Infants' sensitivity to non-adjacent vowel dependencies:

The case of vowel harmony in Hungarian

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Introduction

Languages of the world differ in how they combine sounds into words. Some languages exhibit a phenomenon called vowel harmony, whereby vowels share one or several of their phonological features within a word stem (also known as internal vowel harmony) and/or between word stems and their affixes (external vowel harmony). In Hungarian, for instance, the word *kanál* ('spoon') has back vowels and takes the back vowel allomorph of the inessive suffix *–b**a**n* ('in'), i.e. *kan**á**lb**a**n* [spoon.in, 'in (the) spoon'], whereas the word *kenyér* ('bread') has front vowels and takes the front vowel allomorph *–b**e**n* ('in') to yield *keny**é**rb**e**n* [bread.in 'in (the) bread']. Learning this phonotactic regularity is essential for infants acquiring a harmonic language, as it impacts both the lexicon and the grammar of these languages. Yet, few studies have investigated when young learners first show sensitivity to vowel harmony. These studies have mainly examined Turkish, a language with highly regular vowel harmony (Altan, Kaya, & Hohenberger, 2016; Hohenberger, Kaya & Altan, 2017; Van Kampen, Parmaksiz, van de Vijver, & Höhle, 2008) and English, a language without vowel harmony (Mintz, Walker, Welday & Kidd, 2018). The present study investigates at what age Hungarian-learning infants first show sensitivity to lexical (i.e., internal) vowel harmony (Experiment 1) and compares them with infants learning a non-harmonic language, French (Experiment 2). Interestingly, Hungarian vowel harmony is not as regular as in some other languages, which allows us to explore the effects of input statistics on the acquisition process.

Many of the world's languages, such as Niger-Congo, Finno-Ugric and Altaic languages have vowel harmony (Maddieson, 2013). They may differ in the harmonizing phonological features (e.g. vowel height, backness, roundedness etc.), the harmonizing levels (i.e., lexicon, morphology or both), as well as in the extent to which vowel harmony is regular. In some languages, vowel harmony is pervasive, having relatively few exceptions: a large percentage of the lexicon (i.e. of word stems) shows harmony, and most affixes have different harmonic allomorphs. In Turkish, for example, the majority of the lexicon is harmonic. Indeed, 85% of a very large corpus, comprising 500,000,000 word tokens, of adult-directed written text was found to be harmonic (Avar, 2015). Similarly, 89% of the 200 most frequent word types in infant-directed speech in the Turkish subcorpora of the CHILDES database was shown to be harmonic (Ketrez, 2014). Moreover, external (i.e. suffix) harmony in Turkish occurs almost without exceptions (Avar, 2015). However, in other languages, a smaller proportion of the lexicon may show harmony, due, for example, to non-harmonic loan words or historical changes affecting the harmonic status of some vowels. Hungarian is a case in point. In present-day Hungarian, the vowel /i/, although phonetically front, may take either front or back suffixes, depending on the lexical item concerned: *h**í**db**a**n* [bridge.in ‘in (the) bridge’] vs. *v**í**zb**e**n* [water.in ‘in (the) water’]). Furthermore, while some Hungarian suffixes have two (front/back) or three different harmonic allomorphs (front rounded/front unrounded/back), others do not harmonize (e.g. *–ért* (‘for’): *h**á**z**é**rt* [house.for ‘for (the) house’], *k**é**z**é**rt* [hand.for ‘for (the) hand’]).

Languages thus exhibit vowel harmony at different levels (lexicon, morphology or both) and to different extents. For a better understanding of how and when infants start to learn about vowel harmony in their native language, it is important to have a quantitative assessment of the input young learners receive. However, only a few studies to date have investigated the frequency of harmonic vs. non-harmonic forms in different languages (Goldsmith & Riggle, 2012; Hayes & Londe, 2006; Avar, 2015; Rebrus & Törkenczy, 2015), and even fewer have done so in infant-/child-directed speech (Ketrez, 2014). Yet, the prevalence of harmonic forms might impact how rapidly young learners discover the harmonic regularities of their native language. Furthermore, the existing quantitative studies do not always distinguish between internal (i.e., lexical) and external (i.e., morphological) harmony. Nevertheless, this distinction might impact language development, and these two kinds of harmony might be learned at a different pace. The present study explores when internal vowel harmony, which is related to lexical acquisition, is learned. The current paper will, therefore, quantify the degree of harmonicity in Hungarian, the native language of the participants in our main experiment, considering both internal and external harmony.

So far three studies have investigated early knowledge of vowel harmony in infants acquiring a highly regular harmonic language, namely Turkish. Van Kampen, Parmaksiz, van de Vijver and Höhle (2008) showed that Turkish-learning infants were sensitive to backness harmony at 6 months of age. When presented with a list of 4 vowel-harmonic pseudowords (i.e., paroz, kuvatt, letinn and söpüll) and a list of 4 non-harmonic pseudowords (i.e., nelock, rolipp, rivar and dünamm), Turkish-, but not German-learning 6-month-olds showed a preference for the harmonic stimuli, establishing an early, language-specific sensitivity to vowel harmony in Turkish-learning infants. Using low frequency words (i.e., real stems and real suffixes), Altan and colleagues (2016) showed sensitivity to external backness harmony at 6 months for Turkish stem-suffix sequences. Hohenberger et al. (2017) also used low frequency words and extended this early sensitivity in 6-month-old Turkish infants to external roundedness harmony.

As discussed above, vowel harmony in Turkish is highly regular. Do infants also show a similarly early sensitivity in less regular harmonic languages, or do input statistics play a role in establishing sensitivity to vowel harmony? Such an effect of statistics has been shown to apply to non-adjacent phonological dependencies that favor *dissimilarity* across phonetic features, such as the labial-coronal (LC) bias for consonants or the posterior-anterior (PA) bias for vowels. The question remains whether it also applies to vowel harmony, a phenomenon based on *similarity* across features.

