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Baby hands that move to the rhythm of language: hearing babies acquiring sign languages babble silently on the hands

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Abstract

The “ba, ba, ba” sound universal to babies’ babbling around 7 months captures scientific attention because it provides insights into the mechanisms underlying language acquisition and vestiges of its evolutionary origins. Yet the prevailing mystery is what is the biological basis of babbling, with one hypothesis being that it is a non-linguistic motoric activity driven largely by the baby’s emerging control over the mouth and jaw, and another being that it is a linguistic activity reflecting the babies’ early sensitivity to specific phonetic–syllabic patterns. Two groups of hearing babies were studied over time (ages 6, 10, and 12 months), equal in all developmental respects except for the modality of language input (mouth versus hand): three hearing babies acquiring spoken language (group 1: “speech-exposed”) and a rare group of three hearing babies acquiring sign language only, not speech (group 2: “sign-exposed”). Despite this latter group’s exposure to sign, the motoric hypothesis would predict similar hand activity to that seen in speech-exposed hearing babies because language acquisition in sign-exposed babies does not involve the mouth. Using innovative quantitative Optotrak 3-D motion-tracking technology, applied here for the first time to study infant language acquisition, we obtained physical measurements similar to a speech spectrogram, but for the hands. Here we discovered that the specific rhythmic frequencies of the hands of the sign-exposed hearing babies differed depending on whether they were producing linguistic activity, which they produced at a low frequency of approximately 1 Hz, versus non-linguistic activity, which they produced at

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a higher frequency of approximately 2.5 Hz – the identical class of hand activity that the speech-exposed hearing babies produced nearly exclusively. Surprisingly, without benefit of the mouth, hearing sign-exposed babies alone babbled systematically on their hands. We conclude that babbling is fundamentally a linguistic activity and explain why the differentiation between linguistic and non-linguistic hand activity in a single manual modality (one distinct from the human mouth) could only have resulted if all babies are born with a sensitivity to specific rhythmic patterns at the heart of human language and the capacity to use them.

Keywords: Sign language; Babbling; Phonological processing; Language acquisition

1. Introduction

Baby babbling fascinates us because of its regular onset and structure in all healthy humans beginning at around 7 months. Of late, babbling has been at the nexus of a lively scientific controversy because it is understood to provide a key window into the origins of language in young humans as well as reflecting vestiges of the evolutionary origins of language in our species.

Unlike the crying and vegetative sounds also produced by babies in early life, "babbling" (more technically referred to as "syllabic" or "canonical" babbling) only involves vocalizations that exhibit these key properties: (i) use of a reduced subset of possible sounds (phonetic units) found in spoken language (e.g. de Boysson-Bardies, 1999; Jusczyk, 1997; Locke, 1983); (ii) possession of syllabic organization (well-formed consonant–vowel (CV) clusters; e.g. Jusczyk, 1997; Oller & Eilers, 1988); and (iii) use without apparent meaning or reference (Elbers, 1982); typically, a baby's babbling forms are also reduplicated, produced with the general prosodic (rhythmic, timing, stress) contours of natural language and follow characteristic stages (e.g. de Boysson-Bardies, 1999; Elbers, 1982; Jusczyk, 1997). Some have noted that an individual baby's preferred early babbling forms, for example, "bababa", can be continuous with the predominant phonetic forms that appear among its first words, like "baby" (e.g. Vihman, 1985; for an excellent account of babbling see de Boysson-Bardies, 1999).

Although babbling is judged to be one of the monumental milestones in early development, the major controversy in contemporary science concerns what is its basis. One possibility is that babbling is a fundamentally motoric behavior, deeply akin to the brain's maturation of other general motor capacities that are also emerging during this time such as sitting, standing and walking (Van der Stelt & Koopmans-van Bienum, 1986) – indeed, exhibiting the same pattern of false starts, starts and stops along the way to motor mastery. On this view, babbling is a kind of motor flexing of the mouth and jaw muscles as the brain grows better at mastering the fundamentally motoric job of forming speech sounds. Ultimately, newly mastered speech productions are wed through classical association and learning principles with the ambient linguistic system, hence the appearance of a baby's first word at around 12 months (e.g. Studdert-Kennedy, 1991). Interestingly, some researchers have viewed the assertion that baby babbling in ontogeny is first a non-linguistic motoric activity that later takes on linguistic status as supporting one phylogenetic claim about the evolutionary origins of language in which speech production mechanisms evolved first, then language. In other words, the view that human language as we know it today ostensibly evolved its present grammatical structure because of selection pressures arising from constraints on the mechanics of speech production, per se (Liberman, 2000; but see especially Pinker & Bloom, 1990; Rizzolatti & Arbib, 1998).

The alternative is that babbling is a fundamentally linguistic activity and part of a developing complex system of mechanisms that contribute to an individual's mature knowledge of language. Here, the presence of fundamentally linguistic units in babbling, such as repeated consonants and vowels, in combination with its universal onset and highly regular structure, have led to the conclusion that babbling is a robust index, and that aspects of human language acquisition are under biological control.

In the present paper, we test the motoric versus linguistic hypotheses about the basis of babbling in babies. But before explaining how, we first take a closer look at these two hypotheses because one thing should now be clear: over the years, the investigation of babbling in babies has expanded into a topic of great importance with very high theoretical stakes. Scientists now understand that knowledge of the basis of babbling will provide insight into its biological foundations and, by extension, the biological foundations of human language. It will reveal the nascent mechanisms subserving language in the species, including at what point in development these mechanisms emerge, and what types of input are necessary for their development.

1.1. Motoric hypothesis

Some researchers suggest that the syllabic structure of babbling is determined by the development of the vocal tract, and the neuroanatomical and neurophysiological mechanisms subserving the motor control of speech production (e.g. Davis & MacNeilage, 1995; Locke, 1983; MacNeilage & Davis, 2000; Studdert-Kennedy, 1991; Thelen, 1991; Van der Stelt & Koopmans-van Bienum, 1986). Davis and MacNeilage (1995) state that the consonant–vowel alternations characteristic of syllabic babbling are determined by rhythmic mandibular oscillations. According to the frame/content theory, MacNeilage (1998) proposed that syllabic "frames" might have derived from the cyclic alternations of the mandible present from the onset of babbling. These frames may have evolved when mastication took on communicative significance in apes. The "content" of syllables, on the other hand, which is provided by a finite number of fixed consonant–vowel sequences, is a direct consequence of lip and tongue placement. MacNeilage and Davis (2000) have recently supported the frame/content theory with empirical evidence. In a statistical analysis of ten babies raised in an English environment, three patterns of syllabic babbling were observed. This finding, coupled with similar findings in babies raised in five other language environments, led MacNeilage and Davis to propose a universal pattern of babbling which is guided by the physiological properties of the jaw (i.e. the syllabic "frames").

According to the frame/content theory, modulations of jaw oscillations then account for the next phases in human linguistic development, as the child proceeds from the prespeech to the first-word stage. The rhythmic alternations of the jaw first appear at approximately 5 months of age in the human child and are accompanied by phonation at approximately

7 months of age (Meier, 1997; see also Locke, Bekken, McMinn-Larson, & Wein, 1995). Through general association and learning strategies, babies' babbles are subsequently paired with meaning, and only then, after maturation of motor control has been completed, does a discreet linguistic system emerge, giving rise to babies' production of words. While the frame/content theory supports the idea that babbling is under maturational control and develops in a similar manner to other aspects of motoric development, it does not take into account principles of linguistic development. In this view, early babbling and more specifically, early language development, simply emerge as a biological "side-effect" or "natural accident" of motor development.

In response to MacNeilage, Davis, and other proponents of the motor driven theory of babbling, several researchers have examined the early vocal productions of babies cross-linguistically to determine whether a universal pattern of babbling "content" exists (e.g. de Boysson-Bardies, 1993, 1999; Elbers, 1982; Oller & Steffens, 1994; Vihman, 1992). Vihman (1992), for example, observed a common pattern of consonant–vowel alternation bound by the motoric constraints of the jaw, which is consistent with the frame/content theory. However, the more salient finding from this study was large individual differences in the consonant–vowel associations found in the most common syllables of babies exposed to the same language. Given the common physical characteristics of the jaw of babies at the babbling stage, it is difficult to explain these production differences in terms of a strictly motoric theory of babbling. As noted by de Boysson-Bardies (1993, p. 361), "…babies have a particular type of vocal apparatus at their disposal, but the constraints this apparatus puts on the production must be distinguished from the use to which babies put it".

1.2. Linguistic hypothesis

Proponents of the linguistic hypothesis of babbling view it as one key mechanism that permits babies to discover and produce the patterned structure of natural language (e.g. de Boysson-Bardies, 1993, 1999; Jusczyk, 1993, 1997; Petitto, 1993; Vihman, 1996). Babies are sensitive to the patterns in natural language that correspond to the temporal contrasts and rhythmic characteristics of phonology (Jusczyk, 1986; Mehler, Lambertz, Jusczyk, & Amiel-Tison, 1986). Thus, patterned input with maximally contrasting syllabic and phonetic rhythmic organization may be what triggers babies' babbling (Petitto & Marentette, 1991). The production of babbles, in turn, allows babies to discover the particular restricted set of phonetic units and permissible combinations of their target language. This view is consistent with Vihman's (1996) observation that some babies initially possess a large range of possible sound sequences, which only emerge as a canonical pattern after having matched their initial sound repertoire with the adult form of the language.

