Eyes can tell. Attention to the eyes and the mouth during audiovisual vowel processing in monolingual and bilingual infants

Jovana Pejovic^{1,2}, Eiling Yee^{3,4}, and Monika Molnar^{5,6}

¹ Center of Linguistics, University of Lisbon, Portugal

² BCBL. Basque Center on Cognition, Brain, and Language

³ Department of Psychological Sciences University of Connecticut

⁴ Connecticut Institute of Brain and Cognitive Sciences

⁵ Department of Speech-Language Pathology, University of Toronto

⁶ Rehabilitation Sciences Institute, University of Toronto

Funding statement: This research was funded by the Social Sciences and Humanities Research Council (SSHRC) of Canada Insight Development Grant (430-2019-00495) to MM, and by the Basque Government “Programa Predoctoral” grant to JP, in addition to the Ayuda Centro de Excelencia Severo Ochoa SEV-2015-0490 grant awarded to the BCBL.

Declaration of interest: None.

Ethics approval statement: The study has been approved by internal BCBL’s ethical committee and followed the Declaration of Helsinki.

Corresponding author:

Jovana Pejovic

Laboratorio de Fonetica & Lisbon Baby Lab

Centro de Linguistica, Faculdade de Letras, Universidade de Lisboa,

Alameda da Universidade, 1600-214 Lisboa, Portugal.

e-mail: jpejovic@edu.ulisboa.pt ; **ORCID ID:** <https://orcid.org/0000-0001-9375-4503>

Abstract

After 6 months of age monolingual infants look more to the mouth of a speaker when there is a mismatch (as opposed to match) between heard and (visually) articulated native *consonants*. Here, we examined whether monolingual and bilingual infants increase their attention to speakers' mouth when processing *vowels*. We compared 4.5- and 8-month-old monolingual and bilingual infants' attention to the eyes and the mouth while presented with native vowels in audiovisual match and mismatch conditions. We observed that 4.5-month-old monolingual and bilingual infants detect the AV mismatch by increasing their attention to the eyes, not to the mouth – as has been previously observed for consonants. However, by 8 months of age monolingual and bilingual infants' attention to the eyes and the mouth is not affected by audiovisual disruption. Our findings suggest that audiovisual vowel and consonant processing differ during the first year of life, and that the specific type of linguistic experience does not modulate selective attention to the mouth or the eyes during vowel processing.

Keywords: Audiovisual speech; Infants; Eyes-mouth preference; Bilingualism; Selective attention; Eye-tracking

Eyes can tell. Attention to the eyes and the mouth during audiovisual vowel processing in monolingual and bilingual infants

1. Introduction

From birth, infants exhibit a preference to attend to faces (e.g., De Haan et al., 2002; Valenza et al., 1996). This is not surprising, as faces are a source of essential communicative information, including the audiovisual (AV) aspects of spoken language (e.g., lip and articulatory movements accompanying speech sounds). Adults spend a lot of time looking at the eyes and the mouth of their communicative partner (i.e., interlocutor). They generally attend more to the eyes than to the mouth (Hillairet de Boisferon et al., 2016; Lewkowicz & Hansen-Tift, 2012), however when listening conditions are not ideal, adults tend to look more to the mouth of an interlocutor, to facilitate comprehension (e.g., Barenholtz et al., 2016; Lansing & McConkie, 2003).

The development of the eyes-mouth preference (henceforth, the *EM preference*) has been the focus of many recent investigations in infants. It is now well documented that when scanning talking faces under ideal listening conditions, 4-month-olds generally spend more time looking at the eyes than the mouth, but by 8 months of age infants' bias to look towards the eyes is reduced, and a preference for the mouths emerges (this change in preference has been referred to as an '*attentional shift*'; e.g., Lewkowicz & Hansen-Tift, 2012; Mercure et al., 2018; Morin-Lessard, Poulin-Dubois, Segalowitz, & Byers-Heinlein, 2019; Pons, Bosch, & Lewkowicz, 2015b; Tsang, Atagi, & Johnson, 2018). By around 12 months of age, when an interlocutor speaks a familiar language, infants begin to shift their attention back to the eyes (e.g., Lewkowicz & Hansen-Tift, 2012; Morin-Lessard et al., 2019).

There is also some evidence that disruptions to the AV signal can modulate infants' visual attention, strengthening their mouth preference: When presented with a native consonant contrast either in an AV matched (i.e., visual /ba/ paired with auditory /ba/) or an AV mismatched condition (i.e., visual /ga/ paired with the auditory /ba/), English-learning infants between the ages of 6 and 9 months looked longer to the mouth in the mismatch condition, possibly to use information from the mouth as a cue to interpretation (Tomalski et al., 2013).¹ But greater attention to the mouth is not inevitable when young infants are presented with AV mismatching consonants. In a study that presented AV match and mismatch consonants similar to the ones described above to 4-8-month-old monolingual (English-learning) and bilingual (English + various other languages) infants, only older (6.6- to 8-month-olds) monolingual infants attended more to the mouth in the AV mismatch condition—the younger, and the bilingual infants showed no increase in attention to the mouth (Mercure et al., 2018). Therefore, thus far it seems that only monolingual infants over 6 months of age show increased attention to the mouth when presented with AV disrupted native consonants.

