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The co-development of manual and vocal activity in infants

Holly Meadowsweet Koegler
James Madison University

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The Co-Development of Manual and Vocal Activity in Infants

Holly Meadowsweet Koegler

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Abstract

Manual and vocal actions in humans are coupled throughout the lifespan, from the anticipatory opening of the mouth as the hand moves to meet it in natal development to the more sophisticated co-expressive gesture of the proficient communicator (Iverson & Thelen, 1999). By adulthood, the systems supporting both speech and manual actions of gesture are so wholly integrated that the expression of both actions together is seamless and effortless (Gentilucci & Nicoladis, 2008). Both systems, though controlled by different muscles moving different articulators, exhibit parallels in their development and organization (Meier & Willerman, 1995). The manual control supporting gesture emerges earlier than the vocal control supporting speech (Ejiri & Masataka, 2001), and the actions of the hands and arms may encourage organization and patterns of vocal control (Iverson & Fagan, 2004). No research has yet shown the nature of this manual development in the context of vocal development. This study investigates the emergence and practice of manual configurations during vocal and linguistic development in eight typically developing infants. By observing the manual system only during vocal actions, while the participants progress through babble but before referential word use, this study demonstrates the nature of the development between these systems before being structured by language. These results illustrate the unique coupling of the vocal and motor systems and demonstrate the existence of manual configurations analogous to the practiced vocal patterns that support the development of language.

Introduction

Manual and vocal actions in humans are coupled throughout the lifespan, from the anticipatory opening of the mouth as the hand moves to meet it in natal development to the more sophisticated co-expressive gesture of the proficient communicator (Iverson & Thelen, 1999). Because so many components within an organism are mutually interactive, each contributes a unique set of constraints and properties to the overall expression (Thelen & Smith, 1994). There is mounting evidence to support claims that throughout development the two systems of vocal and manual expression provide support for each other and that development in the manual system may even facilitate linguistic development (e.g., Capone & McGregor, 2004; Gentilucci & Dalla Volta, 2008; Goldin-Meadow, 2009; Goodwyn & Acredolo, 1993; Iverson, Capirci, Volterra, & Goldin-Meadow, 2008). The focus of this study extends beyond the output of the primary expressive modality and observes the manual expressions produced by infants simultaneous to their vocal expressions in early stages of language acquisition.

The expression of gesture in individuals who communicate through spoken language conveys the speaker's intent with efficiency and accuracy (Goldin-Meadow, 2009; Guidetti & Nicoladis, 2008; McNeill, 1992). The cognitive processes supporting communication are equally accessible to vocal and manual expressions and are able to come together in the seamless and effortless integration of speech and gesture in proficient communicators (Guidetti & Nicoladis, 2008; Iverson & Thelen, 1999). These sophisticated and effortless expressions are the product of a history of development among the involved vocal, manual, and cognitive systems (Iverson & Fagan, 2004).
The production of a controlled, voluntary manual movement or gesture acts initially as a

main force of communication (i.e., reaching and pointing) to express an internal cognitive state or to influence the cognitive states of others (Goldin-Meadow, 2009); soon after the gestures are produced with accompanying vocalizations such as grunts and early words (Goldin-Meadow, 2009; Iverson & Fagan, 2004). Through their observations of these early productions, researchers have described infants' dynamic use of manual actions or gestures (Goldin-Meadow, 2009; Iverson et al., 2008). The first gestures at approximately eight months are deictic, or context-bound, and accompanied by vocalizations such as grunts in an act of establishing common attention, rather than specific communication, with another person (Goldin-Meadow, 2009). The expression of gesture as a means of communication becomes apparent after approximately nine months of age, a time at which the hands begin to take on the representational capacity later expressed in speech (McNeill, 1992). The first gestures accompanied specifically by speech emerge some time after the child is able to produce at least one word, generally around ten to 12 months of age. These particular gestures are redundant to the accompanying vocalization (or in this case, word), often naming an object while pointing to or reaching for it (Goldin-Meadow, 2009). Gestures later are produced accompanying a supplementary vocal message, such as in asking and pointing (i.e., gesturing rather than naming and then conveying the force of the message through a word). Iverson et al.'s (2008) observations of gestural productions of children between 10 months and 24 months of age suggest that gestures may provide a means for the child to begin integrating multiple pieces of information into a communicative output and may later begin to use appropriate words in place of the gestures. These manual actions appear to be the forerunners of more sophisticated linguistic expression, providing a means of communication when spoken language is yet unable to carry the full burden of the message and allowing for the combination of multiple pieces of communicative information (Capone & McGregor, 2004; Goldin-Meadow, 2009; Goodwyn & Acredolo, 1993). All of the uses of gesture leading to these combined communicative messages support their production, and the supplementary gestures themselves are an individual's first foray into the highly coordinated speech-associated gestures of adulthood (Goldin-Meadow, 2009; Iverson et al., 2008; McNeill, 1992).

The early gestures themselves serve important functions beyond the role of supporting speech, acting also to capture and maintain adult attention (Capone & McGregor, 2004; Iverson et al., 2008). These gestural actions elicit communication from adults, who provide longer, slower, and/or more specific utterances, consequently affording the child essential opportunities for language-learning. In dyadic caregiver-child interactions, the expression of gestures with words influences the linguistic input the child receives. Adults provide descriptions and commentaries of the action or situation, providing important linguistic information that acts to encourage the child to create more mature expressions of two-word combinations (Iverson et al, 2008). These combinations in early communication, at around fourteen to 16 months, have been shown to be significantly related to or predictive of vocal production at 20 months (Capone & McGregor, 2004) and of vocabulary at 42 months (Guidetti & Nicoladis, 2008).

This representational use of gesture with vocalization may influence language beyond increasing the individual's awareness of and capacity for abstract representation. The coactivation of both the vocal and manual systems may also provide opportunities for mutual motoric influence and help to strengthen the link between both systems

(Goldin-Meadow, 2009; Iverson & Fagan, 2004; McNeill, 1992). The gestures infants use in these early communications, such as points, reaches, etc., are the products of the environment and infants' experiences with objects. Exploration of the environment allows the hands to receive the tactile qualities available in the world, and the memory or representation of physical experience is stored as motor knowledge (Gentilucci & Dalla Volta, 2008; Fogassi & Ferrari, 2008). Sensorimotor schemes of interaction with objects and people may gradually evolve into communicative symbols, through this obtention of an adult's attention and recruiting of the motor or tactile knowledge associated with an object that is not immediately present (Capone & McGregor, 2004). Gentilucci, Dalla Volta & Gianelli (2008) suggest that as infants are developing a lexicon, the tactile qualities experienced in environmental exploration are stored with the entire representation of an object; when its phonetic form is retrieved, so too is the tactile information of the object. The manual actions of gesture may help support the retrieval or activation of a particular phonetic form at will by activating the mutual motor commands for the representation (McNeill, 1992; Gentilucci, Dalla Volta & Gianelli, 2008).

Action's role in cognitive expansion continues throughout development (Raikson & Woodward, 2008) and contributes to more than simply the ability to express ideas beyond the spoken message. The actions of communicative expression through gestures, both redundant and supplemental, emerge near the same age as word comprehension (Guidetti & Nicoladis, 2008; Goldin-Meadow, 2009) and attentional reorganization resulting from expanded mobility (Raikson & Woodward, 2008). That is, as the child is able to move with more freedom and direction throughout the environment, different aspects of it become more salient to the child, and attention is directed to or captured by new objects and experiences, soon reorganized to accommodate the awareness of these new features. The child's interaction with the environment changes, leading to different and expanded knowledge (Raikson & Woodward, 2008; Thelen & Smith, 1994). In gestures, the actions not only create the opportunity for language learning as the child engages with an adult, but they also signal great cognitive advances and expanded capacities for expression. The infant is able to both recall and represent actions and objects salient in the environment, necessary precursors to the capacity for language use (Capone & McGregor, 2004; Goldin-Meadow, 2009). The development of the skills of both vocal and manual expression, and the expression of both together, allow for the creative output of language production. The skills supporting these outputs gain control and purpose throughout early development through exploratory action and become such a useful means of communication that they may appear to be entirely linguistic (Iverson & Fagan, 2004; Iverson & Thelen, 1999; Petitto, Holowka, Sergi, Levy & Ostry, 2004), but this evidence indicates that rather than appearing or emerging as an isolated novel behavior, symbol use and language production emerge out of new combinations of basic skills.

The basic skills of vocal expression are in part the product of control emergent in early infancy, explored and expanded through the production of babble (McCune & Vihman, 2001). This behavior is a stereotypic cyclic oscillation, or a rhythmically organized behavior typical of immature motor systems and observable across typically developing children of approximately the same developmental age. The earliest productions of babble are dominated by gross mandibular movement and exhibit very little differentiation in articulatory configurations. Through action and practice, the articulators of the mandible, tongue, lips, and velum gain more independent control and may be volitionally directed to varied configurations. The gaining of independent and finer control over the movements, as well as feedback from the actions and from other people in the environment, allows and encourages the creation of more distinct, discrete, functional, and eventually more mature vocal outputs. This development of control over the behavior of the vocal system is a necessary precursor to the production of first words and skillful communicative expressions (Davis & MacNeilage, 1995; McCune & Vihman, 2001).

The vocal-motor system is not unique in its exhibition of stereotypic cyclic oscillatory patterns. The motor systems controlling arm and leg movements provide especially visible examples of rhythmic oscillations during emergent control. Both of these systems display this rhythmic organization around the same time as the emergence of babble, and during this rhythmic period the actions allow the infant explore functional patterns of control (Ejiri & Masataka, 2001). The actions of the manual system are of particular interest, not only because the practice of manual action supports the development of speech-associated gestures and consequently language, but also because rhythmic manual actions become more highly associated and often produced with rhythmic vocal actions (Iverson & Fagan, 2004; Iverson & Thelen, 1999).

Parallels in the rhythmic action of the vocal and manual motor systems have been reported in several studies (e.g., Ejiri & Masataka, 2001; Goldin-Meadow, 2009; Iverson et al., 2008; Iverson & Fagan, 2004; Iverson & Thelen, 1999; Petitto et al, 2004; Willems, Ozyurek & Hagoort, 2007). The co-occurring production of rhythmic activity in both systems (such as produced by infants engaged in bouts of babbling while simultaneously shaking a rattle or banging a toy on a tabletop) may be the expression or product of high levels of excitement or activity combined with low or underdeveloped motoric control (Iverson & Fagan, 2004; Iverson, Hall, Nickel & Wozniak, 2007; Iverson & Thelen, 1999). Iverson & Fagan's (2004) observations of the coordination between vocal and manual rhythmic movements in infants aged six to nine months indicate that the systems are linked in a mutually influential capacity by seven months. The manual system described here refers to the proximally controlled arm and shoulder rather than the somewhat more distal hand and digital articulators. The actions of this manual oscillation influence the motor output of the oscillating vocal system to varying degrees, such that the vocalizations accompanied by rhythmic limb (or specifically, manual) are produced in an according rhythmic pattern. The rhythmic synchrony may range from a tight and temporally matched coordinated production to an overlap of some action in the vocal system while the arm is moving rhythmically. This entrainment allows the manual motor system, practiced in motor control beginning as early as 5 ½ months of age (Ejiri & Masataka, 2001), to encourage and organize the behavior of the complementary or coupled vocal motor system as it develops motor control (Iverson & Fagan, 2004). As both systems are still exploring patterns of control and because they are closely linked in production and function throughout development, the self-organizational nature of these active, dynamic motor systems likely allows them to draw each other into similar, stable, functional configurations.

An underlying explanation for the close relationship of the systems and their self-organization may be the adjacency of their neural control in the left inferior frontal cortex, specifically in the regions associated with Brodmann's area 45 or Broca's area (Iverson & Thelen, 1999; Capone & McGregor, 2004; Gentilucci & Bernardis, 2006; Iverson et al., 2007; Fogassi & Ferrari, 2007; Skipper et al., 2007; Willems et al., 2007). Theories of entrainment (Iverson & Fagan, 2004), based on the behaviors of dynamic systems (Iverson & Thelen, 1999; Thelen & Smith, 1994), suggest that during development this neural proximity encourages self-organization of control to influence both of the linked systems of vocal and manual action. The systems' exploration of patterns of activation and control may be such that neural activity in one system may expand and instigate similar patterns of action in the adjacent region. That is, when one system is sufficiently active or excited, the activation spreads; the linked system, also under immature control, is easily drawn into the similar pattern of initiated action (Iverson & Fagan, 2004). As these systems develop a history of action and control, stable states emerge and begin to mutually constrain the actions of both systems (Iverson & Thelen, 1999; Thelen & Smith, 1994).

The stable states of control over the vocal system have been briefly described in the emergence and development of skillful and distinct vocal expressions and communicative expressions. Given the importance of gesture to the development of language, it is important to also examine the accounts of the emergence of the basic manual skills that act as the stable attractor in entrainment and that support skillful and distinct gestural communication. Evidence suggests that coordination of the components of the manual system – that is, the arms, hands, and fingers – is fairly stable and controlled by the time vocal control is developed for word production (Iverson & Thelen, 1999; Capirci, Iverson, Montanari, & Volterra, 2002), through practice in environmental exploration and the use of the hands for functional grasping (Bernardis, Bello, Pettenati, Stefanini & Gentilucci, 2008; Boyes Braem, 1990; Wallace & Whishaw, 2003).

Wallace & Whishaw's (2003) observations of infants' spontaneous manual movements in the first 5 months of life show a progression of gross-to-fine control over the hand and digital articulators. The infants' movements showed a reliable developmental progression through four general configurations, from vacuous whole-hand movements with little to no digital differentiation, to pre-precision grips with the thumb meeting the side of the index finger, to finer precision grips, to self-directed grasp patterns involving all of the digits closing around a stimulus associated with the infant's body, such as clothing. While these observed behaviors, with the exception of the self-directed grasps, did not involve actual grasping of objects in the hands, they do appear to be predecessors of the movements exhibited by older infants. Further, as Wallace & Whishaw suggest, these manual movements appear to be associated with the vocalizations preceding babble in their exploratory nature and the elimination of non-functional configurations.