According to this linguistic hypothesis of babbling, the open–close alternations of the jaw that are characteristic of babbling reflect the maximally contrasting syllabic units of the target language. This hypothesis lies in sharp contrast to the motor driven account, which states that babbling is simply a byproduct of motoric development. Through babbling, babies actively discover the phonological inventory of their native language upon which all the words of their language will be built. This suggests that babies may have peak sensitivity to the rhythmic patterning of language about the size of the babbling syllable that babies produce (Mehler et al., 1986; Petitto, 1993, 2000; Petitto, Holowka, Sergio, & Ostry, 2001). In turn, this sensitivity may afford them the means to segment the linguistic stream and to discover word boundaries and enable the acquisition of meaning and first words. Thus, by attending to the structured rhythmic and temporal patterns of the ambient language and, crucially, by producing them, the baby acquires the rudiments of its language (Petitto, Holowka et al., 2001). In this respect, babbling is viewed as a systematic and fundamentally linguistic behavior, which reflects the particular patterns inherent to natural language, and which develops in addition to general motoric development (see also Elbers' (1982) cognitive continuity theory, and Vihman's (1996) model that considers both motoric and linguistic influences). While providing a potential account of babies' babbling, the linguistic hypothesis of babbling also raises the following question: how much of language development is under biological control, and how much of it is due to influences of the ambient language?

In addressing this question, some researchers argue that audition is necessary to ensure normal language development (Locke, 1990; Locke & Pearson, 1990; Oller & Eilers, 1988; Oller, Eilers, Bull, & Carney, 1985). In the course of examining deaf or hearing-impaired babies devoid of any known cognitive deficits, Oller and Eilers (1988) observed these babies to have reduced and/or delayed vocal canonical babbling as compared to hearing babies. Locke (1990) elaborated on this point, stating that auditory stimulation both from the environment and from the feedback that babies receive from their own vocalizations is crucial for vocal babbling to emerge. Locke and Pearson (1990) further qualified this observation by examining a tracheostomized, aphonic girl with normal hearing. Following decannulation she demonstrated delayed vocal development. Collectively, these findings led researchers to conclude that the role of audition is crucial to early language development in general, and babbling in particular.

Petitto and Marentette's (1991) discovery of "manual babbling" on the hands of profoundly deaf babies challenged the above views in at least two fundamental ways. First, the finding challenged the notion that the opening–closing of the mouth and jaw, and a baby's emerging neurological control over them, is the exclusive driving force underlying babbling. Second, it challenged the assertion that audition *alone* is critical for babbling to emerge, and suggested instead that babies require patterned linguistic (as opposed to strictly auditory) cues from the environmental input in order for babbling (hence, human language acquisition) to proceed.

Why "babbling" on the hands? In the course of examining profoundly deaf babies exposed to a sign language, Petitto and Marentette (1991) observed a class of hand activity that was like no other. It was not like the deaf babies' gestures nor anything else that they did with their hands; nor was it like any class of hand activity observed in the hearing control babies. As in the criteria standardly used to establish the existence of vocal babbling in hearing babies, this unique class of hand activity in the deaf babies (i) contained a reduced subset of the possible linguistically relevant "sign-phonetic" units in natural sign languages, (ii) possessed "sign-syllabic" organization, and (iii) was produced in meaningless ways. This hand activity was also reduplicated, produced with the general prosodic (rhythmic, timing, stress) contours of natural sign languages, and followed the identical characteristic stages observed in vocal babbling. Each individual deaf baby's preferred early babbling sign-phonetic form was continuous with the predominant sign-phonetic forms that appeared among its first signs. Petitto and Marentette had discovered "babbling" in profoundly deaf babies, albeit on the human hand.[1]

Moreover, Petitto (1993) observed through qualitative analyses that the reduplicated temporal patterning of the sign syllables produced by the deaf babies appeared to be fundamentally different from the temporal patterns of all other hand and arm movements. However, the precise physical, quantitative measurement of the phenomenon was not understood.

Recently, researchers have corroborated Petitto and Marentette's manual babbling finding in another group of babies (Cormier, Mauk, & Repp, 1998; Meier & Willerman, 1995). While both Meier and colleagues and Petitto and Marentette have observed that deaf babies indeed produce manual babbling, Meier's team asserts that hearing babies also produce similar hand activity. Further, they viewed such ostensible similarities between deaf and hearing babies' manual babbling as demonstrating that all baby babbling – be it on the hands or tongue – is therefore a fundamentally motoric activity, wholly commensurate with MacNeilage's (1998) frame/content theory. While Meier and Willerman suggested that manual babbling requires the coordination of proximal and distal articulators (e.g. the shoulder and wrist, respectively), they did not specify phonetic criteria for coding manual babbles. This omission is crucial. In all studies of vocal babbling, as well as in the manual babbling studies of Petitto and Marentette, the attribution of "babbling" is applied only after using strict, standard criteria. These criteria include using a system of standard diacritics to characterize the physical properties of vocal/hand activity. These attributions are then further subjected to standard psycholinguistic frequency and distributional analyses to identify possible phonetic units *for the child* (rather than for the adult researcher) and their combinatorial properties (the basic phonetic and syllabic units and their sequencing regularities). Having established a possible set of phonetic/syllabic forms, the criteria for "babbling" is then applied (see above, de Boysson-Bardies, 1999; Elbers, 1982; Locke, 1983; Oller & Eilers, 1988). Thus, it is possible that the coding system of Meier and his colleagues did not reliably differentiate between linguistic and non-linguistic hand activity in the deaf (acquiring sign) and the hearing (acquiring speech) babies.

Despite the methodological concerns raised here, the studies by Meier and colleagues suggest an intriguing hypothesis. Perhaps the "manual babbling" observed in deaf babies is not "babbling" at all, but instead is hand activity fundamentally similar to that observed in all babies, even hearing babies not exposed to sign languages. All babies produce an array of hand activity in early life as a consequence of developing motor control. Thelen (1979, 1981, 1991), for example, has described the emergence of repetitive, cyclic movements involving rotation around an axis or simple flexion and extension as rhythmic

[1] Like spoken languages, all signs (homologous to the words) and sentences in sign languages are formed from a restricted/finite set of meaningless units called sign-phonetic units (e.g. Brentari, 1999; e.g. the unmarked, frequent phonetic unit in American Sign Language involving a clenched fist with an extended thumb), which are further organized into syllables. Like the consonant–vowel syllable structure in spoken language, the structural nucleus of the "sign-syllable" consists of the rhythmic opening and closing alternations and/or the rhythmic movement-hold alternations of the hands/arms (e.g. Liddell & Johnson, 1989; Perlmutter, 1991, 1992).

stereotypies. The frequency of rhythmic stereotypies (including the oral and manual articulators) peaks between 24 and 42 weeks of age, and then declines thereafter. The regularity of onset ages of these behaviors suggests that they are on a maturational timetable for the development of neuromuscular pathways. Further, baby motoric stereotypies are not observed in parents or siblings, making it unlikely that these types of activities are imitated or emerge as a result of extrinsic factors.

Also between the ages of approximately 6 and 10 months, babies enter the syllabic babbling stage. Recall that at this stage in development, babies' productions possess well-formed consonant–vowel reduplications (e.g. ba-ba-ba). Stated differently, while babbling, babies produce repetitive, cyclic open–close movements of their jaws, much like the fundamentally motoric stereotypies observed by Thelen. Hence, at this particular stage in development the motoric stage parallels the linguistic stage, but differs in one critical respect: no clues from the input are necessary for its emergence.

To summarize, the field of early child language is at a fascinating juncture. In an attempt to gain insight into the origins of language in young babies, researchers have turned to studies of vocal babbling. On the one hand, MacNeilage and colleagues maintain that vocal babbling and, by extension, human language evolve from the fundamentally non-linguistic maturation of the motor development of the oral articulators that only later take on linguistic significance as the child learns associations between their natural ability to produce sounds and word meanings in the world around them. On the other hand, de Boysson-Bardies, Jusczyk, Vihman, and others say that babbling is determined by the child's sensitivity to and production of abstract linguistic units and their distributional patterns from the very beginning. For a brief moment in time, it appeared that the competing motoric–linguistic hypotheses might be resolved with the finding by Petitto and Marentette (1991), in which they showed that deaf babies produce complex sign-phonetic and syllabic babbling units on their hands. This new evidence suggested that deaf babies babble even though they neither hear speech nor produce speech sounds – thereby providing support for the linguistic view. In response to Petitto and Marentette's findings, Meier and his colleagues suggested that deaf babies exposed to sign language and crucially hearing babies exposed to spoken language *both* produce rhythmic manual babbling that is fundamentally similar. Given that these hearing babies acquiring speech never saw sign language input, and given Meier's claim that they, like deaf sign-exposed deaf babies, are producing rhythmic "manual babbling", this renewed the hypothesis that *all* babbling is governed exclusively by motoric principles. The key question is this: is the rhythmic hand activity in babies exposed to sign language and the rhythmic hand activity in babies exposed to spoken language indeed fundamentally similar?

1.3. Hypothesis testing

In the present study, we tested the motoric versus linguistic hypotheses by taking an entirely novel route. To pose the strongest possible test of these two hypotheses, we chose to study two groups of *hearing* babies. One group of hearing babies was exposed to spoken language from birth (with no sign language input whatsoever). The second group of hearing babies received no systematic exposure to spoken language whatsoever, only sign language input from their profoundly deaf parents.

