Infant-directed speech to infants at risk for dyslexia: A novel cross-dyad design

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Keywords: Infant-directed speech; language input; vowel hyperarticulation; dyslexia; pitch

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When mothers speak to infants at-risk for developmental dyslexia, they do not hyperarticulate vowels in their infant-directed speech (IDS). Here we used an innovative cross-dyad design to investigate whether the absence of vowel hyperarticulation in IDS to at-risk infants is a product of maternal *infant-directed* behaviour or of infants' *parent-directed* cues. Interactions between mothers and infants who were at-risk or not at-risk for dyslexia were recorded in three conditions: when mothers interacted (i) with their own infants, (ii) infants who were not their own but of the same risk status, and (iii) infants who were not their own and of the opposite risk status. This design revealed both infant and parent effects. Mothers of not at-risk infants hyperarticulated vowels significantly more when speaking to not at-risk than to at-risk infants. In contrast, mothers of at-risk infants hyperarticulated vowels significantly less than NAR mothers, and this was irrespective of infant status. Mothers of not at-risk infants thus adjusted their IDS to the infant's risk status, while mothers of at-risk infants did not. We suggest that IDS is determined reciprocally by characteristics of both partners in the dyad: both infant and maternal factors are essential for the vowel hyperarticulation component of IDS.

Keywords: Infant-directed speech; language input; vowel hyperarticulation; dyslexia; pitch

It is well established that adults adjust their verbal and non-verbal behaviours when interacting with young infants (Papoušek, 2007). Specifically, parents and other adults adjust the properties of their infant-directed speech (IDS) in ways that can facilitate the task of language acquisition for their young infant (Kuhl, 2000). However, in the case of infants at family risk for dyslexia, a neurodevelopmental disorder affecting reading and spelling (Snowling, 2001), mothers adjust their production of IDS in ways that appear counter-intuitive. Kalashnikova, Goswami, and Burnham (2018) studied mothers' speech to nine- and 11-month-old infants who were and were not at family risk for dyslexia comparing the extent of vowel hyperarticulation, which refers to parents' tendency to produce acoustically exaggerated vowel categories in IDS compared to adult-directed speech (ADS). Vowel hyperarticulation is proposed to result in clearer speech sounds that are easier for infants to discriminate and later reproduce in their own vocal tract (Kuhl et al., 1997). Analyses showed that while the mothers of not at-risk infants hyperarticulated vowels in their IDS relative to their ADS, mothers of at-risk infants did not. This absence of vowel hyperarticulation to at-risk infants was found irrespective of whether the mothers themselves were dyslexic, or whether the infants were at-risk due to their *fathers'* dyslexia.

This finding is surprising given that vowel hyperarticulation in mothers' IDS has been proposed to facilitate speech processing and subsequent language acquisition (Kuhl, 2000). However, this 'facilitation' view is not uncontroversial (Cristia, 2013), as a number of studies have failed to detect vowel hyperarticulation in maternal speech in English (e.g., Green, Nip, Wilson, Mefferd, & Yunusova, 2010) and other languages (e.g., German - Audibert & Falk, 2018; Dutch - Benders, 2013; and Norwegian - Englund & Behne, 2005). Furthermore, even in cases in which vowel hyperarticulation is present, it has been found to co-occur with a high degree of within-category variability, which may exacerbate the difficulty of infants' task of learning discrete phonological categories in their native language (Cristia & Seidl, 2014;

McMurray, Kovack-Lesh, Goodwin, & McEron, 2013). This view has been supported by computational evidence demonstrating that models perform more successfully in tasks of phonetic categorisation when trained with ADS compared to IDS (Martin et al., 2015; McMurray et al., 2013; Miyazawa, Shinya, Martin, Kikuchi, & Mazuka, 2017, but see De Boer & Kuhl, 2003; Werker et al., 2007). In light of these findings, it could be argued that there are no direct implications of the absence of vowel hyperarticulation in IDS to infants at-risk for dyslexia for early linguistic development. This argument rests on findings of within-category variability in IDS, but it must be noted that the relationship between the exaggeration of vowel space and within-category variability is not fully understood. For instance, it has been proposed that both these features, despite appearing to counteract each other, may be consistent with acoustic adjustments aimed at facilitating language teaching (Eaves, Feldman, Griffiths, & Shafto, 2016). In addition, infants *have* been shown to benefit from exposure to exaggerated vs. non-exaggerated vowels in experiments assessing vowel perception (Peter, Kalashnikova, Santos, & Burnham, 2016; Zhang et al., 2011) and lexical processing (Song, Demuth, & Morgan, 2010). Moreover, the degree to which individual mothers hyperarticulate vowels in IDS is positively related to their infants' concurrent and later linguistic abilities: mothers who exaggerate vowels to a greater extent have infants who are more successful in discriminating native phonetic contrasts at the ages of six to eight and 10 to 12 months (Liu, Kuhl, & Tsao, 2003) and have infants who have larger vocabulary sizes in the second year of life (Hartman, Ratner, & Newman, 2017; Kalashnikova & Burnham, 2018).

Considering this ongoing debate about the origin and role of vowel hyperarticulation in IDS, it is particularly important to determine the factors – infant or maternal – that may lead to the presence of vowel hyperarticulation in IDS to not at-risk infants and its absence in IDS to at-risk infants. Accordingly, in this study, we assess vowel hyperarticulation in IDS to at-risk and to not at-risk infants. Vowel hyperarticulation is measured by extracting the first and second formant values (F1 and F2) from all the tokens of the three corner vowels, /i, u, a/, produced by the speaker, calculating their means, and plotting these values in two-dimensional space, which results in a vowel triangle shape. The area of the triangle denotes the size of the speaker's acoustic vowel space, and it has been found to be significantly larger in IDS than in ADS (Burnham, Kitamura, & Vollmer-Conna, 2002; Kuhl et al., 1997).

As a comparison, elevated pitch height will also be measured here as this is an IDS feature that has *not* been found to relate to later language development (Kalashnikova & Burnham, 2018). Elevated pitch height refers to parents' tendency to produce speech with higher fundamental frequency (F0) in IDS than in ADS (Fernald et al., 1989), which results in more attentionally salient speech (Cooper & Aslin, 1990; Fernald & Kuhl, 1987). These two components tend to co-occur in IDS, but they are independent. For example, Lam and Kitamura (2012) showed that a reduction in vowel hyperarticulation in IDS to infants who are unable to hear their mother's speech occurs independently of adjustments to pitch, and Uther, Knoll, and Burnham (2007) showed that there is vowel hyperarticulation in speech to both infants and foreigners, but elevated pitch only to infants. Furthermore, in the Kalashnikova et al. (2018) study, mothers of infants at-risk for dyslexia produced heightened pitch in their IDS even though they did not hyperarticulate vowels. As these two components can be manifested independently, they are ideal dependent variables for the current study.