The progressive mastery of control over the hands and digital articulators is further illustrated in Boyes Braem's (1990) observation and description of the stages of handshape acquisition in typically developing infants. She observed the development of spontaneous, adaptive handshapes produced by infants in terms of the shapes of American Sign Language (ASL) and described the anatomical constraints driving their emergence. Throughout the development of early, functional, directed control between approximately eight to 12 months of age, Boyes Braem reported "what may be called a proximal-distal shift" (p. 111). The earlier handshapes, her "Stage I" (extending from approximately eight to 12 months of age), begin as largely whole-hand shapes; that is, there is little differentiation between the digits in their movement and manipulations of objects. Before eight months of age, the handshapes produced in grasps appear to be bound largely by the configuration of the "ulnar group", or the middle, ring, and little fingers: the A handshape of ASL. Then, at approximately eight months of age, control over the "radial digits", or index finger and thumb, emerges and infants are able to create finer pincer grasps or points; these configurations are analogous to the G or L handshapes of ASL. The handshapes produced within this period of eight to 12 months do not differentiate much: she reports the additional mastery of the baby-O (bO, a somewhat flattened version of the O handshape with the ular group closed, produced in a pincer grasp), C, and 5 handshapes. It is reported that these Stage I shapes are mastered by "all children, no matter what language they are exposed to" (p. 112). The next stage of handshapes, explored and mastered between 12 months and "the hearing child's age of initial language acquisition" (p. 112) still involve the ulnar group acting as a whole. The Stage II handshapes (B, F, and O), though not used as often, are still shapes produced in environmental exploration and without any structured modeling or ASL linguistic input.

Bernardis et al.'s (2008) investigation of the influence of the manual actions of grasping and object manipulation during vocalizations of preverbal infants suggests that infants' manual activities are most important to language development between eight and 14 months of age; that is, between the emergence of control over the vocal system and the onset of verbal production. In their vocal and manual actions, the infants studied demonstrated reliably similar and concurrent articulatory changes in both systems. Bernardis and colleagues speculate that the motor commands for manual manipulation spread to activate and organize a parallel command to the vocal system. Taken with the parallels in emergent control and rhythmic action described earlier, it appears that the systems exert influence over each other as they self-organize and develop voluntary control. It has been suggested that the early actions of the manual system and its articulators may be functionally comparable to vocal babble, both in gross to fine development and in the adoption of useful movements through practice and elimination of ineffective action, much like the progression of vocal skills in babble (Wallace & Whishaw, 2003; Petitto et al., 2004). Though these systems are controlled by different muscles moving different articulators, they exhibit parallels in their development and organization (Meier & Willerman, 1995).

The early and continued evidence and evolution of the links between these systems not only suggests that the combined action of the vocal/oral and manual systems serves an important linguistic function, but also that they are mutually influential: development in one system may very likely have profound effects on its linked partner. From the evidence of such parallels as have been described, the development of the manual and vocal systems during mutual activation likely display patterns that contribute to later skill in both systems separately and the continued strength of the coupling between them. The possibility has been suggested that both modalities are equipotentially available for linguistically structured output, especially if oral and manual activities have equal access to cognition (Iverson & Thelen, 1999). The activities of these systems, as they both gain finer control and break free of their rhythmic organization but before they are structured by the ambient language, should show parallel patterns of gross-to-fine configurations as the individuals each settle into functional patterns of both manual and vocal actions. Given that there are general early parallels and that the systems remain importantly and differently liked throughout the lifespan (Goldin-Meadow, 2009; Iverson & Thelen, 1999; Thelen & Smith, 1994), investigation of the early influence the systems have on each other would likely provide important evidence of the nature of the early coupling and later development of language. However, no research has yet observed the influence these systems may have on each other in their mutual development.

The focus of this study extends beyond the development of the primary expressive modality of speech and observes the manual expressions produced by infants simultaneous to their vocal expressions in early stages of language acquisition. The infants reported here were chosen out of a larger investigation of the vocal development supporting language production, followed from the early production of babble at approximately nine months of age, to an age of approximately 18 months. The observations occurred once weekly, beginning at approximately nine months, until they produced two stable consonant forms. After it was determined that they had developed two stable states of control or stable, repeatable vocal configurations, the participants were then observed once monthly they had reached 18 months of age. The eight infants selected for the present study were observed to the development of two stable, repeatable vocal configurations or “vocal-motor schemes” (McCune & Vihman, 2001).

By observing infants after the onset of babble but before word production, the window of observation frames the period of development where the actions are emerging and exploring stability but are not yet bound by the structure of the ambient language. This study asks if, during mutual activation and in the exploration of functional configurations, the action of each system exerts action and configuration constraints on the other. Do both systems exhibit mutual activation? Since the vocalizations have been established for these participants, do the observed manual actions produced during vocalizations exhibit corresponding preferences? That is, are there manual actions that correspond to the stable vocal configurations? Does the pattern of stability in the configurations produced by the vocal system correspond or relate to patterns of stability in the configurations of the manual system? If , as we expect, these two linked systems do entrain and influence each other in these similar ways across participants, does this indicate the existence of a “manual-motor scheme”, analogous to the “vocal-motor scheme” (McCune & Vihman, 2001) produced by infants? The observation of infants during known or established vocalizations that become their own particular VMS will allow us to compare the emergent manual actions to the pre-established or pre-observed vocal actions and to suggest similar development across infants.

Methods

The current study is based on data collected from an investigation of language development conducted by the University of York Infant and Toddler Language Studies laboratory. Researchers observed vocal development in 59 typically developing infants, beginning at approximately nine months of age and continuing until 18 months of age. The study aimed to explore developing oral motor control and its influence on an individual's production of the sounds of the language environment. Infants were observed and recorded in the home while involved in play with age-appropriate, familiar materials already present in the environment, with a primary caregiver present and interacting with the child. At 10 months of age the infants were observed and recorded in naturalistic play in a laboratory setting for one session. Infants wore a vest containing a hidden microphone to record vocalizations. Each session was 30 minutes in length, and occurred once a week until the infant developed two stable consonant forms, or "vocal-motor schemes" (VMS) (McCune & Vihman, 2001). The sessions after the two VMS point occurred once a month until the infant reached 18 months of age.

The vocalizations of these sessions were transcribed in IPA format by research assistants at the University of York, using ELAN (EUDICO Linguistic Annotator) software. These transcriptions were used to determine consonants meeting the criteria for threshold for VMS, measured by a participant's repeated production of a given consonant at least 10 times in three of four weekly sessions (McCune & Vihman, 2001).

The participants reported here serve to provide a foundation for research in progress on the comparison of vocal and manual development of infants who are and are not exposed to a manual system of communication. Observations of one child led to questions about participants' exposure to sign language or the popular "baby sign" method of manual communication. Consequently, two groups of children were identified: those whose mothers reported using "baby sign" and those whose mothers reported no sign experience. The eight children reported here had no exposure to any structured manual communication or sign language.

In addition, since the University of York study was ongoing when this study began, the selection of participants was also constrained by the availability of data on individual infants. Finally, only infants whose parents had given permission for their data to be used outside of the UK were included in this study

Participants

Data for the current investigation were collected from the videotaped sessions of eight typically developing infants selected from the aforementioned study. The selection of these participants was constrained by the availability of complete data on individual infants, since the University of York study was ongoing when the current investigation began. Additionally, only those infants whose parents had given permission for their data to be used outside the United Kingdom were included in the selection. The eight selected participants were observed from the beginning of the study, at approximately nine months of age, to the point at which they were determined to be producing two stable VMS. Of these eight participants four were female and four were male. A more detailed profile of the participants' ages and milestones is shown in Table 1.

Transcriptions

Sessions were transcribed for manual categories using ELAN (EUDICO Linguistic Annotator) software. The sessions had been previously transcribed for vocalizations by researchers in the aforementioned study. We observed the video and transcribed our own categories only during these transcribed vocalizations. Our transcriptions were based on two general categories, handshape and activity, and each category was transcribed separately for both the right and left hand.

Handshape.

The transcriptions of the participants' manual configurations were based on the handshapes and allochers of American Sign Language (Stokoe, Casterline & Cronenberg, 1976). These allochers, much like allophones in speech, are handshapes that are considered to be so minimally contrasting that an untrained infant would not be able to control for the differences and so are treated as the same handshape (e.g., the thumb position in the A hand versus the S hand, and the ulnar group position or configuration in the D hand versus the G hand differ so minimally that an infant still developing control and untrained in producing specific and contrasting configurations would be unlikely to produce them differentially).

If the handshape(s) changed throughout the utterance, they were transcribed as such. For example, if the participant waved during a transcribed utterance, the configuration usually changed from a "5-hand" to an "A-hand" and back to a "5-hand" and "A-hand" again. In this instance, the handshape would have been transcribed as "5-A-5-A-hand".

Any shapes produced by coarticulation or transition between gross configurations that may have been visible in a frame-by-frame analysis were eliminated. A full list of the handshapes (as well as the vocalizations) is listed in Table 2.

Activity.

As the infants' motor systems remain under fairly immature control, it is expected that activity throughout the entire manual system, not simply the hand in isolation, provides opportunities for mutual motoric influence and a stronger link between both systems (e.g., Ejiri & Masataka, 2001; Gentilucci & Dalla Volta, 2008; Goldin-Meadow, 2009; Iverson & Fagan, 2004; McNeill, 1992). Activity was transcribed as present or absent based on the observation or lack of movement along the entire limb, from the shoulder to the fingertips of the hand in observation. If at any point during the utterance the handshape was considered active, the entire utterance was marked as active. That is, activity at any point during the utterance was marked active overall; a hand could only be active or inactive within an utterance.

Exclusions of categories.

In many cases, not all of these categories were visible or determinable as a consequence of the oral and vocal focus of the study and video recording. If any category was indeterminable, i.e., if one of the hands was not visible or the handshape was not discernable, none of the categories were transcribed and the entire utterance was marked accordingly with a shorthand description of why it was not included. Specific criteria determined when the categories were eliminated from analysis. The most frequent reasons for exclusion were:

- Hands not visible: if both hands were not observable during the utterance, from either being out of view (not in the camera's shot or obscured by an object) or from an inability to discern the configuration (out of focus or unable to determine the location or configuration of all of the fingers),

- Support hands: if either of the hands were used to support balance, such as in crawling or "posting" for balance by touch or grasp on walls, sturdy objects, or furniture, and/or
- Hands in mother's: if hands were holding or held by another individual's hands.

If any of these criteria applied to the utterance, all categories were eliminated from analysis for that utterance. For example, if only one hand was visible or one handshape discernable, the "handshape" category was marked "hands not visible" and no other categories were transcribed for that utterance, regardless of whether the other hand was visible or action could be determined.

Reliability.

The data for analysis for the current study were collected at James Madison University's Infant and Toddler Language Laboratory. Three first year master's students in the Department of Communication Sciences and Disorders began coding this data in the fall of 2008 and established guidelines through several sessions of training. Reliability was checked by all researchers each coding several sessions of two participants and comparing the transcriptions. If a discrepancy was noted, it was re-coded to agreement of at least two out of the researchers' transcriptions. Overall reliability for the research in 2008-2009 was 80% agreement for handshape, 85% agreement for presence or absence of activity, and 100% for right versus left hand. Two researchers left the project and one remained to train one new first year master's student at James Madison University and two at Gallaudet University in fall 2009.

In spring 2010, all four researchers were convened for a "reliability check." A new videotape was viewed by the four coders and one of the principal investigators. Agreement across the five coders was calculated at 100% agreement for right versus left hand, 83.3% agreement for handshapes, and 78% for the presence or absence of manual activity during vocalization. All researchers worked to re-establish criteria for determining the presence or absence of manual activity and reviewed and discussed discrepancies; by the end of the training session reliability was accepted at no less than 80% for presence or absence of manual activity and remained no less than 80% for handshape, and 100% for right versus left hand.

Table 1

Profile of Participant Milestones

Subject	Age at VMS 1 (year;month.day)	Session number of VMS 1	Age at VMS 2	Session number of VMS 2 (year;month.day)
Beatrice	0;9.19	2	0;10.3	4
Calvin	0;10.17	7	0;11.06	10
Henry	0;9.29	4	0;10.6	5
John	0;9.12	2	0;10.25	7
Leila	0;9.22	3	0;9.22	3
Rachel	0;9.10	2	0;9.10	2
Rosie	0;9.21	3	0;10.12	6
Simon	0;10.20	4	0;11.14	5

Table 2

Consonants and Handshapes

VMS Consonants	Consonants below VMS threshold	Potential MMS Handshapes	Handshapes below Potential MMS threshold
t/d	ð/θ	5	L
p/b	β	C	3
k/g	ʃ/Ʒ	A	Y
m	ʧ/ʤ	B	X
n	w	O	W
l	r	D/G	I
ŋ	j	E	
s	f/v	F	
	ɹ	V	
	B		

Results

Transcribed vocal utterances were tallied for all consonants produced within a session by researchers at the University of York. Transcribed manual categories were tallied for each session. Data for right and left hands were tallied separately. Individual or discrete handshapes were tallied; handshapes that were in a sequence of handshapes were tallied for the individual productions, so every instance of a particular handshape was totaled for each session.

To determine whether both systems were mutually active, manual activity was calculated as the percentage of transcribed manual actions wherein at least one of the hands was considered active, measured from shoulder to fingertips, out of the total number of transcribed manual actions. This was calculated for each participant and for all participants (Beatrice = 97.4%; Calvin = 88.6%; Henry = 100%; John = 98%; Leila = 97.4%; Rachel = 100%; Rosie = 100%; Simon = 95.5%; Total = 97.4%). See Figure 1 for the distribution.

Many consonants and handshapes were produced by all participants, but not all participants produced all of the possible observed consonants and handshapes across all of their sessions. The total possible handshape types produced by all participants was slightly lower (*n* = 14) than the total possible consonant types produced by all participants (*n* = 19). However, a large portion of these vocal and manual configurations were not produced by all participants. Eleven of the possible consonants were not produced in any sessions by three of the participants; the other five participants never produced them with enough stability or repetition to reach threshold for VMS (as determined for the original study by research assistants at the University of York) within the observation period, and so these consonants were eliminated from analysis. The consonants and handshapes eliminated are indicated in Table 2.

With no established repeatability criteria for handshape production, we determined that four of the handshapes could be eliminated from analysis on the basis that they accounted for less than 1% of the handshapes for those participants that produced those handshapes and that they accounted for less than 2% of the total production of handshapes.

No significant difference was found between the number of handshapes produced on the right hand compared to the left hand ($t(63) = 0.427$, $p = 0.671$). Consequently, data from the right and left hands was combined for these analyses.

Given the variability of the participants' overall vocal and manual activity across sessions, it was more informative to analyze the collected vocal and manual data in terms of percentages or proportions within and across sessions. Participant's proportions of production of consonants and proportions for handshapes were calculated within and across all sessions. Proportions were also calculated for all participants by summing the total productions of each consonant, and then of each handshape, then divided by the total number of productions for all participants to give descriptive numbers that were ranked based on overall preference. The overall/total proportions of production for consonants and for handshapes can be seen in Figures 2 and 3. See Appendix A for plots of individual preferences.