Crucially, the two hearing baby groups studied here were equal in all developmental respects, with the only difference being in the form of the language input that they received, by tongue or by hand. All of these babies can and do hear, and all of the babies can and do produce vocalizations. This then shifts the focus from the presence of audition and use of the mouth to the presence and use of patterned linguistic cues in the input and the human baby's capacity to make use of them. This is the key prevailing hypothesis that the hearing babies acquiring sign allow us to test: is it audition/the mouth (peripheral speech production/hearing mechanisms) that drives babbling/language acquisition or the species' more central and specific sensitivity to specific patterns in the input that correspond to aspects of the patterning of natural language?

We were also interested in discovering whether the hearing sign-exposed babies would produce rhythmic hand babbling and whether they would produce other rhythmic hand activity – both in the same manual modality. If so, we were especially eager to learn whether there existed a principled and patterned separation between the two. We were further interested to learn the extent to which these sign-exposed hearing babies' hand activity (be it "manual babbling" or other rhythmic hand activity) was fundamentally similar or dissimilar to that of our hearing babies who never viewed signs. Finally, as will be seen below, we studied these questions both in speech-exposed and sign-exposed hearing babies with Optotrak, opto-electronic position tracking technology. Here, diodes were placed on each baby's hands, which permitted quantitative measurements of the baby's hands in our pursuit to adjudicate between the motoric versus linguistic underpinnings of human language.

1.4. Predictions

Two competing hypotheses have been offered to account for the presence of similar structures unique to babbling in both the manual and vocal modes. The motoric hypothesis suggests that babbling in both modes is simply a stereotyped behavior controlled by the mechanisms subserving general motor development. Because hearing babies exposed to sign language do *not* use their mouth and jaw to learn speech (which presumably makes possible the babbling behavior), the motoric hypothesis therefore predicts that their hand activity should be fundamentally similar to that of hearing babies acquiring spoken language. In other words, this view predicts that rhythmic hand activity will be independent of patterned linguistic input and thus fundamental similarities should be evident in the hand activity across the two groups of hearing babies.

The linguistic hypothesis suggests that babbling reflects the child's emerging discovery of the underlying patterning of natural language structure, beginning with the tacit identification of its meaningless set of units (phonetic units) and their combinatorial regularities (syllables). If babies are born with sensitivity to specific rhythmic patterning that is universal to all languages, even signed ones, then this view predicts that differences in the form of language input should yield differences in the hand activities of the two groups. Specifically, fundamental differences should be observed between the *linguistic* rhythmic hand activity and the *non-linguistic* rhythmic hand activity in babies exposed to a sign language as compared with those exposed to speech. Further, this view predicts similarities between both sign-exposed and speech-exposed babies' *non-linguistic* rhythmic hand activity.

2. Participants

Six hearing babies were studied in 60 minute experimental sessions, at approximately 6, 10, and 12 months of age. These ages were chosen to compare the babies' motoric versus linguistic development, as this age range corresponds to both developing motoric stereotypies, and to developing linguistic (babbling) activity. The sign-exposed (Experimental) group consisted of the extremely rare situation in which three hearing babies of profoundly deaf parents received no *systematic* exposure to spoken language in early life and were instead exposed exclusively to sign language input.[2] In the cases of babies E1 and E2, one parent signed Langue des Signes Québecoise (LSQ, used in Québec and other parts of French Canada) and the other signed American Sign Language (ASL, used in the United States and parts of Canada). The deaf parents of Baby E3 signed LSQ only. The speech-exposed (Control) group consisted of three typical hearing babies of hearing parents who received no sign language input; parents of babies C1 and C2 spoke English, and parents of Baby C3 spoke French. Table 1 provides the precise ages of all subjects at each of the three experimental sessions.

3. Methods

Babies were seated in a baby car seat located in our Optotrak Laboratory at McGill University, which was filled with baby posters, blankets, hanging mobiles, and had brightly-colored wall partitions to shield them from viewing the equipment. First, infrared emitting diodes (IREDs) were placed on the baby's hands (below) while one of the parents played with the baby. After this, Optotrak sensors tracked the trajectory and location over time of the baby's hands while the baby engaged in a variety of play activities. For example, the baby was presented with age-appropriate toys (e.g. a rattle, stuffed bunny, plush ball) that were first shown to the baby and then given to it. Other activities included one of the parents playing peek-a-boo games with the baby, talking/signing to the baby while looking in a mirror, an activity where mom simply smiled at the baby, or another

[2] These hearing babies were raised entirely immersed in a highly exclusive signing deaf world, with deaf parents and deaf extended family members, all of whom were active in weekend local deaf social clubs, etc., from birth until approximately age 3. To be sure, all of these sign-exposed hearing babies were immersed in this signing deaf context well within the key time period relevant to the present study, ages 6–12 months. While we followed these babies closely to determine that they were not exposed to radio and television in these deaf homes, they no doubt must have heard instances of speech; for example, at a gas station or in a supermarket. However, no baby in this study received *systematic* exposure to any spoken language and certainly none had spoken language systematically directed to them. Both points are important: systematic exposure within key maturational time periods of human development is utterly crucial in human language acquisition. Furthermore, one stunning example that this extremely occasional speech was not salient to and/or used by these hearing babies is the fact that they did not produce *systematic* syllabic vocal babbling, and they should have if they were attending to/analyzing this overheard speech.

Table 1
Ages of subjects at videotaped sessions

Group	Session		
	1	2	3
Sign-exposed			
E1	0;07.02	0;09.26	1;00.02
E2	0;05.24	0;10.06	1;00.01
E3	0;06.03	0;09.28	1;00.00
Speech-exposed			
C1	0;06.07	0;10.00	1;00.02
C2	0;05.26	0;10.01	1;00.08
C3	0;06.04	0;09.31	1;00.08

where mom and experimenter conversed while the baby looked on. The goal was to create relaxed, but varied contexts in which babies would have an opportunity to produce as wide a range of hand activity as would be natural to the age.

All sessions were recorded using Optotrak (Northern Digital Inc., Waterloo, ON, Canada). Although Optotrak technology is well established in the motoric development field (e.g. Ostry, Vatikiotis-Bateson, & Gribble, 1997; Sergio & Ostry, 1995), the present study is the first study to our knowledge that has applied Optotrak technology to studies of babies' early linguistic development. The sensors of the Optotrak system can accurately measure the location over time and trajectory of IREDs placed on the babies' limbs with a precision of 0.1 mm even at high sampling frequencies. Eight IREDs (four on each of the left and the right hand/arm) were strategically placed on the babies' hands and forearms: two adjacent IREDs were placed on the back of both the right and the left hands of the babies. An additional IRED was placed on the ventral surface of each wrist near the baby's thumb. A fourth IRED was placed on the dorsal surface of the forearm 3–5 cm proximal to the wrist. As the IREDs are tiny and lightweight, interference with the babies' movements was minimal. Thus, the three-dimensional location of the limbs over time was measured with high precision.

Crucially, Optotrak computations were calculated *completely* separate from any videotape analysis. These Optotrak computations were performed without being visually influenced by images of the child, thereby providing the most accurate and rigorous quantitative analysis of moving hands to date. In particular, it provides a significant advance over previous subjective classification methods whereby researchers look at baby videotapes exclusively and decide whether they think a particular hand activity is or is not a babble (e.g. Cormier et al., 1998; Meier, Mauk, Mirus, & Conlin, 1998; Meier & Willerman, 1995; Petitto & Marentette, 1991). To be clear, the data yielded from Optotrak recordings are strictly numeric representations of the babies' hand/arm movements and were coded "blind" as to whether the children were in the speech-exposed or sign-exposed groups.

Independently, on-line videotapes were made of all babies for post-Optotrak analyses. The babies' hand activity in all three sessions was videotaped onto S-VHS videocassettes from two camera angles. The S-VHS video recordings of the babies were transferred onto

Hi-8 videocassettes formatted with a time code that was precisely matched with the corresponding time code provided by the Optotrak recordings. Thus, at any given time, data from both the Optotrak and video recording methods were available.

Initially we recorded 2082 movement segments across all babies and ages. We defined a *movement segment* as any hand activity produced by the babies involving a single type of movement. An open–close movement of the hand, for example, would be considered one movement segment. The start of a new movement segment was indicated if a different type of movement then began (e.g. a waving motion of the hand, as in waving "goodbye"). All movement segments in which there were objects in the babies' hands and segments of activity which involved babies making contact with an object (e.g. toy, car seat, adult) were excluded from all analyses. Likewise, any activity that was not fully within the field of view of the cameras was excluded (e.g. activity that was blocked by an adult or by the chair). For these reasons, 633 movement segments were excluded from the total corpus of data. From the remaining 1449 movement segments recorded, 595 segments were produced by the sign-exposed group and 854 segments by the speech-exposed group. As would be expected in equal 60 minute experimental sessions, the number of movement segments that the babies produced differed across babies and ages (i.e. some babies produced more activity than others, and the amount of activity varied over time – due to this fact, and for ease of comparison across babies, here, and in all subsequent analyses, the data are reported in percentages; see Table 2). To ensure that a representative sample of the babies' manual activity was analyzed, we used stratified random sampling to obtain 400 movement segments (200 per group) for Optotrak and, subsequently, for video analyses. So, for example, of the 595 movement segments produced by the sign-exposed group, 75% of this activity was produced at 6 months, 16% at 10 months and 8% at 12 months. In obtaining 200 movement segments, these same proportions (percentages) were maintained such that 75% of the 200 segments were produced at 6 months, 16% at 10 months, and 8% at 12 months. The identical procedure was applied to the speech-exposed babies' data, also yielding 200 movement segments. Thus, Table 2 presents

Table 2
Percentage of all manual activity produced and, in parentheses, the actual number of movement segments analyzed by the (a) sign-exposed and (b) speech-exposed babies at 6, 10 and 12 months

Group	Age (months)		
	6	10	12
(a) Sign-exposed			
E1	68 (25)	16 (6)	16 (6)
E2	84 (42)	10 (5)	6 (3)
E3	74 (84)	23 (26)	3 (3)
Mean	75.3 (151)	16.3 (37)	8.3 (12)
(b) Speech-exposed			
C1	78 (60)	14 (11)	8 (6)
C2	72 (58)	26 (21)	2 (2)
C3	79 (33)	12 (5)	9 (4)
Mean	76.3 (151)	17.3 (37)	6.3 (12)

the percentage of all manual activity produced by each baby at each age (e.g. 68% of all of Baby E1's manual activity was produced at 6 months), and following our sampling procedures, the actual number of movement segments analyzed (e.g. 25 movement segments produced by Baby E1 at 6 months were analyzed).