For dissimilarity-based regularities, it has been shown that by 10 months of age infants become sensitive to non-adjacent dependencies between consonants (Nazzi, Bertoncini, & Bijeljac-Babic, 2009; Gonzalez-Gomez & Nazzi, 2012a, 2012b; Gonzalez-Gomez, Hayashi, Tsuji, Mazuka, & Nazzi, 2014), and three months later they become sensitive to non-adjacent non-harmonic dependencies between vowels (Gonzalez-Gomez & Nazzi, 2015). Specifically, in French, words starting with a labial consonant (consonant articulated with one or both lips, e.g., /b/, /p/), followed by a coronal consonant (consonants articulated with the front of the tongue in the front of the mouth cavity, e.g., /t/, /d/), as in the word "bat", are approximately twice as frequent as words having the reverse, coronal-labial pattern, as in the word "tab". Studies on the acquisition of this non-adjacent consonantal regularity, known as the labial-coronal (LC) bias, have established that 10- but not 7-month-old French-learning infants listen longer to lists containing the more frequent LC pattern compared to the CL pattern, attesting acquisition. This pattern was found for plosive and nasal sequences, for which there is an LC bias in the input (Nazzi et al., 2009; Gonzalez-Gomez & Nazzi, 2012a, 2012b), and even when the stimuli presented had been recorded in a non-native language, Japanese (Gonzalez-Gomez et al., 2014). Additional studies established the role of frequency regularities in the input. Indeed, an opposite CL preference was found for sequences of fricative consonants (e.g., /f/ and /s/) in French-learning infants (Gonzalez-Gomez & Nazzi, 2014), and for sequences of plosives in Japanese-learning infants (Gonzalez-Gomez et al., 2014), two cases in which CL biases are found in the input.

The role of frequency and input was also found in studies on non-adjacent dependencies over vowels. Segal, Keren-Portnoy and Vihmann (2015) showed that 8- to 11-month-old Hebrew-learning infants prefer listening to CVCVC pseudowords containing frequent vowel sequences (e.g., ó-o; a-ó) over pseudowords containing non-existent (e.g., ó-o) or infrequent vowel sequences (e.g., a-é). Furthermore, Gonzalez-Gomez and Nazzi (2015) investigated infants' sensitivity to the posterior-anterior (PA) bias in French, which is a statistical regularity whereby words in which a posterior (back) vowel (e.g., /u/ or /o/) is followed by an anterior (front) vowel (e.g., /i/ or /e/) are almost twice as frequent as words having the opposite pattern. At 13, but not yet at 10 months of age, French-learning infants listened longer to lists containing the more frequent PA pattern as compared to the AP pattern.

The results on vocalic dependencies suggest that sensitivity to vowel harmony in Turkish emerges earlier than sensitivity to frequent vowel sequences in Hebrew, which in turn emerges earlier than sensitivity to the non-harmonic PA bias in French. This might result, in part, from a methodological difference between these studies. In Gonzalez-Gomez and Nazzi's (2015) experiments, the adjacent and positional frequencies of the phonemes used in the stimuli were fully controlled for and matched between the two experimental conditions, whereas in Van Kampen et al.'s (2008), Altan et al.'s (2016), Hohenberger et al.'s (2017), and Segal et al. (2015) they were not, raising the possibility that infants reacted not solely to the non-adjacent dependencies, but also to adjacent and/or positional properties of the stimuli (as found for 7-month-old French-learning infants in Gonzalez Gomez & Nazzi, 2012). Nevertheless, it is also possible that there is a real difference between the ages of acquisition of vowel harmony and non-adjacent dependencies such as the PA bias, for at least two reasons. First, similarity in phonological features might be easier to identify/learn than dissimilarity (Cristià & Seidl, 2008). More importantly, the prevalence of vowel harmony in Turkish is far higher than the prevalence of the PA bias in French. About 90% of the 200 most frequent words in infant-directed Turkish are harmonic (Ketrez, 2014), whereas words with PA vowel sequences account for only 71-75% of the adult French lexicon (Gonzalez-Gomez & Nazzi, 2015). This account predicts a later acquisition of vowel harmony in Hungarian because of its less regular input.

Taken together, the above results suggest that towards the end of the first year of life, infants become sensitive to non-adjacent dependencies between segments. Nevertheless, there is at present no data regarding when vowel harmony is learned in harmonic languages other than Turkish, and it is still not clear what factor(s) might underlie the difference between the ages at which sensitivity to different non-adjacent (vocalic) dependencies are learned. In particular, previous results regarding the acquisition of the vocalic PA and the consonantal LC biases suggest that input statistics may play a key role. However, this factor was not directly considered for the acquisition of vowel harmony before. In the present study, we will address this question by testing whether and, if so, at what age, sensitivity to vowel harmony can be observed in infants exposed to a less pervasively harmonic language, Hungarian, and a non-harmonic language, French, and link this to the input statistics of child-directed speech computed for Hungarian.

Corpus Analyses

We conducted a quantitative analysis of the frequency of harmonic vs. non-harmonic words in child-directed Hungarian using the Hungarian subcorpora (MacWhinney, 1974; Réger, 2004) of the CHILDES database (MacWhinney, 2000), considering word stems and morphologically complex word forms both separately and jointly, in order to quantify the extent to which the lexicon and the morphology are regular in terms of harmony in Hungarian.

Only one previous study investigated the frequency of harmonic forms in infant-directed Hungarian (Ketrez, 2014). This study found that among the 200 most frequent word types in the CHILDES subcorpora of Turkish, Hungarian, Farsi and Polish, 89.47%, 77.40%, 32.4% and 54.6%, respectively, were harmonic (i.e., contained only front or only back vowels). Hence, harmonic words appear to be more frequent in Hungarian than in the two non-harmonic languages, Farsi and Polish. At the same time, they appear to be less frequent than in Turkish. However, these results remain suggestive since that previous study only took into account type frequency, not token frequency, and only considered a small number of very frequent words. Furthermore, it pooled roots and morphologically complex words together, thus it did not evaluate the prevalence of harmony in the lexicon and in morphology separately.

Here, we will, therefore, investigate the Hungarian subcorpora of the CHILDES database taking into account *all* word types. We will also run our counts over word tokens. We will further distinguish between monomorphemic stems and morphologically complex words. Below, we first overview the relevant properties of Hungarian vowel harmony, then describe the corpora and the computed measures in detail, followed by the results of the analysis.