Why bilingual infants do not show increased attention to the mouth when presented with AV mismatching native consonants is unclear. One potential explanation is the differences in bilingual infants' experience with the presented speech sounds. For instance, the consonant contrast presented to infants in Mercure et al. (2018) was an English contrast produced by an English speaker, making it a native contrast for the monolingual English group but unlikely to be a native to the other languages of the heterogeneous bilingual group. For this reason, the bilingual group was likely to be less familiar the presented contrast, and thus, compared to monolinguals, the bilinguals may have had weaker expectations about what the AV relationship should be, making them more tolerant of the disruption.

Thus, previous studies suggest that (i) under ideal listening conditions infants between 4 and 8 months of age increase their attention to the mouth when scanning faces producing continuous familiar speech, possibly explained by their emerging interest in speech production at this age (Lewkowicz & Hansen-Tift, 2012; Pons et al., 2015); (ii) when listening conditions are less than ideal (i.e., mismatch AV signal for consonants) monolingual infants between 6 to 9 months of age increase their attention to the mouth, possibly to facilitate speech processing (Mercure et al., 2018; Tomalski et al., 2013), however (iii) when experiencing less familiar consonant contrast and/or tested with less native-like consonants, bilingual infants are more tolerant to AV disruption in consonants and do not increase their attention to the mouth (Mercure et al., 2018). It remains an open question whether bilinguals' attention to the mouth would be affected when processing familiar speech segments (i.e., native-like) that are comparable to those that their monolingual peers experience.

1.1. Current Study

The goal of the current study is to test bilingual and monolingual infants' EM preference with vowels that are equally familiar to both groups. To do so, we tested EM preference in response to AV presented vowels in monolingual and bilingual infants at 4.5 and 8 months of age in a cross-sectional design. A few studies have looked at infants' processing of consonants (Danielson et al., 2017; Mercure et al., 2018; Tomalski et al., 2013); however, no prior studies have assessed infants' EM preference during AV vowel processing. There are at least two reasons to believe that AV processing may differ for consonants and vowels during the first year of life: (i) consonants and vowels have different roles in speech processing and language acquisition (Nespor et al., 2003); (ii) the development of native vowel and consonant categories follows

different timelines when assessed in the auditory domain (Polka & Werker, 1994; Werker & Tees, 1984).

Importantly, our stimuli consisted of vowels (/i/ and /u/) that are native to the two languages under investigation. All infants were presented with the vowels in both match (the interlocutor produced the same vowel as heard by the infants) and mismatch conditions (the interlocutor produced an opposite vowel from the one heard by the infant). We tracked infants' eye movements to assess their EM preference. As an exploratory measure, we also video recorded the infants during the experiment to quantify their babbling and to observe their imitation of the target vowels during the experiment, since a link between attention to the mouth and vowel vocalization has been demonstrated (Imafuku et al., 2019).

Spanish and Basque languages provide an ideal test bed for AV vowel processing in bilinguals. Both languages rely on the same vowel inventory consisting of 5 vowels [a, e, i, o, u].² These vowel categories are virtually the same across the two languages. In this way, our stimuli were equally familiar to both the monolingual and bilingual infants, and potential between-group differences due to implicit language recognition/discrimination demands were also minimized. Further, infants were recruited from the San Sebastian region of the Basque Country, where both languages are spoken with similar rhythmic properties (syllable-timed), as quantified by acoustic measures (Molnar, Gervain, et al., 2014; Molnar, Lallier, et al., 2014). Therefore, Spanish and Basque represent two languages that are close in terms of rhythm and phonetic inventory³. In addition, we presented two different speakers across the infants, as our previous investigation revealed that natural inter-speaker differences in articulation affect infants' EM preference (Pejovic et al., 2019).

By presenting 4- and 8-month-old monolingual and bilingual infants with vowels that are equally familiar to both language groups, we are able to examine whether *AV mismatch* elicits more mouth looks by 8 months of age for *vowels* as well as consonants, and whether the attentional shift observed in prior work holds for *vowels* across both monolinguals and bilinguals, depending on inter-speaker differences.

2. Method

2.1. Participants

A total of 91 healthy, full-term infants without known history of language and/or hearing disorders were included in the analyses. Fifty at 4 months of age (24 monolinguals, age range 123-146 days, 8 females; 26 bilinguals, age range 122-146 days, 12 female) and 41 at 8 months of age (21 monolingual, age range 240-255 days, 11 female infants; 20 bilinguals age range 237-259 days, 9 female infants). All infants came from similar SES profiles (i.e., mid to mid-high). Informed consent was obtained from all infants' caregivers.

Infants' exposure to Spanish and Basque was carefully evaluated via a language exposure questionnaire. The monolingual group included only infants exposed at least 95% to one language. Among the 4-month-olds, average exposure to one of the languages in the monolingual group was 99.4 % (range 95.3-100, 7 exposed to Basque and 17 to Spanish). Among the 8-month-olds, the average exposure to one language in the monolingual group was 99.4% (range 95-100; 10 infants were exposed to Basque, and 11 to Spanish). In the bilingual group, average exposure to the other language at 4 months of age was 31.04% (range 15.-48.2; 9 infants were predominantly exposed to Basque, 13 to Spanish, and 4 were balanced in their exposure to Basque and Spanish). At 8 months, the average exposure to the other language in the bilingual

group was 30.4 % (range 15.-49.3; 6 infants dominantly exposed to Basque, 7 to Spanish, and 7 balanced in their exposure to both languages).