We expected to see the majority of all babies' manual activity produced between 6 and 10 months (irrespective of the nature of the activity, be it linguistic or non-linguistic), because both normally developing motor stereotypies (Thelen, 1979, 1991) and manual babbles (Petitto & Marentette, 1991) peak during this period of development. What is important to note, however, is that manual activity continued to be produced through to 12 months, and that the precise amount of activity produced at any given age differed by individual baby. This is due to the fact that individual differences across babies result in varying ages of onset of developing behaviors (much in the same way that most normally developing babies begin walking by their first birthday, but a range certainly exists for when babies actually achieve this milestone). Moreover, the continued production of any given behavior differs by baby throughout development (some babies will continue crawling after learning to walk; similarly, babies will continue to babble even after the production of their first words). This observation therefore highlights the importance of collecting and analyzing data over the normal age *range* of emerging behavior (i.e. from approximately 6 to 12 months), rather than exclusively at the average age (i.e. at approximately 7 months) that researchers would expect the behavior to appear.

3.1. Optotrak recordings

At a sampling rate of 100 Hz, the Optotrak system recorded the time-varying three-dimensional positions of the IREDs on the babies' hands/arms. Each movement segment was analyzed using commercially available data analysis software (MATLAB, The Mathworks Inc., Natick, MA). The raw three-dimensional position data from each IRED were first analyzed to select those that most consistently captured the babies' movement (i.e. were seldom obscured), and yielded the final two IREDs (one from each hand, per baby) that provided the data for all subsequent analyses (i.e. the IRED nearest to the thumb on each hand).

Multiple kinematic measures were then calculated for each movement segment. First, the resultant vector of the x, y, and z position data over time was computed to give the trajectory of the hand in three-dimensional space. This trajectory was then differentiated to give the tangential velocity of the hand throughout the movement segment. From these measures, the frequency (in Hertz) was calculated for each cycle of hand activity within a movement segment. As is standard, movement start was defined as 10% of the maximum velocity of the cycle, and movement end was the point at which the tangential velocity reached 10% of the peak cycle velocity (Sergio & Ostry, 1995). The frequency for a given movement segment was determined by taking the average of the frequencies of all the complete cycles in that movement segment. This procedure yielded frequency values (in Hertz) for all 400 movement segments.

3.2. Video recordings

After Optotrak analyses were completed, temporal matching of the Optotrak data to the videotaped data was performed for all 400 movement segments. By matching the frequency values of the movement segments provided by the Optotrak technology with the corresponding videotaped data of the babies' hand activity, we were able to see for the first time what the babies were actually doing during a particular Optotrak segment.

In addition to seeing what the babies were doing during Optotrak segments, we were able to transcribe and subsequently analyze the precise nature of the hand activity performed by the babies. We did this by transcribing and entering into a computer database all of the movement segments using a standard, widely used transcription system (below) that permitted a direct comparison of the hand activity of both groups of babies (Petitto & Marentette, 1991). This previously established transcription system enabled us to reliably differentiate between manual babbles, gestures, and the non-linguistic, motoric hand activity produced by all normally developing babies.

Following Petitto and Marentette (1991), for each of the 400 movement segments produced by the babies, we transcribed the following: (i) the physical form of the babies' hands using a set of diacritics that was first created by the sign linguist William Stokoe (1960) to be analogous to the International Phonetic Alphabet used in the transcription of spoken languages (but created here for the transcription of signed languages) and that has been perfected over several generations of sign linguistic research (e.g. see Brentari, 1999; Neidle, Kegl, MacLaughlin, Bahan, & Lee, 2000; Petitto, 1987). Here, internal features of the human hand are transcribed along several dimensions (e.g. handshape, location in space, palm orientation, movement). (ii) All forms were transcribed according to the manner of use, for example, whether the form was used with or without objects in hand, whether the form was used referentially and/or with apparent communicative intent, and whether the form was a standard sign in ASL or LSQ (e.g. Petitto, Katerelos et al., 2001; see also Holowka, Brosseau-Lapré, & Petitto, 2002). (iii) Following standard methods used for the identification of potential vocal babbles in hearing babies (e.g. Oller & Steffens, 1994), all forms that were produced *without* reference and/or apparent communicative intent and all forms that were not genuine attempts to sign were analyzed for the presence/absence of systematic physical organization using standard child language frequency and distributional analyses (e.g. Holowka et al., 2002; Petitto, Katerelos et al., 2001). If the hand activity showed systematic organization, then these forms were further examined to determine whether they had unique organizational properties, or whether the forms shared formational properties with the phonetic and syllabic organization common to signed and spoken languages. To make this more concrete, extreme care was taken not to prejudge a baby's hand form as having sign-phonetic (syllabic) status until the frequency and distributional analyses told us that this was warranted. This is similar to the way that much care is taken not to prejudge a hearing baby's acoustic vocalization as being a "babble" without a combination of evidence – including evidence from frequency and distributional analyses that a specific vocalization is indeed a phonetic unit (in syllabic organization; Oller & Steffens, 1994).

Finally, if a sign-phonetic unit was identified, attribution of "manual babbling" status to this hand activity was done by adhering to the strict set of standard criteria used for decades in attributing vocal babbling status to the vocalizations of hearing babies (e.g. Elbers, 1982; Locke, 1983; Oller & Eilers, 1988), and that were used by Petitto and Marentette (1991), and, as stated above, include three hallmark characteristics: forms must (i) be produced with a reduced subset of combinatorial units that are members of the phonetic inventory of all natural languages; (ii) demonstrate the syllabic organization seen only in natural languages (which inherently involved reduplication); and (iii) be produced without meaning or reference. If a hand form met these three criteria, it was coded as *babble*. All other forms were coded as *non-babble*. Taken together, this video transcription system enabled us to investigate *qualitatively* the different types of hand activity produced by all of the babies relative to the *quantitative* analysis of rhythmic frequency provided by the Optotrak technology.

To further understand the linguistic versus non-linguistic nature of the hand activity produced by all babies, a "location-in-space" analysis was performed. We were curious about this because in signed languages one striking index that a hand activity is linguistic (as opposed to non-linguistic) is that it must occur within a highly restricted space in front of the signer's body that is bound by strict rules of the grammar of the sign language. Hand activity that falls outside of these obligatory linguistic spaces is judged to be either a non-linguistic gesture or simply not in the language (ungrammatical). Each movement segment was assigned a location in egocentric, or body-centered, space, in consultation with the videotaped data. Raters who were blind to the babies' group assignments and who did not know sign language coded the location of the babies' hand activity in space. To ensure objective coding, each rater was given a visual template of a young human form in four divisions vertically and laterally (from top to bottom; side to side) that provided locations by number with named anatomical landmarks, which only the experimenters knew also corresponded to established obligatory linguistic spatial constraints of sign language, especially ASL (Klima & Bellugi, 1979; Neidle et al., 2000) and LSQ (Bourcier & Roy, 1985; Petitto, Charron, & Brière, 1990). Location 1 was the space between the top of the baby's head and the shoulders. Location 2 was the space between the baby's shoulders and the chest at the lower margin of the sternum (xiphoid compress; vertically) and from center chest to the length of an extended bent elbow (laterally; this is the linguistically "unmarked" or most used/canonical adult "signing space" and the signing space acquired first and used most frequently by young children acquiring sign languages; see Conlin, Mirus, Mauk, & Meier, 2000; Petitto, 1987). Location 3 was the space between the baby's lower margin of the sternum and waist (crest of the iliac). Finally, Location 4 was the space below the waist (crest of the iliac). For statistical purposes, the 400 movement segments were then coded as falling either within the *sign-space* (Location 2) or outside of the signing space (Locations 1, 3, and 4), which was coded as *non-sign-space*. Hand activity that crossed all four locations in space (i.e. large waving motions of the hand and arm) was excluded from the analysis, and constituted 47% (188/400) of the corpus.

3.3. Reliability measures

Inter-rater reliability measures were taken on all aspects of the procedure. One rater performed the Optotrak analyses, which yielded frequency values for 400 movement segments. Reliability tests were then performed on all 400 movement segments by a second rater, and a third independent rater conducted reliability tests on random samples of this corpus. Similarly, all 2082 movement segments captured on videotape were transcribed once by a single rater. The 400 movement segments that were randomly sampled and analyzed using the Optotrak technology were also fully transcribed from the videotapes by a second independent rater. Reliability tests were further performed by a third observer on random samples of the 400 movement segments from the videotapes. All conflicts with respect to the coding of all fields were resolved through discussion with agreement reaching 100%.

