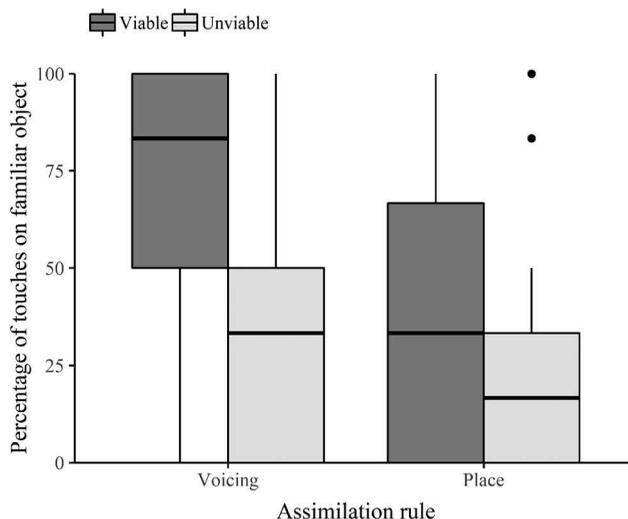


Figure 2. Boxplots representing the percentage of touches of the picture of the familiar object per condition for monolingual children in experiment 1. The bold horizontal line inside each box represents the median, while the bottom and top boundaries represent the first and third quartiles, respectively. Vertical lines extend to the highest and lowest values within 1.5 times the interquartile range above and below the boundaries. Individual dots represent outliers.

⁴In treatment coding, the estimate of the intercept corresponds to the mean of the baseline level, and the estimates for the independent variables correspond to *simple* effects (as opposed to *main* effects) of these variables with respect to the baseline (e.g., the estimate for context given *voicing viable* as baseline corresponds to the difference between voicing viable and voicing unviable trials).

⁵In order to evaluate a potential effect of trial order, the model originally contained block as an additional fixed effect. This factor did not yield a significant effect ($\beta = -0.20$, $SE = 0.22$, n.s.), and was therefore excluded from the model reported in the main text. We also checked that the overall model fit was not better when this factor was included (likelihood-ratio test: $\chi^2(1) = 0.87$, $p = 0.35$).

Table 2. Summary of the generalized linear mixed model for monolinguals.

fixed effect	β	SE	z	p
Intercept (<i>voicing, viable</i>)	1.82	0.97	1.86	0.06
Context (<i>unviable</i>)	-3.30	0.80	-4.11	<.0001
Rule (<i>place</i>)	-3.48	0.97	-3.59	0.0003
Interaction: Rule x Context	2.94	1.19	2.47	0.01

A likelihood ratio test of the resulting GLMM against the null model showed an overall good fit of the data ($\chi^2(3) = 16.3, p = .001$). As shown in Table 2, the estimated intercept shows a marginally significant preference for the familiar object over the cross in *voicing viable* trials. Crucially, the analysis revealed significant effects of rule and context, as well as an interaction of rule by context. The negative estimate for rule indicates that the picture of the familiar object was more often touched when hearing *voicing viable* than *place viable* trials. The negative estimate for context indicates that children touched the picture of the familiar object more often when hearing voicing assimilation in a viable than in an unviable context. As to the interaction, it suggests that the effect of context is smaller for place than for voicing assimilation. In order to examine whether there is an effect of context in place assimilation trials, the rule variable was relevelled with *place* as the baseline level. This releveling revealed no significant difference between viable and unviable contexts for place assimilation ($\beta = -0.37, SE = 0.82, n.s.$).

In line with previous findings with toddlers (Skoruppa et al., 2013, 2013), these results show that French monolingual children compensate for voicing assimilation – a phonological rule that applies in their language – in a context-specific manner, but not for place assimilation, a rule that applies in English but not in French. Furthermore, this experiment successfully allowed for testing a native and a non-native rule within the same group of children, and showed for the first time a significant difference between compensation for the native rule and lack of compensation for the non-native rule, similarly to what has been reported for adults (Darcy et al., 2009). Most importantly, this provides a suitable method for testing bilingual children, as it allows us to simultaneously assess their interpretation of native and non-native rules.