Each individual participant's configurations were compared to the preferred manual configurations across all sessions to determine whether the consonants and handshapes maintained similar patterns of production throughout this period of observation. These comparisons revealed significant correlations between the preferred consonants and handshapes over time for each participant (Beatrice: $r = 0.797$, $p < 0.001$; Calvin: $r = 0.356$, $p = 0.007$; Henry: $r = 0.707$, $p < 0.001$; John: $r = 0.454$, $p < 0.001$; Leila $r = 0.547$, $p = 0.006$; Rachel: $r = 0.856$, $p < 0.001$; Rosie: $r = 0.725$, $p < 0.001$; Simon: $r = 0.437$, $p = 0.005$).

A multidimensional scaling (MDS) technique was used to determine if the participants' configurations exhibited an underlying pattern in production or preference. The MDS program, run through MatLab, measures "distance" or difference in production, through an iterative least squares technique, between all possible comparisons of the data and presents each point, or configuration, in a "group stimulus space" that best fits all of the data. The group stimulus space is a geometrical representation of the differences in production, such that the distances between points in the output are proportional to the differences in production preferences (Gray, 1997).

By taking the percentages of consonant and handshape production for all participants over all sessions and inputting them to MDS, a map was created representing the patterns in preference and production for all participants. The map in Figure 4 is a plot of the points representing the consonant preferences for all participants; Figure 5 is a map of handshape preferences for all participants over all sessions; Figure 6 is a map of both consonant and handshape preferences for all participants over all sessions. The squares in these maps represent the configurations of the vocal and/or manual system, and the circles represent the participants. The ellipses surrounding each participant represent the participant's expanding development across the mapped data points and may be envisioned in ripples of expanding development. The orientation of the ellipses in relation to the data points indicate the particular participant's individual development such that when the ellipse is expanded, it reaches the data point(s) corresponding to the participant's highest preferred configuration first and continues to the next preferred or next-often produced configuration, and so forth. The arrangement of the data points consequently indicates those configurations which, over time, are important to all participants.

All points in these maps are arranged with respect to every other data point, or configuration preference, and to every participant, such that each map provides the best fit and best geometric representation of the data. MDS provides a measure of correlation between the input data and corresponding distribution between the mapped points as an r – value (Figure 4 $r = 0.87782$, $p < 0.01$; Figure 5 $r = 0.9652$, $p < 0.01$; Figure 6: $r = 0.86571$, $p < 0.01$). The r – value can be used to determine how well this data fit the output map, as an r^2 – value (Figure 4 = 0.7706; Figure 5 = 0.9316; Figure 6: $r^2 = 0.7495$). The pattern of the map for consonant preference (Figure 4) accounts for approximately 77% of the variation of the data; the pattern of the map for handshape preference (Figure 5) accounts for approximately 93% of the variation of the data; the pattern of the map for consonant and handshape preference (Figure 6) accounts for approximately 75% of the data.

To determine whether the participants were producing a wide range of consonants or handshapes within a session or whether they were producing a large portion of a single consonant or handshape within a session, H-prime (H\`) values were calculated for consonants and for handshapes each participant for each session. $H$\`, or Shannon's index, is calculated as:

$$H` = -\sum_{i} p_i \, log_e(p_i)$$

where p_i is the percentage of the category i of either consonant or handshape produced by a subject. This was calculated for each session for each subject as a measure of homogeneity or diversity within the “signal,” or vocal or manual output (Gray, 1979; Shannon & Weaver, 1964). The range of results varies between zero and $log_e(i)$, where i is the number of categories between a minimum of 0 and a maximum of 2.0794. The higher the $H`$ value within this range, the greater the diversity of the signal; that is, higher $H`$ values indicate a greater variety or diversity in the types of consonants or handshapes produced. Lower $H`$ values indicate a greater preference for a single category (a particular consonant or handshape) and little to no variance or diversity.

The calculated $H`$ values were then plotted together and marked with confirmed VMS sessions to illustrate preferences and infer stability over time. The plots of $H`$ tended to parallel each other over time, to trade off over time, or to trade off at VMS 1 and parallel by VMS 2. The implications of the patterns will be discussed in the next chapter. The most illustrative examples of the different patterns of $H`$ are shown in Figures 7-9.

