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Running Head: Production and processing in prelinguistic infants

Do production patterns influence the processing of speech in prelinguistic infants?

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Abstract

The headturn preference procedure was used to test 18 infants on their response to three different passages chosen to reflect their individual production patterns. The passages contained nonwords with consonants in one of three categories: (a) often produced by that infant (‘own’), (b) rarely produced by that infant but common at that age (‘other’), and (c) not generally produced by infants. Infants who had a single ‘own’ consonant showed no significant preference for either ’own’ (a) or ‘other’ (b) passages. In contrast, infants’ with two ‘own’ consonants exhibited greater attention to ‘other’ passages (b). Both groups attended equally to the passage featuring consonants rarely produced by infants of that age (c). An analysis of a sample of the infant-directed speech ruled out the mothers’ speech as a source of the infant preferences. The production-based shift to a focus on the ‘other’ passage suggests that nascent production abilities combine with emergent perceptual experience to facilitate word learning.

Keywords: Infant Speech Perception, Infant Speech Production, Headturn Preference Paradigm, The Articulatory Filter, Babbling, Vocal Motor Schemes

1.0 Introduction

One factor often overlooked in the research into infant speech perception is the effect that early pre-lexical production or babble may have on perception of and/or attention to incoming speech, even though infants typically begin rhythmic production of adult-like syllables – 'canonical babbling' – between six and eight months (Oller, 2000), the period of the first major advances in speech perception (cf., e.g., Jusczyk & Aslin, 1995; Tincoff & Jusczyk, 1999; Shi & Werker, 2001; Soderstrom, Seidl, Kemler-Nelson, & Jusczyk, 2003; Jusczyk, Houston, & Newsome, 1999; Nazzi, Jusczyk, & Johnson, 2000; Soderstrom, Kemler-Nelson, & Jusczyk, 2005). This study tests the idea that increasing use of consonants in production will directly affect the processing of running speech.

From a Dynamic Systems perspective, language development can be viewed as a process in which relatively simple skills interact to create more complex ones (Thelen, 1991). Babble is one such simple skill. Its effect on speech perception has not yet been seriously investigated despite the fact that there is ample evidence that motoric experiences affect perception, with wide-ranging effects on social as well as cognitive development. For example, Piaget (1952) emphasized the importance of the child experiencing and acting on the world, suggesting that intelligence is derived from sensorimotor activity. Recent work with locomotion has also highlighted the way in which secondary effects of self-produced locomotion can initiate more complex cognitive advances (see Campos et al., 2000 for a review). In brief, the onset of self-produced locomotion leads to improvements in communicative gesturing, attention, spatial search, visual-vestibular coupling and depth perception. Thus, a notable consequence of this motoric advance is its ripple effect across multiple cognitive domains.

There is evidence that babble produces a similar ripple effect. McCune and Vihman (2001) tracked the emergence of frequently used consonants (‘vocal motor schemes’: VMS), on the assumption that repeated practice with a particular phonetic form might lessen the processing load of recognizing or categorizing sound sequences (or word forms) that contain such a consonant, freeing up processing resources for the pairing of form and meaning. This would facilitate the learning of referential words. McCune and Vihman defined a VMS as a supraglottal consonant (stop, nasal, fricative, excluding /h/, or affricate) that the infant produced consistently and stably over several observational sessions. They found that the use of at least two VMS was a prerequisite for the transition into referential word use in the 20 children they observed. In the same way that self-produced locomotion facilitates the development of spatial awareness, the ability to produce consistent patterns in babble can be taken to support memory for word forms (Keren-Portnoy, Vihman, DePaolis, Whitaker, & Williams, 2010), which in turn facilitates the recognition that a word form can symbolize events or entities in the world.

This relationship between VMS and referential word use raises the possibility that babble might be an early steppingstone that has effects on other aspects of cognitive development. For example, as babbling begins to systematically and consistently incorporate one or more adult-like consonants, it could potentially speed the processing of these practiced sounds when heard in input speech as well as when self-produced. Logically, a child’s knowledge of the speech sounds that he or she has produced might well be stronger and richer than that the knowledge of sounds not yet produced. Babbling necessarily involves hearing one’s own vocal output and integrating auditory and proprioceptive percepts, although the process need not be considered conscious or explicit.

Thus, sounds produced by the child provide the double information afforded by both auditory and articulatory experience. This suggests that babbling that leads to regularly produced consonants should boost the perceptual salience of practiced sounds in adult (input) speech as well as in self-produced vocalizations (see Elbers, 1997, who emphasizes the importance of 'output as input'). It has been suggested that an infant develops an individually fashioned 'articulatory filter', based on the particular sound patterns that the infant has mastered motorically (Vihman, 1993, 1996). According to the articulatory filter hypothesis, familiarity with speech sounds from an infant's own production implicitly enhances the salience of those same sound patterns when they occur in surrounding speech (see also Locke, 1993, p. 204). The articulatory filter was proposed to account for the finding that infants' first words tend to be produced accurately as well as being comprised of consonants that the infant is experienced in producing.

The purpose of this study was to test the hypothesis that there is a direct influence of production on what is salient in input speech. We do not mean to suggest that this is the only direction of causality between production and perception. On the contrary, the effect of perception on early infant production has already been demonstrated in several studies. Specifically, acoustic analysis has shown early ambient language effects on babbling (at 6-12 months for prosody: Whalen, Levitt & Wang, 1991 and at 10 months for vowel and consonant production: Boysson-Bardies, Hallé, Sagart & Durand, 1989, Boysson-Bardies & Vihman, 1991). In each case the findings reflect a biasing of the child's output in the direction of the ambient language. However, this study was designed to explore the possibility of the reverse effect, that is, the idea that a child's production experience might also affect the way he or she listens to speech.

It is important to recognize that we do not know how an infant settles upon his or her own well-practiced (or favorite) consonants. This process must be, at the very least, a combination of biological predisposition (Davis & MacNeilage, 1995), perceptual salience (Lindblom, 1992), input frequencies and their effect on the development of speech categories (Jusczyk, 1993) and the particular history of production practice of the individual child (Thelen & Smith, 1994).