The current underlying assumption in the IDS literature is that vowel hyperarticulation and exaggerated pitch are IDS components that *parents direct to* the infant. For instance, it has been proposed that these IDS components are the product of parental intentions to express emotion and regulate infant behaviour (Benders, 2013; Singh, Morgan, & Best, 2002; Trainor, Austin, & Desjardins, 2000). Most recently, it has been argued that these components are the product of parents' unconscious intention to sound more like their infant (Englund & Behne, 2005), or similarly, parents' unconscious intention to appear smaller and less threatening (Kalashnikova, Carignan, & Burnham, 2017).

On the other hand, there is now evidence that IDS components could also be the result of cues that *infants direct* to the parent; that both parents' infant-directed *and* infants' parent-directed behaviours may play significant roles in determing the nature of IDS. Two studies with typically-developing infants provide direct evidence that adjustments to the pitch and to the vowel articulation components of maternal IDS occur in *response* to communicative cues from the infant. Both used a 'double video' set-up in which the mother and infant sit in different laboratory rooms and communicate via audio-visual equipment, allowing the experimenters to manipulate the information from the mother to the infant, unbeknown to the mother. In the first, Smith and Trainor (2008) assessed mothers' adjustments to their pitch height when interacting with their four-month-old infants. The mother could see and hear her infant on the video screen of the double-video set-up, and she was told that her infant could also see and hear her. Instead, the infants actually interacted with an experimenter who received cues about the mother's speech over headphones. In the contingent condition, when mothers produced higher pitch the experimenter engaged with the infant by producing positive facial expressions, and when mothers lowered their pitch, the experimenter maintained a still face. In the non-contingent condition, the experimenter's facial expressions to the infant were the opposite, still face for higher pitch and positive for lower pitch. Results showed that mothers in the contingent condition raised their pitch significantly more over the session than did mothers in the non-contingent condition. This indicates that feedback from the infant (whatever that feedback may be) can and does affect the strength of a particular component, pitch in this case, of mothers' IDS.

In the second double video study, Lam and Kitamura (2012) assessed the effects of infant feedback on mothers' degree of vowel hyperarticulation in IDS. Mothers and infants sat in different rooms and could both see and hear each other via video screens. However, half-way through the interaction, the volume of the mother's voice to the infant was either reduced by 50% or switched off entirely. Results showed that mothers produced hyperarticulated vowels when their speech was audible to the infant, produced less vowel hyperarticulation in the partially audible condition, and ceased hyperarticulating vowels altogether when their infants could not hear them. Crucially, half of the mothers were made aware of the manipulation of the volume of their voice to the infant, while the other half remained unaware. This did not affect the results; vowel hyperarticulation decreased as a product of the audibility of the mothers' speech to the infant irrespective of whether the mothers knew or did not know about the decreased audibility. Clearly, infants conveyed some feedback that affected their mothers' behaviour, in this case their vowel hyperarticulation.

These two studies show that the two components of mothers' IDS to typically-developing infants that are the focus here, vowel hyperarticulation and elevated pitch, are both affected by feedback from the infant, that is by *parent-directed cues*. In addition, the Kalashnikova et al. (2018) study of IDS to at-risk infants also provides evidence for the infant's role as a driver of the acoustic adjustments in their mothers' speech. Compared with the not at-risk infants, the at-risk infants showed significantly poorer perceptual discrimination of amplitude envelope rise time, an acoustic parameter known to be related to the neural encoding of speech (Doelling, Arnal, Ghitza, & Poeppel, 2014). Importantly, there was also a significant correlation between mothers' degree of hyperarticulation in IDS and infants' rise time discrimination scores for the whole sample (at-risk and not at-risk infants). Thus, mothers hyperarticulated vowels more to infants with better rise time discrimination, and as mothers had no knowledge of their infants' level of rise time discrimination ability, it appears that their degree of vowel hyperarticulation in IDS was a product of their infants' degree of rise time discrimination acuity. The causal relation between these two measures remains unclear, but it may well be that some aspect of *infants' parent-directed cues* is responsible for the lack of mothers' vowel hyperarticulation to at-risk infants (Kalashnikova et al., 2018). That is, mothers may unconsciously perceive the level or nature of their infants' perceptual processing and adjust their input accordingly.

In this study, we employ the double-video technique in order to investigate whether the presence (or absence) of vowel hyperarticulation in IDS to infants at-risk for dyslexia is determined by factors inherent to the speaker, i.e., the *infant-directed* nature of mothers' speech to infants, or by specific *parent-directed* cues that infants provide for their adult interlocutors, or both. Specifically, mothers of not at-risk infants spoke to infants at-risk for dyslexia and vice versa. The complete experimental design necessitated three conditions. We measured (1) mothers' IDS when speaking to their own infants, (2) mothers' IDS when speaking to another infant who was from the same risk category as their own infant (e.g., mother of a not at-risk infant speaking to another not at-risk infant), and (3) mothers' IDS when speaking to another infant who was in the opposite risk category from their own infant (e.g., a mother of a not at-risk infant speaking to an infant at-risk for dyslexia). In addition to vowel hyperarticulation, pitch elevation was measured in all three conditions in the at-risk and not at-risk samples in order to provide a within-subject comparison.

Based on the Kalashnikova et al. (2018) findings we predicted that when speaking to their own infants, mothers of not at-risk infants would hyperarticulate vowels, but mothers of at-risk infants would not. Regarding the cross-dyad interactions, we predicted two possible outcomes related to the role of mothers' infant-directed and of infants' parent-directed behaviours in the manifestation of vowel hyperarticulation in IDS.

1. If *infant-directed behaviours* are related to the degree of vowel hyperarticulation, then we expected that mothers' previous *experience* of IDS with their own infant would be the determining factor in all interactions. That is, mothers of not-at-risk infants would

hyperarticulate vowels in IDS to not-at-risk infants and to at-risk infants, and mothers of at-risk infants would produce reduced vowel hyperarticulation in IDS to at-risk infants and to not-at-risk infants.

2. Alternatively, if infants' *parent-directed cues* guide mothers' use of hyperarticulation, then we expected that the infants' risk status would be the determining factor irrespective of the mothers' experience. That is, not at-risk infants would elicit hyperarticulated vowels from mothers of both not-at-risk and mothers of at-risk infants, and that at-risk infants would fail to elicit hyperarticulated vowels from mothers of both at-risk and mothers of not at-risk infants.