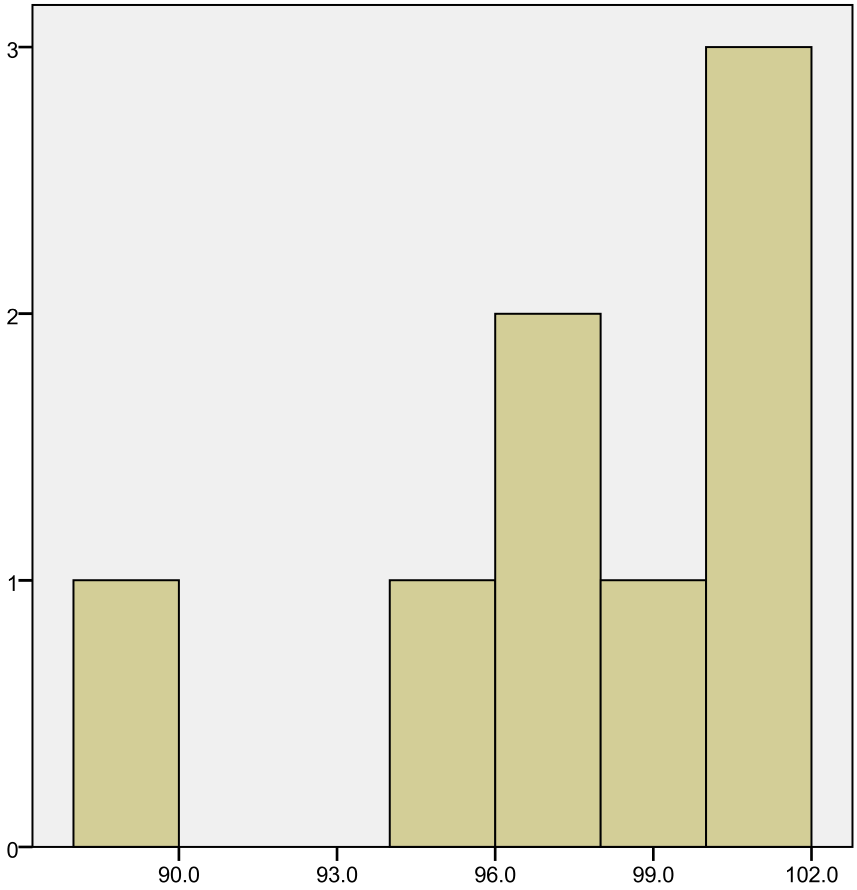

Figure 1: Distribution of activity (%) across all participants

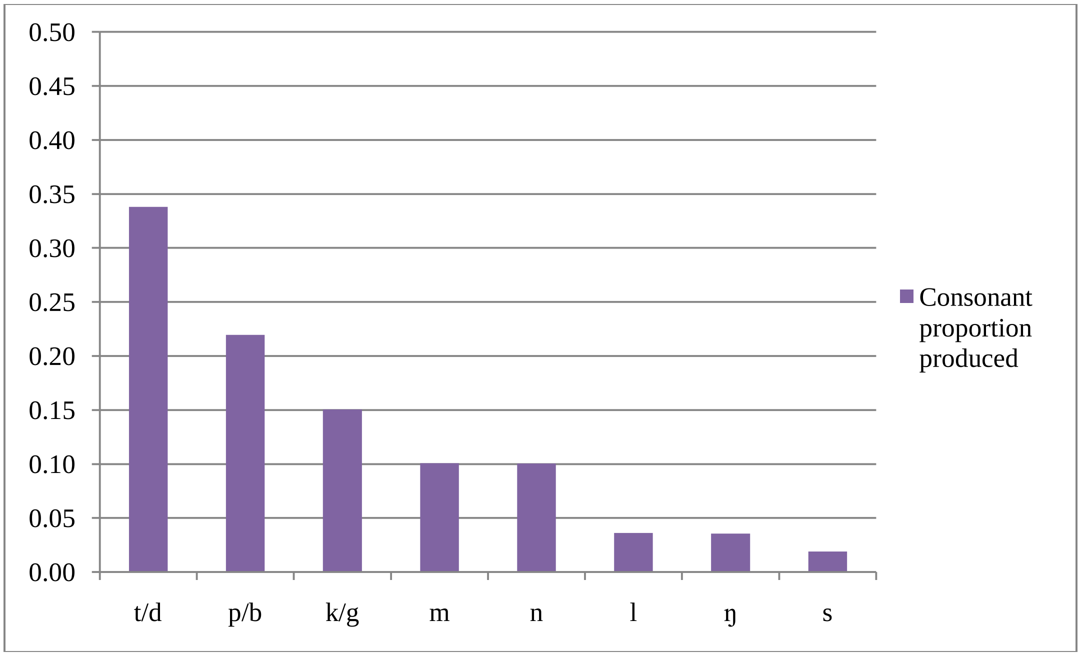

Figure 2: Total consonant proportions for all participants

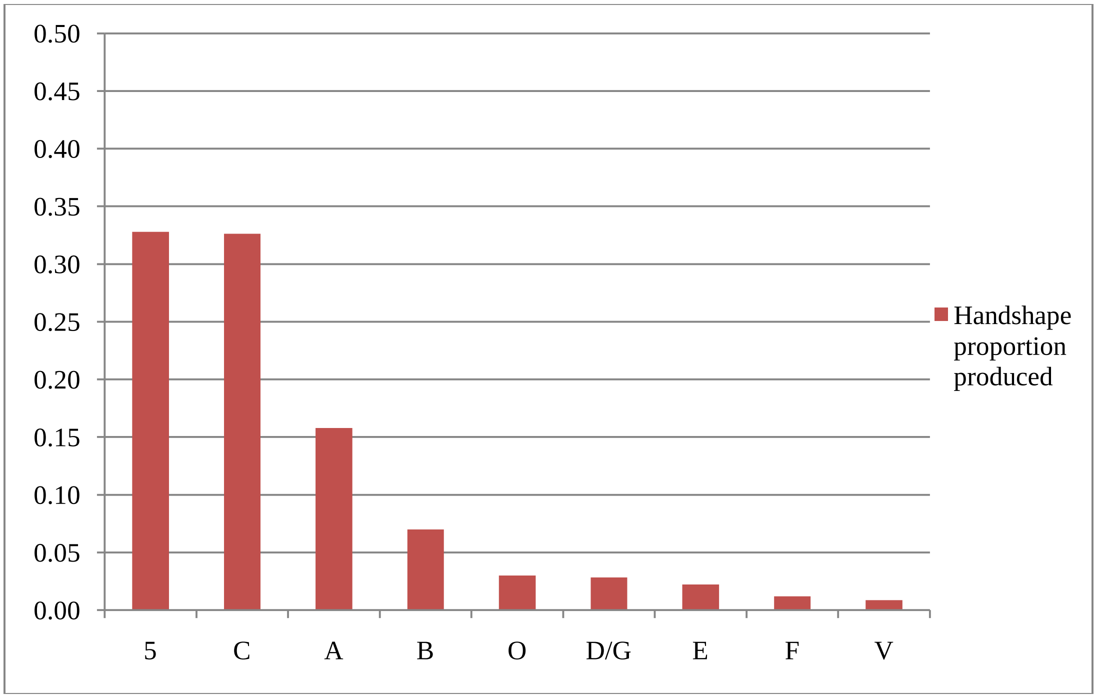

Figure 3: Total handshape proportions for all participants

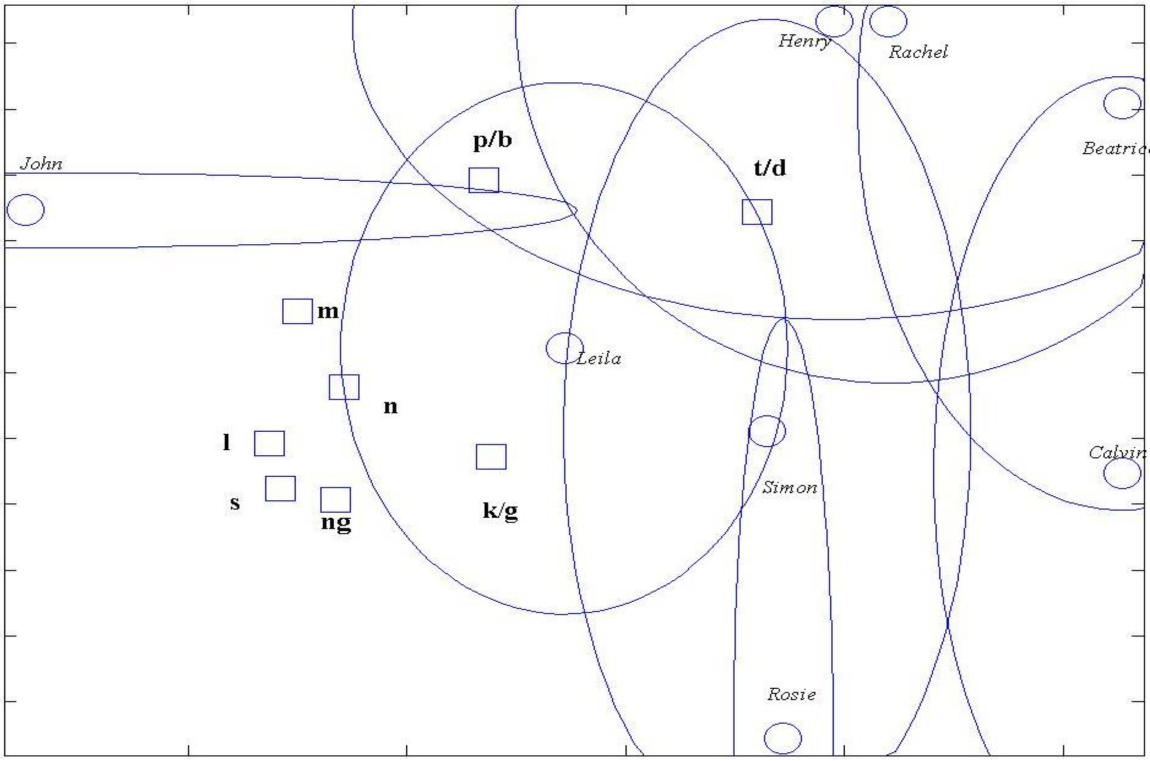

Figure 4: MDS map of consonant preferences for all participants

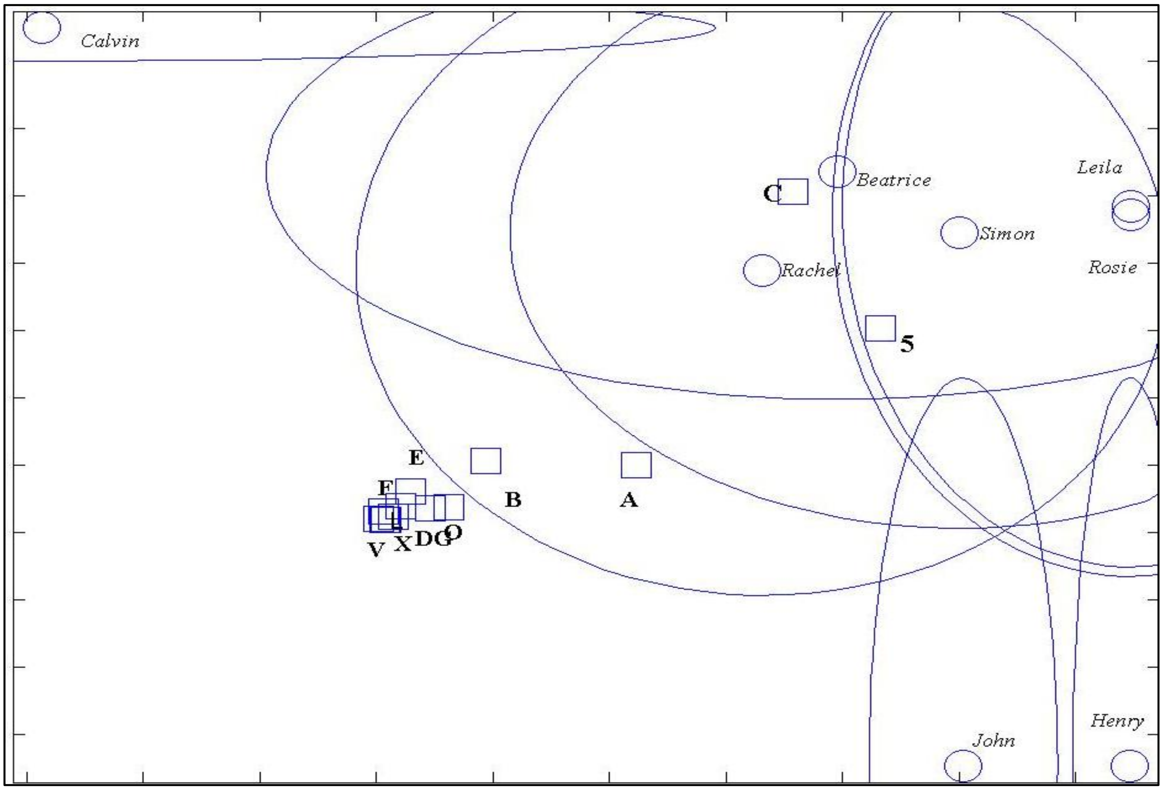

Figure 5: MDS map of handshape preference for all participants

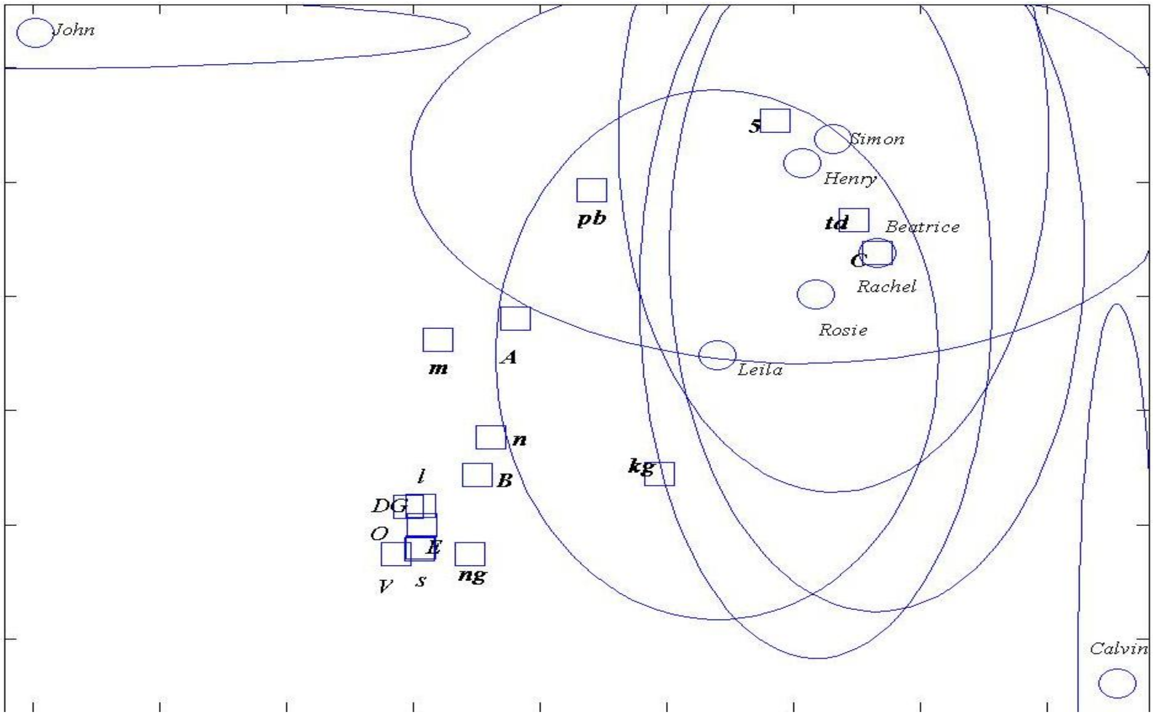

Figure 6 MDS map of consonant and handshape preference for all participants:

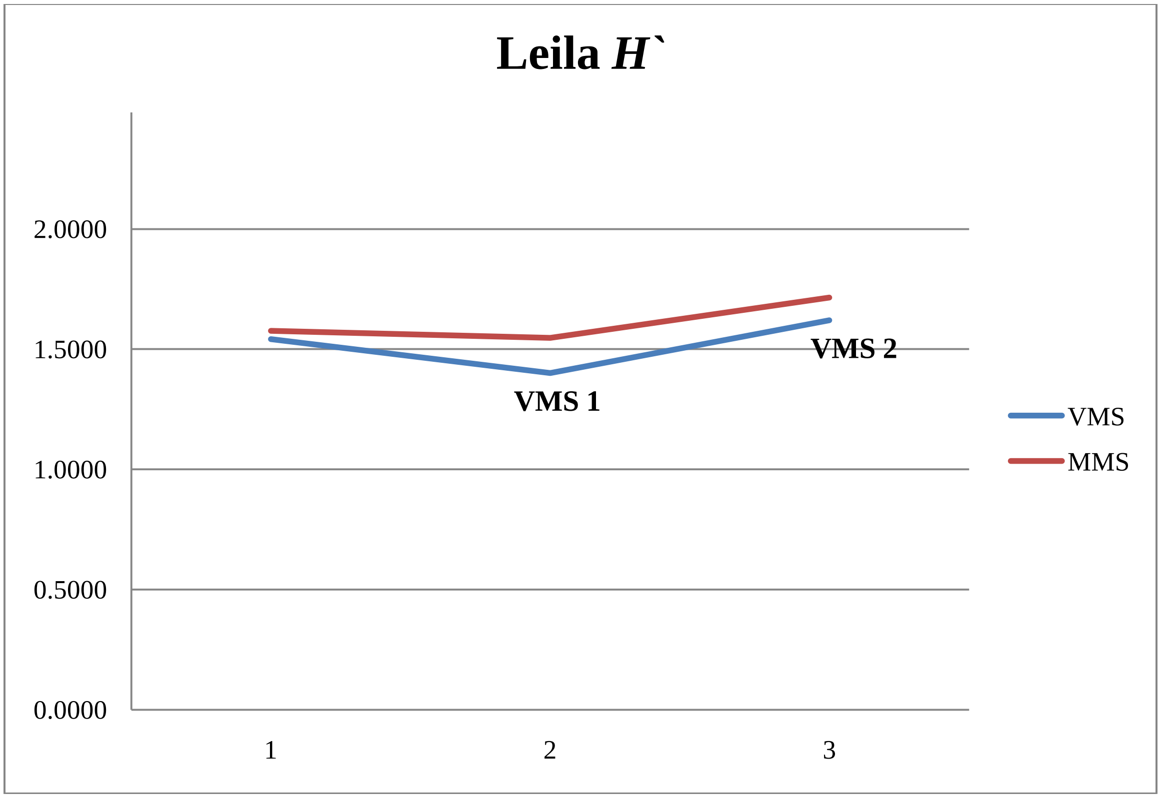

Figure 7: Parallel homogeneity and diversity of consonant and handshape preference

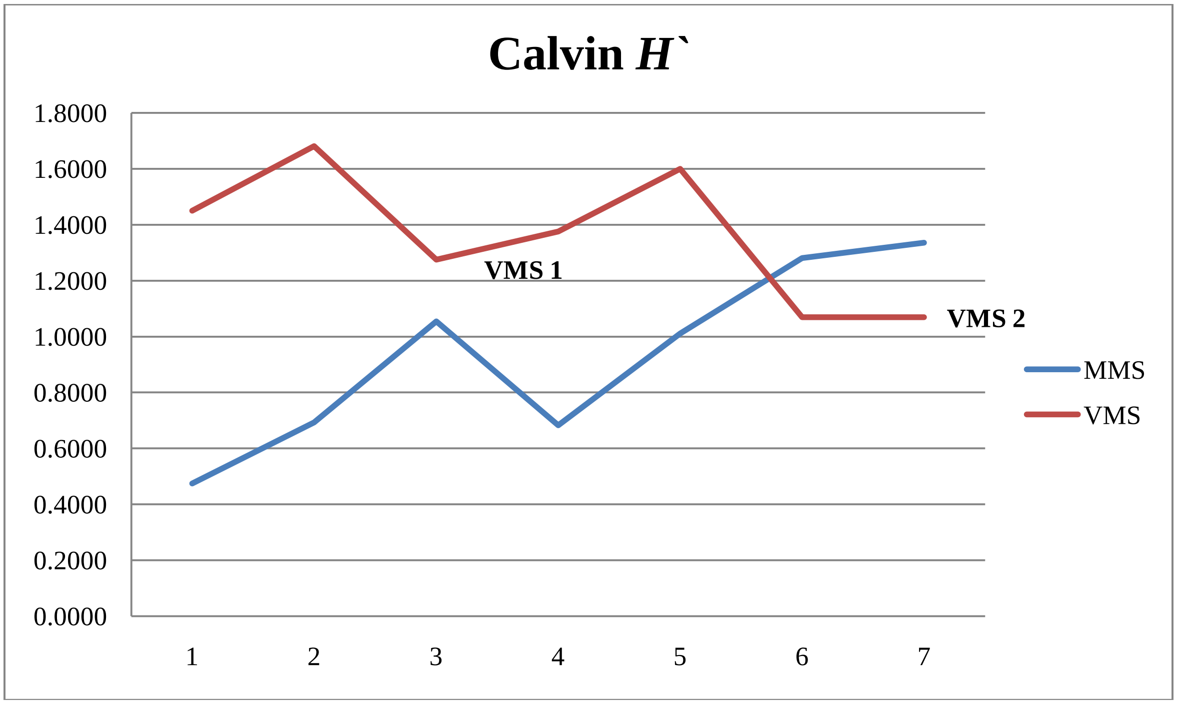

Figure 8: Alternating homogeneity and diversity of consonant and handshape preference

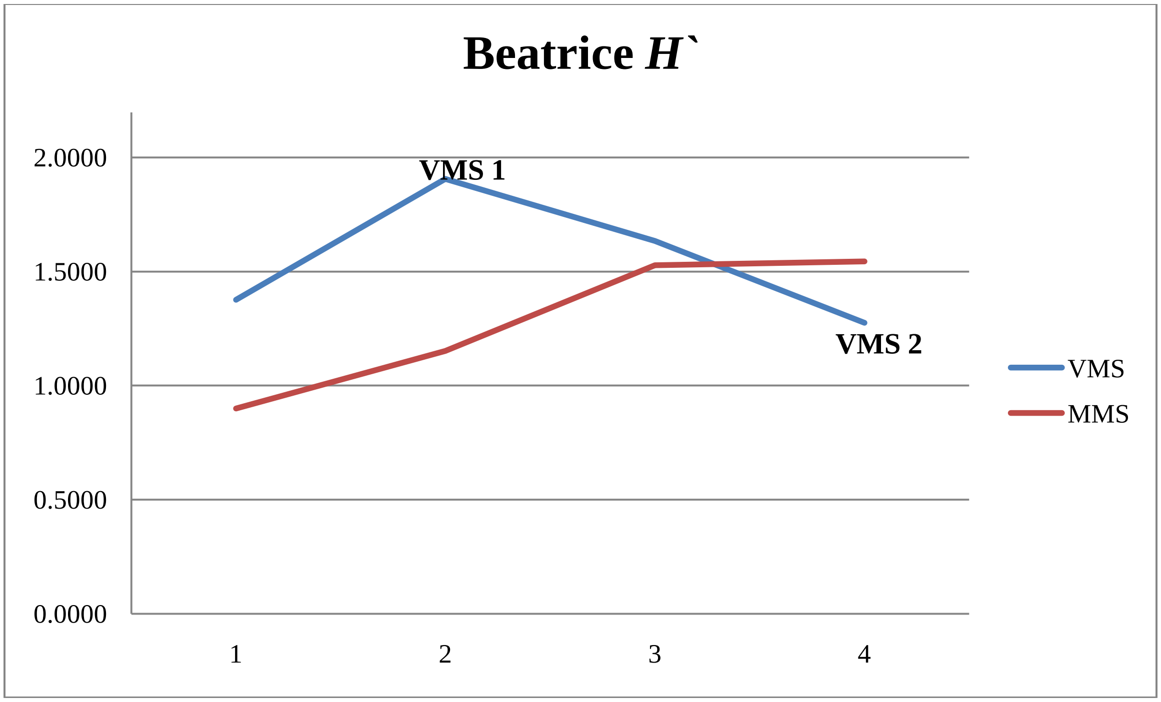

Figure 9: Parallel and alternating homogeneity and diversity of consonant and handshape preference

Discussion

Dynamic systems theory and entrainment suggest that the actions of one system will influence and organize a similar or liked system in early motor development (Iverson & Fagan, 2004; Iverson & Thelen, 1999; Thelen & Smith, 1994). The vocal and manual systems have been shown to be linked throughout the lifespan (Bernardis et al., 2008; Capirci et al., 2002; Ejiri & Masataka, 2001; Fogassi & Ferrari, 2007; Gentilucci & Dalla Volta, 2008; Goldin-Meadow, 2009; Iverson & Fagan, 2004; Iverson et al., 2008; Iverson & Thelen, 1999; Meier & Willerman, 1995; Petitto et al., 2004; Skipper et al., 2007; Wallace & Whishaw, 2003; Willems et al., 2007). By observing the manual actions of infants as they develop vocal control, the present data suggest that the coordination developed through environmental exploration and co-activation between the systems exhibits mutual influence. We have been able to demonstrate that the actions of the vocal system and the actions of the manual system exert a motoric influence over each other before either one is recruited for referential language production. These eight participants all demonstrated individual and overall patterns of manual development corresponding to patterns of vocal development as the vocal systems settled into the patterns the individuals later recruited for speech.