1.1 The current study

We examined the interplay between production and perception *after* well-practiced consonants have emerged, intending this study to be a first step in the search for an effect of production on the way infants listen to input speech. In order to test this complementary possibility of production affecting perception we developed a procedure using individual infant production patterns adaptively in a headturn experiment. This is a novel paradigm that fills a gap resulting from the fact that typical infant speech perception experiments are based upon large numbers of infants seen in the lab for a single session, while infant vocal production studies typically involve a small number of infants followed intensively over a long period of time. In the current study production was documented with multiple observations of infant-caregiver interactions via recordings and transcription (following Vihman, Macken, Miller, Simmons & Miller, 1985) and perception was tested using the Headturn Preference Procedure (HPP) (Kemler-Nelson et al., 1995), which quantifies infants' response to speech as either a familiarity or a novelty effect reflected in looking times. This enabled us to identify well-practiced consonants in individual infants and, through the use of individually designed stimuli, to test for a link between production and perception.

To this end, we presented nonword stimuli embedded in three contrasting passages, each nonword highlighting a consonant belonging to one of the following three categories: (a) a VMS stop consonant produced by the infant being tested ('Own-VMS'), (b) a common VMS stop consonant produced by many infants but not by the infant being tested ('Other-VMS'), and (c) a fricative consonant that was rarely produced by any of the infants ('Non-VMS').

We chose to embed nonwords in passages instead of using isolated nonwords as stimuli since previous studies have shown that by 7.5 months infants can extract words from passages (Jusczyk & Aslin, 1995, Jusczyk et al., 1999). All infant tested in this study were older than 9 months. In addition, we felt that the presentation of lively passages was likely to capture the attention of the infants, leading to a lower attrition rate than might result from the use of isolated words. Also, since this work was designed to test the salience in input speech of consonants that are either produced or not produced by the infant, essentially a test of the Articulatory Filter hypothesis, passages are the more appropriate stimuli.

We included a fricative passage to test the infants' response to consonants that no infant could be expected to produce to any significant extent. This makes it possible to contrast a signal-based vs. a production-based infant response to the stimuli. In the absence of a production effect, infant interest in the fricatives might be expected, based on the salient acoustic differences between stops and fricatives. In effect, without a production effect the stop passages would all sound similar and the fricative passages would stand out and prompt a novelty effect. This would be worth noting only if no production-based effect were to be found, however. In contrast, if a difference in looking times is found in response to the produced vs. not-produced consonants, that difference will be all the more compelling since the Own and Other consonants in this study are all stops with similar temporal and frequency characteristics.

Succinctly stated, our hypothesis was that infants would show a difference in looking time between Own- and Other-VMS passages – that is, we tested for a production-based difference in the salience of the nonwords embedded in the passages. When we began the study we did not intend to use number of VMS as an independent variable, and we therefore had no a-priori hypothesis regarding possible differences in the patterns of looking times between infants with many or with only a single VMS. But once we began recording infants it became clear that not all of them could be tested before they passed criterion for a second VMS. We thus ended up with two groups of infants whose production experience differed by the number of VMS they had acquired; we did not expect to find a difference between the groups. Finally, if the infants exhibited no difference in looking times in response to Own- versus Other-VMS passages, we hypothesized that they would look longer in response to the fricative passages due to the signal-based differences between stops and fricatives.

2.0 Methods

2.1 Production Data Collection

Twenty-eight infants participated in the production study. All infants passed a National Health Service hearing screening; none had reported health problems at the time of the study. Infants were recorded on audio and video in unstructured half-hour play sessions with a caregiver, beginning between 9 (25 infants) and 11 (3 infants) months of age. The sessions took place in the infant's home (25) or in a friend's house (3) and continued monthly (3), biweekly (10), or weekly (15) until vocal motor schemes were identified. The original goal was to identify the emergence of a single VMS in each infant. We initially visited infants monthly, then biweekly and finally weekly as it became obvious that even with weekly visits it would not always be possible to identify the emergence of a single VMS before a second VMS met criterion. It is unclear whether this would be possible even with daily visits, since some infants seemed to develop consistent use of multiple consonants simultaneously. The experiment was thus adapted to include both single- and multiple-VMS infants. Recordings were made using a wireless microphone and transmitter (AKG, Sennheiser or Beyerdynamic) placed in an inside pocket of a soft vest worn by the infants. The caregiver also wore a wireless microphone and transmitter. Both audio and video were recorded using a Sony DSR-PDX10P digital video recorder.

All audio recordings were digitized at 48 KHz and digitally transferred to DVD with video, but not audio, compression. Each session was transcribed on the basis of both the audio and video signal. Two separate criteria were used to define the acquisition of a VMS. The first criterion, following McCune & Vihman (2001), was that a consonant be produced at least 10 times in each of three sessions, with no more than one session intervening with fewer than 10 occurrences. Second, since this study required a more dynamic approach to identifying VMS to permit timely perceptual testing, 50 occurrences of a consonant within one to three sessions was also accepted as evidence of a VMS. If an infant had thirty or more occurrences of a consonant within the three most recent sessions (without that consonant reaching criterion for VMS status), the infant was considered to be in transition to the acquisition of a VMS. Voicing was not considered distinctive, since there is little evidence that infants control voice onset time at this age (Macken, 1980). Thus, the VMS categories were grouped by place of articulation (for example /p,b/, /t,d/, and /k,g/). Difficult utterances were transcribed with the aid of an additional transcriber, and if there was no consensus, these utterances were not used in the VMS counts. No utterance masked by noise was transcribed. Transcriber reliability (based on two independent ten-minute transcriptions of each of three infants, 10% of the participants) was 81% for VMS consonants (/p,b/, /k,g/, /t,d/, /m/, & /n/). This is consistent with or higher than what has been reported for other large-sample studies of transcription reliability for consonants produced by prelinguistic infants (Davis & MacNeilage, 1995; McCune & Vihman, 2001). It might be expected, given the quality of the video and audio signal, that reliability would be higher than previously reported in the literature, but the nature of the study required rapid transcription to identify acquisition of VMS in as timely a way as possible. In most cases, the sessions needed to be transcribed within a day of the observation so that, if necessary, the HPP test could be scheduled within three days of the observation. If more time elapsed we scheduled another observation session since it was likely that the infant would have progressed to the point of either having or being in transition to having another VMS. This made it impossible to use such a time-intensive method as acoustic analysis to support transcription.