4. Results

The analyses yielded both an intriguing similarity and an intriguing difference between the two baby groups: both speech- and sign-exposed baby groups were similar in that they produced a *high*-frequency hand activity at around 2.5–3.0 Hz (roughly three complete hand movement cycles per second), which was found to be non-linguistic excitatory hand/arm activity common to all babies at this age. However, the baby groups were different in that only the sign-exposed hearing babies produced an additional class of *low*-frequency hand activity with a unique rhythmic signature of around 1 Hz. Further analyses revealed that this second class of activity was "manual babbling" and was produced largely within the linguistically-constrained signing space. These findings are based on the following analyses.

4.1. Optotrak analyses

Analyses of the Optotrak quantitative data provided frequency values in Hertz for all 400 movement segments (200 per group) produced by the babies. The distribution of frequency values was then plotted and compared across groups of babies (sign- versus speech-exposed) across all ages (6, 10, and 12 months). As is visible in Fig. 1, the sign-exposed babies' frequency values of movement segments appear to be bimodally distributed. The major mode (on the left) falls around 1 Hz and the minor mode (on the right) falls around 2.5 Hz. In contrast, frequency values of the speech-exposed babies' movement segments appear to be unimodal, with their mode falling around 3 Hz (also on the right in Fig. 1).[3] A comparison of the two groups further revealed that the frequency of the movement segments produced by the sign-exposed babies was significantly different from the activity of the speech-exposed babies at the same ages ($\chi^2(20, N = 200) = 389.65$, $P < 0.001$).[4]

The results obtained through analyses of the Optotrak data provided a quantitative description of the rhythmic hand activity produced by the two groups of babies.

[3] Perhaps the sign-exposed babies' motor activity was slightly lower in frequency than the speech-exposed babies' motor activity because the sign-exposed babies are producing another type of activity (manual babbling) in the same modality and thus it may be acting as some kind of "attractor pole" pulling the motor activity into its lower-frequency "orbit".

[4] The χ^2 statistic was calculated at 21 quarter intervals and is shown in Fig. 1 at half-intervals for clarity.

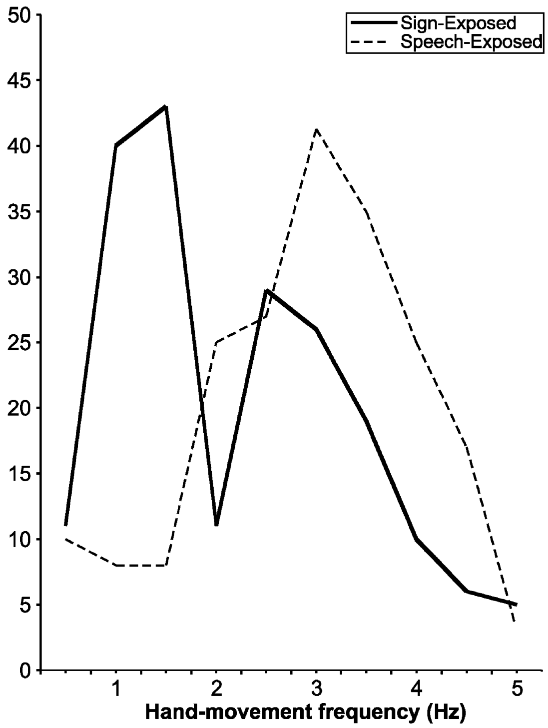

Fig. 1. Distribution of the frequencies of sign-exposed and speech-exposed babies' movement segments.

The objective measurements of the frequency of the babies' hand activity clearly indicated that the sign-exposed group of babies was producing two distinct types of hand activity. Stated differently, the frequency at which hand activity is performed depends on whether babies are exposed to sign or speech. As only the sign-exposed group of babies was receiving systematic exposure to linguistic stimuli in the manual modality, we had hypothesized that the differences between the two groups of babies could be attributed to manual babbling. It is evident from the distribution of activity illustrated in Fig. 1 that only the sign-exposed group of babies produced a low-frequency type of hand activity. We had hypothesized that this activity produced at approximately 1 Hz was manual babbling.

The high-frequency activity produced by both groups of babies, on the other hand, was hypothesized to be the non-linguistic motoric activity akin to that which Thelen (1979, 1991) has described of all normally developing babies.

4.2. Videotape analyses

After having discovered solid quantitative differences between the two baby groups' hand activity using the Optotrak technology, we then turned to the videotaped data to test our hypotheses by visually examining, transcribing, and analyzing the same 400 movement segments produced by the babies. We hypothesized that manual babbling would (i) be observed only in babies exposed to sign language, (ii) be produced at a frequency that differed from the frequency of the non-linguistic hand activity that all babies perform as part of normal motor development, (iii) adhere to the well-established babbling criteria (both oral and manual), and (iv) show other indices of being linguistically constrained, for example, being produced within the adult linguistic "signing space". The Optotrak analyses were suggestive with regards to points (i) and (ii), and thus we explored the two remaining criteria to better understand the nature of the group differences.

To provide further insight into the nature of the manual activity produced by the sign-exposed babies across all ages, we therefore needed to partition the observed movement speeds (or frequencies) into their respective low- and high-frequency modes. To do this, we used a classification algorithm, a K-Means Cluster Analysis, which assigned each individual movement segment produced by the sign-exposed babies into categories. The K-Means Cluster Analysis isolated homogeneous groups of cases (based on frequency, that is, speed of movement), and an iteration process maximized fit. The algorithm defined two categories (clusters) of movement segments produced by the babies (again, based on the speed of their movements). The first cluster identified by the K-Means Analysis (i.e. the babies' "low-frequency" activity) contained 53% (107/200) of the babies' total activity, and had a cluster center of 1.03 Hz. The second cluster identified by the K-Means Analysis consisted of the remaining 47% (93/200) of the movement segments produced by the babies (i.e. the babies' "high-frequency" activity), and had a cluster center of 3.04 Hz.

Using the low- and high-frequency clusters defined by the K-Means Analysis, we evaluated the final two points of our criteria for manual babbling to shed light on the nature of the movement segments produced by the sign-exposed babies. Specifically, we were interested in determining whether movement segments observed in the low-frequency cluster were coded as "babbles" from the videotape analyses, and whether the activity was produced in the adult linguistic "sign-space" (points (iii) and (iv) respectively of our criteria for manual babbles). We therefore matched every instance of "babble" and every instance of activity produced in the linguistic sign-space with its corresponding frequency value, and hence, its corresponding low- or high-frequency cluster determined by the K-Means Analysis. The results are presented for each sign-exposed baby individually, for the group as a whole, at each experimental age, and across all ages (as in the Optotrak analyses; see Table 3). Each baby will be discussed in turn.

A striking aspect of the data from Table 3 is that approximately 80% of the babies' low-frequency activity was babbles and produced in the sign-space. This overall pattern holds for all three babies, at each experimental session, and across all ages. The movement segments produced by Baby E1 coded as "babble" or as falling within the sign-space, for example, are plotted in Fig. 2 relative to the total distribution of movement segments (in Hertz) produced. Across the three ages tested, 69% of Baby E1's manual activity was coded as babble, and 77% was produced within the linguistic sign-space. In contrast, only 17% and 25% of the high-frequency activity produced was determined to be a manual babble or produced in the sign-space, respectively. Moreover, little variation in this overall pattern was observed at each individual age (between 60% and 75% of the low-frequency activity produced from 6 to 12 months was coded as a babble, and between 75% and 80% as falling within the sign-space, whereas only 0–20% of the high-frequency activity was babbles, and 0–30% was produced in the sign-space; Table 3).

Table 3
Percentage of all (a) low-frequency and (b) high-frequency manual activity produced by the sign-exposed babies coded as “babble” or as falling within the linguistic “sign-space” at 6, 10 and 12 months

	Age (months)							
	6		10		12		All ages	
	Babble	Sign-space	Babble	Sign-space	Babble	Sign-space	Babble	Sign-space
(a) Low frequency								
E1	60	80	75	75	75	75	69	77
E2	93	90	100	100	100	100	94	90
E3	98	85	67	67	100	100	90	81
Mean	84	85	81	81	92	92	84	82
(b) High frequency								
E1	20	30	0	0	0	0	17	25
E2	39	23	20	20	0	0	32	21
E3	27	32	18	36	0	0	24	32
Mean	29	28	13	19	0	0	24	27

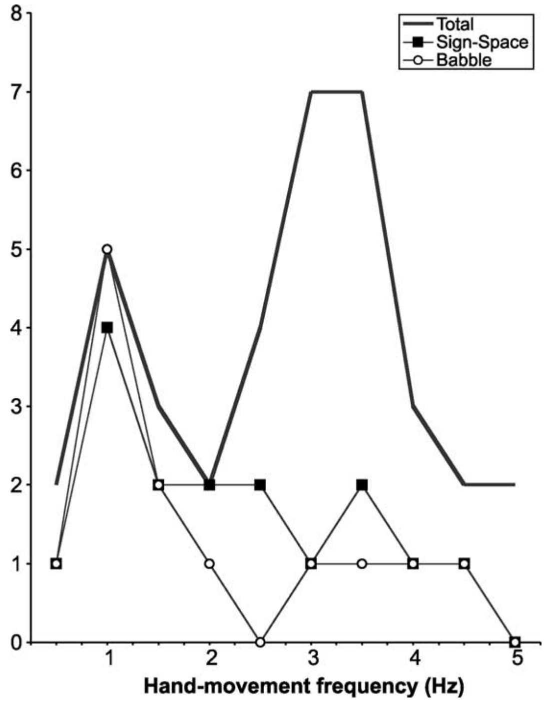

Fig. 2. Distribution of the frequencies of sign-exposed Baby E1’s babbles and sign-space activity relative to the distribution of all movement segments produced.