Note that the critical difference between these two possible outcomes is in the cross-status conditions: in the *infant-directed* outcome, NAR mothers *would* show hyperarticulation to AR infants, but AR mothers *would not* show vowel hyperarticulation to NAR infants; and in the *parent-directed* outcome, NAR mothers *would not* show hyperarticulation to AR infants, but AR mothers *would* show vowel hyperarticulation to NAR infants.

Conditions in which mothers spoke to another baby of the same risk status as their own were included to control for the potential confound of mother-infant familiarity – the fact that when mothers speak to a baby from a different risk status, they are also speaking to a baby who is not their own. It was expected that vowel articulation patterns by mothers of not at-risk infants and at-risk infants would be maintained in speaking to other babies of the same status as their own, in which case our predicted results from cross-status pairings could be interpreted unambiguously.

Finally, based on Kalashnikova et al. (2018) we expected that pitch elevation would be unaffected either by the status of the mother (having a not at-risk vs. an at-risk infant), or by the status of the infant (own infant/other infant, at-risk/not at-risk).

Method

Participants

Fifteen mother-infant dyads participated. All mothers were monolingual speakers of Australian English, and their infants were raised in a monolingual environment. In eight dyads the infant was at family risk for dyslexia (AR group) by virtue of having a dyslexic parent (*M* age = 46.9 weeks, *SD* = 6.05, range 35 to 51 weeks; 3 female). In two cases, the parent with dyslexia was the mother who participated in the study, and in the other six cases, it was the father (the two sub-groups were collapsed for this study given that maternal dyslexia status was not expected to influence the results, Kalashnikova et al., 2018). In seven dyads the infant was not at risk for any language disorders (NAR group) (*M* age = 51.2 weeks, *SD* = 5.4, range 39.1 to 57.9 weeks; 2 female). Infant age ranged from 8 to 13 months, and age did not differ between the two groups, $t(13) = -1.688$, $p = .115$, $d = -.75$.

Mothers and their infants were recruited from a database of families who had expressed interest in participating in university infancy research. Dyads were selected based on their family history of dyslexia (one of the infants' parents had a dyslexia diagnosis) in the case of the AR group, and in the case of both the AR and NAR groups, based on their availability to visit the lab on 2 or 3 occasions scheduled several days apart. All infants came from mother-father households, and the mothers did not report having any experiences of parenting children with a different family history of dyslexia (e.g., adoptees or children from different partners). All families were from a white middle-class background. Maternal education level was used as a proxy for socio-economic status. The median education level was an undergraduate university degree, and this did not differ between the two groups, Kolmogorov-Smirnov $Z = .587$, $p = .882$. In the AR group, 1 mother had a high-school degree, 5 had a university degree, and 2 had a post-graduate degree. In the NAR group, 3 mothers had a college or technical diploma, 3 had a university degree, and 1 had a post-graduate degree. Infants were all born full-term and were not at-risk for any additional developmental disorders. This study was conducted according to guidelines laid down in the Declaration of Helsinki, with written informed consent obtained from each mother on her and her child's behalf before any assessment or data collection. All procedures involving human subjects in this study were approved by the Human Ethics Committee at Western Sydney University (approval number: H9142).

A total of 60 recordings were collected including 15 ADS (1 × 15 mothers) and 40 IDS (3 × 15 mother-infant dyads). An additional 5 sessions (2 NAR mother to not her own AR infant, 1 AR mother to not her own NAR infant, 2 AR mother to not her own AR infant) could not be completed because the infant became upset or fussy when separated from their mother, so these sessions were not included in the analyses.

Procedure

Each mother's speech was recorded in four sessions: speaking to an adult (ADS), speaking to her own infant, speaking to another infant who had the same risk status as her own infant, and speaking to another infant who had a different risk status from her own infant. Mothers were only aware of the risk status of their own infant and did not know that risk status was one of the variables manipulated in this study.

All sessions were recorded using the double-video set-up. Even though this design did not involve manipulations of the audio or visual signal that would require the use of double-video, this set-up was used in order to control for any potential effects of individual mothers' interaction styles with babies who were and were not their own. IDS involves physical components such as touch (Abu-Zhaya, Seidl, & Cristia, 2017) and actions (Brand, Baldwin, & Ashburn, 2002), and these components influence infants' attention to speech and their engagement with their interlocutor and toys used in the interaction (Deák, Krasno, Jasso, & Triesch, 2018). However, it is unknown whether mothers would produce these behaviours differently when interacting with a baby who was not their own. The use of a double-video set-up prevented all mothers and infants from engaging physically with each other, thus ensuring that infants were not potentially distracted by holding toys or pictures while listening to speech.

Mothers and infants sat in different laboratory rooms and saw each other's image via closed circuit cameras (Panasonic WV-CL920), which also provided feed for video recordings. Each camera was pointed directly at mother/infant to provide the other with a head and shoulder image, but was hidden behind half-silvered mirrors placed at a 45-degree angle behind the teleprompter, so that they saw the other's face but not the camera. Mothers listened to the infants via headphones and wore a head-mounted microphone (Audio Technica AT892CWTH) connected to a recording device (Digital audio recorder Zoom H4n). Infants listened to their mothers over audio speakers set to a comfortable volume. In the ADS condition, an experimenter was seated on the mother's side of the double video and the mother on the infant's side of the double video set-up.

Mothers were told that the study was concerned with how women speak to different babies, and they were asked to interact naturally with each baby as they would with their own. In order to measure vowel hyperarticulation, instances of the three corner vowels /i, u, a/ were required. Following previous IDS studies (Burnham et al., 2002; Kalashnikova et al., 2017; 2018; Kalashnikova & Burnham, 2018; Lam & Kitamura, 2012), mothers were given a toy sheep, a baby shoe, and a toy shark (note that 'r' is non-rhotic in Australian English), and a set of pictures that depicted these three items in different situations (e.g., shoe, sheep, and shark superimposed on a beach scene) to aid conversation using those three words. The length of the sessions ranged from 5 to 10 minutes. During the ADS sessions, mothers interacted with an experimenter (a native speaker of Australian English) in a brief interview. In order to elicit instances of the three target words in the ADS session, mothers interacted with an experimenter via the double-video set-up and were asked to comment on the play session with their own babies.

All four sessions were completed over two or three visits to the lab. In all cases, the IDS session between a mother and her own infant was conducted first. The order of the subsequent sessions varied across participants depending on their availability to attend the lab at the same time as another family. Three experimenters were present during the sessions. The first experimenter monitored the interactions from a control room adjoining the two testing rooms where the mother and infant were separately seated. Another experimenter was present inside the infants' room so that infants were not left alone, but this experimenter was required to stay behind the infant's chair to avoid seeing the infant's and the mother's face. A third experimenter cared for the infants when their mothers interacted with a different infant or with the experimenter.