2.2 Perception Test

2.2.1 Participants. Twenty-two of the 28 infants who were followed for identification of VMS participated in the Headturn experiment. Six infants were excluded for the following reasons: no evidence of a VMS during the course of the recordings (2), infant transitional on all remaining VMS consonants used in the perception test (2), family dropped out just after evidence of VMS (1), and infant acquired non-VMS consonant between the last recording session and HT test, as judged both by direct experimenter observation and by caregiver report (1). Eighteen of the 22 infants tested successfully completed the HT experiment. Attrition in the headturn task was due to inability to complete the test trials (2), crying (1), and experimenter error (1). Of the 18 infants tested successfully, the mean age at testing was 1;0.20 for single and 0;10.15 for multiple VMS infants. The difference in age was due to three single-VMS infants being older than 15 months at the time of the test (see Table 3). The assignment of infants to the single- or multiple-VMS group was dictated by the identification of either one or two VMS. The first nine infants to acquire the requisite number of VMS were included in each group. Since age at first VMS was not controlled in the experiment, the presence of the three older infants in the single-VMS category was a function of the normal developmental process. The median age at testing, for single- and multiple-VMS groups, respectively, was 0;10.24 and 0;10.10.

2.2.2 Stimuli. A native speaker of British English, using a lively speech style, recorded passages consisting of five sentences, with nonwords near both the beginning and the end of each of four of the sentences and a fifth sentence with a single medial nonword receiving phrasal accent. The duration of the passages was between 13 and 14 seconds. The maximum length for both the pretest and test trials was 13.8 seconds. All items were recorded in a sound-treated room using a Sennheiser ME 66 microphone (with K6 power module) connected to a Tascam DA-P1 digital recorder sampling at 44.1 K Hz. The speech peaks of all stimuli were within ± 1.5 dB as measured on a mechanical VU meter (Marantz PMD 222). The stimuli were transferred digitally onto a PC hard drive for eventual output. Acoustic analysis across the three passages revealed no difference in amplitude (rms and peak), F0 (mean, minimum, maximum, and range) or duration ($p > 0.05$).

The nonwords used as stimuli are listed in Table 1. Each nonword consisted of a disyllable with a CVCVC structure. The consonant was a stop or fricative with a consistent place of articulation that alternated in voicing (i.e. the /t/ and /d/ in the nonword /tɪdɛt/), consistent with the definition of a VMS (given above). The consonant-vowel co-occurrences used were consistent with those predicted by the frame dominance model of early vocalizations (Davis & MacNeilage, 1995), which successfully predicts that infants' early babble will follow patterns dictated by the physiology of mandibular oscillations (or frames) – i.e., of whole-syllable production, with alveolars followed by front vowels, velars by back vowels and labials by central vowels. The three carrier passages are listed in Table 2. Each carrier passage contained 24 syllables in addition to nine disyllabic nonwords including the targeted VMS consonants only. Each passage highlighted one pattern: Own-VMS, Other-VMS or Non-VMS. In order to avoid changes of consonant manner between Own- and Other-VMS passages, only bilabial, alveolar and velar stops were used as Own- or Other-VMS. The non-VMS passage contained nonsense words including as consonants only /f/ and /v/, which are not typically mastered by infants until the second or third year of life (Ferguson, 1975). No infant in this study produced /f/ or /v/ to VMS criterion. We decided not to use nasals (which are also early favored consonants) as VMS in the Head Turn task but to limit ourselves to stop consonant VMS. Nasals have distinctive acoustic signatures – such as shifts and/or reductions in energy of the formants of the surrounding vowels (Kent & Read, 2002) and high average amplitude during their occluded portion – that make them perceptually distinct from stops. Even though nasals were not included in the HPP task, it was possible for an infant to have multiple VMS with a stop consonant and a nasal rather than two stop consonants. Note that any supraglottal consonant that the infant produced to VMS criterion would have counted as a VMS. McCune and Vihman (2001) found that a small number of infants produced /s/ or /l/ to VMS criterion. In this study only alveolar, bilabial and velar stops and velar and bilabial nasals were produced to VMS criterion. Only infants with at least one stop VMS could be included in the sample since we chose not to use nasals as test stimuli. We did not actually have to exclude any infants since a stop was either the first or the second VMS for every participant.

Passage 1 was recorded with /t,d/, passage 2 with /p,b/, passage 3 with /k,g/; the passages containing /t,d/, /p,b/, or /k,g/ were used as Own- or Other-VMS passages, depending in each case on which VMS a particular infant had already acquired (Own) or had not yet acquired (Other). All three carrier passages were recorded with /v,f/ so that each infant would hear three different carrier passages, one for each type of consonant. The passages with /f,v/ were used as Non-VMS passages.

[Insert Tables 1 and 2 about here.]

2.2.3 Procedures. The HT procedure used was similar to that described in Kemler-Nelson et al. (1995). Seated on the caregiver's lap in a quiet darkened room, the infants faced the central panel of a three-sided test booth where a camera and red light were mounted. A blue light and speaker were mounted on each side panel. A PC and video monitor were located in the adjoining room where the experimenter controlled stimulus presentation and recorded infant looking times by pressing the left and right mouse buttons. The computer initiated and terminated trials in response to signals from the experimenter. In each trial, the infant's gaze was centered by the blinking red light. The experimenter then initiated the computer run trial involving a blinking blue light on the left or right of the infant. When the infant was judged to orient to the blue light, a trial was presented from that speaker. If the infant looked away from the speaker for more than two seconds, the trial was terminated and another begun. Multi-talker babble created from the same speaker of the stimuli used in the experiment was delivered to the headphones worn by the experimenter and caregiver to mask the actual test stimuli. The caregiver also wore foam-insert hearing protection. All stimuli were presented at an average level of 65 dB (Tenma 72-6635 sound level meter).

Each experimental session consisted of a pretest and test phase. In the pretest phase the infant was presented with one passage of each of the three test conditions, own-VMS, other-VMS, and non-VMS, counterbalanced for order and randomized for side. This condition was intended to expose the infant to the test procedures since our previous experiments using the headturn paradigm have indicated that the initial trials lead to overly long looking times that do not seem to be indexed to the type of stimuli presented.

The test phase of the experiment consisted of 15 trials, five each of the three test conditions. Each trial, pretest and test, consisted of a randomized presentation of the five sentences of each test passage. The order of presentation in the test phase was such that the first three trials were counterbalanced across test conditions. The order of the final three trials was a reverse of the first three. The counterbalancing at both the beginning and the end was designed to control for an anticipated decrease in looking times, independent of the stimuli, over the course of the test trials (see Vihman, Nakai, DePaolis, & Hallé, 2004 for an analysis of looking time by trial). The middle nine trials were pseudo-randomized such that no more than two identical test trials occurred together. In both phases, the side of presentation was pseudo-randomized such that no more than three successive presentations from one side were allowed. Reliability was assessed by offline coding, by a separate researcher, of two of the infants' HPP video recordings ($r=.927$, $p<.01$).