To determine whether the systems exhibit mutual action, the manual categories were observed and transcribed during vocal utterances, which are necessarily the product of action in the vocal system. The presence of manual activity, determined by any movement from the shoulder to the fingertips, during transcribed utterances suggests that not only is the vocal system linked to the manual but also that the actions themselves may be influential over each other (e.g., Bernardis et al., 2008; Goldin-Meadow, 2009; Iverson et al., 2006; Iverson & Thelen, 1999; Petitto et al., 2004). The presence of activity in both systems was high over all participants, but there was variability among the subjects (see Figure 1). This range of rates of mutual activation is unsurprising and encouraging in the light of the nature of the link between these two systems: the influence of these systems can vary across individuals and over time, from a tight and direct coupling to a loose, general influence (Goldin-Meadow, 2009; Iverson et al., 2006; Iverson & Fagan, 2004; Iverson & Thelen, 1999).

The participant with the lowest percent of activity in both systems, Calvin, appeared to follow a somewhat different trajectory than the rest of the participants beyond the level of activity in both systems (see appendices for more detailed representations of his and all other participants' development). Though the current observations of activity may be a result of exclusions based on the nature of our data collection, it nevertheless appears that the processes supporting his vocal, gestural, and consequently linguistic, development operate in a way slightly different than the other participants in the study. Given the individual nature of development, Calvin's profile, though slightly deviant in some ways than the other seven participants, still fits this description of normal development.

Before comparing the configurations of the systems to investigate their contributions and constraints over each other, common patterns in overall production were examined before deeper investigation began.

Each participant produced a wide range of configurations, some with much greater preference than others. There was great variety in the configurations produced by all participants, but not all participants produced the same range of consonants or handshapes. Several consonants and handshapes were eliminated from the analyses (see Table 2), not because they were more mature configurations or because they were more difficult, but because they were not produced with enough frequency or stability (i.e., produced with similar or increasing frequency over time) across all participants to provide an accurate description of normal development. These eliminated configurations may become stable for these, or any, infant(s) over time, but within this period of observation they did not appear to contribute meaningfully to the mutual development of the vocal and manual systems. Similarly, the manual configurations produced by the right hand did not exhibit a significantly different pattern when compared to the configurations of the left hand, so the productions of the right and left were combined for these analyses.

The amounts of the various configurations within the systems were calculated as proportions or percentages for each session and then compared across sessions (individual plots of these preferences are illustrated in Appendix A). Individuals varied in their different preferences, but all participants showed similar preferences (see Figures 2 and 3 for consonant and handshape preferences over all sessions for all participants combined). The two consonants produced with greatest overall preference, t/d and p/b, were the most often produced for each individual. This is consistent with McCune & Vihman's (2001) findings from 20 children, aged nine to 16 months, observed in linguistic development. Furthermore as the research suggests, these consonants are present and highly common in the earliest stable words (McCune & Vihman, 2001). The two handshapes produced with greatest overall preference, C and 5, were also the most often produced for each individual. While their contributions to early gesture and linguistic development are not well reported, they do correspond to Boyes Braem's (1990) Stage I handshapes and are among the 3 most common handshapes produced spontaneously during adults' narratives (McNeill, 1992). Taken together, these suggest that the handshapes, or manual configurations, practiced in infancy and early stages of language development, contribute to later gesture and linguistic development and production.

Comparisons of vocal and manual configuration preferences over time revealed significant correlations for each participant and showed maintenance of similar patterns of production throughout the period of observation. These significant correspondences between configurations not only suggest that the systems have a strong link over time but also further support their importance to later language outcomes.

Further comparison of the vocal and manual configuration preferences over time was done using a multidimensional scaling (MDS) technique to combine the data into a unified geometrical representation of the preferences over time. Again each participant had a unique set of preferences and progression to stability in each system, separately and when compared together (see Appendix B for individual maps of vocal and handshape preferences combined). These MDS outputs highlight those configurations which over time have developed importance or preference for the participants, underscoring the established development of vocal behaviors and consonant production. The addition of manual preference data not only gives a vocal context for the patterns but also establishes a reliable analysis of manual configurations and their development.

The comparison of each participant's preferred configurations in each system over time revealed significant trends for each infant; that is, as their manual preferences changed or stabilized, the vocal configurations changed or stabilized in a similar pattern. Taken together with the correlations calculated conventionally, the evidence indicates not only that the systems share a specific relationship over time but also that the observed manual actions produced during vocalizations exhibit preferences corresponding specifically to stable vocal configurations. Such correlations are unlikely to exist between two unrelated systems.

That all participants fit these maps, and that these maps explain 75% to 93% of the group variance suggests the importance of these configurations over these participants over time and very likely extends to other typically developing infants. Variance for these subjects is listed individually in Appendix B. Additionally, since these stable vocal configurations and consonants are necessary to the production and development of language and are represented in a vocal-motor scheme (e.g., McCune & Vihman, 2001), that there are manual configurations or handshapes that correspond or correlate highly with vocalizations over time suggests that these handshapes are part of a manual-motor scheme.

To be considered a VMS, the consonants produced must be practiced and produced reliably over time. Practicing a particular consonant indicates a greater preference for one consonant over all others, at least within a particular session. To compare manual configuration patterns to VMS, there must be a similar measure of practice in the handshapes over the same time. The *H*` values calculated for the consonant and handshape preferences illustrate the homogeneity or diversity of each participant’s productions for each session and, when compared over time, suggest times of stability, or greater practice of preferred configurations rather than a wide range of configurations. Plotting both trajectories of *H`* illustrates that multiple processes appear to be at work in this group of participants. One process appears to be parallel development (Figure 7), wherein both systems in their mutual action seem to draw each other into more homogeneous, stable regions of control and then, from a place of greater stability, are able to continue exploration and more easily reach another functional, repeatable, stable configuration together. This type of development suggests the systems are linked in a very close, influential relationship. In systems linked in this way, the action and configuration in one encourages and configures the actions in the other and together the systems self-organize into similar stable states (Iverson & Fagan, 2004). However, not all participants developed in this way. The plots also exhibit patterns of one system reaching a more homogeneous or stable state as the other varies, usually with the manual system becoming more homogeneous, likely practicing a preferred configuration and stabilizing while the vocal system explores a greater variety of different configurations (see Figure 8). This initial homogeneity or stability in one system appears to act somewhat like a magnet for the other linked system, encouraging homogeneity or practice in configurations rather than exploring a range of possible shapes. The first homogenized system is then free to explore and find another stable and functional configuration and appears to lead the other system again to the new state of stability, a trade-off often seen in developing systems with varying levels of influence (Iverson & Fagan, 2004; Iverson & Thelen, 1999; Thelen & Smith, 1994). In yet another pattern exhibited by some participants, the two systems appear to be tightly coupled and develop together; after more homogeneity in its productions, one particular system becomes more diverse in production while the other becomes more homogeneous, reaching a stable state, and they lead each other to homogeneity and diversity throughout the period of observation (as in Figure 9). Both systems appear to engage in similar degrees of homogeneity and diversity over time; that the vocal system's practice of preferred consonants supports language, and that the manual system's actions and configurations follow a pattern similar to the manual system, shows not only the importance of actions in the manual system during vocal development but also that the manual system likely influences aspects of vocal development.

The use of data from a study on language development has been especially beneficial in understanding the role of the manual system as infants gain control over the motor systems. The vocalizations of these participants have been analyzed and their importance to linguistic development illustrated in the participants' use of their VMS in their early word productions. That these vocalizations are so important to language gives credence to the role and importance of the observed co-occurring manual configurations. The configurations of these systems show clear influence over each other during this pre-linguistic period, and the vocal configurations, once stable, become available for the production of language. The manual configurations, once stable, are available to be recruited not only for everyday functional actions but also for communicative actions, in gesture.

The role of gesture in development has been well studied and discussed, and it is apparent that gestures play an important role in language development and production and in effective communication (Capirci et al., 2002; Capone & McGregor, 2004; Fogassi & Ferrari, 2007; Goldin-Meadow, 2009; Guidetti & Nicoladis, 2008; Iverson et al., 2008; Iverson & Fagan, 2004; McNeill, 1992; Skipper et al., 2007; Willems et al., 2007). The stability of manual control explored during vocal development supports not only the production of the gestures themselves but also the seamless integration of both motor commands in a communicative act.

The evidence presented of the development within and between the vocal and manual systems shows not only significant parallels and a strong relationship over time, but it also suggests that the systems exert a mutual influence over each other and are both important to the other's development and to the development of the individual. The parallels and correlations would not exist in two unrelated systems. These results seem to support the existence of a pattern of development in the manual system analogous to the development of a vocal-motor scheme in the vocal system and suggest the existence of a true manual-motor scheme.

This is exciting evidence and an important discovery of the nature of both vocal and linguistic development. An ongoing investigation from the same original data as the present study focuses on the same development in children exposed to structured manual communication, and it is expected that the data will not only support the findings reported here but may also show clearer trajectories in manual development and potentially earlier stability in the vocal system. Further studies with a wider focus to include the manual system during vocal development may also provide a more robust account of development within and between the linked systems. For the data presented here, the evidence from this new study of co-developing systems provides new evidence of and insight into the mutual development of the manual and vocal systems as they become the foundations for the production of language.

Appendix A: Descriptive Data for Individual Participants

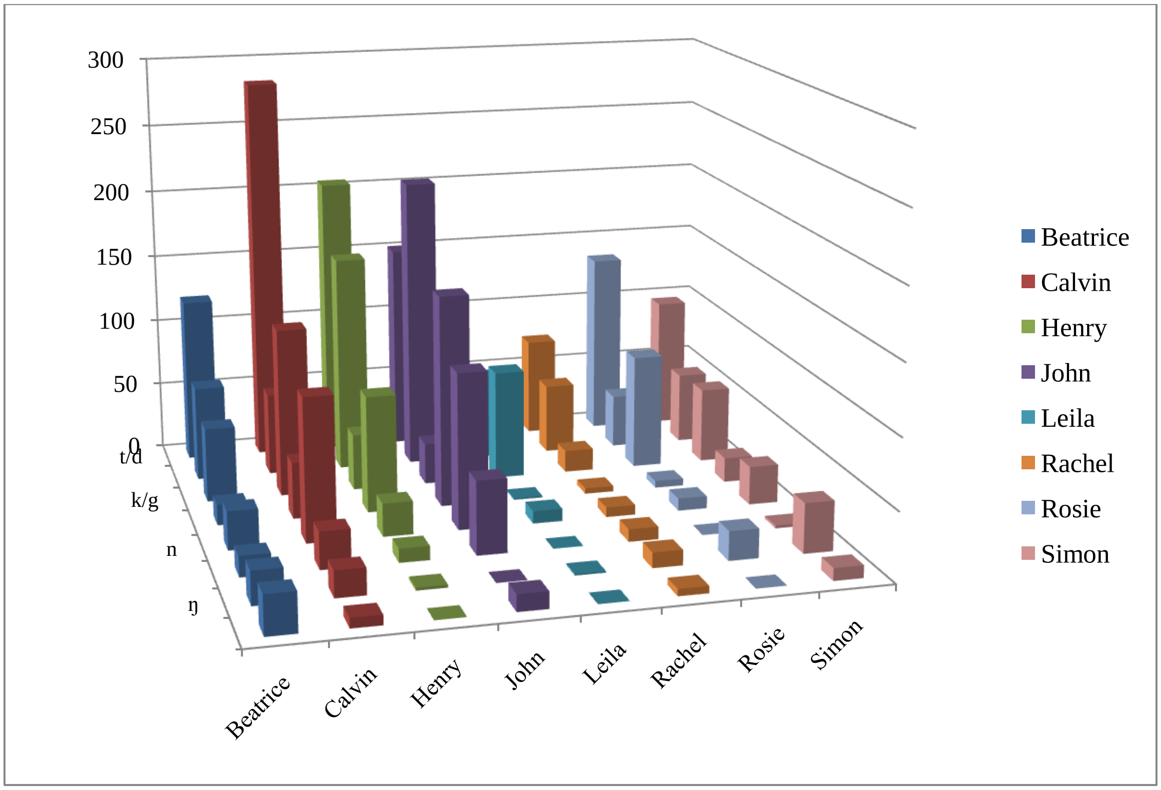

Figure 1A: Raw totals of consonants produced by each participant over all sessions

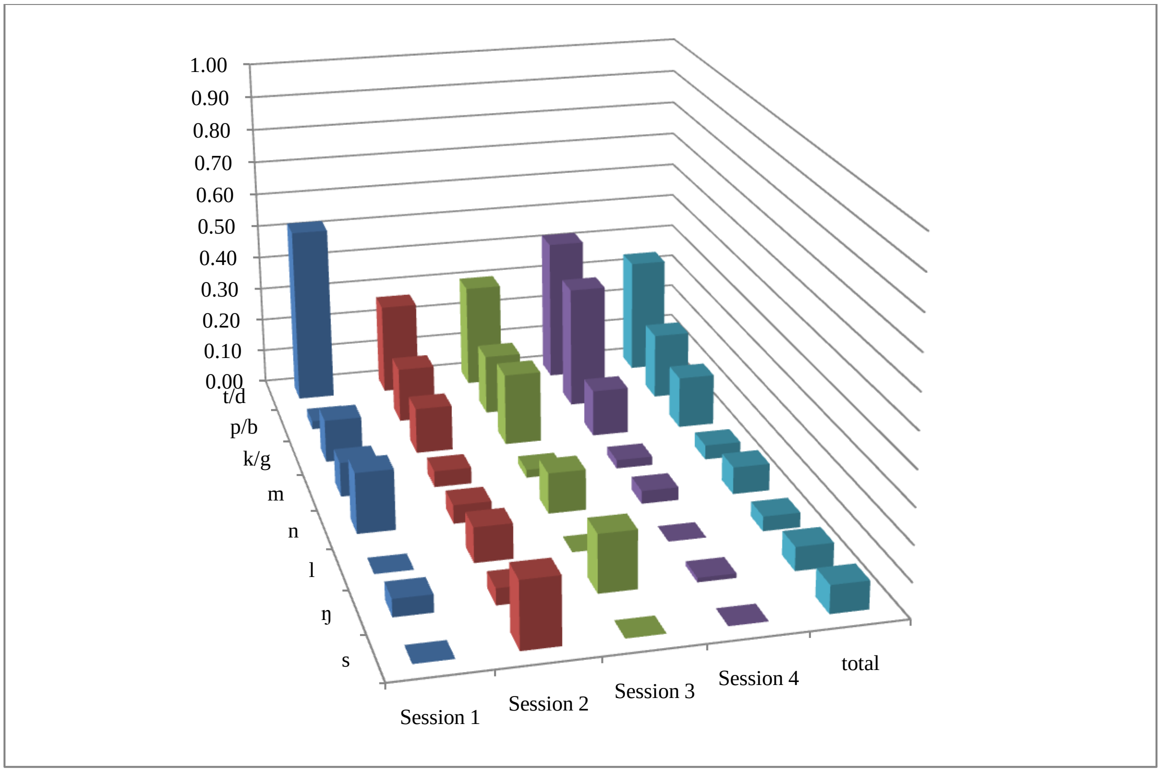

Figure 2A: Proportion of consonants over all sessions and overall preference for Beatrice