Thirty-two additional infants were tested but were unable to complete the experiment due to crying/fussiness (15), failure to calibrate/poor calibration (13), equipment failure (2), inattentiveness (2). An additional 14 infants completed the task but were excluded from analyses because of excessive movement that lead to data loss (4), not looking at the face of the speaker (3). Finally, we set a criterion for being bilingual with minimum of 15% exposure to other language (as in Tsang et al., 2018). For the monolingual group we set a more conservative criterion (95%) than previous studies (e.g., 90% in Morrin-Lessard et al, 2019; Pons et al., 2015). The source of the estimated 5% of exposure to the other language was always outside of the infants' family (e.g., family friends). We did this, because it is still unclear what amount of exposure to another language during early infancy is sufficient to induce a bilingual environment. Therefore, all infants with an estimated language exposure between 85-95% were excluded (7).

2.2. Stimuli and areas of interest

We used AV stimuli from our prior study (Pejovic et al., 2019) that has been created as follows. First, videos of two female Spanish-Basque speakers producing the vowels /i/ and /u/ were recorded. To avoid potential confounds due to only one condition being dubbed and to match vowels across conditions in length, both match and mismatch stimuli were created via dubbing these videos (which were muted during dubbing). To create match stimuli, speakers dubbed by uttering the same vowel that they produced in the video. For mismatch stimuli, speakers dubbed by uttering an opposite vowel (i.e., for visually articulated /i/, speakers uttered /u/; for visually articulated /u/, speakers uttered /i/). Each trial contained nine sequential vowel

productions with ~ 2 seconds interval between the productions, creating approximately a 30-second-long video. Crucially, as demonstrated in our previous study (Pejovic et al., 2019) the speakers *naturally* differed in their visual articulation (i.e., degree of mouth opening for /u/ and degree of mouth spreading for /i/), and these differences affected infants' ability to detect AV mismatch. In particular, 4.5-month-old monolingual infants only detected mismatch when presented with a speaker that articulated vowels in an acoustically/visually more distinctive manner (here, Speaker 2). In the current study we test whether monolingual and bilingual infants have similar sensitivity to these inter-speaker differences. For more details on auditory and visual properties of the stimuli see (Pejovic et al., 2019). Similarly to previous studies (Lewkowicz & Hansen-Tift, 2012; Pons, Bosch, & Lewkowicz, 2015), we selected three areas of interest (AOI), the face, the eyes and the mouth (Figure 1).

Figure 1. Three interest areas: the eyes (in blue), the mouth (in red), and face (in orange) marked on the still-example frames for the two vowels /i/ and /u/. Note that the colored rectangles are for expository purposes—they were not visible during testing.

2.3. Experimental Design

Each infant was presented with both vowels in both the match and mismatch conditions. In the match condition, both auditory and visual signals corresponded (i.e., visual vowel /i/ paired with auditory /i/, and visual vowel /u/ paired with auditory /u/). In the mismatch condition auditory and visual signals did not correspond (i.e., visual vowel /i/ paired with auditory /u/, and visual vowel /u/ paired with auditory /i/). The trials were grouped into two blocks; (1) vowel /i/ and (2) vowel /u/. Each block consisted of three sequentially presented matched and three mismatched trials. In total, each infant was presented with 12 trials. The order of the matched and mismatched trials and of the vowel blocks was counterbalanced across infants. The two speakers were presented as a between-subject factor (i.e., each infant saw only one speaker).

2.4. Procedure

Infants' eye-gaze was collected with a monocular EyeLink 1000-eye-tracker (SR Research). Auditory stimuli were played over speakers with 65-70 dB intensity. Infants were seated in their caregivers' laps, facing a monitor placed 55-60 cm away from the infants. Caregivers wore noise-cancelling headphones and opaque glasses to prevent any influence on the infant's behavior. Before the testing session, infant's eye-gaze was calibrated with a 5-point calibration system. Each experimental trial started with an infant-friendly attention-getter displayed centrally on the screen, accompanied with infant-friendly sounds. The attention-getter also functioned as drift correction, by which we maintained a high eye-tracking accuracy throughout the session. After a gaze at the attention-getter was registered and the drift correction was performed, the trial began. The trial presentation was fully infant-controlled: when infants looked-away for more than two seconds, the trial ended and the attention-getter appeared on the screen. The maximum trial duration was 30 seconds. The maximum duration of the experiment

was 6 minutes, after which information on the language background was assessed via interview with the infant's caregiver.

3. Results

First, in the same way as it has been done in prior EM preference studies (e.g., Lewkowicz & Hansen-Tift, 2012, Pons et al., 2015), we firstly calculated the proportion of looking time to the eyes and the mouth in relation to the time infants spent looking at the entire face of the speaker. Then, we calculated the eyes-mouth (EM) preference score (i.e., proportion of looking time to the eyes minus the proportion of looking time to the mouth). Individual EM scores in each language group, age group, and AV condition are plotted in Figure 2.

Using the EM scores as the dependent variable, we performed a repeated measures ANOVA to test whether the AV congruency (*matching* or *mismatching*), Language background (*monolingual* or *bilingual*), Age (4.5 or 8 months of age) affected the infants' looking preference to the eyes vs. the mouth. As predicted, the ANOVA revealed a main effect of Age ($F_{(1,87)} = 14.89$, $p < .001$, $\eta^2_p = .14$), where the EM scores significantly decreased from 4 months of age ($M = .4$, $SD = .33$) to 8 months of age ($M = .10$, $SD = .39$). The results are depicted in Figure 2. Other effects and interactions, however, did not reach significance (all $F_s < 1.7$, all $p_s > .19$). To ensure that the observed pattern is not due to fatigue that may have increased throughout the experiment, we performed the same analysis on (1) only the first trial, and on (2) only on the first block. The results were the same as with the full dataset (the first trial analysis revealed significant the Age effect $F(1,83) = 9.48$, $p = .002$, all other $p_s > .14$; the first block analysis revealed significant the Age effect $F(1,87) = 6.04$, $p = .01$, all other $p_s > .2$).