Similarly, Baby E2 produced a remarkable number of babbles and activity in the sign-space at a low-frequency across all ages (94% and 90%, respectively; Fig. 3), and these percentages ranged only from 93% to 100% from ages 6 to 12 months for babbles, and from 90% to 100% for low-frequency activity produced in the sign-space. As is evident from Fig. 3, Baby E2 produced few babbles at a high frequency (32% overall), and few high-frequency movement segments were produced in the sign-space (21% overall). Again, these findings held at each individual age (between 0% and 39% babbles, and between 0% and 23% sign-space activity were produced from 6 to 12 months).

Finally, the breakdown of activity coded as a manual babble or as being produced in the sign-space for Baby E3 is presented in Fig. 4. On average, 90% of Baby E3's activity produced at a low frequency was coded as a babble, and 81% was produced in the sign-space. From 6 to 12 months these percentages varied between 67% and 100% for Baby E3's production of babbles and activity produced in the sign-space at a low frequency. Few babbles (24% overall; 0–27% from 6 to 12 months) and few movement segments occurring in the sign-space (32% overall; 0–36% from 6 to 12 months) were produced by Baby E3 at a high frequency.

Unlike the sign-exposed babies, the speech-exposed babies' distribution of manual activity was unimodal across all babies, across all ages (recall Fig. 1). In order to compare the nature of the manual activity produced across groups, however, we applied

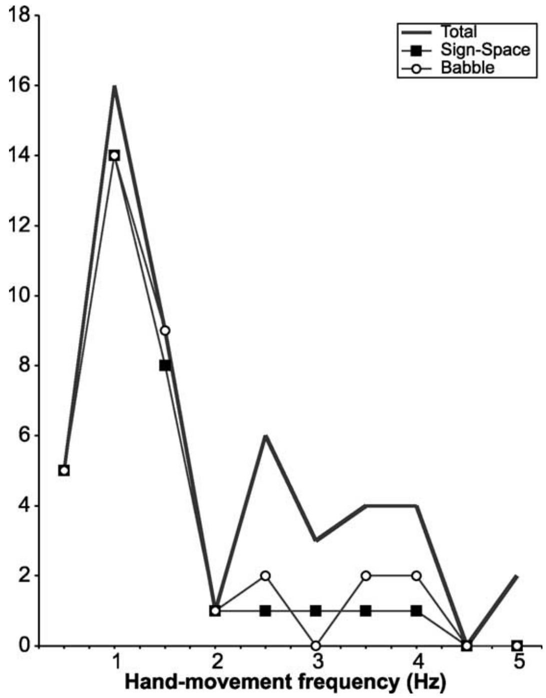

Fig. 3. Distribution of the frequencies of sign-exposed Baby E2's babbles and sign-space activity relative to the distribution of all movement segments produced.

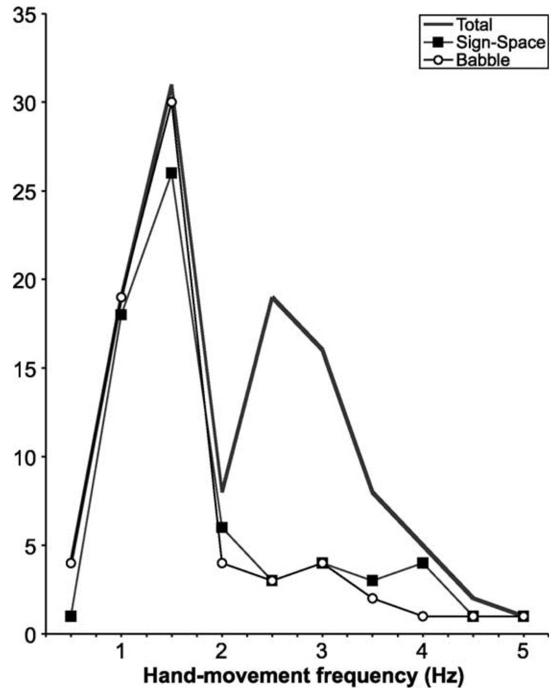

Fig. 4. Distribution of the frequencies of sign-exposed Baby E3's babbles and sign-space activity relative to the distribution of all movement segments produced.

the identical K-Means Cluster Analysis to the speech-exposed babies' data. This procedure classified the total number of movement segments produced by the speech-exposed babies into the following two groups: the low-frequency cluster, comprised of 39% (78/200) of the babies' total activity, and with a cluster center of 1.58 Hz, and the high-frequency cluster, containing the remaining 61% (122/200) of the babies' activity, and centered at 3.42 Hz. What is immediately apparent following the K-Means Analysis (and obvious from Fig. 1) is that the speech-exposed babies' data are shifted to the right (both the low- and high-frequency cluster centers are at higher frequencies than the sign-exposed babies). In other words, overall, the speech-exposed babies produced their manual activity at a higher frequency. Nonetheless, it is interesting to note that, like the sign-exposed babies, the speech-exposed babies produced some activity at a low frequency (albeit at a higher frequency than the sign-exposed babies' low-frequency activity). The question then is how much of this low-frequency activity is manual babbling. Following the same procedure outlined above for the sign-exposed babies, we addressed this question by classifying each instance of manual activity coded as a babble and each instance of manual activity coded as being produced in the sign-space for the speech-exposed babies into either the low- or high-frequency clusters specified by the K-Means Analysis. The results of this procedure are illustrated for each speech-exposed baby individually in Figs. 5–7.

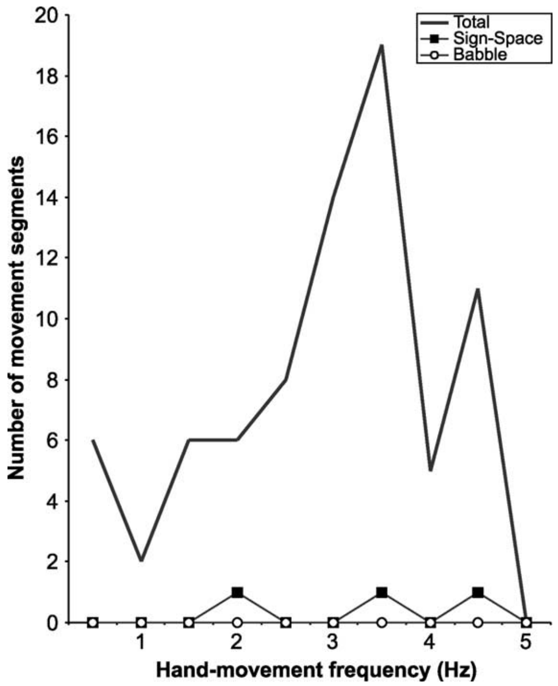

Fig. 5. Distribution of the frequencies of speech-exposed Baby C1's babbles and sign-space activity relative to the distribution of all movement segments produced.

The speech-exposed babies' individual plots confirm that these babies do indeed produce more manual activity at a higher frequency than we saw for the sign-exposed babies (cf. Figs. 2–4). Moreover, none of the activity produced by the speech-exposed babies was coded as babble from the videotapes, and only 8% of all of the speech-exposed babies' activity was coded as falling within the linguistic sign-space. While our video analyses and strict criteria for attributing babbling status to manual activity revealed that none of the activity produced by the speech-exposed babies was babbles, clearly some activity produced by the speech-exposed babies was produced at a low frequency, as was determined through the Optotrak analyses. This low-frequency activity was observed in the original figure of the two groups of babies' distributions of hand-movement frequency (Fig. 1; the overlapped activity falling below approximately 2 Hz), and is scattered throughout the individual plots here. A hypothesis as to the nature of this low-frequency activity observed in the speech-exposed babies is presented in Section 5.

In sum, we discovered through the blind, quantitative Optotrak analyses that only the sign-exposed babies produced hand movement segments that appeared to be bimodally distributed with respect to the speed of their movements. The plot of the frequency at which the sign-exposed babies produced these movement segments revealed both visually and statistically a significant difference between the sign-exposed and speech-exposed groups of babies, and that the low-frequency hand activity in the sign-exposed babies was linguistic babbling.

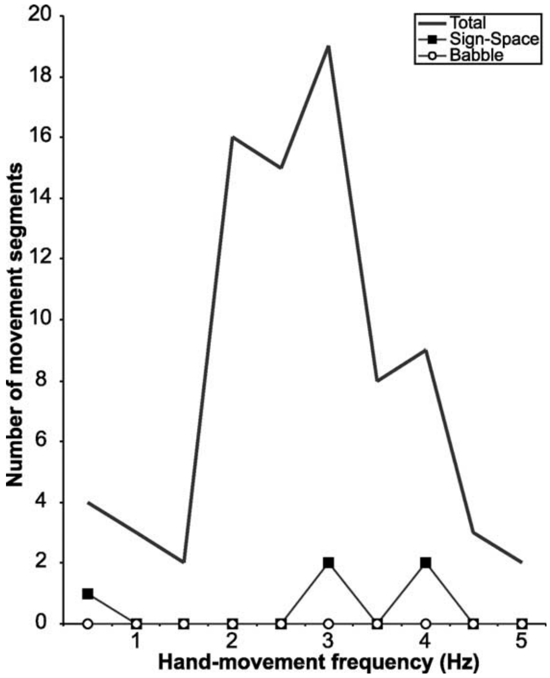

Fig. 6. Distribution of the frequencies of speech-exposed Baby C2's babbles and sign-space activity relative to the distribution of all movement segments produced.