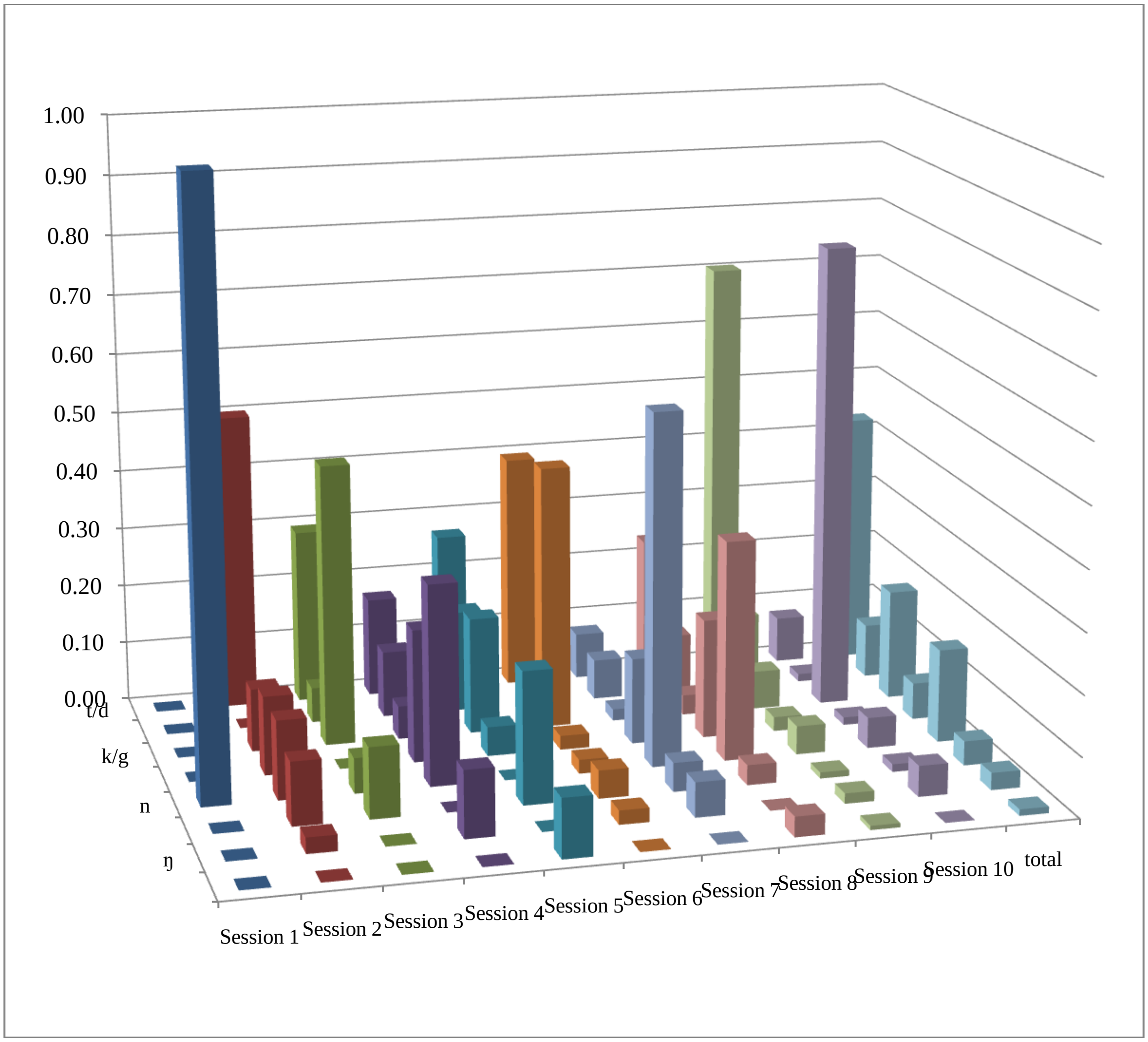

Figure 3A: Proportion of consonants over all sessions and overall preference for Calvin

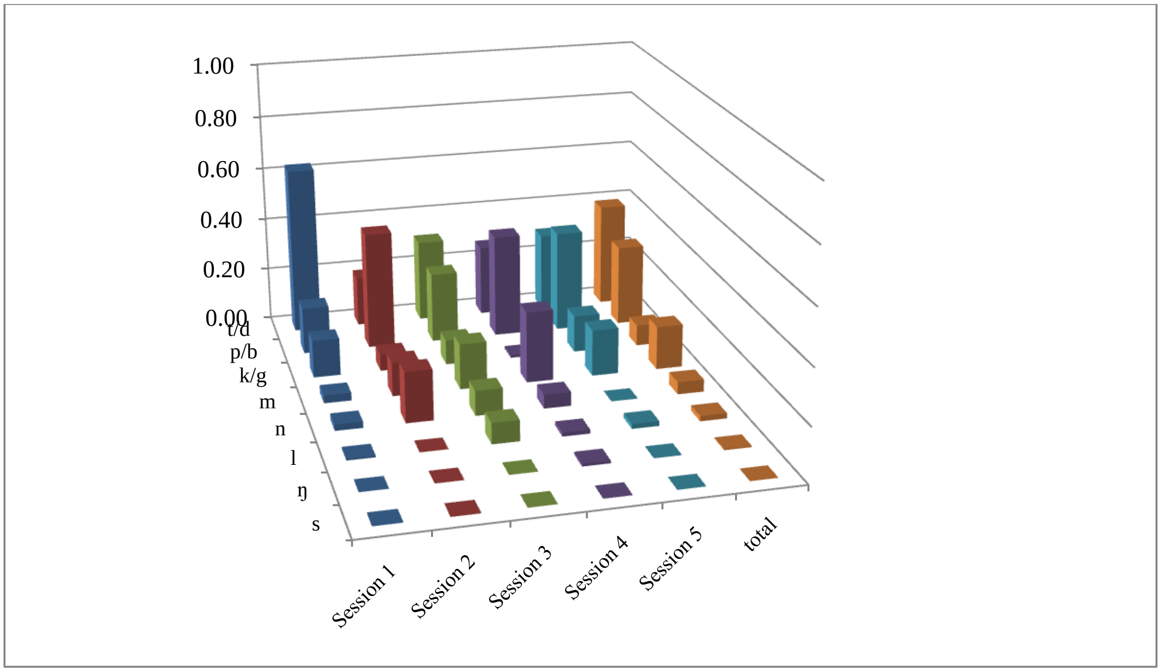

Figure 4A: Proportion of consonants over all sessions and overall preference for Henry

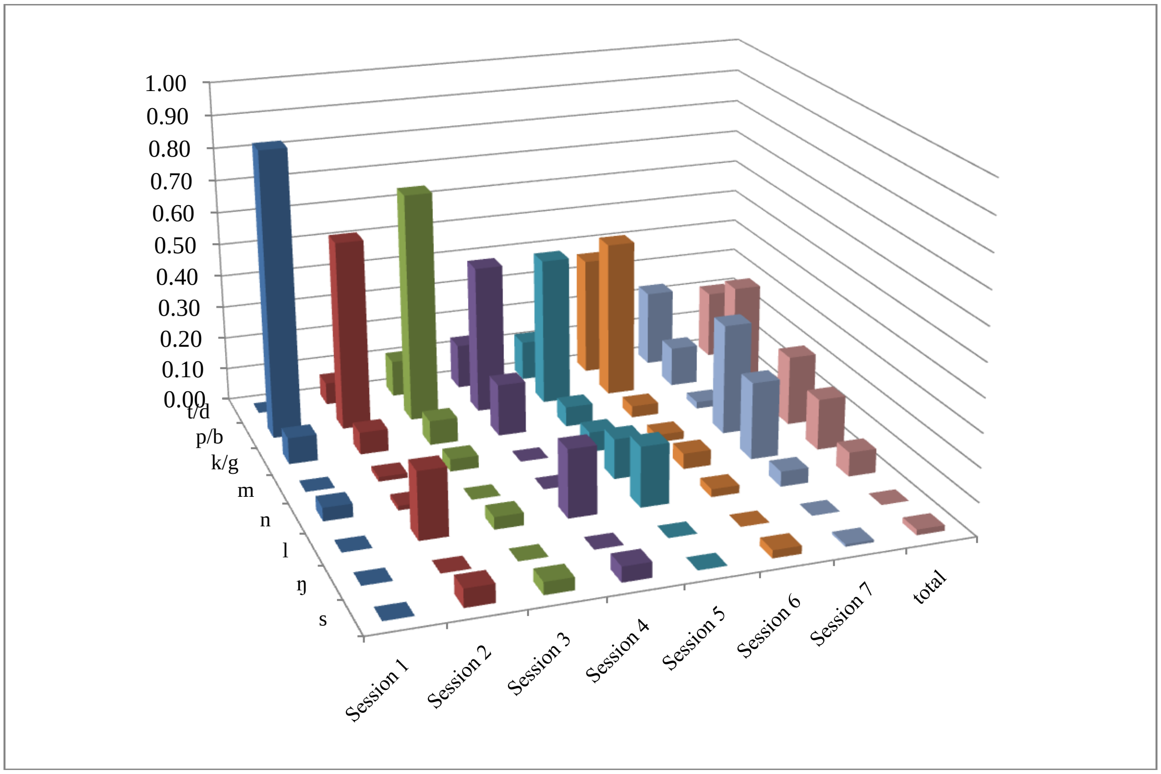

Figure 5A: Proportion of consonants over all sessions and overall preference for John

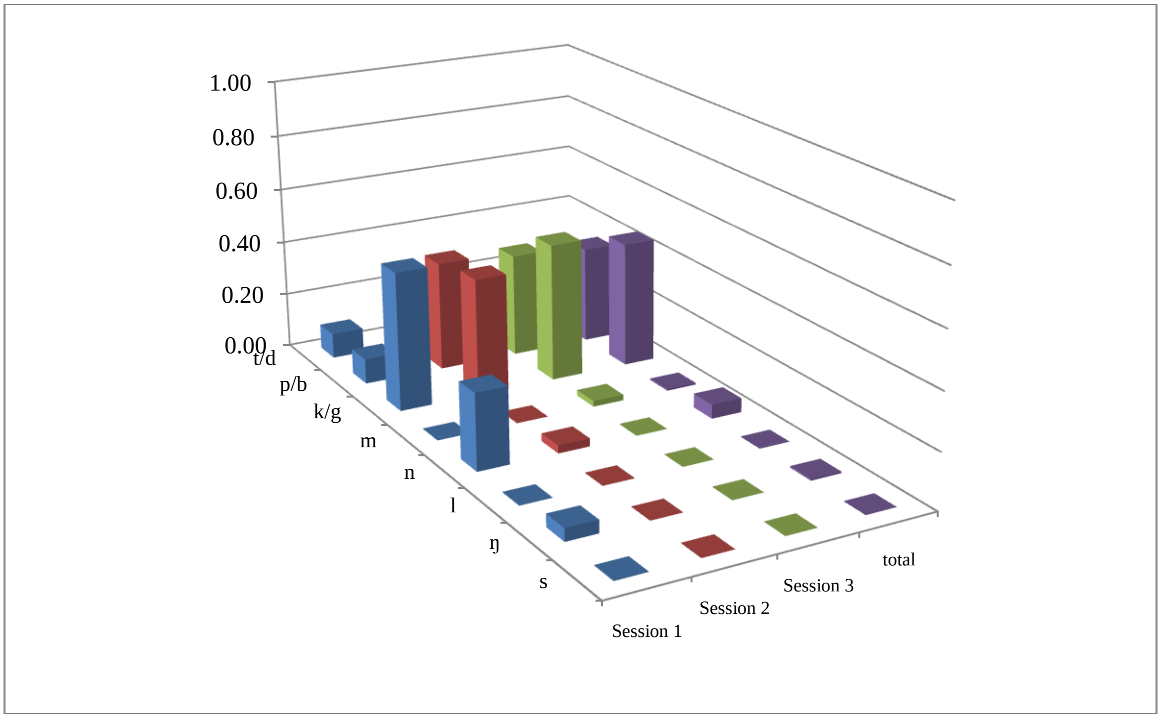

Figure 6A: Proportion of consonants over all sessions and overall preference for Leila

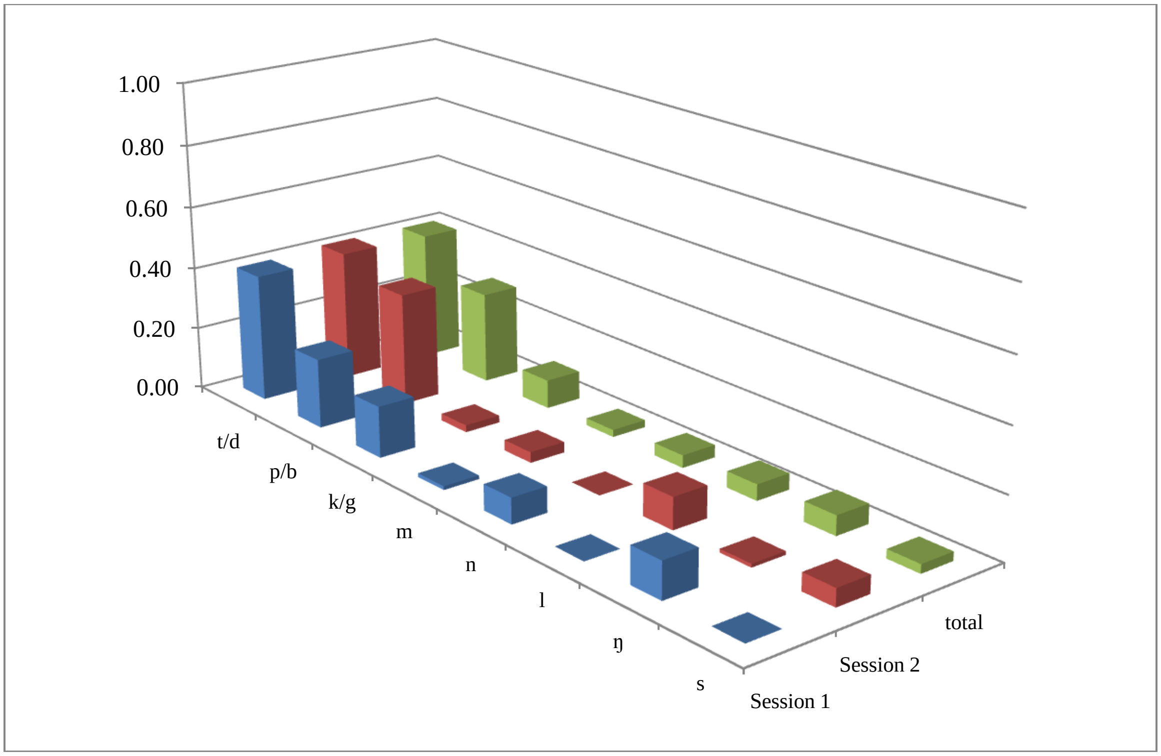

Figure 7A: Proportion of consonants over all sessions and overall preference for Rachel