Figure 2. The mean eyes-mouth (EM) preference score across age groups, language groups, and the two conditions. The positive values represent an eyes preference, the negative values represent a mouth preference, and the dashed line represents equal looking time between the eyes and mouth. The dots represent individual scores of each infant. The error bars represent 1 (+/-) standard error of the mean.

Previous studies observed that infants attend more to the mouth when presented with AV mismatch than with AV match condition (e.g., Tomalski et al., 2013). For this reason, we analyzed infants' attention in AV matching and AV mismatching condition, separately for the eyes and the mouth. In addition, we included *Speaker* as a factor because in our previous study that employed the same stimuli and paradigm, 4-month-old infants detected an AV mismatch (as measured based on overall looking time and not EM preference scores) only when looking at a speaker who produced more prominent visual cues (Pejovic et al., 2019). In particular, the speaker (here, Speaker 2) who naturally produced vowels that were visually more distinct from one another provided more cues for AV mismatch detection than the other speaker (here, Speaker 1) who naturally produced the vowels in a less visually distinct manner. To test whether infants

from the current study are equally sensitive to these inter-speaker differences when looking at match vs. mismatch trials, we introduced *Speaker* as a factor in following analysis. In the younger group, 11 bilinguals and 14 monolinguals were presented to Speaker 1 (25 in total), while 9 bilinguals and 10 monolinguals were presented to Speaker 2 (25 in total). In the older group 11 bilinguals and 8 monolinguals were presented to Speaker 1 (19 in total), while 9 bilinguals and 13 monolinguals were presented to Speaker 2 (22 in total). To better understand infants' ability to AV mismatch detection we conducted the analysis separately for each age group. The results are illustrated in Figure 3.

3.1. 4-month-old group

In the same way as Tomalski and colleagues' (2013), a repeated measures ANOVA on proportion of looking time to the *mouth* (in relation to the face) as the dependent variable, *Condition* as a within-group factor, and *Group* and *Speaker* as between-group factors was conducted. The analysis revealed no significant main effects or interactions (all $ps > 0.1$). Second, we conducted the analysis with same factors, but on proportion of looking time to the *eyes* (again, in relation to the face). Like in the mouth analysis, in the eyes analysis there were no main effects of *Condition* or *Group*, but interestingly, the analysis revealed significant main effect of *Speaker*, where Speaker 2 elicited more looks to the eyes than the Speaker 1 ($F(1,46)=5.29, p = 0.02, \eta^2_p = .09$). More importantly, we observed a significant *Speaker*Condition* interaction ($F(1,46)=16.33, p = 0.0002, \eta^2_p = .03$). post-hoc comparisons (Bonferroni-adjusted) revealed that infants' attention to the eyes increased in response to the AV mismatch event is present with *Speaker 2* ($t(46) = -4.1, p < .001$), but not with *Speaker 1* ($t(46) = 1.6, p = .11$) as can be seen in Figure 2, bottom-right panel B. Therefore, 4-month-old infants

did look more to the eyes during the AV mismatch than match condition, but only when the stimuli were delivered by the speaker who provided more visual cues. In contrast, attention to the mouth did not change as a function of AV match vs. mismatch.

3.2. 8-month-old group

For the 8-month-old group we conducted the same analysis as for the younger group. The analysis on the *mouth* proportion did not reveal any significant main effect or interaction (all $ps > .2$). The analysis on the *eyes*, however, revealed a trend whereby the bilingual infants attended more to the eyes than did their monolinguals peers ($F(1,37)=3.75, p = 0.06, \eta^2_p = .08$). Other main effects and interactions were not significant (all $ps > .1$).

A Speaker 1 **B Speaker 2**

Figure 3. Mean proportion of looking time for the mouth (left graphs) and the eyes (right graphs) in relation to the face, across conditions, and speakers (Panel A and Panel B). The dots represent individual scores of each infant. The error bars represent 1 (+/-) standard error of the mean. The star represents a significant p-level of <.001).

3.3. *Relation between attention to the mouth and babbling*

Finally, we explored the high variability apparent in infants' attention to the mouth, by assessing whether there is a relationship between infants' expressive language (i.e., babbling) and mouth looking. It has been proposed that infants with better expressive language skills spend more time looking at the mouths of interlocutors (Lewkowicz & Hansen-Tift, 2012; Pons et al., 2015; Schonberg, Sandhofer, Tsang, & Johnson, 2014; Tenenbaum et al., 2015; Young, Merin, Rogers, & Ozonoff, 2009). However, our analyses (detailed in Appendix) did not reveal a relationship between babbling and mouth looking.

All anonymized pre-processed results files are available on
https://osf.io/m972t/?view_only=fbce5342a9a8413c8d79fccd4395196a

4. Discussion

Our study revealed four main findings in regard to infants' attention to the eyes and the mouth when processing vowels produced in an AV match or mismatch context. First, native vowels do not elicit more mouth looks when presented in an AV mismatch (relative to an AV match) context at either 4.5 or 8 months of age in either monolinguals or bilinguals. Second, infants attended more to the eyes in response to an AV mismatch context, but only when a speaker provided more prominent visual cues. Third, when processing vowels presented in an AV context, both monolingual and bilingual infants exhibit an attentional shift from the eyes to the mouth between 4.5 and 8 months of age. Finally, at 8 months of age we observed a trend for eyes preference in bilinguals, in comparison to their monolingual peers. We elaborate on each of these findings in turn below.