Hungarian vowel harmony

Vowel harmony is certainly the most studied aspect of Hungarian morphophonology. While theoretical debates exist (Hayes & Londe, 2006; Hayes, Siptár, Zuraw, & Londe, 2009; Polgárdi, 1998; Rebrus & Törkenczy, 2015; Ringen & Vago, 1998; Törkenczy, 2011), the key empirical generalizations are well established and have been described in great detail (Törkenczy, 2011). We will review only the most important ones here.

Vowel harmony applies within what is called the harmonic domain. In Hungarian, the harmonic domain is a stem and its suffixes, if any. Compound words (e.g. *öröm|anya* joy|mother ‘mother-of-bride/groom’) and preverbal particles (*össze|rak* together|put ‘assemble’) constitute two harmonic domains.

Hungarian vowels can be classified phonologically/phonetically as shown in Table 1. In terms of vowel harmony, they fall into three categories: back vowels, rounded front vowels and unrounded front vowels. Vowel harmony concerns two features: backness harmony (i.e., back vs. front), which fully applies within stems as well as between stems and harmonizing suffixes, and roundedness harmony (i.e., rounded vs. unrounded), which concerns only front vowels, and applies within stems as well as between stems and a subset of the harmonizing suffixes. As roundedness harmony is much more restricted than backness harmony and is parasitic on it (so much so that some analyses consider it a local agreement phenomenon rather than genuine harmony), we will not be concerned with it here.

Table 1. The Hungarian vowel system. IPA symbols are given between slashes, the corresponding orthographic characters appear in square brackets. Since there is a one-to-one correspondence between the two, we will be using the orthographic characters throughout the paper to identify vowels.

	Anterior				**Posterior**			
	Unrounded		Rounded		Unrounded		Rounded	
	Short	Long	Short	Long	Short	Long	Short	Long
High	/i/ [i]	/i:/ [í]	/y/ [ü]	/y:/ [ű]			/u/ [u]	/u:/ [ú]
Mid		/e:/ [é]	/ø/ [ö]	/ø:/ [ő]			/o/ [o]	/o:/ [ó]
Low	/ɛ/ [e]					/a:/ [á]	/ɑ/ [a]	

The general rule of external (i.e. suffix) harmony is that the harmonic category of the last vowel of the stem determines the harmonic category of the attached suffix(es), as can be seen in non-harmonic stems containing both back and front vowels (e.g., the suffix -nek/-nak ‘to’ as in *sofőrnek* driver.to ‘to (the) driver’ vs. *nüansznak* nuance.to ‘to (the) nuance’). There are 73 productive suffixes in Hungarian that harmonize in backness or backness and roundedness, and 21 that only have a single, non-harmonizing form. It is debated whether vowel harmony is an active rule in stems, that is, if internal harmony is a productive rule, or whether it is simply a (probabilistic) constraint on co-occurrence. Indeed, non-harmonic stems are not uncommon.

From a theoretical perspective, (some) unrounded front vowels are considered neutral with respect to vowel harmony, because although they are phonologically front, some stems containing these vowels, especially *i* and *í*, take the back, rather than the expected front allomorph of harmonizing suffixes. Specifically, there is a closed set of about 60 monosyllabic words containing neutral vowels that behave this way [e.g. *h**í**dn**a**k* bridge.to ‘to (the) bridge’, and not *h**í**dn**e**k*]. Some stems containing a rounded front vowel, followed by one or several neutral vowels, called mixed stems, also behave this way [e.g. *pap**í**rn**a**k* paper.to ‘to (the) paper’, and not *pap**í**rn**e**k*], or vacillate between the front and back suffixes within and, more commonly, across speakers (*dzsung**e**ln**a**k* jungle.to ‘to (the) jungle’, or *dzsung**e**ln**e**k*).

This variation, i.e. the existence of non-harmonic and mixed stems and their non-harmonic or vacillating suffixes, constitutes a serious challenge both for linguists to explain (hence the strong theoretical interest in Hungarian vowel harmony) and for infants to learn. The current analysis aims at quantifying this variation in child-directed Hungarian.

Corpus

We used the two Hungarian subcorpora (MacWhinney, 1974; Réger, 2004) of the CHILDES database (MacWhinney, 2000), as pre-processed in Gervain and Guevara Erra (2012) and available at http://childes.psy.cmu.edu/derived/. The MacWhinney subcorpus (MacWhinney, 1974; 1975) contains orthographic transcripts of recordings of six Hungarian children (age: 1;5-2;10, 3 boys and 3 girls) in their usual kindergarten environment over a period of 10 months. The Réger corpus (Réger, 2004) contains orthographic transcripts of the recordings of a Hungarian boy between the ages 1;11 and 2;11 in his family environment.

From these subcorpora, we extracted all the adult utterances, except those of one adult, who is not a native speaker of Hungarian. This way, a corpus of 15,231 utterances, 54,881 word tokens and 8,234 word types was compiled. Of these, 28,243 word tokens and 7,471 word types were multisyllabic and thus included in the harmonicity analyses (see section Measures below). This corpus, containing both mono- and multimorphemic words, was further processed by one of the authors (JG), who is a trained linguist as well as a native speaker of Hungarian, to extract all monomorphemic word types and tokens for an analysis of harmonicity in lexical stems only.

The corpus was purged of untranscribed material, but onomatopoeic words, sound imitations, fragments and other linguistic 'noise' were kept unchanged under the assumption that they form a natural part of the input to young learners. All punctuation marks and spaces were deleted, except for utterance boundaries, which infants are sensitive to (Jusczyk, 1999) and can make use of during segmentation. Utterances were phonologically transcribed following similar principles as in Roach et al. (1996) by the author JG. For further details about the corpus, see Gervain and Guevara Erra (2012).

Measures

We conducted two analyses measuring the prevalence of harmony specifically in the lexicon and in the Hungarian input overall. These analyses included all the fourteen vowels of Hungarian (see Table 1). First, we calculated the percentage of harmonic vs. non-harmonic (i.e., mixed sequences, containing a front and a neural vowel, and disharmonic sequences, containing a front and a back vowel; for more details, see p. 9) forms among all monomorphemic words (i.e. stems/roots with no suffixes) that consisted of at least two syllables. We computed both type and token frequency. The purpose of this analysis was to assess the prevalence of harmonic monomorphemic words in the lexicon. Second, we calculated the percentage of harmonic vs. non-harmonic (mixed and disharmonic) forms among all words that consisted of at least two syllables, whether morphologically complex or not. We again computed both type and token frequency. The purpose of this analysis was to assess the prevalence of harmonic words in the input Hungarian infants receive.