5. Discussion

To understand the origins of the human language capacity, scientists have turned to clues provided by the regular onset and structure of baby babbling. Yet the biological basis of baby babbling has been debated for decades, with one hypothesis about the origins of babbling (including language acquisition and language origins) being that it begins as a purely non-linguistic motor activity tied to the opening and closing of the mouth and jaw (Locke, 2000; MacNeilage & Davis, 2000; Studdert-Kennedy, 1991). By contrast, others have offered that babbling is a linguistic activity reflecting the babies' sensitivity to specific patterns at the heart of human language and, in turn, their natural propensity to produce them (de Boysson-Bardies, 1999; Jusczyk, 1997; Petitto, 1993, 2000; Vihman, 1996); see especially Pinker and Bloom (1990), regarding the possible utility and evolutionary significance of positing a contemporary brain with sensitivity to the grammatical patterns of natural language (see also Rizzolatti & Arbib, 1998).

In pursuit of the strongest possible test of these two hypotheses, we studied three hearing babies acquiring spoken language and a remarkable group of three hearing babies acquiring only sign language (no speech). Petitto and Marentette (1991) had previously compared hearing and deaf babies, discovering babbling on the hands of deaf babies only, but differences may have resulted from the two groups' radically different sensory experiences. Here, however, the two groups of hearing babies were equal in all

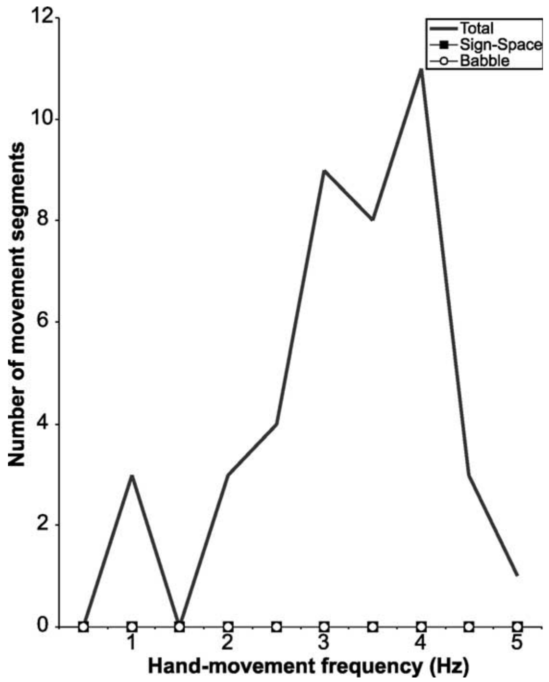

Fig. 7. Distribution of the frequencies of speech-exposed Baby C3's babbles and sign-space activity relative to the distribution of all movement segments produced.

developmental respects, but differed only in the form of the language input – by hand or by mouth.

Both groups are hearing and make vocal productions. If early human language acquisition is determined exclusively by the maturation and control of the mouth and jaw muscles, then what these two groups of babies do with their hands should be irrelevant; the two groups of babies should have produced fundamentally similar hand activity. Said another way, we would not expect to see any differences in these two groups of babies' hands (despite one receiving sign language input) because this does not involve the mouth and, again, it is mouth motor development that presumably functions like the "master switch" that drives early language acquisition.

But what if there were more to acquiring language – more than the development of the peripheral control of the mouth and jaw? What if the brain possessed tissue specialized to detect specific patterns in the input that initially correspond to key aspects of the grammatical patterning of natural language (Petitto, 1993, 2000; Petitto, Katerelos et al., 2001)? Petitto et al. (2000) conducted PET/MRI brain-scanning research with deaf signers and hearing controls, and found that *all* brains have specialized tissue that is uniquely sensitive to specific *rhythmic* patterns at the core of natural language structure – those with the rhythmic duration, and maximal contrast, of linguistic phonetic–syllabic units – irrespective of whether the rhythmic phonetic patterns are coming in on the hands in sign language or the tongue in speech. Here, the young hearing baby equipped with this sensitivity should perceive these key patterns coming in on its caretakers' hands and attempt to produce them. This would be so even though the patterns were expressed and received in a way that had nothing to do with the mouth and jaw. In this extraordinary situation, their baby hands should show us differences in the way that they use their hands for linguistic versus non-linguistic activity and, further, their use of hands for linguistic activity should be different from anything seen in hearing babies acquiring speech. At the same time, one component of their use of hands should be similar to what all babies do, because as a developing human organism, there is no reason to expect that they would not exhibit the typical developmental milestones of motor growth.

In the present study, this is precisely what we discovered, and in a novel way. The application of the Optotrak technology to study early linguistic development enabled us to examine the frequencies at which hearing babies exposed to signed and spoken languages produce their rhythmic hand activity. Here we discovered that the hearing babies acquiring sign produced two distinct types of rhythmic hand activity: one type of low-frequency activity was produced at approximately 1 Hz, and one type of high-frequency activity was produced at approximately 2.5 Hz. We also discovered that the hearing babies acquiring speech produced only one class of high-frequency hand activity at approximately 3 Hz, and that this was fundamentally similar to the sign-exposed babies' high-frequency hand activity. The Optotrak technology thus provided the first quantitative measurement of babies' rhythmic hand activity in pursuit of fundamental linguistic questions.

Next we turned to qualitative analysis of the videotaped data to examine the precise nature of the low- and high-frequency activity produced by the babies. These analyses revealed that the low-frequency activity was indeed "manual babbling" (Petitto & Marentette, 1991), was produced within the rule-governed obligatory signing space, and was only produced by the sign-exposed babies.

The present findings therefore fail to confirm the ubiquitous motoric hypothesis of baby babbling as well as its application to accounts of early language acquisition and the basis for the evolutionary origins of language. MacNeilage and Davis (2000) argue that language evolution (language phylogeny) is due to the affordances provided by the biomechanical properties of the jaw, which, in turn, suggests that speech *determines* the emergence of early language production in ontogeny. Remarkably, and without relying on the mouth, we observed that hearing babies acquiring sign produced manual babbling that was conveyed on their hands with a different class of movement frequencies from the frequencies of their non-linguistic hand activity. This finding is indeed noteworthy because the movement frequencies that distinguished between linguistic and non-linguistic hand movements were carved out of a single manual modality and yielded two classes of behavior in sign-exposed babies (whereby 52% was low-frequency babbling and 48% was high-frequency non-linguistic hand activity); by contrast, the hearing speech-exposed babies produced non-linguistic hand activity nearly 100% of the time (with only a small proportion of their high-frequency hand activity falling within the low-frequency mode *and even here it was higher in frequency than the sign-exposed babies' low-frequency activity*). Therefore, we suggest that the present findings provide strong support for the linguistic hypothesis of babbling and, by extension, human language acquisition. That the linguistic and non-linguistic hand movements were robustly differentiated by distinct rhythmic frequencies could only have resulted if babies find salient and can use the specific rhythmic patterns that underlie natural language.[5]

Clearly, motoric development contributes to the production of syllabic babbling in both the manual and vocal modalities in some capacity, but not in the exclusive way that MacNeilage and Davis (2000) and Locke (2000) have proposed. If this were the case, then linguistic babbling should *not* have been present in the manual mode in our hearing babies acquiring sign (nor deaf babies acquiring sign; Petitto & Marentette, 1991). But if a strictly motoric explanation cannot account for the onset of human language production, then what is guiding the convergence of linguistic structure across both the signed and spoken modalities?

We propose an alternative account of babbling that has implications for the origins of language in babies, one which integrates both linguistic and motor control principles. Ours is a view consistent with the linguistic hypothesis of babbling above, which suggests that babbling makes possible the baby's discovery and production of the most rudimentary structures of natural language, phonetic–syllabic units (e.g. de Boysson-Bardies, 1993, 1999; Jusczyk, 1986, 1993, 1997; Vihman, 1996). Here, however, we hope to take this notion further by articulating how the baby might discover the core syllabic babbling unit in the first place. What appeared to differentiate non-linguistic hand activity from manual babbling in the present study was the unique *rhythmic signature* of natural language. A hypothesis that we are testing further is that sign-exposed babies are initially sensitive to rhythmic bursts of about 1 Hz and all linguistic units that fall within it. This, then, would afford babies with the means to discover the particular babbling segments that they will produce in the first place. Further, the specific rhythmic and reduplicated act of babbling

[5] Interestingly, the motoric hypothesis, with its focus on the emerging control over the mouth and jaw, would also predict that both baby groups should have babbled *vocally*. As growing young humans, by default, both groups of babies were developing more and more control over their mouth and jaw muscles – just like both groups of babies were developing the abilities to sit, stand, and walk. But our sign-exposed hearing babies acquiring sign did not vocally babble like other hearing babies, thereby providing a further challenge to the motoric hypothesis. Although beyond the scope of the theoretical goals of this paper, our hearing babies exposed only to sign language did of course produce vocalizations and at times they even hit upon a syllabic *vocal* babble. But these babies' vocal babbling was distinctively "off", different from a baby who receives systematic exposure to speech. Their vocal babbling was not systematic in the way seen in other hearing babies acquiring speech, did not contain the normal range of phonetic units and syllable types, was produced with dramatically reduced frequency as compared to the typical speech-exposed baby (indeed they never hit Oller's 20% babbling ratio as compared to other vocal productions and instead hovered around 1%), and the onset times and babbling progression were different from the regular patterns typically seen (for corroborating evidence see also Oller & Eilers, 1988). Precisely how our sign-exposed hearing babies' vocal babbling was different (and similar) to the babbling of hearing babies receiving systematic speech input is presently under investigation. As we suggest below, these hearing babies acquiring sign do not vocally babble like other hearing babies because they are not receiving the patterned language input that they need (in this case, in speech) to initiate the language analysis–babbling loop. Although these babies do hear sounds and fragments of speech, they teach us that fragmentary and unsystematic input is, evidently, just not enough. Babies need systematic exposure to the specific patterns found in natural language (in this case, spoken language); what they do with the fragmentary speech input can only go so far – especially here with regard to their absence of normal vocal babbling and in general with regard to the inherent limits of language invention (creation) that any child can construct without formal systematic patterned input (e.g. Goldin-Meadow, 1981).

may reflect the neurological integration of the motor production systems and the mechanisms sensitive to specific rhythmic signatures unique to natural language.