The next experiment assesses compensation for voicing and place assimilation in French-English bilingual children, using the same design and stimuli as in Experiment 1.

Experiment 2: bilinguals

Methods

Preregistration

This experiment was pre-registered – after completion of Experiment 1 – through the Open Science Framework platform (available at <https://osf.io/52z9g/>). At the moment of pre-registration, two bilingual children had already been recruited but their data had not yet been downloaded from the application nor examined in any way. The preregistration document specifies the number of participants, exclusion criteria, and data analysis plan. With the exception of a small modification to the exclusion criteria (see below), the study was conducted as pre-registered.

Participants

Twenty-one French-English bilingual 6-year-olds (10 girls, 11 boys, mean age: 71.44 months, age range: 66.66– 77.40 months) participated in this study. An additional five children were tested but not included in the analysis due to failure to pass the training criteria ($n = 3$), lack of knowledge of one of the training items according to parental report ($n = 1$, see details of exclusion criteria below), or because their age was more than 3SD above the average age of the monolingual group ($n = 1$).

All children had received regular exposure to both French and English since their first year of life (20 children had begun their bilingual exposure at birth, the remaining one had heard French since

birth and English from the age of 6 months). Their language background was assessed through a parental questionnaire, in which parents estimated the percentage of exposure to each language both since birth and in the past six months, as well as the percentage of the child's output in each language. They were also asked to rate their child's comprehension and expression skills in each language on a scale from 1 (doesn't speak the language) to 5 (comparable to a monolingual of the same age). Finally, they provided information regarding their own native language(s) and language use with their child. The questionnaire data are summarized in Table 3. Exposure to each language was comprised between 25% and 75% of the children's total exposure. The majority of the children had a native English speaking mother who had talked to them mostly or only in English since birth ($n = 18$), but overall children heard more French than English. English-speaking parents spoke a variety of English dialects (British, North American, Australian and South-African).

In addition, the parents of nine children used a "one parent one language" approach, meaning that their children had received no direct exposure to any form of foreign-accented speech (although they might have had indirect exposure to it); eight children probably had received some direct exposure to English-accented French, since their native English-speaking parent used some French with them; the remaining four children had one parent who was an early bilingual him- or herself and who spoke some French to the child, which might or might not have been English-accented.

Materials

All materials were the same as those used in Experiment 1.

Procedure

The experiment took place either in our babylab ($n = 13$), or in a quiet room at the participant's home located in the Paris region ($n = 8$). About half of the children were tested on the same iPad Air 2 as those in Experiment 1 (model A1566); the others were tested on a 5th-generation iPad (model MP2F2NF/A) running on iOS 10. Both iPads had the same screen size of 9.7 inch.

All procedures were the same as those used in Experiment 1, except that – as bilingual children's vocabulary could be smaller than their monolingual peers' due to their reduced exposure to each

Table 3. Summary of bilinguals' language background.

parents' native languages	n	main language used with the child		t-test	
		mother	father		
both French monolinguals*	1	French	French		
both English monolinguals	1	English	English		
French mother, English father	1	French	English		
English mother, French father**	11	English ($n = 11$)	French ($n = 11$)		
French-English bilingual mother, French father	5	English ($n = 5$)	French ($n = 5$)		
English mother, French-English bilingual father	1	English	French		
both French-English bilinguals	1	French	English		
		French		English	
language input		mean	range	mean	range
percentage of exposure (since birth)		60%	(40% – 75%)	40%	(25% – 60%)
percentage of exposure (current)		62%	(40% – 80%)	38%	(20% – 60%)
		French		English	
language use		mean	range	mean	range
percentage of output (current)		71%	(50% – 100%)	29%	(0% – 50%)
comprehension rating (1– 5)		4.95	(4– 5)	4.55	(3.5– 5)
expression rating (1– 5)		4.95	(4– 5)	3.79	(1– 5)
					t(20) = 4.06, $p = .0006$

* This family lived in Singapore. the child heard French at home and English from his nanny as well as from staff and classmates at an English kindergarten.