Results and Discussion

The percentage of harmonic and non-harmonic monomorphemic words is shown in Figure 1, left panel. Of the 704 monomorphemic word types, 501 (71%) were harmonic, 203 (29%) were non-harmonic. Of the 11,356 monomorphemic word tokens, 7,749 (68%) were harmonic, 3,607 (32%) were non-harmonic. The percentage of harmonic and non-harmonic forms when all words (i.e. monomorphemic as well as morphologically complex words) are taken into account is shown in Figure 1, right panel. Of the 7,471 word types, 5,157 (69%) were harmonic, 2,314 (31%) were non-harmonic. Of the 28,243 word tokens, 21,536 (76%) were harmonic, 6,707 (24%) were non-harmonic.

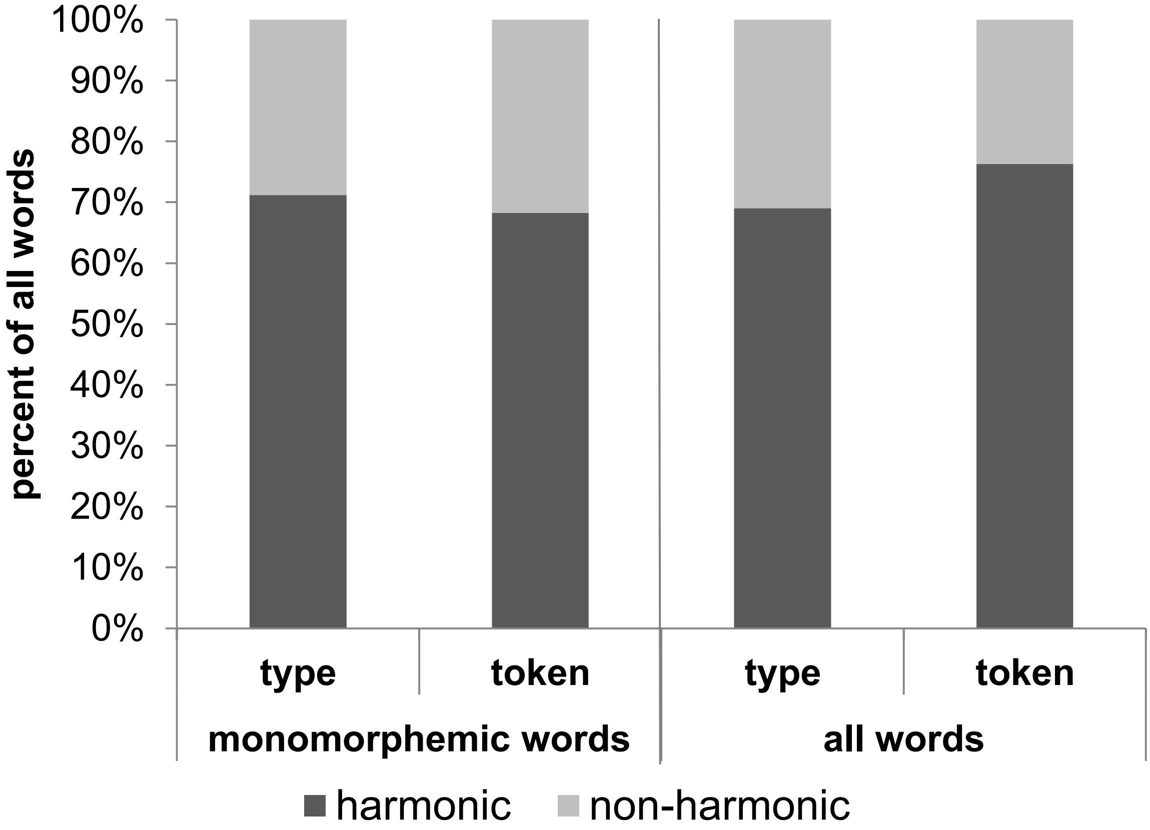

Figure 1. Percentage of harmonic and non-harmonic forms among monomorphemic words (left panel) and all word forms (right panel) in the Hungarian CHILDES subcorpora

These results show that vowel harmony in Hungarian is frequent, but not without exceptions. Indeed, about one-third of the input Hungarian infants receive is not harmonic.

Our findings mesh well with previous results. They are relatively similar to those found by Ketrez (2014) for the 200 most frequent word types of the Hungarian CHILDES subcorpora, 77.40% of which were found to be harmonic. Our results for all word types are somewhat lower, 69%, while for word tokens (76%) they match closely those of Ketrez. When considering monomorphemic words only, we still find that the predominant pattern is harmonic, as is expected, but their prevalence is lower than in Ketrez's results, with 71% of the monomorphemic word types and 68% of the monomorphemic word tokens being harmonic.

In sum, the input to young learners of Hungarian is predominantly harmonic, but contains a large number of exceptions, these exceptions coming both from the lexicon (with about 1/3 of the basic lexicon being non-harmonic), and from non-harmonic morphological derivations. This makes vowel harmony in Hungarian less prevalent than in Turkish (where analyses give percentages of 75 to 90 % of harmonic forms), which might slow down its acquisition compared to what has been found for Turkish-learning infants, for which the earliest evidence of sensitivity to vowel harmony was found at 6 months of age (Altan et al., 2016; Hohenberger et al., 2017; Van Kampen et al., 2008). For this reason, in Experiment 1, Hungarian-learning infants' sensitivity to this probabilistic phonotactic pattern in their native language was tested at a later age, that is, 10 and 13 months. These ages were also selected based on previous studies showing that between 10 and 13 months infants become sensitive to a comparable vocalic phonotactic pattern in terms of frequency of occurrence in the language (Gonzalez Gomez & Nazzi, 2015).

Experiment 1

Method

Participants. Thirty full-term, monolingual infants from Hungarian-speaking families were tested in Budapest: Sixteen 10-month-olds (mean age = 10 months 10 days; range: 10 months 1 day - 30 days; 8 girls, 8 boys) and fourteen 13-month-olds (mean age = 13 months 23 days; range: 13 months 13 days - 31 days; 9 girls, 5 boys). The data of eighteen additional 10-month-olds and nine 13-month-olds were not included in the analyses due to completing fewer than 12 of the 16 trials (n = 14), fussiness/crying (n = 9), too many short looks (n = 2), technical error (n = 1) or parental interference (n = 1).