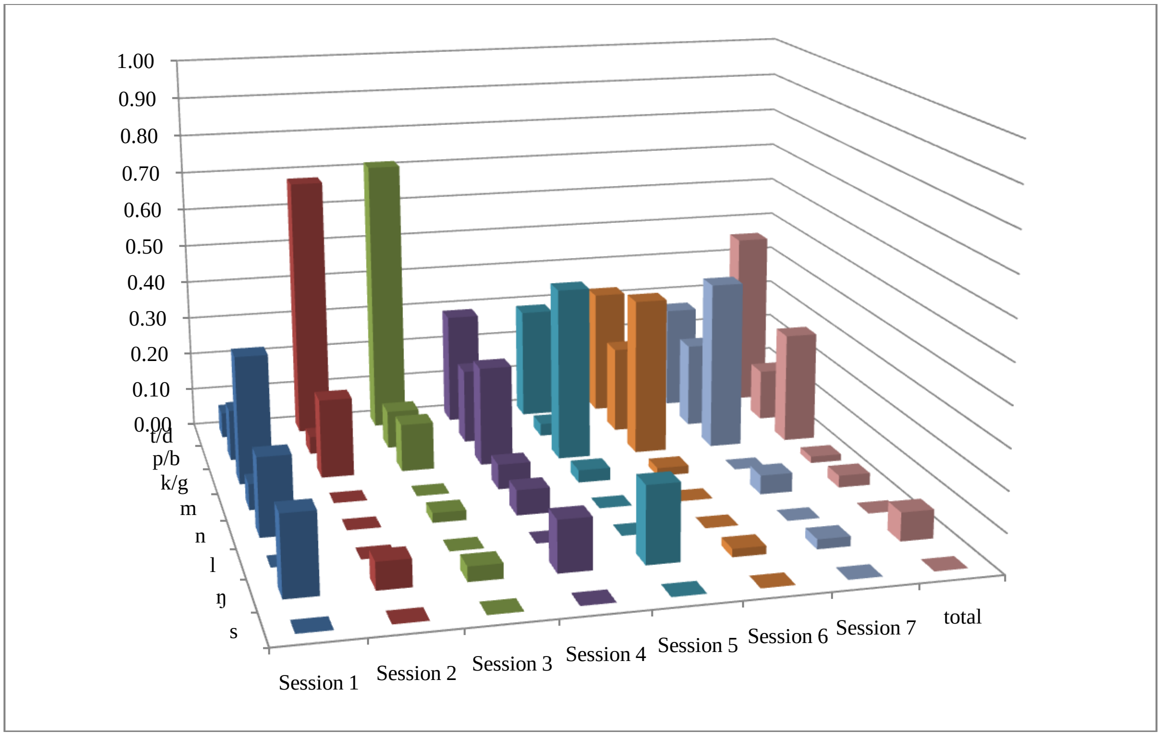

Figure 8A: Proportion of consonants over all sessions and overall preference for Rosie

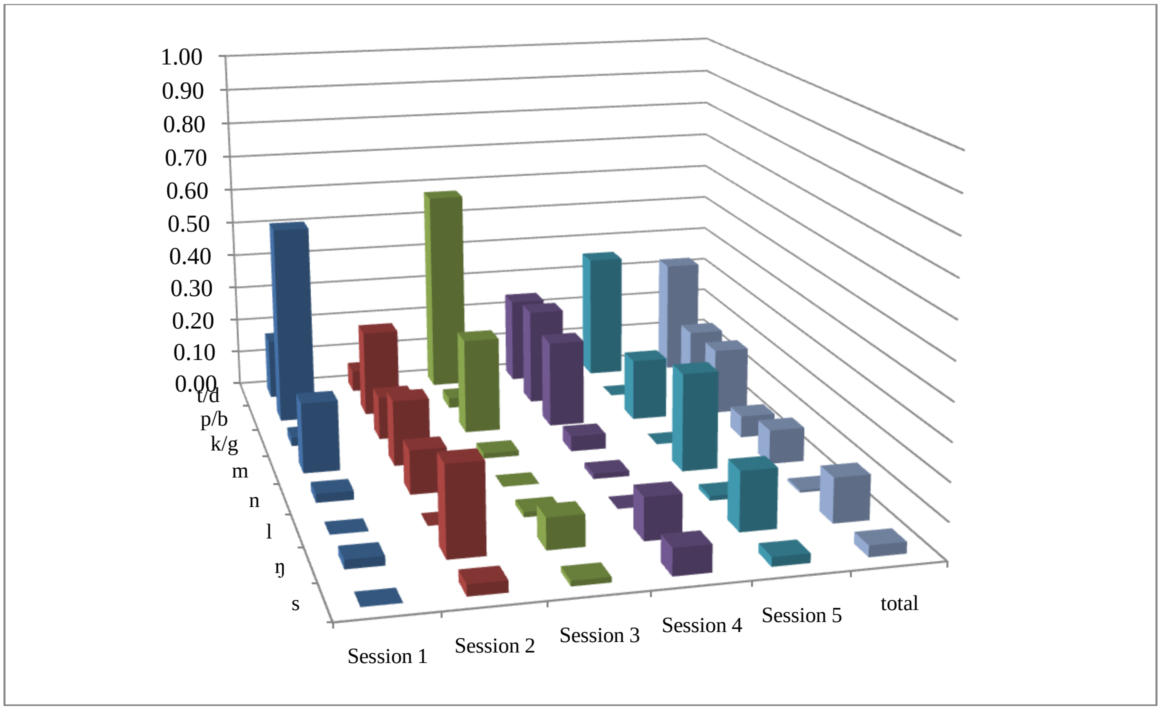

Figure 9A: Proportion of consonants over all sessions and overall preference for Simon

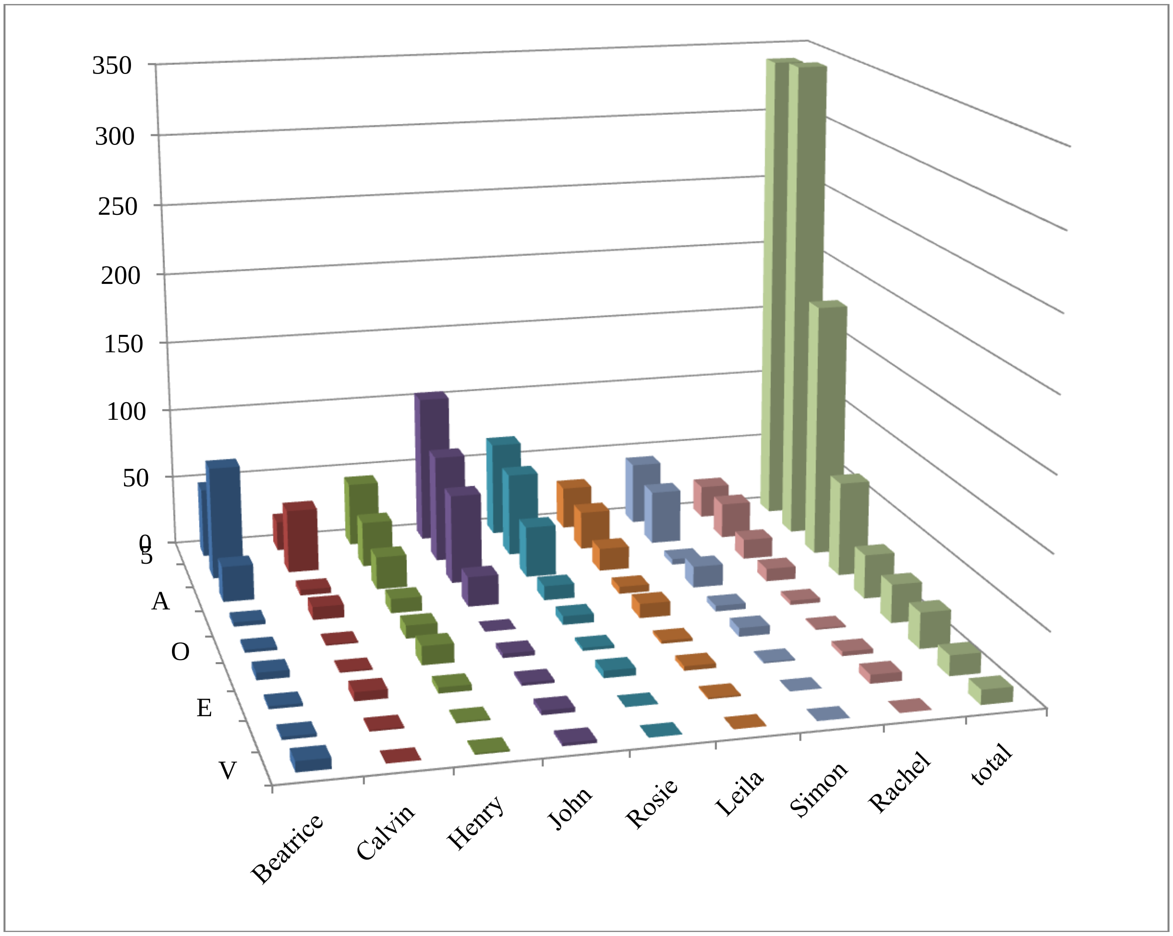

Figure 10A: Raw totals of handshapes produced by each participant over all sessions

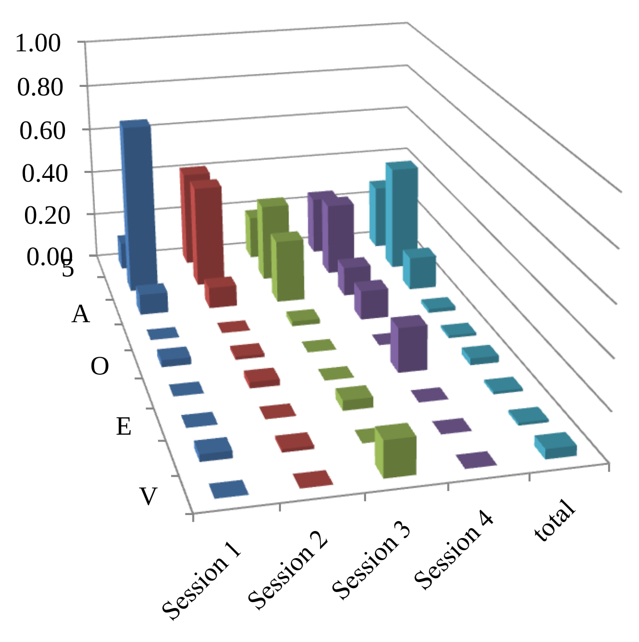

Figure 11A: Proportion of handshapes over all sessions and overall preference for Beatrice

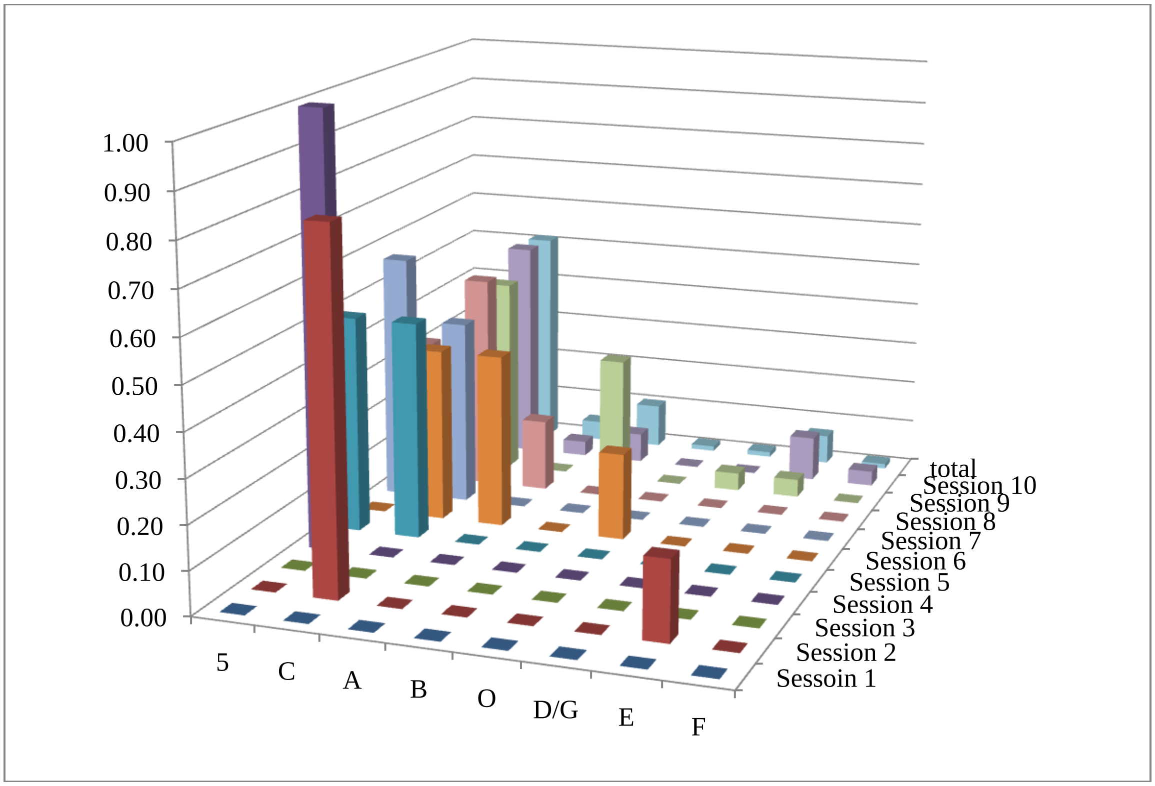

Figure 12A: Proportion of handshapes over all sessions and overall preference for Calvin