To begin with our first two findings, in the current study, presenting native vowels in an AV match vs. mismatch condition did not affect the proportion of mouth looks for either age group or language group. However, in 4.5-month-old infants AV mismatch did elicit more looks to the eyes of the speaker who naturally produced more prominent visual cues in terms of mouth shapes. These findings sound counterintuitive: a speaker who provided more visual cues in terms of mouth shapes elicited more looks to the eyes than the mouth when there was a mismatch between the visual (mouth shape) and the auditory aspects of the vowel. One can only speculate why this might be. Prominent visual articulatory cues could be visible in the eyes region too, as the cheeks are more elevated for the vowel /i/ than for /u/, affecting movements around the eyes. As 4-month-olds have a very strong preference for the eyes region of a speaker in general (e.g., Hunnius & Geuze, 2004; Lewkowicz & Hansen-Tift, 2012), it might be that infants at this age show more sensitivity to mismatch movements in the eyes rather than in the mouth region.

Our findings are in contrast with prior studies examining native *consonants*, where consonants presented in an AV mismatch context elicited *more mouth* looks in monolinguals at 6.5 to 9 months of age (Mercure et al., 2019; Tomalski et al., 2013). Could it be that *audiovisual* processing of vowels is different than processing of consonants, similarly to differences that exist in the auditory domain? Perceptual attunement to native vowel and consonant sound categories have different developmental trajectories during the first year of infancy (e.g., Werker & Tees, 1984; Polka & Werker, 1994). The perceptual attunement hypotheses posit that infants increase their sensitivity to native vowels by 6 months of age and to native consonants by 11 months of age, while their sensitivity to non-native sounds decline during this period (for reviews, see Werker, 2018; Werker et al., 2012). Danielson et al. (2017) tested whether this perceptual reorganization affects EM scores during AV match and mismatch trials. When 6- and 9- month-old monolingual English learning infants were presented with a non-native AV mismatched consonant contrast (i.e., the visual Hindi /ɖa/ mismatched with the auditory Hindi /ɖa/), they moderately increased their attention to the mouth compared to the match condition (the visual Hindi /ɖa/ matched with the Hindi auditory /ɖa/). By 11 months of age, however, the non-native consonants did not elicit increased attention to the mouth in either the match or mismatch condition (Danielson et al., 2017). This is in line with the perceptual attunement hypotheses, that is, infants' sensitivity to non-native AV consonant contrasts decreased by 11 months of age. Given that the data for consonants are consistent with perceptual attunement (Danielson et al., 2017; Mercure et al., 2018; Tomalski et al., 2013), and that perceptual attunement predicts that by 6 months of age, infants should be sensitive to native vowels, it is surprising that in the current study 8-month-old showed no increase in attention to the mouth or the eyes during AV mismatch trials. It is unlikely that 8-month-old infants in the current study are insensitive to AV

vowel correspondence, given that 4.5-month-olds' ability to match AV vowels have been demonstrated using other paradigms (e.g., Desjardins & Werker, 2004; Kuhl & Meltzoff, 1982, 1984; Patterson & Werker, 1999; Yeung & Werker, 2013). Therefore, the lack of difference in mouth looking across match and mismatch trials in the current study suggests that vowel processing in 8-month-old infants may be guided by other principles beyond perceptual attunement and AV match vs. mismatch status.

What other principles might guide AV processing of vowels at this age should be addressed by using various native and non-native vowel contrasts that vary in their acoustic and articulatory distance. In addition, whether vowels and consonants generally elicit the same amount of attention to the mouth should be also tested within the same populations. It might be that vowels generally elicit less mouth attention than consonants, given that none of the groups in the current study showed a clear mouth preference. Visually, vowels and consonants differ in their articulation. During vowel production, the mouth is always open and it remains in a more open position throughout its production. In contrast, consonants are visually more dynamic, with more rapid visual changes occurring in the mouth area. Therefore, it is possible that consonants attract more attention to the mouth. In addition, various theories propose different processing mechanisms for vowel and consonant segments. Consonants and vowels play different roles during language acquisition (Nespor et al., 2003), and it has been proposed that vowels and consonants are processed by distinct neural mechanisms (Caramazza et al., 2000). Further, during typical development, children are more likely to make errors in consonant production than in vowel production (Paul & Norbury, 2012).

Turning to our third finding, both monolingual and bilingual infants showed more interest in the interlocutors' eyes at 4 months than at 8 months of age. This is in line with previous

reports on the attentional shift. However, we also examined individual infant's scores and observed that our data in general are characterized by relatively large individual variability in both age groups (Figure 2). It has been proposed that when canonical babbling emerges (between approximately 6 and 10 months of age), attention to the mouths of interlocutors is advantageous because it can aid in learning about speech production, in part through providing input for imitation. In line with this hypothesis, Tsang et al. (2018) reported that it is expressive language skills rather than age that predicts infants' mouth looking between 6 and 12 months of age. While this hypothesis has some empirical support (Tenenbaum et al., 2015; Young et al., 2009), other studies have found no direct link between attention to the mouth and productive vocabulary (Hillairet de Boisferon, Tift, Minar, & Lewkowicz, 2018; Morin-Lessard et al., 2019). Like these latter studies, we found no link between attention to the mouth and speech production. That is, individual variability in production abilities did not account for the variability that we observed in attention to the mouth