Stimuli. The stimuli were composed of vowel-consonant-vowel (V_1CV_2) sequences. This sequence structure was chosen in order to have only one non-adjacent relation within each item (as done in the study on the PA bias, Gonzalez Gomez & Nazzi, 2015; but differently to stimuli of van Kampen et al., 2008, and Segal et al., 2015). Twenty-four harmonic and twenty-four non-harmonic bisyllabic V_1CV_2 pseudowords were created, combining four anterior vowels /ɛ/, /i/, /ø/ and /y/, and four posterior vowels /ɒ/, /aː/, /o/ and /u/. Those phonemes were chosen to be shared with the French phoneme inventory or to be readily assimilable to French phonemes (see Exp. 2). Pseudowords were used to allow full control of the distribution of the vowels as well as the frequency of the adjacent regularities. For the harmonic items, twelve items had a posterior-posterior vowel structure and twelve items had an anterior-anterior vowel structure. For the non-harmonic items, twelve items had a posterior-anterior vowel structure and twelve items had an anterior-posterior vowel structure (see Table 2). Items in all four lists were made up of exactly the same consonants. Consonants were chosen in order to obtain balanced adjacent regularities between the anterior-posterior and posterior-anterior lists and the posterior-posterior and anterior-anterior lists for the entire V_1CV_2 sequence as well as for the V_1C and CV_2 sequences according to the segmented Hungarian subcorpora of the *CHILDES* database (MacWhinney, 2000; Gervain & Guevara Erra, 2012). A set of paired t-tests confirmed that the mean frequency of the adjacent regularities between the harmonic (i.e., anterior-anterior and posterior-posterior) and non-harmonic (i.e., anterior-posterior and posterior-anterior) stimuli was not statistically significant for V_1CV_2, V_1C or CV_2 (see Table 3). All of these items were pseudo-words that follow the phonotactic regularities of Hungarian.

Table 2. List of Harmonic (i.e., anterior-anterior and posterior-posterior) and Non-harmonic (i.e., anterior-posterior and posterior-anterior) VCV sequences used in Experiment 1.

Harmonic				**Non-Harmonic**			
Anterior-Anterior		Posterior-Posterior		Anterior-Posterior		Posterior-Anterior	
Pseudoword	**IPA**	**Pseudoword**	**IPA**	**Pseudoword**	**IPA**	**Pseudoword**	**IPA**
edü	/ɛdy/	*áko*	/aːko/	ita	/itɒ/	ode	/odɛ/
eki	/ɛki/	*átu*	/aːtu/	ida	/idɒ/	ope	/opɛ/
etö	/ɛtø/	*áda*	/aːdɒ/	ipa	/ipɒ/	ote	/otɛ/
ibe	/ibɛ/	*otá*	/otaː/	ipo	/ipo/	obi	/obi/
igü	/igy/	opa	/opɒ/	igo	/igo/	oki	/oki/
ibö	/ibø/	obu	/obu/	iko	/iko/	ogi	/ogi/
üki	/yki/	*apá*	/ɒpaː/	eta	/ɛtɒ/	adi	/ɒdi/
ügö	/ygø/	adu	/ɒdu/	eba	/ɛbɒ/	ati	/ɒti/
üpe	/ypɛ/	ago	/ɒgo/	eda	/ɛdɒ/	api	/ɒpi/
ödü	/ødy/	uba	/ubɒ/	ego	/ɛgo/	age	/ɒgɛ/
öpe	/øpɛ/	*uká*	/ukaː/	eko	/ɛko/	abe	/ɒbɛ/
öti	/øti/	ugo	/ugo/	ebo	/ɛbo/	ake	/ɒkɛ/

Table 3. Mean frequency (and SDs) associated to the stimuli used in Experiment 1, for the words themselves (V1CV2), and their constituting diphone sequences (V1C and CV2) in the Hungarian subcorpora of the CHILDES database.

	V_1C	**CV_2**	**V_1CV_2**
Harmonic	923 (1228)	269 (219)	11 (12)
Non-Harmonic	1,589 (1344)	407 (284)	8 (8)
H vs NH p-value	.13	.14	.37

The stimuli were recorded in a sound-attenuated booth by a Hungarian female native speaker. Two tokens of each item were selected. Eight lists were created to be used in the test phase: two lists with the twelve posterior-posterior items (using one of the two tokens of each item in each of the two lists, and reversing the order of the items in the two lists), two lists with the twelve anterior-anterior items (same manipulation), two lists with the twelve anterior-posterior items (same manipulation) and two lists with the twelve posterior-anterior items (same manipulation). This resulted in 8 lists, each one used twice in the 16 test trials. The duration of all the lists was 18.00 s.

Procedure and apparatus. The experiment was conducted inside a sound-attenuated room. Each infant was held on a caregiver's lap in the center of the test booth approximately 36 inches away from a 40" TV plasma screen. The TV screen was divided into three vertical regions, left, right and central, and flashing light-like animations were presented on the center of each region. The caregivers listened to music over headphones throughout the study and were instructed not to speak and not to point at the animations. Auditory attention was measured by recording looking time towards the blinking light animations as infants were simultaneously presented with the auditory tokens. A video camera was hidden under the TV screen, and an experimenter observed the infant's eye gaze direction from a monitor in another room, where stimulus presentation was controlled. The experimenter was blind to the sound presented, and recorded infant looking times by pressing predefined buttons according to the direction of the infant's gaze, thus starting and stopping the flashing animations and the presentation of the sounds.