** In two cases one of the parents was bilingual in a second language that was neither English nor French, but never spoke the second language to the child.

language – we verified that the children knew all the training and test items, by asking the main French-speaking caregivers to fill in a short vocabulary questionnaire containing these items before the start of the experiment.

Exclusion criteria

In addition to the exclusion criteria defined in Experiment 1 (which resulted in three excluded participants), two other such criteria were defined for the bilingual group. As pre-registered, children would be excluded from analysis if *a*) any of the items used during training was reported by the parents as not known to the child, or *b*) more than two items in any of the four experimental conditions was reported as not known to the child. Only one child was excluded due to condition *a*), and none due to *b*). As we had initially selected and recorded a few extra training items, we were sometimes able to replace an unknown training item with an alternative known one with the same final contrast, thus preventing participant exclusion. This procedure, which was not pre-registered, was applied on two occasions.

Finally, individual test trials were excluded from analysis if the item was reported as not known by the child in the vocabulary questionnaire.

Results and discussion

Four trials, each from a different child, were excluded from analysis based on their vocabulary questionnaires. Figure 3 shows the proportion of trials where the picture of the familiar object was chosen, split by condition.

The data were analyzed using the same generalized linear mixed model as used for monolinguals in Experiment 1. A summary of the results is shown in Table 4.

The resulting GLMM was tested against the null model through a likelihood ratio test, revealing a good fit of the data ($\chi^2(3) = 16.8, p = .0008$). As monolinguals, bilinguals showed significant effects of rule and context, as well as an interaction of rule by context. The intercept, corresponding to the mean in *voicing viable* trials, revealed a significant preference for the picture of the familiar object over the red cross. The direction of the effects indicates, as in the monolingual group, a higher

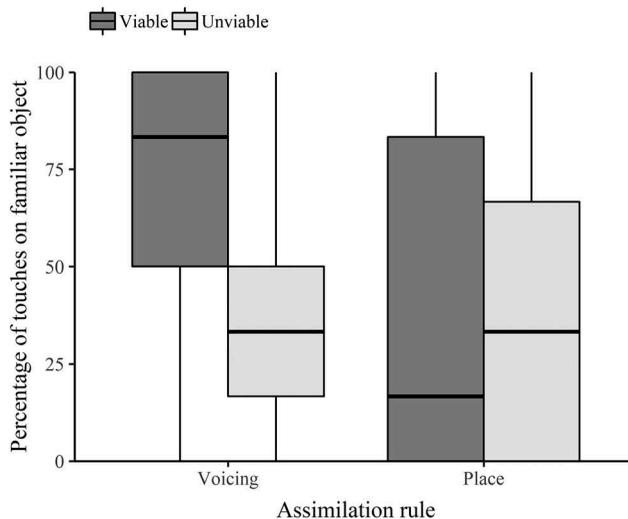


Figure 3. Boxplots representing the percentage of touches of the picture of the familiar object per condition for bilingual children in experiment 2. the bold horizontal line inside each box represents the median, while the bottom and top boundaries represent the first and third quartiles, respectively. Vertical lines extend to the highest and lowest values within 1.5 times the inter-quartile range above and below the boundaries.

Table 4. Summary of the generalized linear mixed model for bilinguals.

Fixed effect	β	se	z	p
Intercept (<i>voicing, viable</i>)	2.77	1.29	2.15	0.03
Context (<i>unviable</i>)	-3.98	0.96	-4.14	<.0001
Rule (<i>place</i>)	-3.65	1.19	-3.06	0.002
Interaction: rule x context	4.34	1.03	4.20	<.0001

preference for the familiar object when hearing *voicing viable* phrases compared to both *voicing unviable* and *place viable* phrases. A releveling of the rule variable with *place* as the baseline revealed no significant effect of context for place assimilation ($\beta = 0.36$, $SE = 0.57$, n.s.); that is, bilingual children did not compensate for this rule. To directly compare the responses of both groups, a post-hoc analysis – not included in the preregistration – was performed, pooling data from both experiments, and including *group* (monolingual, bilingual) as a fixed factor in a triple interaction with rule and context. The resulting model revealed no significant effect of group, neither as a simple effect, nor in interaction with the other fixed factors. Thus, the bilingual children's results do not differ from those of their monolingual peers.