It does not follow from our finding that because sign-exposed babies produced linguistic manual babbling at 1 Hz that speech-exposed babies should also produce vocal babbling at 1 Hz. (Nor does it follow that sensitivity to 1 Hz frequency in the sign-exposed babies should remain stable across all of early development.) We fully expect modality differences to yield frequency differences. The most crucial generalization that we wish to advance, however, is that frequency differences between linguistic and non-linguistic input exist both in the speech and in the sign stream (regardless of the input modality) – even though we may find that the absolute frequency varies from one modality to the next, and, crucially, that all human babies are born sensitive to them. In other words, we are suggesting here that these frequency differences are highly constrained and patterned and that all young babies are tacitly sensitive to this information. It is what the baby uses to discover the phonetic and syllabic segments in the linguistic stream so as to produce babbling in the first place and, ultimately, to crack the code of its native language's structure.

To summarize more generally how language acquisition might have proceeded in the present case, the young hearing baby exposed to sign language, equipped with such a sensitivity to specific rhythmic frequency patterns, would perceive these key patterns coming in on its caretakers' hands. Then, building on pre-existing *multiple* neural pathways to the primary motor cortex (hand, mouth, oral-facial), the baby would attempt to produce these nascent patterns beginning around age 6 months, mirroring the specific modality to which the patterns were inputted/perceived. Here, we propose that it is the human child's sensitivity to specific rudimentary rhythmic patterns that correspond to aspects of natural language structure that is genetically endowed and stable across the species, and that this sensitivity is one of the primary "master-switches" that launches and determines the universal developmental language milestones such as babbling that we see in the first year of life. On this view, the human capacity to *express* language constitutes a neurologically "open" genetic program at birth, with its neural stabilization only coming "on-line" in the first few months of life. This expressive capacity is initially so highly plastic that, as has been shown in the present study (and a generation of others, e.g. see Petitto, 2000, for a review), it can recruit "on-line" either the hands or the tongue without any loss, delay, or trauma to the timing and the achievement of the normal language acquisition milestones. Thus, rather than mouth–jaw motor developments driving all of early human language ontogeny, the most radical proposal being offered here is that the human expressive capacity is not neurologically "fixed" at birth and instead develops and becomes fixed only *after* birth in all humans (actually, this always seemed self-evident to us if only on the grounds that we all agree that babies are not born talking). We shall leave for others to address the evolutionary (phylogenetic) significance of our proposal regarding human language ontogeny and its implication that aspects of the need to rapidly process densely-packed, complex, and *multisensory* input signals could have given rise to a brain that had the capacity to extract away from the raw input modality to the detection of its underlying key patterns – and, with regard to human language, its key underlying grammatical units and their distributional regularities – which could have ultimately afforded selection advantages for successive communication and social organization.

A final puzzle is this: do hearing babies acquiring spoken language produce manual babbling as seen in babies acquiring sign languages? No. But they do produce rhythmic hand activity, and the present study teaches us that all rhythms are not the same. The Optotrak analyses showed us, in a way that no videotape analysis could reveal, that the rhythmic frequencies underlying true manual babbling in sign-exposed babies were different from the rhythmic frequencies underlying non-linguistic hand activity in speech-exposed (and sign-exposed) babies.

This leads us to a key methodological point: although syllabic organization was observed in the Petitto and Marentette (1991) study, nothing was known about the precise rhythmic frequency of manual babbling. For this reason, the precise definition of manual babbling has been subject to controversy and, as such, has eluded researchers thus far. Now Optotrak analyses of rhythmic hand activity provide the quantitative aspect of the definition lacking in previous studies, and we suggest that use of technology such as Optotrak is imperative in all such future studies. Recall that previous attributions about the existence of manual babbling in hearing babies acquiring *spoken language* relied exclusively on subjective decisions made after looking at videotapes of babies' hands (Meier & Willerman, 1995). But this method alone will not do because use of the Optotrak teaches us that there are crucial quantitative data to be discovered that are not possible to obtain with a videotape alone; it would be like trying to *see* the difference between [p] and [b] on a videotape alone without a speech spectrogram. In moving away from the exclusive use of videotapes, we will remove the confusion caused in the literature by subjective coding procedures, and we will alleviate the confusion over various definitions of manual babbling (see Cormier et al., 1998; Meier & Willerman, 1995). Finally, we will remove speculations about the existence of manual babbling in hearing babies acquiring spoken language because, again, it does not occur both in the way and to the extent that have been claimed (see Meier & Willerman, 1995). That young hearing babies acquiring speech do occasionally hit upon true syllabic *manual* babbles is identical to the phenomenon whereby young deaf babies do occasionally hit upon true syllabic *vocal* babbles (Oller & Eilers, 1988; more below). Some of this overlap is due to accidental production affordances inherent in the respective hand–mouth modalities and, crucially, some of it is wholly predicted by the hypothesis we propose here (as well as in Petitto, 1993, 2000; Petitto & Marentette, 1991).

Why do hearing babies acquiring speech (and no sign) produce some occasional and highly reduced instances of manual babbling-type activity on their hands? Petitto (1993) offered a linguistically-based alternative hypothesis, one which also explains how it is possible that profoundly deaf babies can produce instances of vocal babbling. Drawing from the robust similarities between the phonetic and syllabic content of vocal and manual babbling, Petitto hypothesized that the human brain contains specialization to particular input patterns relevant to aspects of the structure of natural language that is linked to rudimentary motor programs to produce them – but that is not initially linked to a particular modality. If so, it follows that speech and manual movements in young babies are *equipotential* articulators, either of which can be recruited "on-line" in very early development, depending upon the language and modality to which the baby is exposed. It further follows that a baby's "alternative" modality – or the modality in which the baby is not receiving linguistic input – may evidence this equipotentiality in the form of motoric "leakage", whereby it may run off in unsystematic ways relative to the baby's corresponding systematic and patterned productions of babbling. As support for this hypothesis, Petitto and Marentette (1991) found through qualitative analyses that although a small portion of their hearing (non-sign exposed) babies' manual activity was indeed like that of deaf babies' manual babbling, it contained far fewer phonetic units (three as compared to 13 in the deaf babies), with far fewer and less complex syllabic organization (one as opposed to four syllable types in deaf babies). Interestingly, the nature of deaf babies' vocal babbling further supports this hypothesis: in addition to deaf babies' systematic hand babbling, deaf babies also produce syllabic vocal babbling, but, here, their vocal syllables exhibit a very reduced set of consonants and vowels with very little variation in syllabic form (Oller & Eilers, 1988; see also Footnotes 2 and 3).

The Optotrak analyses of the babies' rhythmic manual activity in the present study also showed us that some activity in the hearing babies acquiring speech "appeared" to be manual babble-like, in that it carried the same low-frequency rhythmic signature. But this babble-like activity was unsystematic in linguistic form, as revealed by the application of the babbling criteria to the babies' forms, and was further unprincipled as revealed by the location in space analyses. Thus, the systematic and patterned manual babbling observed only in the sign-exposed hearing babies on the other hand was constrained by linguistic principles, as revealed through the following three powerful defining features: their low-frequency movement cycles, the stringent criteria for attributing babbling status to babies' early forms, and the babies' production of this activity in the obligatory signing space – these features together constitute the best definition of manual babbling by which to judge all other hand activity.

Through the unique lens of an extraordinary population of hearing babies acquiring sign language, we discovered that the rhythmic frequencies of their hands differed depending on whether they were producing linguistic versus non-linguistic activity. Surprisingly, without benefit of the mouth, these hearing babies babbled on their hands. This finding fails to support the hypothesis that human babbling (and hence early human language acquisition) is exclusively determined by the baby's emerging control over the mouth and jaw. Instead, it suggests the hypothesis that the differentiation between linguistic and non-linguistic hand activity could only have resulted if all babies are born with a sensitivity to specific rhythmic patterns at the heart of human language and a capacity to use them. This further led to our proposing a new hypothesis to explain the emergence of early language that most certainly warrants much additional research. We hope to have shown that by investigating the basis of babbling from the perspective of another modality, we can finally begin to discern the relative contribution of biological and environmental factors that together make possible the ontogeny of human language.

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