The head-turn preference procedure (HPP) was used (Jusczyk, Cutler, & Redanz, 1993a). Each trial began with a green light on the central region of the TV screen blinking until the infant had oriented to it. Then, a yellow light on one of the side regions of the TV screen began to blink. The setup that was available at the laboratory where the infants were tested is different from the classical HPP setup in that a single very wide plasma screen was used. However, we made sure that three locations on the screen appeared to the infant in such a way (infant seated close to the screen and the side locations being separated from the center by the largest distance possible) that looking to the side lights required a head turn, just like in the traditional setup. When the infant turned in that direction, the stimulus for that trial began to play. Each stimulus was played to completion or stopped after the infant failed to maintain the gaze for 2 consecutive seconds. If the infant looked away from the target in any direction for less than 2s and then looked back again, the trial continued, but the time spent looking away (when the experimenter released the buttons) was automatically subtracted from the orientation time by the program. Thus, the maximum looking time for a given trial was the duration of the entire speech sample. Infants' looking behavior was monitored online by a single experimenter and coded offline by a different experimenter using the video recording made during the experiment. Only the offline data was used for the analyses.

Each session began with two musical trials, one presented on each side, to give infants an opportunity to practice one head-turn to each side before the actual test phase began. The test phase consisted of 16 trials divided into 2 blocks (in each of which the two lists of each type of stimulus, anterior-anterior, anterior-posterior, posterior-anterior, and posterior-posterior, was presented once). The order of the different lists within each block was pseudo-randomized.

Results and Discussion

Mean looking times to the harmonic and non-harmonic lists were calculated for each infant. The data for the 10-month-olds (M_H = 8.79 s, SD = 3.14 s; M_{NH} = 8.68 s, SD = 1.86), and for the 13-month-olds (M_H = 7.64 s, SD = 2.14 s; M_{NH} = 9.95 s, SD = 2.66 s), are presented in Figure 2. A 2-way ANOVA with the between-subject factor of Age (10 months versus 13 months) and the within-subject factor of Harmonicity (H versus NH) was conducted. The effect of Harmonicity was significant ($F(1, 28) = 5.26$, p = .03, η_p^2 = .16), infants having longer orientation times to the NH than to the H lists. The effect of Age was not significant ($F(1, 28) = .006$, p = .94). However, the interaction between Age and Harmonicity was significant ($F(1, 28) = 6.36$, p = .018, ηp^2 = .19), indicating that the effect of Harmonicity changed with age. Scheffe post hoc tests showed that the Harmonicity effect was not significant at 10 months (F(1,

28) = 0.28, *p* = .87), but was significant at 13 months (*F*(1, 28) = 10.86, *p* = .003). The effect size for this analysis (Cohen's dz = 1.21, corresponding to Cohen's d=1.71) was found to exceed Cohen's (1988) convention for a large effect (d = .80). A bias for NH stimuli was found in only 8 of the 16 10-month-olds (*p* = .60, binomial test), but in 11 of the 14 13-month-olds (*p* = .004, binomial test).

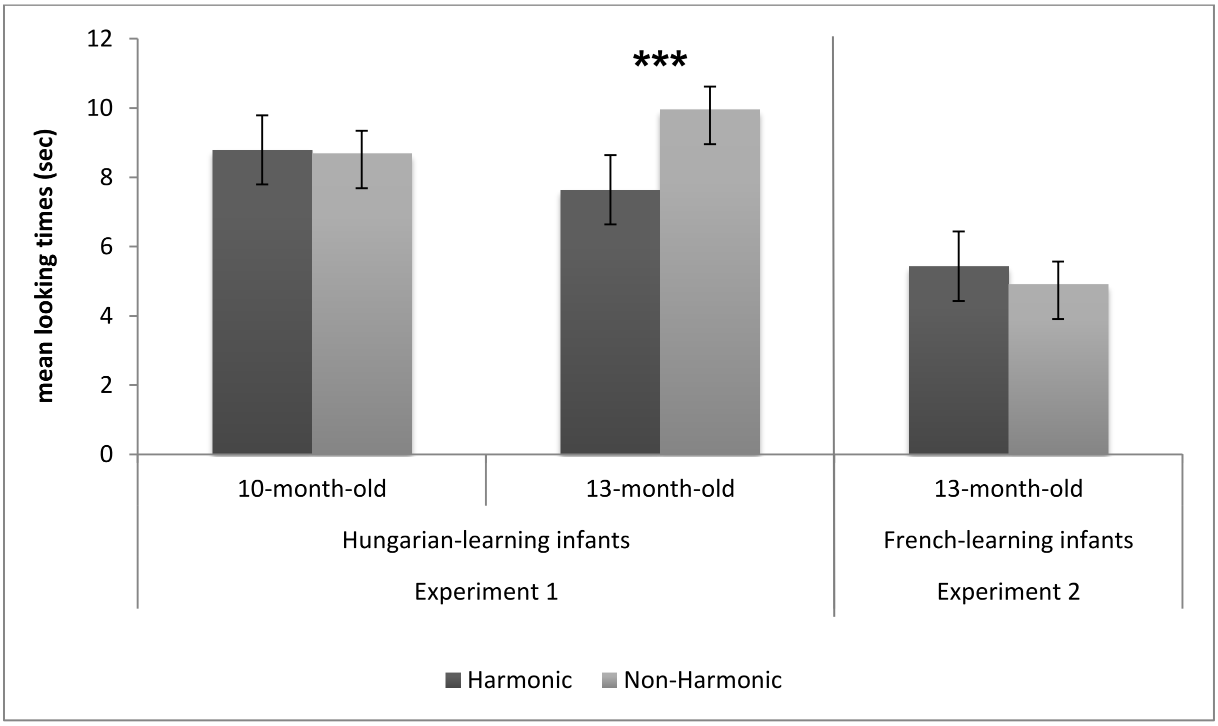

Figure 2. Mean looking times (and standard error of the mean) to the H and NH stimuli in Exp. 1 (left panel: Hungarian-learning infants) and Exp. 2 (right panel: French-learning infants. *** indicate p ≤ 0.001.