Finally, we observed that our bilingual and monolingual infants elicited similar looking patterns while processing AV vowels that are shared across their languages. Although, at 8 months of age we observed a trend that bilingual, but not monolingual infants spent more time looking at the eyes. Interestingly, this trend for the eye preference contrasts with a prior report that bilingual infants learning two similar languages (in terms of their rhythmic, phonological and syntactic properties) were more likely to spend more time looking at the mouth compared to their monolingual peers (Birules, Bosch, Brieke, Pons, & Lewkowicz, 2018; Pons et al., 2015). For instance, Spanish-Catalan learning bilingual 4-month-olds show more interest in the mouth of an interlocutor producing continuous speech than Spanish or Catalan monolinguals (Pons et al., 2015). Similar results emerged in 15-month-old infants and 4-to-6-year-old children learning

Spanish and Catalan (Birules et al., 2018). However, infants learning two more distant languages (e.g., Spanish-German, Spanish-Russian, English-French, etc.) do not show the same increase in mouth looks when processing continuous speech (Birules et al., 2018; Morin-Lessard et al., 2019; Tsang et al., 2018). Infants tested in the current study were learning two close languages in terms of their rhythmic and phonological properties (Molnar, Gervain, et al., 2014; Molnar, Lallier, et al., 2014), yet they spent *less* time looking at the mouth than their monolingual peers at 8 months of age. Thus, as in Birules et al, we observed that learning two close languages in infancy can alter attention to the eyes/mouth compared to monolinguals, but in the current study, this difference manifested in the form of a trend for eye preference. However, it is unclear whether the eye preference pattern is due to the stimuli (i.e., vowels) or other factors. Alternatively, taking into account the attentional shift phenomenon, that is, that eye preference is reduced by 8 months of age (e.g., Lewkowicz & Hansen-Tift, 2012), the fact that bilingual 8-month-olds exhibited more attention to the eyes than monolinguals could be interpreted as the attentional shift being a process that may have a slightly slower trajectory in bilinguals (who were learning the languages that we tested) as compared to in monolinguals.

5. Conclusion

Our findings suggest that young infants differ in their AV processing of vowels and consonants, providing support for theories that suggest a different role for vowels and consonants during language acquisition. Infants' ability to detect AV vowel mismatch around 4 months of age is reflected by increased attention to the eyes, not the mouth of a speaker, as it has been observed for consonants. In addition, AV mismatch detection in this age is shaped by inter-speaker differences, while bilingual vs. monolingual experience does not affect AV mismatch detection. By 8 months of age, AV congruency does not alter infants' attention that is allocated to

the eyes vs. mouth when looking at interlocutors producing native vowel segments. Taken together, the results highlight that there may be no “one size fits all” development of audiovisual speech processing. Instead, infants’ visual speech processing may be modulated not only by monolingual vs. bilingual experience, but also by the inter-speaker differences and the type of speech segment (vowel vs. consonant) that is being processed.

6. References

- Barenholtz, E., Mavica, L., & Lewkowicz, D. J. (2016). Language familiarity modulates relative attention to the eyes and mouth of a talker. *Cognition*, *147*, 100–105.
<https://doi.org/10.1016/j.cognition.2015.11.013>
- Birules, J., Bosch, L., Brieke, R., Pons, F., & Lewkowicz, D. J. (2018). Inside Bilingualism: Language Background Modulates Selective Attention to a Talker's Mouth. *Developmental Science*, e12755. <https://doi.org/10.1111/desc.12755>
- Caramazza, A., Chialant, D., Capasso, R., & Miceli, G. (2000). Separable processing of consonants and vowels. *Nature*, *403*(6768), 428–430. <https://doi.org/10.1038/35000206>
- Danielson, D. K., Bruderer, A. G., Kandhadai, P., Vatikiotis-Bateson, E., & Werker, J. (2017). The organization and reorganization of audiovisual speech perception in the first year of life. *Cognitive Development*. <https://doi.org/10.1016/j.cogdev.2017.02.004>
- De Haan, M., Pascalis, O., & Johnson, M. H. (2002). Specialization of neural mechanisms underlying face recognition in human infants. *Journal of Cognitive Neuroscience*, *14*(2), 199–209. <https://doi.org/10.1162/089892902317236849>
- Desjardins, R. N., & Werker, J. (2004). Is the integration of heard and seen speech mandatory for infants? *Developmental Psychobiology*, *45*(4), 187–203. <https://doi.org/10.1002/dev.20033>
- Hillairet de Boisferon, A., Tift, A. H., Minar, N. J., & Lewkowicz, D. J. (2016). Selective attention to a talker's mouth in infancy: role of audiovisual temporal synchrony and linguistic experience. *Developmental Science*, *20*(3), 1–12.
<https://doi.org/10.1111/desc.12381>
- Hillairet de Boisferon, A., Tift, A. H., Minar, N. J., & Lewkowicz, D. J. (2018). The Redeployment of Attention to the Mouth of a Talking Face in the Second Year of Life.

Journal of Experimental Child Psychology, 172, 189–200.

<https://doi.org/10.1016/j.jecp.2018.03.009>

Hualde, J. I. (1991). *Basque Phonology*. Routledge.

Imafuku, M., Kanakogi, Y., Butler, D., & Myowa, M. (2019). Demystifying infant vocal imitation: The roles of mouth looking and speaker's gaze. *Developmental Science*, 22(6).