Acoustic Analyses

First, IDS and ADS recordings were split into segments of maternal speech un-interrupted by silences longer than 1 second, by infant vocalisations, or by noises from the environment. Praat software (Boersma & Weenink, 2010) was used to extract the mean pitch height for each segment. Given the logarithmic nature of pitch perception, these raw F0 values were converted from Hz to perceptual units (Mels) using the formula: $12LOG_2$(F0 value in Hz). F0 values before and after the transformation are presented in Table 1.

[insert Table 1 here]

Next, the target words *sheep*, *shoe*, and *shark* were identified, and the target corner vowels /i/, /u/, /a/ extracted from each of these words. Praat scripts were used to calculate the mean value in Hz of the first and second formants (F1, F2) for the period between the 40% and the 80% points of each vowel's duration. The formants were extracted based on three vowel categories, for which three formants (F1, F2, F3, with the limits ranging from 0 to

5500 Hz) and fundamental frequency (F0, with the limits ranging from 0 to 500 Hz) were extracted. Praat scripts used to extract pitch and formants are available at https://osf.io/gnrfs/. The output was visually inspected for outliers. Vowel plots for each group and interaction type are displayed in Figure 1. Mean F1 and F2 coordinates were derived for each target vowel for each mother and each session in which she was involved, the centroids of the cluster of values for each vowel were determined, and these then served as the vertices of vowel triangles for each of the four conditions for each mother (ADS, IDS to own infant, IDS to other infant of same risk status, and IDS to other infant of different risk status). Vowel triangle areas were calculated using the formula: $\text{ABS}\ \frac{1}{2} \times [(F1/a/ \times (F2/i/ - F2/u/) + F1/i/ \times (F2/u/ - F2/a/) + F1/u/ \times (F2/a/ - F2/i/)]$, where F1/a/ refers to the average value in Hz of the first formant for the vowel /a/, F2/i/ to the average value in Hz of the second formant for the vowel /i/, and so forth.

[insert Figure 1 here]

Results

Hyper-scores for vowel triangle areas and pitch height were the dependent variables used for analyses. Hyper-scores are calculated by dividing each mother's IDS vowel triangle area and mean pitch height by her own ADS vowel triangle area and mean pitch height respectively, thus allowing each mother to act as her own control, and ensuring that scores used in the analyses are normalised for individual differences in vocal tract morphology, voice quality, and speech articulation. A hyper score >1 indicates that the values were greater in IDS compared to ADS, a hyper score of 1 denotes that the values for IDS and ADS did not differ, and a hyper score below 1 denotes that the values were lower in IDS compared to ADS (Kalashnikova & Burnham, 2018; Kalashnikova et al., 2018).

First, analyses were conducted from the perspective of mothers' experience of producing IDS to NAR or to AR infants. For this purpose, hyper-scores were collapsed across conditions and subject to one-sample *t*-tests against chance (unity) conducted separately for mothers of NAR and AR infants to assess whether they produced exaggerated (>1) or reduced (<1) vowels and pitch regardless of the infant risk status or their familiarity with the infant. Results showed that mothers of NAR infants significantly *hyper*articulated vowels (M = 1.62, SD = 1.26), $t(17) = 2.12$, $p = .049$, $d = .49$, but mothers of AR infants did not (M = .70, SD = .41), $t(21) = -3.94$, $p < .001$, $d = .84$. In fact, AR mothers' vowel production was significantly *hypo*articulated in IDS compared to their own ADS. In contrast, mothers of both NAR infants (M = 1.07, SD = .03, $t(17) = 9.95$, $p < .001$, $d = 2.35$) and AR infants (M = 1.07, SD = .03, $t(20) = 9.50$, $p < .001$, $d = 2.07$) significantly exaggerated pitch in IDS. Therefore, overall, mothers of NAR infants exaggerated vowels and pitch in their IDS, but mothers of AR infants exaggerated pitch but not vowels.

Second, analyses were conducted from the perspective of infants in order to assess the effects of infants' risk status and of infants' familiarity to the mother on IDS. Two Linear Mixed Effects (LME) models were constructed to assess the effects of infants' risk status on vowel hyperarticulation and on pitch elevation components. Both models included as predictor variables the two-level between-subjects factor infant risk group (AR / NAR), and also the three-level within-subjects factor interaction type (own mother / another mother of infant with same risk status / another mother of infant with different risk status), and random intercepts for infant and random slopes for infant risk group by infant (initial models were constructed following the maximum structure (Barr, Levy, Scheepers, & Tily, 2013) including random slopes for interaction type by infant, but they failed to converge). Vowel hyper-scores were included as the dependent variable in the first model and pitch hyper-scores in the second model. The 'lmer' package v. 1.1.1-18-1 in R (Bates, 2005) was used to run the LMEs, with the 'car' package v. 3.0-2 (Fox et al., 2012) to calculate p-values, followed by planned pair-wise contrasts conducted using the 'diffsmeans' function of the 'lmertest' package v. 2.0-20 (Kuznetsova, Brockhoff, & Christensen, 2015) to investigate the sources of the significant main effects and interactions.

Vowel Hyper-scores

Vowel hyper-scores for the three types of interactions for each infant risk group are presented in Figure 2. The LME model yielded a main effect of infant risk group, $F(1, 40) = 4.718$, $p = .036$, indicating that, overall, NAR infants heard more exaggerated vowels than AR infants, $t(40) = 2.17$, $p = .04$ ($\beta = .6$, $SE = .271$, CI[.041, 1.13]). There was no main effect of interaction type, $F(2, 40) = .916$, $p = .408$, but there was a significant interaction of group by interaction type, $F(2,40) = 4.054$, $p = .025$. To understand the source of this interaction, planned pairwise comparisons were conducted.

[Insert Figure 2 here]

First, when the infants in the two groups were addressed by their own mother, there was greater vowel hyperarticulation in IDS to NAR infants than to AR infants, $t(40) = .225$, $p = .015$, $\beta = 1.1$, SE = 0.438, CI[1.995, 0.015] (Figure 2, see columns 1 vs. 4).