3.0 Results

3.1 Production Data

The results presented below are drawn from the 18 infants who successfully participated in the headturn experiment. Table 3 documents the age at test and the particular Own and Other VMS used in the perception test for each infant in the two groups; additionally, the VMS not tested is given for the multiple-VMS infants only ('Non-Test VMS'). Interestingly, all but two infants acquired /t,d/ as one of their first VMS, consistent with the McCune and Vihman (2001) study, in which 13 of the 20 infants followed acquired a coronal first; we return to this point in the discussion. The second VMS acquired by the nine infants in the multiple-VMS group was variable, four producing /p,b/, three producing /n/, two producing /m/ and one producing /k,g/.

[Insert Table 3 about here.]

Figure 1 presents a count of consonants produced in the session prior to the HPP. For each infant we present a token count of all productions of that specific infant's Own- and Other-VMS consonants (the same two consonants to be tested). The figure also presents the total token frequency in that same session of the two most often used consonants for each infant, as well as the results of the perception test (see below for a discussion of the preference ratio)[1]. A consonant was included in the count if it was transcribed within a syllable consistent with English phonotactics. The single-VMS group produced a mean of 65.7 consonants (SD=15.3), as against 122.1 (SD=20.2) for the multiple-VMS group. This difference is significant, $t(16)=2.228$, $p=.041$, suggesting that the division of children into single and multiple VMS groups is based not

[1] Note, that infants with a single VMS are not infants who never produce any other consonants, but those who never produce any other consonant to VMS criterion.

only upon the repeated and consistent phonetic form of at least two consonants, but also upon the children's overall frequency of consonant production.

[Insert Figure 1 about here]

3.2 Perception Test

The results are presented in Figure 2. A mixed two-factor analysis of variance performed on the test trials, with VMS Type (Own, Other, and Non) and VMS Number (Single versus Multiple) as independent variables and the looking time to each passage as the dependent variable, revealed no main effects for either VMS Type ($F[2,16]=.492$, $p=.616$, $\eta^2=.051$) or VMS Number ($F[1,16]=.349$,$p=.563$, $\eta^2=.021$). However, the interaction between VMS Type and VMS Number was significant ($F[2,16]=3.933$, $p=.024$, $\eta^2=.391$), indicating that the preference for passages was dependent upon the number of VMS the infants had acquired. Contrasts of the interaction between Non and Own versus VMS Number (and ignoring Other VMS) were not significant ($p=.424$), while the contrast of the interaction between Non and Other versus VMS Number (and ignoring Own VMS) approached significance ($p=.062$). These results, when taken together with the lack of a main effect of VMS type, suggest that looking times to the Non-VMS passages are independent of the infants' production patterns. The contrast of the interaction between Own and Other VMS versus VMS Number was significant ($p=.01$), indicating that the significant interaction in the ANOVA is mainly due to the differences in looking times of the single- and multiple-VMS infants to the Own- and Other-VMS passages. Paired t-tests of the main contrast of Own- versus Other-VMS show that the multiple-VMS infants looked significantly longer in response to the Other consonant ($M=6.61$, $SD=1.52$ versus $M=5.48$, $SD=1.49$, respectively, $t(8)=-2.519$, $p=.036$), while the single-VMS infants looked longer in response to their own consonant (M=5.98, SD=2.05 versus M=4.99, SD=2.20, respectively), but this preference is not significant (t(8)=1.735, p=.121).

[Insert Figure 2 about here.]

The lack of an effect in the single-VMS group was likely due to the variability of overall looking times in this group (range 2.15 to 8.6 seconds). Often, in a headturn experiment, infants with very low looking times or atypical values are excluded from the final analysis (see, for example, Nazzi, Iakimova, Bertoncini, Frédonie, & Alcantara, 2006). In this study, we chose not to exclude infants for these reasons since the investment in time for each infant was so large. One way to factor out differences in overall looking time across infants and compare the infants' preference for practiced over unpracticed consonants (disregarding the Non-VMS consonants, since they are not significantly affected by production) is to make use of the preference ratios between looking times (LT) for well-practiced over unpracticed consonants (preference ratio = LT(Own)/[LT(Own)+LT(Other)]). With this metric a value of 0.5 would indicate equal looking time to each passage. The preference ratios are plotted against each infants practiced consonants in figure 1. The preference ratio for Own-VMS passages for the single-VMS infants (M=0.55, SD=0.086) was significantly larger (t[16]=2.817, p=0.012) than for multiple-VMS infants (M=0.45, SD=0.063). Six of the nine single-VMS infants show a preference for Own-VMS passages, while eight of nine multiple-VMS infants exhibit a preference for Other-VMS passages.

The categorical nature of VMS allows the separation of infants into two groups that differ significantly in the number of consonants produced and in the frequency and consistency of use of these consonants over time. In order to explore the relationship of the infants' practiced consonants and the HPP results independent of the development of production patterns over time, we ran a simple linear regression using consonant counts in the session preceding the HPP test. Since the design of the HPP test involved identifying each infant's practiced consonants we used the number of each infant's Own-VMS consonant plus the second most practiced consonant (for the 2 VMS infants this was the second VMS) as the predictor and the preference ratio as the dependent variable (See table 4). There was a significant linear relationship between the total production frequency of the two most practiced consonants and the infants' preference for Own- or Other-VMS ($R=.605$, $p<.01$).

Table 4 about here.

3.3 Analysis of the Infant Directed Speech

As mentioned above, what leads an infant to settle upon a practiced or 'favorite' consonant or VMS is unclear. It is possible that the speech directed to the infant has an effect on the consonants produced and thus plays a role in the perceptual salience of those consonants. To investigate this possibility we transcribed the infant-directed speech (IDS) of three mothers. We chose mothers of infants who had multiple VMS since in this group at least one infant had acquired each of the stop consonants (alveolar, velar, and bilabial). We transcribed both the session in which the infant was credited with two VMS and the session preceding it. If there was a problem identifying the consonant, the main transcriber consulted with a second transcriber to arrive at a consensual decision. To assess reliability two independent researchers (not including the second transcriber noted above) transcribed two of the 30-minute sessions, yielding agreement on 90% of the VMS consonants. Agreement rose to 99% when ambiguous consonants were retranscribed by consensus.