Experiment 1 establishes the emergence of a preference for non-harmonic stimuli between the ages of 10 and 13 months in Hungarian-learning infants. Importantly, given that all adjacent regularities were fully controlled, these results support the interpretation that between 10 and 13 months, infants become sensitive to vowel harmony present in Hungarian (language-specific interpretation). However, the fact that 13-month-olds showed a preference for the less frequent structures (NH) rather than the more frequent ones, unlike previously found in similar studies on dissimilarity-based phonotactic regularities (e.g., Nazzi et al., 2009; Gonzalez-Gomez & Nazzi, 2012a,b, 2014; Gonzalez-Gomez et al., 2014), raises an alternative interpretation. Infants' preference observed here might not be language-specific, but a "universal" preference for the more "varied" structures (language-general interpretation). To investigate this possibility, a second experiment was conducted using exactly the same stimuli and procedure, but this time testing an infant population exposed to French, a language without vowel harmony, and in which non-harmonic words are actually more numerous, as confirmed by a set of Chi-square tests of goodness-of-fit conducted on each of the H/NH comparisons (i.e., all words and V_1CV_2 words only). Table 4 presents the analyses confirming that Hungarian is a Harmonic language and that French has a significant Non-Harmonic bias in its lexicon. The level of significance of each value is presented next to its ratio value in Table 4, side by side with the Hungarian data for comparison purposes.

Table 4. *Percentages of cumulative frequency of harmonic and non-harmonic words (in all words and in V_1CV_2 words only) in Hungarian according to the CHILDES database (left panel) and in French according to the Lexique 3 database (right panel). Ratios above 1 indicate a Harmonic bias, ratios below 1 indicate a Non-Harmonic bias (marked in bold).*

	Hungarian (CHILDES)		French (Lexique)	
	All words	V_1CV_2 words only	All words	V_1CV_2 words only
Harmonic	76.41	75.56	45.79	42.68
Non-Harmonic	23.59	24.44	54.21	57.32
Ratio H/**NH**	3.24***	3.09***	**0.85*** **	**0.75*** **

Chi-square test of goodness-of-fit: ***: p ≤ 0.001.

Experiment 2

Method

Participants. Fourteen monolingual, full-term 13-month-old infants from French-speaking families were tested in Paris (mean age = 13 months 20 days; range: 13 months 15 days - 29 days; 8 girls, 6 boys). The data of five additional infants were not included in the analyses due to fussiness/crying.

Stimuli, Procedure and Apparatus. The stimuli and the procedure were identical to the ones in Experiment 1. The apparatus had some minor differences. First, the lights were arranged on three separate panels, one central and one on each side of the infant. Second, if a trial lasted less than 1.5s, the software automatically repeated the trial and only the looking time of this second trial was used. Third, infants had to accumulate 15 seconds of listening time to musical trials before the testing phase began.

Note that the Hungarian pseudowords, which had been created for Experiment 1 to have balanced adjacent regularities in Hungarian, also had balanced adjacent regularities in French, as attested by analyses conducted on the French database *Lexique 3* (New, Pallier, Ferrand, & Matos, 2001). A set of paired t-tests confirmed that the mean frequency of the adjacent regularities between the harmonic (i.e., anterior-anterior and posterior-posterior) and non-harmonic (i.e., anterior-posterior and posterior-anterior) stimuli was not statistically significant for V1CV2, V1C or CV2 (see Table 5). All of these items were pseudo-words that also follow the phonotactic regularities of French.

Table 5. Mean frequency (and SDs) associated to the stimuli used in Experiment 2, for the words themselves (V_1CV_2), and their constituting diphone sequences (V_1C and CV_2) according to Lexique 3 (New, Pallier, Ferrand, & Matos, 2001).

	V_1C	CV_2	V_1CV_2
Harmonic	47,959 (81272)	70,135 (111087)	896 (1489)

Non-Harmonic	80,285 (162853)	72,132 (88449)	1,294 (1761)
H vs NH p-value	.30	.49	.96

Results and Discussion

The mean looking time results are shown in Figure 2 (right panel). A one-way ANOVA with the within-subject factor of Harmonicity (H versus NH) was conducted. Results show that, for 13-month-old French-learning infants, the difference in mean looking times between the Harmonic and Non-Harmonic lists (M_H = 5.83 s, SD = 2.07 s; M_{NH}= 5.21 s, SD = 2.80 s; cf. Fig. 1, right panel) was non-significant (F (1,13) = .43, p = .52). A preference for harmonic stimuli was found in only 8 of the 14 13-month-olds (p = .40, binomial test). In order to estimate the degree of confidence in this null finding we calculated the Bayes factor for this result. The Bayes factor was .02, indicating that the null hypothesis is more likely than the alternative hypothesis, as this value is below the .33 threshold conventionally associated with “substantial support for the null hypothesis” (Lee & Wagenmakers, 2014). Furthermore, we conducted a power calculation to exclude the possibility that our study is underpowered to detect a preference in French infants if there is one. If we assume the effect to be of the same size as in the Hungarian 13-month-old sample (Cohen’s dz=1.21), then with n=14 infants, we have 0.98 achieved power to detect the effect if there is one, which is well above the conventionally required 0.8 threshold.

Additionally, we compared the results of the 13-month-old French- and Hungarian-learning infants by conducting a 2-way ANOVA with the between-subject factor of Language (Hungarian versus French) and the within-subject factor of Harmonicity (H versus NH). The effect of Harmonicity approached significance (F(1, 26) = 3.59, p = .07, ηp2 = .12), infants tending to have longer looking times to NH than to H lists. The effect of Language was significant (F(1, 26) = 20.72, p < .001,

$\eta p2$ = 34), indicating that mean looking times were longer in the Hungarian group. Importantly, the interaction between Language and Harmonicity was also significant ($F(1, 26) = 8.99$, $p = .006$, $\eta p2 = .26$), indicating that the effect of harmonicity changed with language. This pattern of interaction is due to the fact that harmonicity only had a significant effect on the Hungarian-learning infants.

Taken together these results suggest that the NH bias found for the Hungarian-learning infants at 13 months reflects a language-specific bias, and not a language-general/”universal” preference for the more “variable” sequences (i.e., non-harmonic sequences). Importantly, note that although the vowels in the stimuli were chosen to be close to the French phoneme inventory, the recordings were made by a Hungarian speaker. Thus there are minor acoustic differences in the realizations of some of the phonemes. However, in previous studies from our laboratory, French-learning infants have been found to show preferences when presented with foreign stimuli (i.e., French-learning infants showing an LC bias when presented with stimuli recorded in Japanese, Gonzalez-Gomez et al., 2014). It is therefore unlikely that the minor acoustic differences between the Hungarian and French realizations of the vowels could explain the null results found for the French-learning infants.