Next, comparisons were conducted to assess the hyper-scores for the cross-dyad interactions. For the NAR infant group there were no significant differences in vowel hyper-scores when the infants were addressed by their own mother or by a mother of another NAR infant, $t(40) = .76$, $p =.454$, $\beta = -0.4$, $SE = 0.471$, CI[-1.307, 0.596] (Figure 2, see columns 1 vs. 2. However, vowel hyper-scores were significantly lower when mothers of AR infants spoke to an NAR infant (Figure 2, see column 6) than when mothers of NAR infants spoke to their own NAR infant, $t(40) = 1.862$, $p = .043$, $\beta = -0.9$, $SE = 0.452$, CI[-1.862, -0.034] (Figure 2, see column 1), or to another NAR infant, $t(40) = 2.255$, $p = .009$, $\beta = 0.471$, $SE = 40.0$, CI[-2.255, -0.352] (Figure 2, see column 2). Thus, even though as a group NAR infants heard vowels hyperarticulated to a greater extent than AR infants, mothers of AR infants showed reduced vowel hyperarticulation when speaking to NAR infants compared to NAR mothers. This suggests that, compared to mothers of NAR infants, mothers of AR infants were *less sensitive* to whatever "want vowel hyperarticulation" cues NAR infants displayed, which is presumably an effect of mothers' experience of IDS use.

In the AR infant group, as for the NAR infant group, vowel hyper-scores did not differ significantly when the infants were addressed by a mother of an AR infant who was or was not their own, $t(40) = .64$, $p = .527$, $\beta = -0.3$, $SE = 0.438$, $CI[-1.165, 0.606]$ (Figure 2, see columns 4 vs. 5). However, in contrast to the NAR infant group, there were no significant differences between AR infants being spoken to by a mother of another AR infant or a mother of an NAR infant, $t(40) = 1.44$, $p = .157$, $\beta = 0.7$, $SE = 0.482$, $CI[-0.279, 1.671]$ (Figure 2, see columns 5 vs. 3). Thus, there were no statistically significant differences in the degree to which mothers hyperarticulated vowels when speaking to AR infants, regardless of whether their own baby was AR or NAR. This is interpreted as an effect of infant risk status. Infants' *parent-directed cues* appear to control the interaction, and these cues appear to operate instantaneously for the mothers of NAR infants, but not for the mothers of AR infants.[1]

[1] The vowel hyper-scores used as the dependent variable in these analyses were computed using raw F1 and F2 values extracted in Hz. However, it is noteworthy that these values do not reflect the perceptual nature of formant frequencies, and that analyses employing values transformed to a perceptual scale may be appropriate. To reflect this, we transformed the F1 and F2 values to a Mel scale and repeated the analysis models. The resulting model reflected our original findings by yielding a main effect of infant group, $F(1, 40) = 4.14$, $p = .05$, no effect of interaction type, $F(2, 40) = .96$, $p = .39$, and a group by interaction type interaction, $F(2, 40) = 3.20$, $p = .05$. As reported in the main analyses, vowel hyperarticulation scores were significantly greater in IDS to NAR than to AR infants, $\beta = .57$, $t(40) = 1.94$, $p = .05$, and NAR mothers produced significantly higher vowel hyperarticulation scores in IDS to their own NAR infant compared to IDS to an AR infant who was not their own, $\beta = .85$, $t(40) = 1.79$, $p = .08$, and in IDS to an NAR infant who was not their own compared to IDS to an AR infant who was not their own, $\beta = 1.23$, $t(40) = 2.49$, $p = .02$. There were no significant differences in vowel hyperarticulation scores for IDS produced by mothers of AR infants when speaking to their own AR infant and an NAR infant who was not their own, $\beta = .72$, $t(40) = 1.43$, $p = .16$, and to an AR infant who was not their own vs. an NAR infant who was not their own, $\beta = .33$, $t(40) = .72$, $p = .53$.

Pitch Hyper-scores

Figure 3 shows the pitch hyper-scores in each interaction type involving NAR infants and AR infants. To assess pitch exaggeration in the IDS interactions, an identical LME model to that used for the hyper-vowel scores was constructed, with the exception that only random intercepts for infant were included in the model as the model did not converge when random slopes for infant group were included. The model yielded no main effects of infant risk group, $F(1, 14.414) = .185$, $p = .673$, or interaction type, $F(2, 25.756) = .173$, $p = .842$, and no significant interaction for infant group by interaction type, $F(2, 25.756) = .031$, $p = .969$. Therefore, mean pitch hyper-scores did not differ between groups or between interaction types.

[Insert Figure 3 here]

These findings for pitch rule out any explanation of the vowel hyperarticulation findings based on familiarity with the infant and show that the infants' parent-directed cues are specific to vowel hyperarticulation and are not the product of some change in infant behaviour that has global effects on a range of components of mothers' IDS.

Discussion

Previous research has indicated that vowel hyperarticulation in IDS is impacted by infant risk status; Kalashnikova et al. (2018) reported no vowel hyperarticulation in IDS to infants at-risk for dyslexia. The current study aimed to pinpoint more precisely the mechanisms that underlie this counter-intuitive finding and that drive the degree of vowel hyperarticulation in IDS. In particular, we were interested to discover whether vowel hyperarticulation in IDS is affected by a mother's experience with their particular infant, or by their infant's parent-directed cues. The results show that vowel hyperarticulation in IDS is not driven solely by the mother nor solely by the infant, but rather by a *combination* of maternal and infant factors.

When mothers of NAR infants spoke to NAR infants, either their own or not their own, they produced hyperarticulated vowels. However, when these same mothers of NAR infants spoke to AR infants, they hyperarticulated vowels to a significantly lesser extent. Thus, it appears that mothers of NAR infants adjust their vowel production in IDS in response to infants' parent-directed cues; they respond to cues from NAR infants that elicit hyperarticulated vowels and cues from AR infants that do not elicit hyperarticulated vowels. As these NAR mothers were unaware of other infants' risk status, it can be inferred that they must have perceived different parent-directed cues from NAR and AR infants, and unconsciously altered their behaviour accordingly.

In contrast, and in concert with Kalashnikova et al. (2018), mothers of AR infants showed significantly lower degrees of vowel hyperarticulation to their own AR infants, or to another AR infant. Mopreover, this was also the case in the cross-status condition, when AR mothers spoke to NAR infants, which is contrary to the NAR mothers' shift in the cross-status condition. These NAR infants were presumably providing cues that should elicit vowel hyperarticulation, as these cues were picked up and acted upon by NAR mothers, even though they were unaware of other infants' risk status. Accordingly, AR mothers (who were also unaware of other infants' risk status) appeared to be less *senstitive* to the different cues from NAR and AR infants and so produced reduced degrees of vowel hyperarticulation in IDS to NAR infants compared to mothers of NAR infants.