Figure 3 is a plot of the proportion of each VMS consonant in the IDS directed to the infant. For ease of comparison, an asterisk indicates the VMS for each infant. It is clear from this figure that although VMS consonant frequency from each mother's IDS was similar, the VMS consonants developed by the infants are quite diverse. In particular, the infant in panel b produced the two consonants with the least frequency in the input, while the infant in panel c produced the two consonants that were most frequent in the IDS. A Chi-Square test comparing the relative frequency in the infants' production of the five VMS consonants (stops: alveolar, velar, and bilabial, nasal: bilabial and alveolar) to the relative frequency in the mothers' IDS revealed a significant difference for each mother-infant pair ($\chi^2(4, n=186, 82, 41)=86.0, 483.7, 84.2, p<.005$, for the three infants in figures 2a, 2b, and 2c, respectively).

4.0 Discussion

The profile of consonant use for the infants who completed the study was consistent with that found by McCune and Vihman (2001). The most common initial VMS was identified as /t,d/ in both studies, although the 18 British-English infants were even more likely than the 20 American-English infants to start with this VMS (88% vs. 72%). After /t,d/, the remaining stops and nasals were the most likely VMS in both studies. Of the stops, /k,g/ were the most likely to be acquired last. These findings are consistent both with predictions of early consonant development based on diary reports and markedness theory (Jakobson, 1941/68) and with later accounts of perceptual salience and/or bio-mechanical constraints (Lindblom, 1992; Davis & MacNeilage, 1995); they also agree with empirical findings reported for a wide range of languages (Locke, 1983).

The results of the headturn experiments show that the infants' looking times were influenced *both* by their own consonant production experience (as indexed by the number of VMS that they had acquired) and by whether or not they produced the particular consonant featured in the nonwords embedded in the passages. This finding confirms our hypothesis that looking times would be influenced by the infants' production patterns and accordingly supports the postulation of an articulatory filter. The lack of any relationship between three individual infant's production patterns and the IDS they were exposed to strongly suggests that this finding is not due to the frequency of consonants used in the input.

The difference in looking times between the single- and multiple-VMS infants was unexpected. The multiple-VMS infants displayed longer looking times in response to the passage that featured the consonant that they were not yet consistently producing, while infants with a single VMS showed no significant preference for either passage. The difference in preference between the groups was revealed in the significant interaction between Own- and Other-VMS and VMS number as well as in a t-test comparing the preference ratio between the single- and the multiple-VMS groups (using the preference ratio effectively reduced the 'noise' in the paradigm). The same type of relationship was also evident when production experience was measured continuously, in the correlation and regression that showed that the amount of production experience an infant has with one or two consonants can predict their pattern of preference for the test passages. These results suggest that production advances may incrementally alter the manner in which infants attend to aspects of the speech signal.

It is worth emphasizing that the presence of a novelty effect in the multiple VMS group can occur only if the Other passage stands out as different from the Own passage (novel). In this case the it is likely that the Own passage introduces overly familiar sounds, making the Other passage, with its novel sounds, more interesting. This is consistent with Hunter and Ames (1988), who showed that greater attention to a familiar stimulus will eventually be replaced by greater attention to the novel stimulus.[2] It is likely that the infants who are more practiced at consonant production (as indexed by VMS in this study) will be the ones tending to exhibit a novelty (versus familiarity) effect to a comparison of produced versus unproduced consonants.

The discovery of this novelty effect was serendipitous, as had the study been carried out with single-VMS infants only, as originally planned, we would have been unaware that the transition from one to two VMS indexes a change in looking times. This raises the question, why

[2] Interestingly, a change from engagement with familiar to engagement with unfamiliar stimuli can sometimes even be seen to occur for individual infants across experiments (Roder, Bushnell, & Sasseville, 2000) as well as in the course of a single experiment (Vihman et al., 2004).

should the move from producing one to two stable consonants change the infants' response to the Other passages? One possibility is that acquiring a second stable consonant (or VMS) indexes cognitive advance, as suggested by McCune and Vihman,2001 (see introduction for a more detailed description). In addition, DePaolis, Keren-Portnoy, and Vihman (1997) found that 10-month-old infants who had acquired two VMS were significantly more variable in their looking times to familiar words on a headturn task than infants who had not acquired two VMS. Both of these results support the notion that reliably producing two stable consonants affects the way that infants process consonants.

Another interpretation is that the change in looking times is not necessarily dependent upon the infants producing two consonants to VMS criterion, but simply reflects the fact that they are producing large numbers of consonants. For example, from figure 1 it is clear that the infants with the largest consonant counts are the ones most likely to show a preference for the 'Other' passages. This interpretation is also supported by the simple regression, in which the count of the two highest consonants produced is a significant predictor of the preference ratio. Although this interpretation is plausible, since 8 of the 11 infants who show a preference for the 'Other' passage are producing two consonants to VMS criterion, it is likely that both ways of operationalising practice in consonant production are really complementary: Infants who produce many consonants seem to be producing many *tokens* of perhaps only a few consonant *types*. Therefore, it is hard to disentangle the role of the specific consonants produced from that of sheer amounts of consonant production. It is probable that both these things combine to influence infants' preference for what is familiar vs. what is novel.

We included the Non-VMS condition to test the contrasting hypothesis that production has no effect on looking times. Looking times to the Non-VMS passage would have been revealing only if no difference had been found between the Own- and the Other-VMS passages. However, this study did reveal a significant difference between looking times to Own-VMS and Other-VMS. Given that finding, along with the fact that both groups looked equally to the Non-VMS consonant passages (see Fig. 2) and showed no significant difference in looking times to Non-VMS vs. the other types of passages, the results from the Non-VMS passage can be taken to simply reflect the spectral salience of fricatives versus stops.

Two methodological concerns arose in the course of the study. The first was the balance of consonants used in the headturn test. Since each infant's production pattern necessarily dictated the consonants to be presented, the overall profile of consonants could not be planned in advance. The most common Own-VMS consonant was /t,d/; it was presented as Own consonant in 13 of the 18 infant headturn tests (for eight of the single- and five of the multiple-VMS infants), which raises the possibility that infants' looking patterns could be due to their having a preference or dispreference for the specific consonant /t,d/ rather than to their individual production history. However, of these 13 infants for whom /t,d/ was Own VMS, eight preferred the /t,d/ passage and five did not, and this difference, using a binomial test, is not significant. This effectively rules out the possibility that a general preference (or dispreference) for /t,d/ among those infants who produce that segment might explain our findings. In addition, considering the 14, 9, and 13 times that passages featuring /t,d/, /p,b/, and /k,g/ were presented in all 18 of the headturn tests as either Own- or Other-VMS (see Table 3), the preference that the infants showed for each of these passages was no greater than chance (defined as a preference for that passage half of the time it occurred, $\chi^2(2, n=36)=.97313$, $p>.05$), suggesting that properties of the passages are insufficient in themselves to explain the pattern of preferential looking times.