Further post-hoc explorations of the relation between bilingual children's compensation patterns and their language background revealed no correlation between their voicing difference score, defined as the difference between the percentage of touches of the familiar object in the viable minus the unviable conditions in voicing trials, and their percentage of French exposure (since birth: $r = -0.40$, $p = .07$; current: $r = 0.10$, $p > .1$). Similarly, there was no correlation between their place difference score and their percentage of English exposure (since birth: $r = 0.37$, $p = .1$; current: $r = -0.13$, $p > .1$).

Overall, these results show that, like monolingual French children, French-English bilingual children compensate for voicing but not for place assimilation when listening to French. The absence of a correlation between their language input and the magnitude of their compensation for either rule is not surprising given the high overlap between the compensation patterns of monolinguals and bilinguals. However, the number of trials per condition may have been insufficient to observe individual differences. It should also be noted that the bilingual population in this study was relatively homogeneous, as most children had similar language backgrounds (for instance, most of them had an English-speaking mother and a French-speaking father), and the observed range of children's French exposure was narrow (mean exposure to French: 60%, range: 40% – 75%). Different results might thus be observed in a more heterogeneous bilingual sample.

General discussion

Phonological assimilation rules change the surface form of words within sentences in a systematic fashion, and children must learn to undo these changes for the purposes of word recognition; i.e. they must learn to compensate for assimilation. The present study investigated monolingual and bilingual 6-year-olds' compensation for assimilation in French sentences. Using a word recognition task in a tablet-based experiment, we first showed that monolingual French children compensate for a native voicing assimilation rule, but not for a non-native place assimilation rule. That is, they were more likely to recognize the name of a familiar object when presented with a word-final voicing change in a viable context than in an unviable context for voicing assimilation, while they failed to recognize the name when presented with a word-final place change, irrespective of the following context. These results are similar to previous findings with monolingual toddlers (Skoruppa et al., 2013, 2013), but with a critical addition: We simultaneously tested children's processing of native and non-native rules, showing for the first time a significant difference as indicated by the interaction between rule (voicing vs. place assimilation) and context (viable vs. unviable). This interaction was previously reported for adults (Darcy et al., 2009), and it is crucial for our research question on compensation for assimilation in bilinguals.

In our second experiment, we tested French-English bilinguals using the same game, and found that their compensation pattern in French is not different from that of their monolingual peers. That is, they also compensated for voicing but not for place assimilation, and showed a significant interaction between rule and context. Furthermore, their performance did not correlate with the amount of exposure (whether counted from birth or over the last six months) to their two languages. These results indicate that, in spite of their reduced exposure to French, as well as their possible exposure to English-accented French, bilingual 6-year-olds have successfully developed a compensation mechanism for a complex phonological rule, without any apparent interference from the presence of a different assimilation rule in their second language.

One caveat concerning the null results for place assimilation in both mono- and bilingual children is in order. We cannot completely rule out the possibility that some properties of the stimuli for this rule prevented compensation. We deem this unlikely, though, for two reasons. First, a single speaker recorded all the sentences in a single session, and without releasing the target consonants. Second, as shown in the Materials section of Experiment 1, we did not find any differences in the identification of the assimilated consonants in the voicing vs the place items by a group of naïve listeners. It should also be noted that compensation for place assimilation in French sentences *has* been found in adult native English speakers who are beginning learners of French (Darcy, Peperkamp, & Dupoux, 2007). Thus, there is no intrinsic reason as to why the phonetics of French would be incompatible with compensation for place assimilation. Finally, assimilation of /t/, /d/ and /n/ before labial consonants, as in our sentences, is cross-linguistically frequent and hence phonetically natural (Blevins, 2004; Jun, 2004).