Our unique cross-dyad research design has allowed us to isolate with precision the effects of maternal infant-directed behaviours and infants' parent-directed cues. We have differentiated the IDS adjustments made *in situ* by mothers in the lab in response to infant feedback from the adjustments that have been shaped by the dyad's long-standing experience of interacting with each other. Mothers of NAR infants adjusted the quality of their vowels depending on the risk status of their infant interlocutor. This occured within a single five- to

10-minute-interaction with infants previously unknown to them. Thus, this adjustment was spontaneous and immediate, and, as the risk status of the unfamiliar infant interlocutors was unknown to the mothers, unmediated by conscious decision. It could be possible that our findings were driven by global effects of addressing unfamiliar infants in a double-video set up. However, in this case significant differences would be expected in pitch exaggeration across conditions, and second, differences would be expected in both vowel hyperarticulation and pitch exaggeration in IDS to a mother's own baby versus to another baby of the same risk status. However, neither of these results were present in our analyses. With regard to the possible mechanism involved in the adjustments to IDS made by the mothers of NAR infants, the most likely is that the infant is the driver. When mothers receive cues eliciting vowel hyperarticulation from an infant, they exaggerate the pattern of the first and second formants in the vowels in their speech. When they do not receive these cues from an infant (or when they receive different as yet unspecified cues), they do not change the formant pattern, so there is an absence of vowel hyperarticulation in their IDS to AR infants. Nevertheless, elevated attention-getting pitch is retained.

What of the mothers whose own infants were AR for dyslexia who showed reduced vowel hyperarticulation to all of the three infant groups? It is unlikely that risk status triggers opposing developmental mechanisms, i.e., that when the infant is NAR, the infant drives the interaction, but when the infant is AR, the mother drives the interaction. Thus, the parsimonious conclusion is that the results for AR infants are also the result that infants' parent-directed cues modulate the presence of vowel hyperarticulation in maternal speech. If so, then it is possible that since the mothers of AR infants have not encountered the type of cues that elicit hyperarticulated vowels during their ongoiing interactions with their AR infant, they have not developed the ability to identify these cues in *any* infant. This is consistent with previous literature that has proposed that any dynamic adjustments that parents make in their behaviour result from *continuous learning* from their infants' behaviour (Papoušek, 2007). Thus, when interacting with an NAR infant, even though the infant provides cues that elicit hyperarticulation in NAR mothers, AR mothers' learning history results in their inability to comply.

Turning now to compare the hyper-vowel and hyper-pitch results, mothers' pitch height in IDS was equally elevated over that in their ADS across groups and dyadic interaction types. This finding dovetails with previous research on the acoustic qualities of speech registers demonstrating that hyperarticulated vowels and exaggerated pitch do not always co-occur (Burnham et al., 2002; Uther et al., 2010). Crucially, as it has been shown that pitch adjustments in maternal speech occur in response to infant cues (Smith & Trainor, 2008), then our results suggest that during dyadic interactions infants employ one set of parent-directed cues to elicit elevated pitch and a different set of cues to elicit exaggerated vowels (see Lam & Kitamura, 2012 for converging conclusions). It would follow then that in the case of infants at-risk for dyslexia, the cues for eliciting exaggerated pitch are unrelated to the cues for *not* eliciting vowel hyperarticulation, and the cues for eliciting exaggerated pitch are unaffected by their risk status. The dissocation found here supports the view that pitch and vowel hyperarticulation serve distinctly different purposes, and that these purposes can be isolated both in infant-directed speech *and* in parent-directed cues.

Nevertheless, while this and previous studies (Lam & Kitamura, 2012; Smith & Trainor, 2008) demonstrate that mothers are sensitive to cues from the infant even within a short single interaction, our results do not allow us to determine the exact nature of the parent-directed cues that infants produce and the exact nature of this feedback remains unspecified. Identifying the nature of infant cues is particularly challenging in the case of infants at-risk for dyslexia. Unlike other populations in which infant factors may influence parental communicative behaviours (e.g., infants with Autism Spectrum Disorder or Down

Syndrome, Venuti et al., 2012; Quigley, McNally, & Lawson, 2016), there are no visible signs that signal that a child is at-risk for or has dyslexia. In fact, there is approximately a 50% chance that infants who are at-risk for dyslexia by virtue of having a dyslexic parent, will not develop dyslexia later in childhood (Galaburda, LoTurco, Ramus, Fitch, & Rosen, 2006). The only known factor that distinguishes infants AR for dyslexia from typically-developing infants at this age is a subtle auditory processing disorder (Guttorm et al., 2005; Leppänen et al., 2010; Lyytinen et al., 2004). Nevertheless, despite its non-overt nature, Kalashnikova et al. (2018) demonstrated that the degree of vowel hyperarticulation in maternal speech is correlated with infants' auditory processing abilities, so it is possible that this is what mothers are sensitive to, but not necessarily conscious of – nuances in infants' ability to process their speech.

For the moment, we can only speculate about the mechanisms underlying this sensitivity, but research advances into interpersonal communication suggest that it may lie at the level of efficient speaker-listener neural coupling. During linguistic interactions, a process of synchronisation or coupling between the interlocutors' endogenous neural oscillations takes place, which in adults is a predictor of the listeners' ability to comprehend the speech string (Hasson, Ghazanfar, Galantucci, Garrod, & Keysers, 2012). In infants, this process is less studied, but there is evidence for inter-personal neural coupling during mother-child interaction (Leong et al., 2019; Reindl et al., 2018). The effects of potential disturbances to this process on speakers' productions are unknown, but it is possible that they may lead speakers to adjust their speech patterns as a compensatory mechanism. Such an explanation would account for the present cross-dyad findings, and also the results reported by Smith and Trainor (2008). In their study, even though mothers were unaware of the fact that their infants were responding to a different interlocutor, they were sensitive to the disconnect between their own communicative behaviours and their infants' feedback, which resulted in adjustments in their pitch production to their infants. While we do not provide direct evidence that such disturbances are related to infants' risk of dyslexia in our study, there is ample evidence that neural coupling to speech is impaired in children and adults diagnosed with dyslexia (e.g., Di Liberto et al., 2018; Molinaro, Lizarazu, Lallier, Bourguignon, & Carreiras, 2016; Power, Colling, Mead, Barnes, & Goswami, 2016; Power, Mead, Barnes, & Goswami, 2013). To date neural entrainment to continuous speech has not been tested in at-risk infants, but there *is* reduced discrimination of amplitude envelope rise time differences in at-risk infants (Kalashnikova et al., 2018). Amplitude rise time is an acoustic parameter related to the neural encoding of speech (Doelling et al., 2014), and a significant predictor of infants' developing linguistic abilities (Kalashnikova, Goswami, & Burnham, 2019). Moreover, infants' sensitivity to amplitude envelope rise time is precisely the perceptual ability that is positively related to the degree of vowel hyperarticulation in maternal speech (Kalashnikova et al., 2018).