The single-VMS group could also conceivably have a different pattern of preference or dispreference for alveolars from the multiple-VMS group, and these group-dependent preferences could be the primary factor responsible for the pattern of results that we found. For example, the prevalence of alveolars in the input, or some signal-based aspect of alveolars (the high frequency emphasis of the burst, for example), could be driving the results, with different effects in the two groups. However, the data fail to support the idea that alveolars were systematically either preferred or dispreferred in either group (see Table 3 for the preference for Own- versus Other-VMS). In the single-VMS group, five infants showed a preference for alveolars over velars (3) or bilabials (2). On the other hand, three showed a preference for the velar that was contrasted with the alveolar stop. In the multiple-VMS group dispreference for Own VMS is limited to no one place of articulation: We see a dispreference for alveolars in five infants (of whom three showed a preference for velars and two for bilabials), for bilabials in two infants (both showing a preference for velars instead), and for velars (preferring bilabials) in one infant. The pattern of preference appears to be random and convincingly rules out input frequency or signal-based attributes of alveolars as a possible explanation.

The second concern was the age of the participants at the time of the HPP test. Three infants in the single-VMS group were considerably older than the rest of the infants in the study. The age discrepancy was an unintended consequence of our testing infants as soon as we could identify either one or more VMS. The inclusion of these infants is developmentally sound since longitudinal samples of infant consonant production typically include small numbers of later developing infants (for example see McCune & Vihman, 2001). It could be argued that these infants have considerably more experience in processing speech, so their results deserve closer examination. Two of these three infants followed the trend of preferring their own production patterns while one did not (preference ratios of .54, .63 and .44). Removing these three infants from the ANOVA reduces the power from .709 to .563 and changes the interaction from significant (p=.024) to nearly significant (p=.056). The significance of the t-test comparing the single-VMS to the multiple-VMS group on their preference ratio for own versus other VMS does not change when these three infants are removed (p=.012 for all infants and p=.018 with three infants removed). Thus, the behavior of these infants does not change the basic pattern of results.

The fact that this interaction of production and perception is significant with 18 infants suggests that it is highly robust. A preference for own sounds was found in six out of nine infants in the single-VMS group, and a preference for others' VMS was found in eight of nine infants in the multiple-VMS group. Note that, of the four infants who did not show this pattern, three were in the single-VMS group. Due to the fact that our samples were limited to a 30-minute recording once a week at most, it is likely that some of these infants were producing additional consonants that failed to be recorded. To guard against this problem we provided caregivers with a detailed questionnaire to be completed after each session, but it was apparent that parents often misidentified consonants. Thus, while the multiple-VMS infants can be confidently said to have had at least two VMS, it is possible that some infants identified as having only a single VMS were actually producing a second VMS, or were in transition.

Our results suggest the possibility that production initiates shifts in the way that the infant processes input speech. Since the transition from one to two VMS typically occurs in a matter of weeks at most, the infants' preferential shift to a passage featuring a consonant that they are about to produce is noteworthy and suggests that the interplay of familiarity and novelty in early babble provides the infant with attentional pointers toward phonetic advance.

It is worth noting that this shift, as indexed by production operationalized as the transition from one to two VMS, could be a by-product of an underlying cause not identified in this study.For example, it is possible that the perceptual salience of stops in speech directed to the infant is the underlying cause of the results. According to this rationale, the salience of a stop is both the reason for an infant developing that stop as a VMS and the cause of the difference in preferential looking times. This explanation is consistent with the data since the single VMS infants looked longer at their Own VMS (although the difference was not significant). In addition, even though the multiple VMS infants did show a preference for the Other VMS, this could be due to their decreased interest in the stop consonant which had commanded their attention earlier, leading to an increased salience of the stop consonant not yet being produced.

However, the comparison of the frequency of consonants in individual infants' input to their own produced consonants does not favor such an interpretation. There was no clear relationship between input frequency and choice of VMS for production. In addition, the similarity among mothers in the frequency of consonants in their speech makes this an unlikely source for the differences among infants in the identity of the first consonants used stably in babble. Indeed, the lack of an effect of the mothers' speech on the phonetic output of the infant has been reported previously in a larger sample of French, Swedish and American infant-mother dyads (Vihman, Kay, de Boysson-Bardies, Durand, & Sundberg, 1994). The data in this experiment do not provide a definitive answer to the 'chicken and egg' dilemma of how a favorite consonant emerges, but they do suggest that a parsimonious explanation of the results is that the pattern of results reflects a bi-directional influence of production on perception.

Since infants appear to 'notice' often produced phonetic segments in continuous speech, these results also suggest a mechanism for facilitating the production of first words. Over 35 years ago Ferguson and Farwell (1975, p. 433f.) noted that 'at an early stage in which a contrast is absent…the adult words chosen by the child will be highly discriminatory' – i.e., 'selected' for their sound patterns. Following up on this insight, Vihman (1993) suggested that rather than avoiding words or sounds that they cannot produce (as suggested in Menn, 1983, for example), infants 'select' their first words based on implicit matching of their existing babble to words consisting largely of sounds that they *can* produce (cf. also Vihman & Croft, 2007).

If infants could count on hearing words in isolation, this fact would be unremarkable, but at least one study has found that words are not consistently produced in isolation (Aslin, Woodward, LaMendola & Bever, 1996 – but see Brent & Siskind 2001). In the absence of exposure to isolated words, how does an infant extract the word from continuous speech in order to pattern the output after the input? Based upon the results of this study, infants should be predisposed to notice in the ongoing speech stream words that contain sounds that they are just starting to produce. This is consistent with the notion of an articulatory filter (Vihman, 1993, 1996). It could be that, in typically developing children, the ability to effectively process continuous speech in the prelinguistic period is augmented by the formation of a consistently reproducible phonetic pattern in babble.

This is the first study to report evidence for a link between what an infant produces in babble and how that infant processes speech (although see Vihman & Nakai, 2003). The impact of this link beyond the preference or dispreference for favorite consonants is an open question and should be explored further. For example, future work could examine how the relationship between production and perception affects the ability to attach meaning to word forms that either do or do not contain preferred production patterns (see Keren-Portnoy et al., 2010, for a study investigating phonological memory and preferred production patterns). Models could also incorporate proprioceptive feedback into the developmental trajectory of consonant and vowel categorization (for examples see models by Kent, 1981, and Westermann & Miranda, 2004). Most importantly, the findings of this study suggest the possibility that babble channels infants' sensitivity to phonetic aspects of the speech stream that are important for early language acquisition.