The present experiments – like the ones in Skoruppa, Mani and Peperkamp (2013) and Skoruppa, Mani, Plunkett, et al. (2013) – provide evidence for abstract knowledge of voicing assimilation, for two reasons. First, we used sentences with complete assimilations. That is, the assimilated forms did not contain acoustic traces of the canonical word forms (the speaker who recorded the stimuli read sentences in which the assimilated forms were spelled as non-words, reflecting a complete change in voicing or place of articulation). Thus, there were no bottom-up acoustic cues indicating the presence of assimilation. Second, assimilation rules are phonetically grounded, in the sense that they spread a phonetic feature from one sound to a neighboring one. French voicing assimilation comes with a twist, though. The rule involves voicing of voiceless obstruents as well as devoicing of voiced obstruents, but in both cases the rule applies only before obstruents. Thus, nasals and liquids, although they are phonetically voiced, do not trigger voicing of a preceding voiceless obstruent. In our materials, seven out of the 12 items for voicing assimilation ended in a voiceless obstruent, and five in a voiced one. If compensation were phonetically-based, the unviable condition – i.e., with a nasal or a liquid context – should have yielded more touches of the picture of the familiar object for items with a final voiceless obstruent (that was hence pronounced as voiced) than for those ending in a voiced one (that was hence pronounced as voiceless). A post-hoc analysis, however, shows that this was not the case ($p > .1$).⁶ Therefore, the context-specific compensation pattern of results that we observed overall must reflect high-level knowledge of how the rule hinges on a distinction between two types of voiced consonants, obstruents on the one hand and nasals and liquids on the other hand.

It would of course be interesting to know how our group of bilingual children would perform on English sentences. Despite the fact that 80% of them had an English-speaking mother, they were on average slightly dominant in French, both in terms of language input (mean: 60% French) and in terms of language use (mean: 71% French, and higher ratings for both comprehension and expression in French). This leaves open the possibility that their performance on English would not be native-like but show interference from French, with compensation not only for place but also for voicing assimilation. At a younger age, French-dominant bilinguals might even compensate only for voicing assimilation when listening to English. Conversely, testing in an Anglophone country would probably allow us to obtain an English-dominant sample, in which we might observe native-like

⁶Numerically, the pattern actually went in the opposite direction, with 28% compensation for voiceless items, e.g., *Montre la tasse maintenant* ([zm]), and 53% for voiced ones, e.g., *Montre la robe là-devant* ([pl]).

performance on English but not on French sentences. While cross-linguistic transfer in bilingual children's phonology has been shown in production (e.g., Fabiano-Smith & Goldstein, 2010; Paradis, 2001), it has, to the best of our knowledge, so far not been studied in perception. Evidence from adult second language learners, however, suggests that transfer could likewise occur in the acquisition of compensation for assimilation. Darcy et al. (2007) tested native speakers of French learning English and native speakers of English learning French, in both their native and their second language (L2). The results revealed that beginner learners tend to transfer their native-rule perception to the newly learnt language: English learners of French compensated for place but not for voicing assimilation not only in English sentences but also – as mentioned above – in French sentences, and vice versa for French learners of English.

Interestingly, Darcy et al. (2007) also found that advanced learners correctly compensated for their native rule in their native language and for the non-native rule in their L2, thus showing full separation of the phonological rules. In other words, late bilinguals can attain native-like performance in both their languages. Compensation for assimilation therefore differs from other aspects of phonological processing, such as segmentation and stress perception, for which even simultaneous bilinguals do not perform as two monolinguals in one (Cutler et al., 1989; Dupoux et al., 2010). In order to document the developmental pathway of compensation for assimilation in bilingual children, and to examine whether they go through a phase of transfer before reaching full separation of their two languages' rules, future work should assess such children with a fully crossed design at different ages, testing each child not only on both phonological rules but also in both languages. However, given that they often have smaller vocabularies in each language in comparison to monolinguals of the same age (Bialystok et al., 2010; Hoff et al., 2012; Marchman et al., 2010), finding a sufficient number of known assimilable words in both languages and testing children in such a demanding task may prove difficult, especially at younger ages.⁷