It should be considered that mothers of AR infants may have brought additional endogenous factors to the interactions that reduced their sensitivity to infant cues or that prevented them from hyperarticulating vowels in response to infant cues. More specifically, it is possible that mothers' own linguistic abilities may have influenced their speech production, especially in the case of the mothers who were themselves dyslexic (Elbro, Nielsen, & Petersen, 1994). However, since Kalashnikova et al. (2018) showed that hyperarticulation is independent of maternal dyslexia diagnosis, and since only two mothers in the sample in the current study were themselves dyslexic, we propose that the linguistic abilities of the mothers of at-risk infants here were unlikely to have affected the results. Nevertheless, given that this possibility could not be tested directly in this study and has not been extensively investigated in existing research, it is an empirical question left for further study.

The finding that IDS to infants at-risk for dyslexia is characterised by reduced vowel hyperarticulation compared to IDS to not at-risk infants also provides grounds for future research focusing on the effects of early exposure to this reduced-hyperarticulation variant of IDS on AR infants' later language development. We are currently investigating this issue in an ongoing longitudinal study. Vowel hyperarticulation in maternal speech has been related to infants' speech perception and vocabulary development (Hartman et al., 2018; Kalashnikova & Burnham, 2018; Liu et al., 2003), so it is possible that early deficits in these abilities in at-risk infants may also relate to the quality of their mothers' IDS. However, as noted earlier, the view that vowel hyperarticulation aids language learning by infants has not been without controversy. Evidence from modelling suggests that the acoustic features of vowels in IDS do not facilitate phonological category formation and do not yield benefits for infants' language development (Martin et al., 2015). Testing the relation between IDS qualities and children's developing language skills in a population in which the vowel hyperarticulation component of IDS is reduced may directly inform this ongoing debate. Relatedly, we note that the abovementioned research has not taken into consideration the linguistic capacity and needs of the infant who is the recipient of IDS (but see Cristia & Seidl, 2014). Our data necessitate consideration of the *infant as a driver* of IDS, and this conclusion dovetails with previous studies that have manipulated mother-infant interactions via double-video paradigms (Lam & Kitamura, 2012; Smith & Trainor, 2008). This active infant role should be taken into account in any future attempts to investigate directly or model mathematically the role of vowel hyperarticulation and other acoustic components of IDS in early language acquisition.

We have introduced a novel and incisive method for differentiating the role of maternal infant-directed behaviours and infants' parents-directed cues. Nevertheless, there are several important limitations of this method that must be addressed in future research.

Our design required four mother-infant dyads to coordinate their recording sessions across two to three visits to the lab, which resulted in a small sample size compared to previous studies on IDS. Pragmatic considerations also limited our ability to match the number of mothers who were and were not themselves dyslexic. These challenges, related to participant recruitment and orchestration of the experimental sessions also led to the inclusion of infants from a wide age range and interfered with our ability to match the age and gender of mothers' own infants and infants who were not their own. In this regard, it is known that some IDS qualities such as pitch can be influenced by infant gender (Kitamura, Thanavishuth, Burnham, & Luksaneeyanawin, 2001). With regard to age, we did not expect it to impact the degree of vowel hyperarticulation since it has been shown to remain stable from 4 to 20 months of age (E. B. Burnham et al., 2015; Cristia & Seidl, 2014; Kalashnikova & Burnham, 2018). Accordingly, post-hoc correlational analyses of our data showed that the degree of vowel hyperarticulation across conditions did not relate to infants' age in this study (own infant $r = -.28$; other infant same risk status $r = -.53$, other infant different risk status $r = .37$, all $p > .06$). However, there is evidence that infant age can modulate infants' *preferences* for IDS (Hayashi, Tamekawa, & Karitani, 2001; Newman & Hussain, 2006), which could have had an impact on the degree of engagement and attention during the sessions in this study, leading to an indirect effect on vowel hyperarticulation.

In conclusion, early mother-infant interactions are a microcosm in which the mother and the infant exchange information that is unconscious for the participants. This information exchange generally provides the infant with the type of linguistic and social environment that is most optimal for their developmental needs. The aim of this study was to understand the nature of this microcosm by isolating the maternal and infant factors that determine the qualities of IDS. By testing a population of infants at family risk or not at-risk for dyslexia, we were able to study infant and mother effects independently. Our findings suggest that by the time their infants approach their first birthday, mothers of at-risk infants have consolidated a specific IDS style that that exhibits reduced vowel hyperarticulation. Further, when interacting with infants unfamiliar to them, they do not make the dynamic online adjustments to their articulation of vowels that mothers of not at-risk infants do; mothers of not at-risk infants produce IDS that contains vowel hyperarticulation, but only when they receive the appropriate parent-directed cues from the infant. Thus, both infant and maternal factors influence the hyperarticulation of vowels in IDS. These factors are independent of mothers' familiarity with the infant, but are affected by the infant's risk for a developmental language disorder.

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Table 1. *Mean (SD) F0 values in Hz and in Mel.*

	Mean F0 (Hz)	Mean F0 (Mels)
NAR mother ADS	215.58 (24.76)	4.66 (0.10)
NAR mother to her own NAR infant	319.21 (25.44)	5.01 (0.07)
NAR mother to not her own NAR infant	311.08 (27.34)	4.98 (0.08)
NAR mother to not her own AR infant	292.46 (28.65)	4.93 (0.09)
AR mother ADS	216.56 (21.43)	4.67 (0.08)
AR mother to her own AR infant	315.38 (49.54)	4.99 (0.14)
AR mother to not her own AR infant	307.66 (38.79)	4.97 (0.11)
AR mother to not her own NAR infant	322.07 (35.82)	5.01 (0.09)