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Table 1

IPA transcriptions of nonwords used in the passages.

k & g	p & b	t &d	v & f
kɔgʊk	pabəp	tidɛt	vʌfəv
kugʊk	pʌbəp	tɪdɛt	vafəv
gɔkʊg	bapəb	ditɛd	fʌvəf
gukʊg	bʌpəb	dɪtɛd	favəf

Table 2

Carrier passages with open slots for the nonwords in Table 1. Passage 1 was recorded with /t,d/, passage 2 with /p,b/, passage 3 with /k,g/; all three passages were recorded with /v,f/ so that each infant would hear a different passage for each consonant.

Passage 1

So, who should _____ the ____ away?
I can ____ the ____ now.
But ____ go ____ for a while.
This ____ does a ____ for you.
Will you ____ to me?

Passage 2

Wow, my ____ is a ____ one.
Did the ____ go ____ below?
We ____ call ____ a lot.
Are your ____ too ____ over there?
I see the ____ here.

Passage 3

The ____ are by a ____ there.
I may ____ the ____ along.
Oh, the ____ is a ____ now.
So they ____ a ____ away.
Can you play ____ too?

Table 3

Individual infants' Own or Other VMS consonants used in the headturn experiment. The preference ratio is for Own- versus Other-VMS (preference ratio=Own/(Own + Other). The number of sessions indicates the total number of thirty-minute observational sessions required to reach VMS for each infant.

	Age at Test	Own	Other	Non-Test VMS	preference ratio	# sessions
Single	0;10.1	t,d	k,g		.56	3
	0;10.3	t,d	k,g		.47	4
	0;10.7	t,d	p,b		.52	2
	0;10.21	t,d	k,g		.64	4
	0;10.24	t,d	k,g		.47	7
	1;0.25	t,d	k,g		.68	2
	1;3.17	t,d	k,g		.44	4
	1;4.0	p,b	k,g		.64	5
	1;4.0	t,d	p,b		.54	5
Multiple	0;9.8	p,b	k,g	t,d	.36	1
	0;9.29	t,d	k,g	n	.48	2
	0;10.6	t,d	p,b	n	.47	2
	0;10.8	p,b	k,g	t,d	.46	4
	0;10.10	t,d	p,b	m	.37	2
	0;10.20	t,d	k,g	p,b	.47	2
	0;11.0	k,g	p,b	t,d	.44	5

0;11.5	t,d	k,g	n	.44	3
0;11.25	p,b	t,d	m	.58	10

Table 4

Summary of simple regression with the total number of the first two favored consonants produced predicting the results on the HPP test.

Variable	B	SE B	β
Constant	.583	.032	
Number of first two favored consonants produced	-.001	.000	-.605**