<https://doi.org/10.1111/desc.12825>

Imafuku, M., & Myowa, M. (2016). Developmental change in sensitivity to audiovisual speech congruency and its relation to language in infants. *Psychologia*, 59(4), 163–172.

<https://doi.org/10.2117/psysoc.2016.163>

Kuhl, P., & Meltzoff, A. (1982). The bimodal perception of speech in infancy. *Science*, 218(4577), 1138–1141. <https://doi.org/10.1126/science.7146899>

Kuhl, P., & Meltzoff, A. (1984). The Intermodal Representation of Speech in Infants. *Infant Behavior and Development*, 7(3), 361–381. [https://doi.org/10.1016/S0163-6383\(84\)80050-8](https://doi.org/10.1016/S0163-6383(84)80050-8)

Lansing, C. R., & McConkie, G. W. (2003). Word identification and eye fixation locations in visual and visual-plus-auditory presentations of spoken sentences. *Perception and Psychophysics*, 65(4), 536–552. <https://doi.org/10.3758/BF03194581>

Lewkowicz, D. J., & Hansen-Tift, A. M. (2012). Infants deploy selective attention to the mouth of a talking face when learning speech. *Proceedings of the National Academy of Sciences*, 109(5), 1431–1436. <https://doi.org/10.1073/pnas.1114783109>

Mercure, E., Kushnerenko, E., Goldberg, L., Bowden-Howl, H., Coulson, K., Johnson, M. H., & MacSweeney, M. (2018). Language experience influences audiovisual speech integration in unimodal and bimodal bilingual infants. *Developmental Science*, October 2017, e12701. <https://doi.org/10.1111/desc.12701>

- Molnar, M., Gervain, J., & Carreiras, M. (2014). Within-rhythm class native language discrimination abilities of Basque-Spanish monolingual and bilingual infants at 3.5 months of age. *Infancy*, 19(3), 326–337. <https://doi.org/10.1111/infa.12041>
- Molnar, M., Lallier, M., & Carreiras, M. (2014). The Amount of Language Exposure Determines Nonlinguistic Tone Grouping Biases in Infants From a Bilingual Environment. *Language Learning*, 64(s2), 45–64. <https://doi.org/10.1111/lang.12069>
- Morin-Lessard, E., Poulin-Dubois, D., Segalowitz, N., & Byers-Heinlein, K. (2019). Selective Attention to the Mouth of Talking Faces in Monolinguals and Bilinguals Aged 5 Months to 5 Years. *Developmental Psychology*, 1–60. <https://doi.org/10.1037/dev0000750>
- Nespor, M., Peña, M., & Mehler, J. (2003). On the different roles of vowels and consonants in speech processing and language acquisition. *Lingue e Linguaggio*, 2(2), 203–229. <https://doi.org/10.1418/10879>
- Patterson, M., & Werker, J. (1999). Matching phonetic information in lips and voice is robust in 4.5-month-old infants. *Infant Behavior and Development*, 22(2), 237–247. [https://doi.org/10.1016/S0163-6383\(99\)00003-X](https://doi.org/10.1016/S0163-6383(99)00003-X)
- Paul, R., & Norbury, C. (2012). *Language Disorders from Infancy Through Adolescence*. Elsevier Health Sciences.
- Pejovic, J., Yee, E., & Molnar, M. (2019). Speaker matters: Natural inter-speaker variation affects 4-month-olds' perception of audio-visual speech. *First Language*, X, 1–15. <https://doi.org/10.1177/0142723719876382>
- Polka, L., & Werker, J. F. (1994). Developmental Changes in Perception of Nonnative Vowel Contrast. *Journal of Experimental Psychology: Human Perception and Performance*, 20(2), 421–435.

- Pons, F., Bosch, L., & Lewkowicz, D. J. (2015a). Bilingualism modulates infants' selective attention to the mouth of a talking face. *Psychological Science*, 26(4), 490–498.
<https://doi.org/10.1177/0956797614568320>
- Pons, F., Bosch, L., & Lewkowicz, D. J. (2015b). Bilingualism Modulates Infants' Selective Attention to the Mouth of a Talking Face. *Psychological Science*, 26(4), 490–498.
<https://doi.org/10.1177/0956797614568320>
- Schonberg, C., Sandhofer, C. M., Tsang, T., & Johnson, S. P. (2014). Does bilingual experience affect early visual perceptual development? *Frontiers in Psychology*, 5(DEC).
<https://doi.org/10.3389/fpsyg.2014.01429>
- Tenenbaum, E. J., Sobel, D. M., Sheinkopf, S. J., Shah, R. J., Malle, B. F., & Morgan, J. L. (2015). Attention to the mouth and gaze following in infancy predict language development. *Journal of Child Language*, 42(6). <https://doi.org/10.1017/S0305000914000725>
- Tomalski, P., Ribeiro, H., Ballieux, H., Axelsson, E. L., Murphy, E., Moore, D. G., & Kushnerenko, E. (2013). Exploring early developmental changes in face scanning patterns during the perception of audiovisual mismatch of speech cues. *European Journal of Developmental Psychology*, 10(5), 611–624.
- Tsang, T., Atagi, N., & Johnson, S. P. (2018). Selective attention to the mouth is associated with expressive language skills in monolingual and bilingual infants. *Journal of Experimental Child Psychology*, 169, 93–109. <https://doi.org/10.1016/j.jecp.2018.01.002>
- Valenza, E., Simion, F., Cassia, V. M., & Umiltà, C. (1996). Face Preference at Birth. *Journal of Experimental Psychology: Human Perception and Performance* Fantz & Nevis, 22(4).
https://www.researchgate.net/profile/Viola_Macchi_Cassia/publication/14445628_Face_Preference_at_Birth/links/567171d508aececf55536d0.pdf