Another avenue for future research concerns the issue of foreign-accented speech in bilinguals' input. Most parents of children who grow up bilingually have some level of proficiency in their spouse's or partner's language, which they are likely to speak with a foreign accent. Thus, bilingual children might be exposed – directly or indirectly – to foreign-accented speech in one or both of their languages. It has been argued that such exposure can interfere with phonological processing in bilingual children. For instance, toddlers in bilingual Spanish-Catalan families have difficulty with the /e/-/ɛ/ contrast in Catalan word recognition; this might be due to mispronunciations and inconsistencies in the production of Catalan words containing these vowels in the input of their native Spanish-speaking parent (Ramon-Casas et al., 2017, 2009). For the present case, we would need to know whether native assimilation rules are transferred in L2 speech production, like they are in (beginners') L2 speech perception. While this is largely an open question, there is one case study reporting such transfer (Altenberg & Vago, 1983). It would be interesting to gather L2 production data from the parents of French-English bilingual children in order to analyze the possible presence of non-native assimilations, and to examine whether such non-native assimilations influence their children's acquisition of language-specific compensation in their two languages.

Questions as to when and how assimilation rules are acquired remain open both for mono- and bilinguals. Recall that Skoruppa, Mani, Plunkett, et al. (2013) found adult-like compensation for assimilation in 24 month-olds. It is difficult to test much younger infants with a lexical task, as they do not know enough words yet. However, using a mismatch paradigm with EEG recordings, Fort, Brusini, Carbajal, Sun, and Peperkamp (2017) found that even at 14 months of age infants have some knowledge of native assimilation rules. That is, 14-month-old French-learning infants – like French adults (Sun et al., 2015) – failed to discriminate a voicing contrast in a viable assimilation context (e.g., [ofbe] vs. [ovbe]: no mismatch response), while they successfully detected it in an unviable

⁷Recall that even in our experiment with 6-year olds, the data from one bilingual child was rejected because according to parental report they did not know one of the training items, while for four other bilingual children one test item was excluded from analysis for the same reason.

assimilation context (e.g., [ofne] vs. [ovne]: mismatch response). Thus, they appeared to already have acquired the surface pattern of voicing assimilation and perceptually compensate for it at a prelexical level. Fort et al. speculated that infants' acquisition of voicing assimilation is triggered by the tendency of words to be repeated during conversations, and hence for assimilated and non-assimilated forms of words to cluster together within short stretches of speech. Thus, even without having access to word meanings, infants could infer that word-final voicing differences reflect systematic variation induced by voicing assimilation. Still, we cannot rule out an alternative possibility: Fort et al. (2017) did not test French infants on a non-native rule, and to the extent that assimilation is phonetically motivated – it is rooted in coarticulation – it would not be completely unexpected if they likewise compensated for English place assimilation. This would be evidence that rather than acquiring their native assimilation rules, infants have to unlearn non-native rules. Such a scenario would fit well with findings in adults showing different amounts of compensation even for non-native assimilation rules (Darcy et al., 2009; Gow & Im, 2004; Mitterer, Csépe & Blomert, 2006; Mitterer, Csépe, Honbolygo & Blomert, 2006).⁸