General Discussion

The goal of the current study was to examine when during development Hungarian-learning infants become sensitive to vowel harmony, a non-adjacent regularity that requires vowels to agree in backness/frontness (and in some cases roundedness) within and across lexical morphemes. This question was motivated by the fact that while acquisition of vowel harmony has been found for Turkish as early as 6 months of age, Hungarian is a language in which vowel harmony is less prevalent, as confirmed by our corpus analyses, than in Turkish, which could lead to a different acquisition trajectory. To this end, 10- and 13-month-old infants' preference for lists of non-harmonic versus harmonic V_1CV_2 pseudowords was examined. Note that all adjacent regularities were fully controlled for. The results of Experiment 1 suggest that sensitivity to vowel harmony in Hungarian-learning infants emerges between 10 and 13 months of age, infants showing a preference for the non-harmonic lists. This does not reflect a language-general, "universal" preference for more variable patterns, as 13-month-old French-learning infants showed no preference for either pattern in Experiment 2. Our study thus establishes that sensitivity to vowel harmony emerges between 10 and 13 months in Hungarian-learning infants.

This result stands in contrast with the finding of previous studies (Altan et al., 2016; Hohenberger et al., 2017; Van Kampen et al., 2008) showing that Turkish-learning infants are already sensitive to vowel harmony by 6 months of age. There are several possible, and not necessarily mutually exclusive, reasons for this difference. First, these studies investigate different aspects of vowel harmony. Our study examined internal, i.e. lexical harmony, whereas Altan *et al.* (2016) and Hohenberger *et al.* (2017) tested external harmony between stems and suffixes, i.e. the morphological level. Internal and external harmony might follow different developmental trajectories.

Second, as outlined in the introduction, crucial statistical factors were not controlled in the stimuli used in previous studies on vowel harmony in Turkish, such as the adjacent and positional frequencies of the phonemes used. Therefore, it is possible that, in these studies, infants reacted not solely to vowel harmony but also to frequency and/or positional properties of the stimuli (as found for 7-month-old French-learning infants in Gonzalez Gomez & Nazzi, 2012), which will have to be explored in future studies on vowel harmony in Turkish.

Third, the novelty preference found in the present study could indicate that a rather late turning point was caught (i.e., the right side of a U-shaped curve), which means that a familiarity preference like in Turkish-learning infants might be found at an earlier age also in Hungarian-learning infants (see also Hunter & Ames, 1988), provided that the early familiarity in Turkish is not due to confounding factors (as discussed in the previous point). However, such U-shaped developmental curves are more typical of perceptual reorganization or rule-learning type processes, rather than of statistically-based lexical learning biases, tested in the current study.

Fourth, the acquisition trajectory may be influenced by the input statistics. As discussed earlier, harmonic words are more prevalent in Turkish (90% according to Ketrez, 2014) than in Hungarian (between 68-76% depending on the type of count considered according to our corpus analyses). The highly regular nature of vowel harmony in Turkish could facilitate the acquisition of this dependency, hence its earlier acquisition, compared to the less regular input of Hungarian. Indeed, the acquisition of vowel harmony found in the present study is identical in timing to the emergence of the PA bias in French-learning infants, which has also been reported to take place between 10 and 13 months of age (Gonzalez-Gomez & Nazzi, 2015). Interestingly, the prevalence of vowel harmony in Hungarian (around 68-76%) is similar to the prevalence of PA words in French (around 71-75%). This suggests that sensitivity to harmony in lexical items, as tested here, may also be a statistical lexical bias, similarly to the PA bias.

Heuristic lexical biases may have an important role in language acquisition because they could facilitate early lexical acquisition for young infants. Vowel harmony concerns both the lexicon and the morphology of harmonic languages. Consequently, once infants know about harmonic regularities in their native language, they might use them as a cue to speech segmentation, subsequent word and grammatical learning. For the lexical level, changes in harmonicity, such as a transition from back to front or from rounded to unrounded vowels, signal the boundaries of (morphologically complex) words. Indeed, adult speakers of harmonic languages, but not of non-harmonic ones, are able to use such changes in harmonicity as segmentation cues (Kabak, Maniwa, & Kazanina, 2010; Suomi, McQueen, & Cutler, 1997; Vroomen, Tuomainen, & de Gelder, 1998). Similarly, Van Kampen et al. (2008) have shown that in addition to being sensitive to vowel harmony at 6 months of age, Turkish-learning infants are also able to use vowel harmony, together with lexical stress, as a cue to word segmentation. Interestingly, a recent study by Mintz and colleagues (2018) showed that even English-learning 7-month-old infants are able to use vowel harmony as a segmentation cue after a short familiarization phase (less than 1 minute), even though their ambient language does not exhibit vowel harmony. The authors interpret this finding as an indication of a universal perceptual grouping mechanism that is available to all infants first and which is then refined based on the infants' linguistic experience leading to a loss of sensitivity in non-harmonic languages.

According to our results, sensitivity to vowel harmony in Hungarian-learning infants emerges between 10 and 13-months, that is, at an age when it could indeed contribute to word learning. Further research will be needed to test whether Hungarian-learning infants do indeed rely on this cue for speech segmentation and lexical acquisition. It will also be interesting in the future to test at what age Hungarian-learning infants become sensitive to the harmonic relation between stems and their suffixes. Testing the morphological role of vowel harmony will provide a unique window into how word learning and grammar learning are interrelated.

In sum, the current study has revealed, for the first time, that Hungarian-learning infants show sensitivity to vowel harmony, a non-adjacent phonotactic dependency, which is frequent, but not exceptionless in their native language, by 13 months of age, right before the onset of robust word learning. In comparison to studies on Turkish suggesting an earlier acquisition of vowel harmony in that language characterized by more prevalent vowel harmony (Altan et al., 2016; Hohenberger et al., 2017; Van Kampen et al., 2008), our findings suggest that frequency/input have an effect on the acquisition of vowel harmony cross-linguistically. Lastly, while some research has found that similarity in phonological features might be easier to identify/learn than dissimilarity (Cristià & Seidl, 2008), our findings do not establish a developmental advantage for the acquisition of the present similarity-based vowel regularity compared to the acquisition of the dissimilarity-based PA bias in French, which has a similar frequency in the input. Further studies will be needed to explore the link or dissociations in the acquisition of similarity- and dissimilarity-based regularities, and whether they proceed through the same or different mechanisms.

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