- Werker, J. F. (2018). Perceptual beginnings to language acquisition. In *Applied Psycholinguistics* (Vol. 39, Issue 4, pp. 703–728). Cambridge University Press.
<https://doi.org/10.1017/S0142716418000152>
- Werker, J. F., & Tees, R. C. (1984). Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. *Infant Behavior and Development*, 7(1), 49–63.
[https://doi.org/10.1016/S0163-6383\(84\)80022-3](https://doi.org/10.1016/S0163-6383(84)80022-3)
- Werker, J. F., Yeung, H. H., & Yoshida, K. A. (2012). How Do Infants Become Experts at Native-Speech Perception? *Current Directions in Psychological Science*, 21(4), 221–226.
<https://doi.org/10.1177/0963721412449459>
- Yeung, H. H., & Werker, J. (2013). Lip Movements Affect Infants' Audiovisual Speech Perception. *Psychological Science*, 24(5), 603–612.
<https://doi.org/10.1177/0956797612458802>
- Young, G. S., Merin, N., Rogers, S. J., & Ozonoff, S. (2009). Gaze behavior and affect at 6 months: predicting clinical outcomes and language development in typically developing infants and infants at risk for autism. *Developmental Science*, 12(5), 798–814.
<https://doi.org/10.1111/j.1467-7687.2009.00833.x>

7. Endnotes

¹ Similarly, 6-, but not 12-month-old Japanese-learning infants attend more to the mouth of a face that is mismatching the heard fluent speech (Imafuku & Myowa, 2016).

² Note that here we are referring to the vowel system in Castilian Spanish language and most Basque dialects because subjects are recruited from the region where those dialects are spoken. Other dialects may differ in their vowel systems. For instance, the Soule dialect of Basque has an additional vowel /ü/ (Hualde, 1991).

³ Despite that the two languages are rather distinct in terms of their syntactic properties (i.e., language Spanish follows a verb-object word order, while Basque relies on an object-verb order).

8. Appendix

Relation between EM preference score and expressive language

We tested whether infants' EM preference is influenced by speech-like vocalizations during the experiment. Each infant was recorded during the experiment using a camera placed under the stimulus presentation screen. The purpose of these videos were twofold: (i) record whether the infants imitated the vowels presented during the experiment; (ii) record the infants' other speech production patterns during the experiment. Two trained experimenters coded the infants' speech-like vocalizations: vowel-like (V), consonant-like (C), or their combinations (VC, CV, VCVC, or CVCV, etc.) from videos recorded during the experimental task, which lasted about 7 minutes for each infant (pre- and post-task vocalizations were excluded due to variability in the duration of pre- and post- task recordings). Vocalizations that were not speech-like (i.e., grunting, laughing, crying, etc.) were excluded from analyses. Due to technical difficulties, videos for only 66 infants were available (33 4-months-olds, 11 bilinguals; 33 8-months-olds, 16 bilinguals).

As demonstrated in Table A1, infants did not produce many speech-like vocalizations during the experiment. Despite the unexpectedly low overall frequency of vocalizations, an expected increase in vocalization was present between 4 and 8 months of age ($t(64) = 4.09$, $p < .001$). Numerically it appears that the monolingual group at 8 months of age vocalized more than their bilingual peers but this trend did not reach statistical significance (due to the small sample size a Mann-Whitney test was conducted, $z = -1.78$, $p = .08$).

Table A1. Description of infants' production during the AV vowel matching task.

Age group	Language group	Mean of vocalizations	Range of vocalizations	N of infants that vocalized
4.5	Monolingual	1.5	1-3	2 out of 22
	Bilingual	1	1-1	1 out of 11
8	Monolingual	4.2	2-6	6 out of 17
	Bilingual	2.4	1-6	7 out of 16

Note. Values for the mean and range of vocalizations refer only to those infants that vocalized during the experiment.

To test whether there is a relationship between the infant's vocalization during the task and their mouth looking, we conducted a non-parametric Spearman's correlation analysis between infants' EM scores and their sum of vocalization at 8 months of age, for each language group separately. The results revealed no significant correlation at 8 months of age in either language groups ($r_{s \text{ monolingual}} = .00, p = .99, N = 17$; $r_{s \text{ bilingual}} = -.07, p = .78, N = 16$).

Finally, we analyzed whether the 8-month-olds imitated the presented vowels and whether their imitation pattern interacted with their EM score. We coded vocalization as an imitation if an infant produced vowel-like sounds (/i/ and /u/), regardless whether the infant imitated the auditory, visual (in AV mismatch condition) or audiovisually (AV match condition) presented vowel. In the entire 8-month-old group we detected only 7 infants who imitated the vowels at least once (5 bilingual and 2 monolingual; Imitation range per infant: 1-6; see Figure A1). While such low number of data points would not mandate statistical analyses, a Spearman's rho correlation coefficient between the EM scores and imitation frequency yielded non-significant results ($r_s = .2, p = .13, N = 33$).

Figure A1. The relation between the mean eyes-mouth (EM) preference score and imitation frequency in the 8-month-old group. The positive values on the EM score (y-axis) represent an eyes preference, the negative values represent a mouth preference, and the dashed line represents equal looking time between the eyes and mouth. The dots represent individual scores of each infant.