Whether native assimilation rules must be acquired or non-native ones unlearned, bilinguals must be able to fully separate their two languages' phonologies in order to attain native-like compensation in both. This is easier for some language pairs than for others (Mehler et al., 1988; Nazzi, Bertoncini, & Mehler, 1998; Ramus, Nespor, & Mehler, 1999). French and English, the languages under scrutiny in our study, belong to different rhythmic classes (Ramus et al., 1999). Moreover, their phoneme inventories are very different, and while they share many stop consonants – which constitute about half of the consonants that undergo either voicing or place assimilation – these consonants have different phonetic implementations (French contrasts voiceless unaspirated with prevoiced stops, while English contrasts aspirated with voiced stops). We therefore expect that the acquisition of the respective assimilation rules by French-English bilingual children should be relatively easy. An example of a harder case is provided by Spanish and Catalan, which not only belong to the same rhythmic class but whose phoneme inventories are also largely overlapping and whose shared phonemes have similar phonetic implementations. Bilingual Spanish-Catalan children must learn that while both of their languages have nasal place assimilation, Catalan additionally has voicing assimilation in word-final obstruents (Recasens & Mira, 2012; Wheeler, 2005). Thus, we expect bilingual Spanish-Catalan to be delayed compared to bilingual French-English children as far as language-specific compensation for voicing assimilation is concerned.

We conclude with a few methodological considerations: From a conceptual point of view, our design differed from those of Skoruppa, Mani and Peperkamp (2013) and Skoruppa, Mani, Plunkett, et al. (2013), which were based on minimal pairs of known and novel words. That is, toddlers in these studies were introduced to unknown objects (say, a spinning wheel), whose labels (e.g., [byz]) differed from that of known objects (a bus, in French: [bys]) in just the final consonant. In the viable condition, the sentences were therefore ambiguous as they could refer both to the known and to the novel object. Piloting showed that the use of such minimal pairs did not work well with older children (nor with adults).⁹ In our design, known objects were therefore always contrasted with a red cross; children were asked to touch the object if its label was pronounced correctly and the red cross otherwise. Thus, there was no ambiguity; if they had perfect knowledge of assimilation, children should touch the known object in the viable condition and the red cross in the unviable condition. This is akin to the word recognition task used in the studies with adults by Darcy and colleagues (Darcy et al., 2007, 2009), in which participants first heard a target word and then had to decide whether it was present and correctly pronounced in a following sentence. It would be interesting to

⁸The fact that neither we nor Skoruppa et al. (2013) and Skoruppa et al. (2013) found some small amount of compensation for non-native assimilation might be due to a lack of power. Indeed, experiments with toddlers and young children typically have a small number of trials (e.g., our experiment had 6 trials per condition, compared to 16 for adults in Darcy et al., 2009).

⁹On the one hand, if both the familiar and the novel object were introduced by their names prior to the touching request, 5-year old children (as well as adults) performed the task at an acoustic level; that is, they showed a bias for the novel object. On the other hand, if neither of the objects was named prior to the request, they showed a bias for the familiar object, regardless of context.

use the present design with younger children (provided they can grasp the concept of the game); given the absence of ambiguity in the viable condition, we expect the compensation effects to be larger than those found previously in toddlers (Skoruppa, Mani & Peperkamp, 2013; Skoruppa, Mani, Plunkett, et al., 2013).

Our design also differed from those used previously in that we used a video-game for tablets, adapted from Cristia (2016), rather than a traditional setting in which the child sits in front of a computer screen. A wide range of tasks can be implemented on tablets to study cognitive development (Semmelmann et al., 2016). Moreover, in a direct comparison with 1- to 4-year-old children on a word-recognition task, Frank, Sugarman, Horowitz, Lewis, and Yurovsky (2016) found that a tablet-based paradigm compared favorably both with an eye-tracking paradigm and an in-person storybook paradigm. Our use of a tablet facilitated the recruitment of participants in different locations, and allowed us to keep children engaged in the task for the whole duration of the experiment, with none of them abandoning before the end of the game. During pilot tests, children as young as 4 years likewise showed low drop-out rates. This fun and portable low-cost setup can thus be used in further research investigating the acquisition of assimilation and other phonological rules in diverse populations of young children around the world.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability statement

The data described in this article are openly available in the Open Science Framework at <http://doi.org/10.5281/zenodo.1205532>.