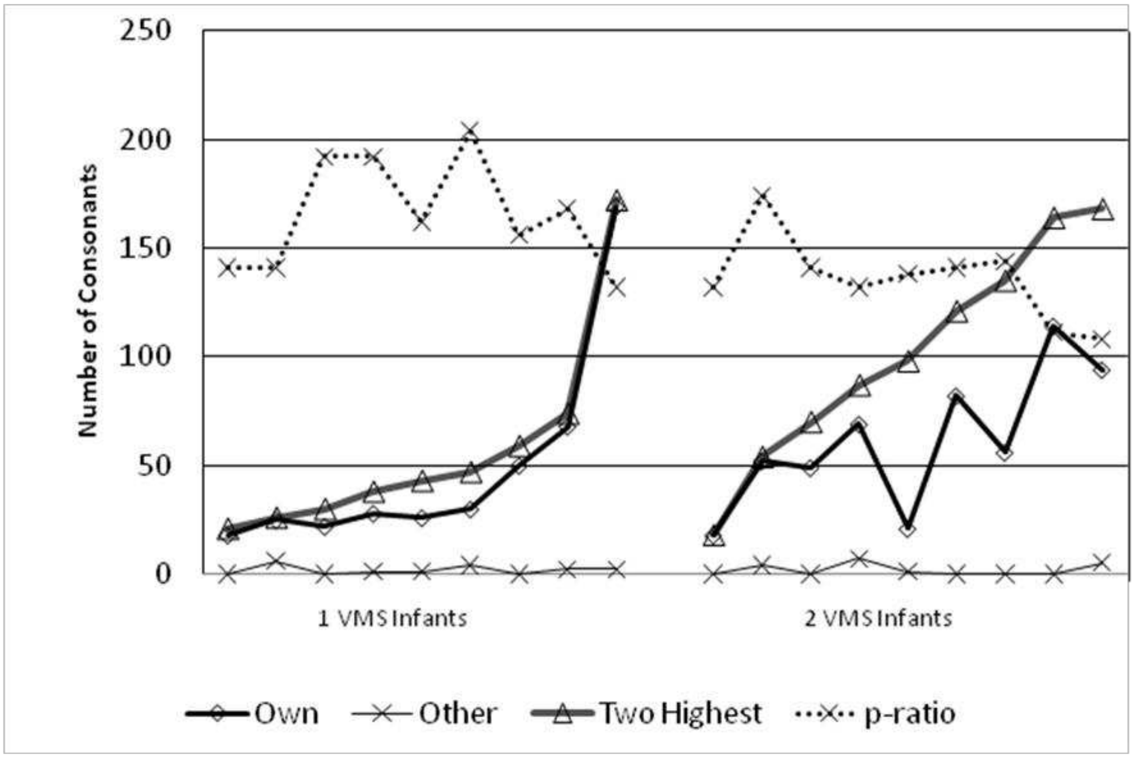
R^2 = .366, **p<.01

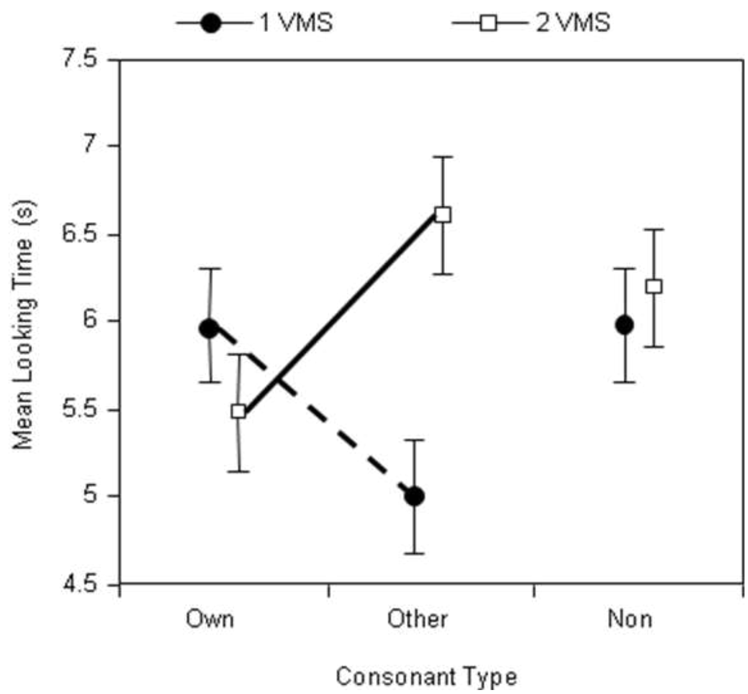
Figure 1. Production data for each participant from the session previous to the HPP test. Own- and Other-VMS consonant counts refer to the contrasts used in the HPP test. Two Highest refers to the summed frequency of the two most-practiced consonants for each infant (for 2-VMS infants this is the summed frequency of the first and second VMS). The preference ratios for the HPP test are also plotted in the dotted line against the scale on the right. The data are arranged in ascending order of Two Highest consonant counts.

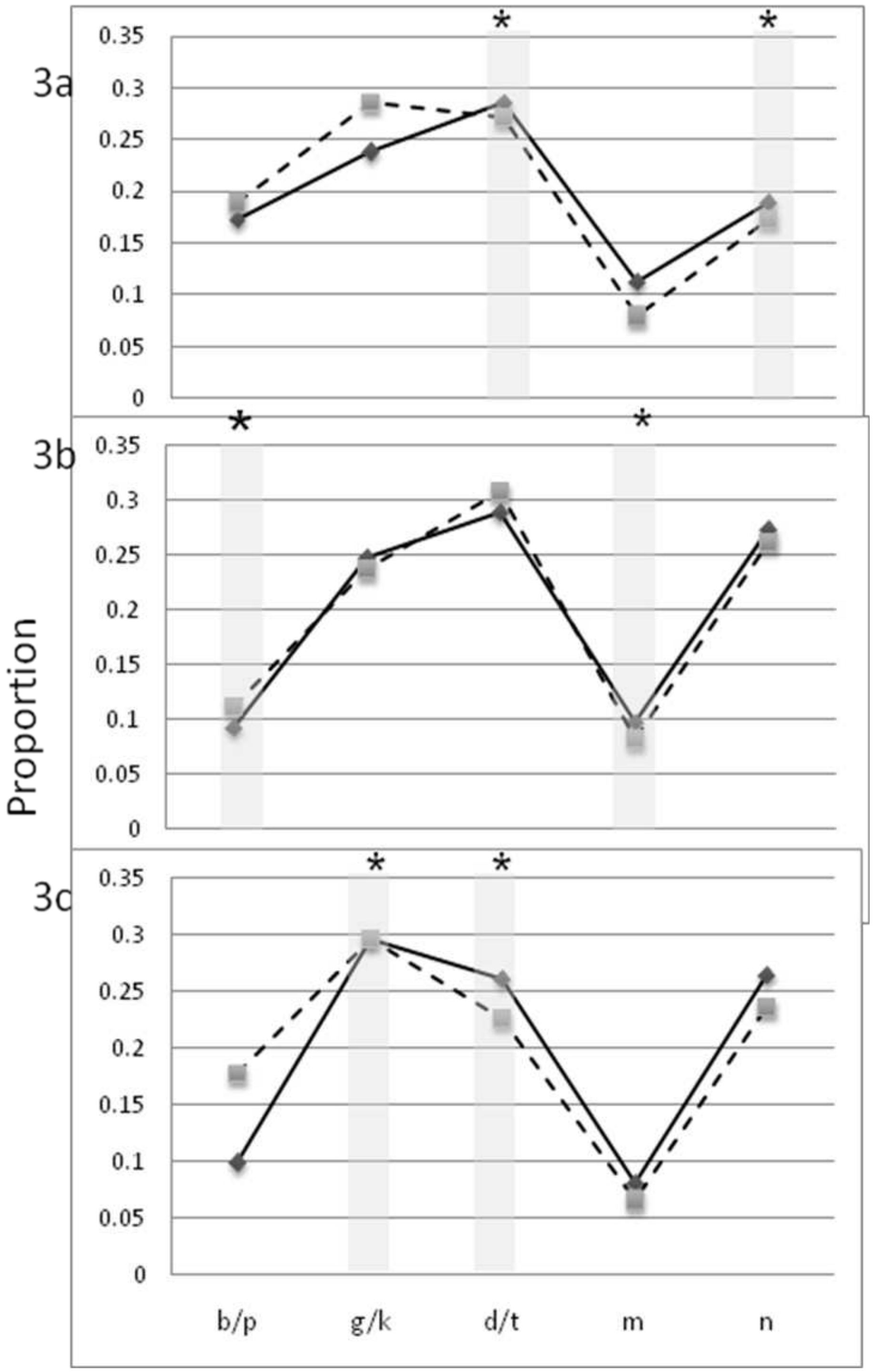
Figure 2. Average looking times per test trial in the headturn experiment.

Figure 3. Infant-directed speech (IDS) for three infants' mothers. The solid line represents the pre-VMS session while the dashed line represents the session in which two VMS were credited to the infant. The asterisks indicate the VMS for the child whose mother's IDS is plotted in the figure. Figure 3a is a plot for an infant with /d,t/ and /n/, 3b for an infant with /b,p/ and /m/, and 3c for an infant with /g,k/ and /d,t/.

Figure(s)


250
200
150
100
50
0
Number of Consonants
.67
.5
.33
Preference ratio
1 VMS Infants
2 VMS Infants
Own
Other
Two Highest
p-ratio


1 VMS
2 VMS
7.5
7
6.5
6
5.5
5
4.5
Mean Looking Time (s)
Own
Other
Non
Consonant Type


3a
3b
3c
Proportion
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
*
b/p
g/k
d/t
m
n

Research Highlights

-Favored babbling patterns affect the processing of speech in the pre-linguistic period
- Infants who have developed mastery of more than one consonant in babbling show preferential interest in consonants not yet in their repertoire
- The distribution of consonants produced in Infant directed speech cannot explain individual infant babbling patterns