List of Figures

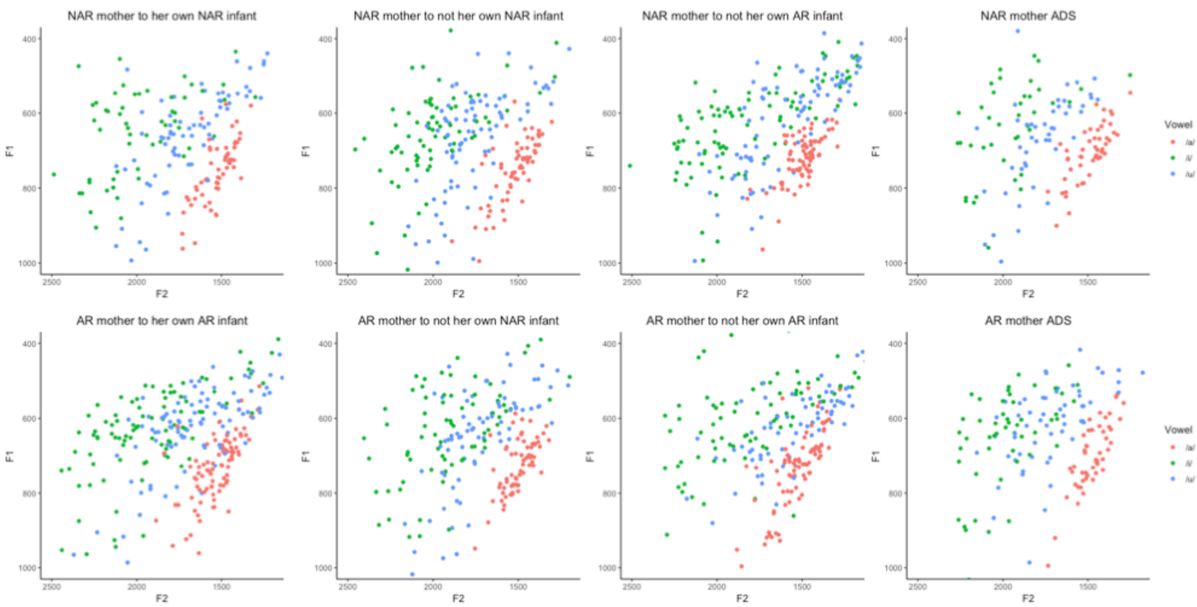

Figure 1. Plots of individual vowel tokens in speech produced by NAR (top panel) and AR (bottom panel) mothers, from left to right: in IDS to their own infant, in IDS to not their own NAR infant, in IDS to not their own AR infant, and in ADS.

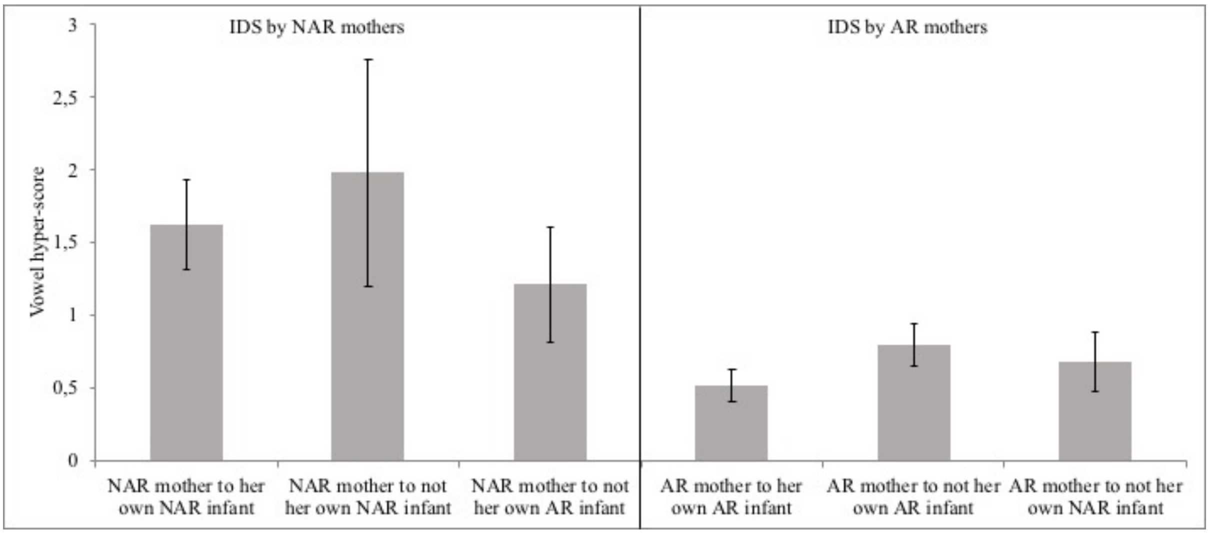

Figure 2. Vowel hyper-scores in IDS to NAR (from left, columns 1-3) and to AR infants (columns 4-6) (error bars represent SEM).

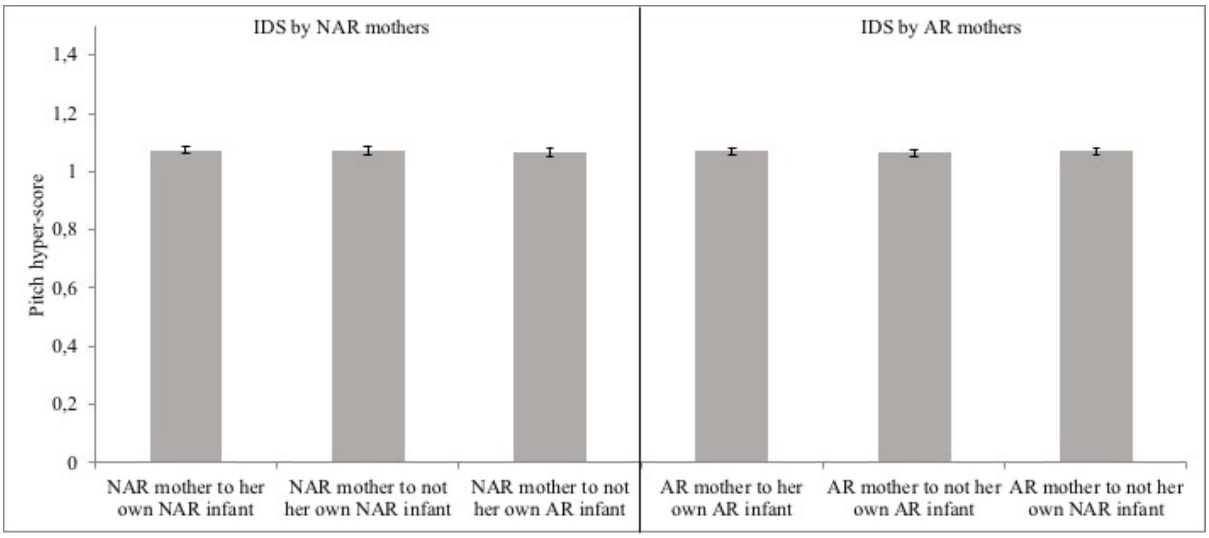

Figure 3. Pitch hyper-scores in IDS to NAR (from left, columns 1-3) and to AR infants (columns 4-6) (error bars represent SEM).