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Appendix: List of test items used in Experiments 1 & 2

a. Voicing items

Canonical form			Altered form	Viable context	Unviable context
<i>brosse</i>	[bʁɔs]	“brush”	[bʁɔʒ]	<i>devant toi</i> “in front of you”	<i>là-bas</i> “over there”
<i>chaise</i>	[ʃɛz]	“chair”	[ʃɛs]	<i>par ici</i> “over here”	<i>maintenant</i> “now”
<i>couche</i>	[kuʃ]	“nappy”	[kuʒ]	<i>devant toi</i> “in front of you”	<i>là-devant</i> “there in front”
<i>crêpe</i>	[kʁɛp]	“pancake”	[kʁɛb]	<i>juste ici</i> “just here”	<i>là-devant</i> “there in front”
<i>douche</i>	[duʃ]	“shower”	[duʒ]	<i>devant toi</i> “in front of you”	<i>là-devant</i> “there in front”
<i>fraise</i>	[fʁɛz]	“strawberry”	[fʁɛs]	<i>par ici</i> “over here”	<i>là-devant</i> “there in front”
<i>langue</i>	[lɑ̃g]	“tongue”	[lɑ̃k]	<i>s’il te plaît</i> “please”	<i>là-devant</i> “there in front”
<i>porte</i>	[pɔʁt]	“door”	[pɔʁb]	<i>juste ici</i> “just here”	<i>maintenant</i> “now”
<i>robe</i>	[ʁɔb]	“dress”	[ʁɔp]	<i>s’il te plaît</i> “please”	<i>là-devant</i> “there in front”
<i>singe</i>	[sɛ̃ʒ]	“monkey”	[sɛ̃ʃ]	<i>s’il te plaît</i> “please”	<i>là-bas</i> “over there”
<i>tasse</i>	[tas]	“cup”	[taz]	<i>devant toi</i> “in front of you”	<i>maintenant</i> “now”
<i>vache</i>	[vaʃ]	“cow”	[vaʒ]	<i>devant toi</i> “in front of you”	<i>là-bas</i> “over there”

a. Place items

Canonical form			Altered form	Viable context	Unviable context
<i>boîte</i>	[bwat]	“box”	[bwap]	<i>maintenant</i> “now”	<i>devant toi</i> “in front of you”
<i>botte</i>	[bɔt]	“boot”	[bɔp] ^a	<i>maintenant</i> “now”	<i>devant toi</i> “in front of you”
<i>chaîne</i>	[ʃɛn]	“chain”	[ʃɛm] ^b	<i>par ici</i> “over here”	<i>devant toi</i> “in front of you”
<i>clown</i>	[klun]	“clown”	[klum]	<i>par ici</i> “over here”	<i>s’il te plaît</i> “please”
<i>corde</i>	[kɔʁd]	“rope”	[kɔʁb]	<i>par ici</i> “over here”	<i>là-devant</i> “there in front”
<i>crotte</i>	[kʁɔt]	“poop”	[kʁɔp]	<i>maintenant</i> “now”	<i>là-devant</i> “there in front”
<i>goutte</i>	[gut]	“water drop”	[gup]	<i>maintenant</i> “now”	<i>là-devant</i> “there in front”
<i>lune</i>	[lyn]	“moon”	[lym] ^c	<i>par ici</i> “over here”	<i>là-devant</i> “there in front”
<i>monde</i>	[mɔ̃d]	“world”	[mɔ̃b]	<i>par ici</i> “over here”	<i>là-devant</i> “there in front”
<i>pâtes</i>	[pat]	“pasta”	[pap] ^d	<i>maintenant</i> “now”	<i>là-devant</i> “there in front”
<i>reine</i>	[ʁɛn]	“queen”	[ʁɛm]	<i>par ici</i> “over here”	<i>s’il te plaît</i> “please”
<i>viande</i>	[vjɑ̃d]	“meat”	[vjɑ̃b]	<i>par ici</i> “over here”	<i>là-devant</i> “there in front”

^aThis form corresponds to the infrequent word *bop* “bop” (cf. be-bop).

^bThis form corresponds to the infrequent word *schème* “scheme”.

^cThis form corresponds to the infrequent word *lûmes* “read” (1st person plural of simple past tense, used only in written language).

^dThis form corresponds to the infrequent word *pape* “popé”.