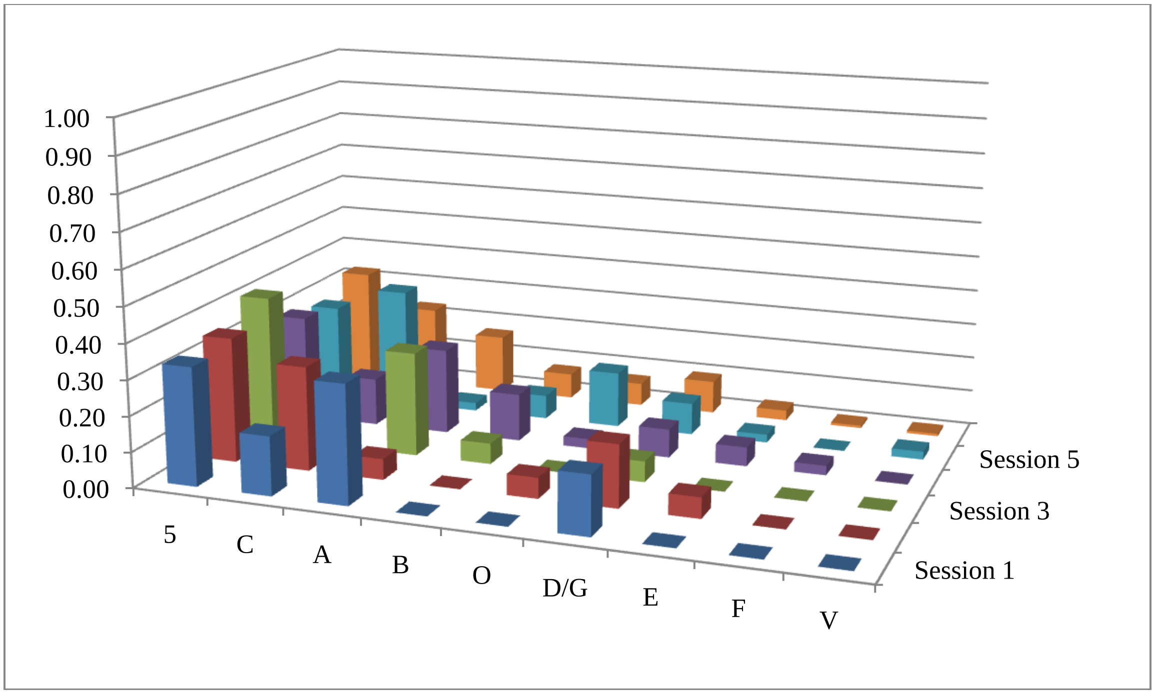

Figure 13A: Proportion of handshapes over all sessions and overall preference for Henry

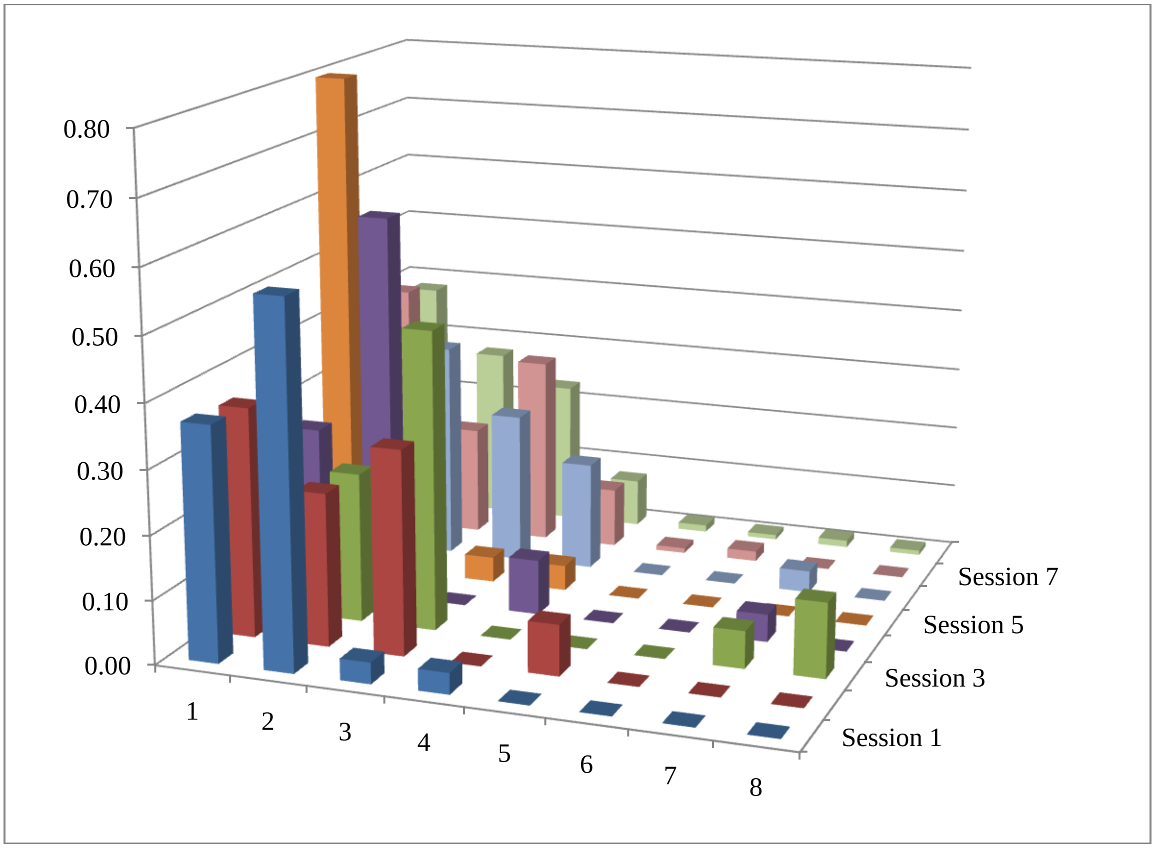

Figure 14A: Proportion of handshapes over all sessions and overall preference for John

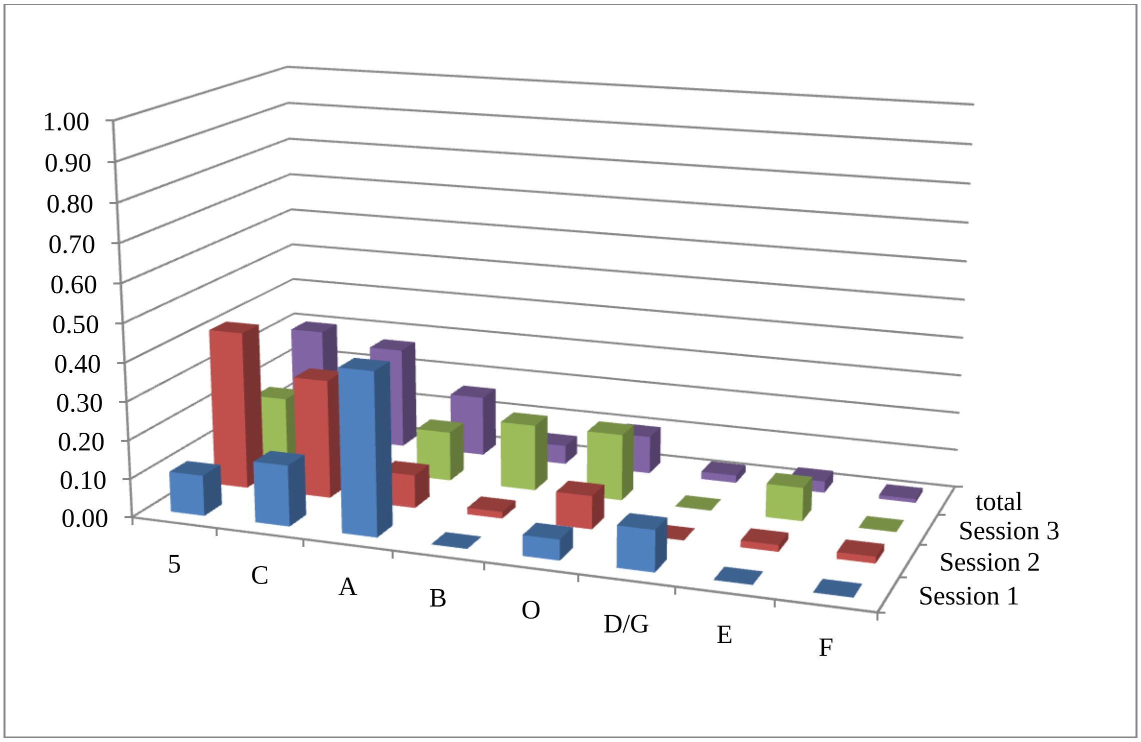

Figure 15A: Proportion of handshapes over all sessions and overall preference for Leila

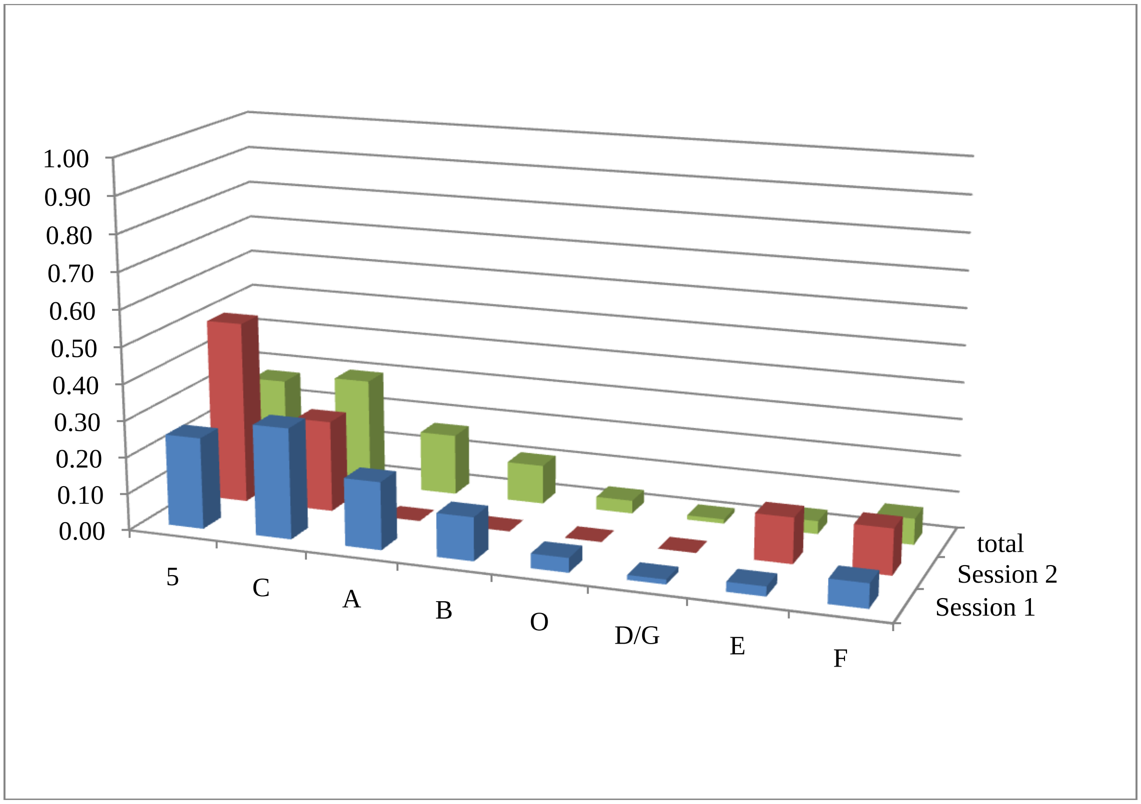

Figure 16A: Proportion of handshapes over all sessions and overall preference for Rachel

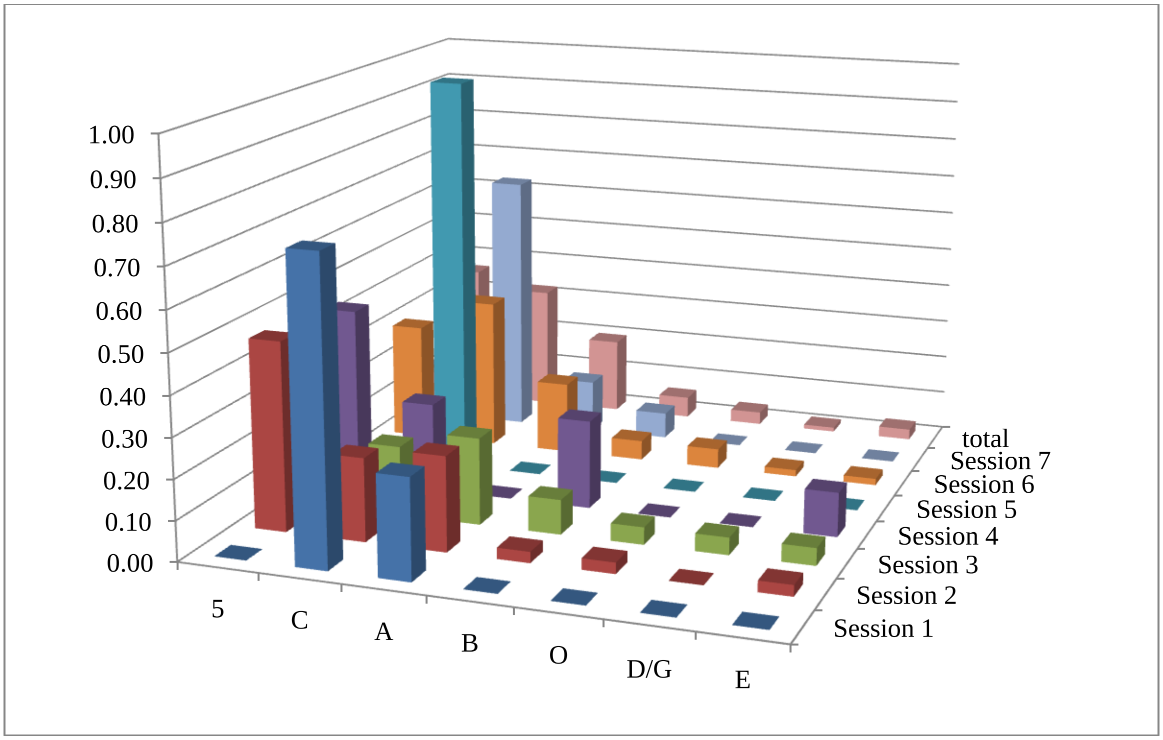

Figure 17A: Proportion of handshapes over all sessions and overall preference for Rosie

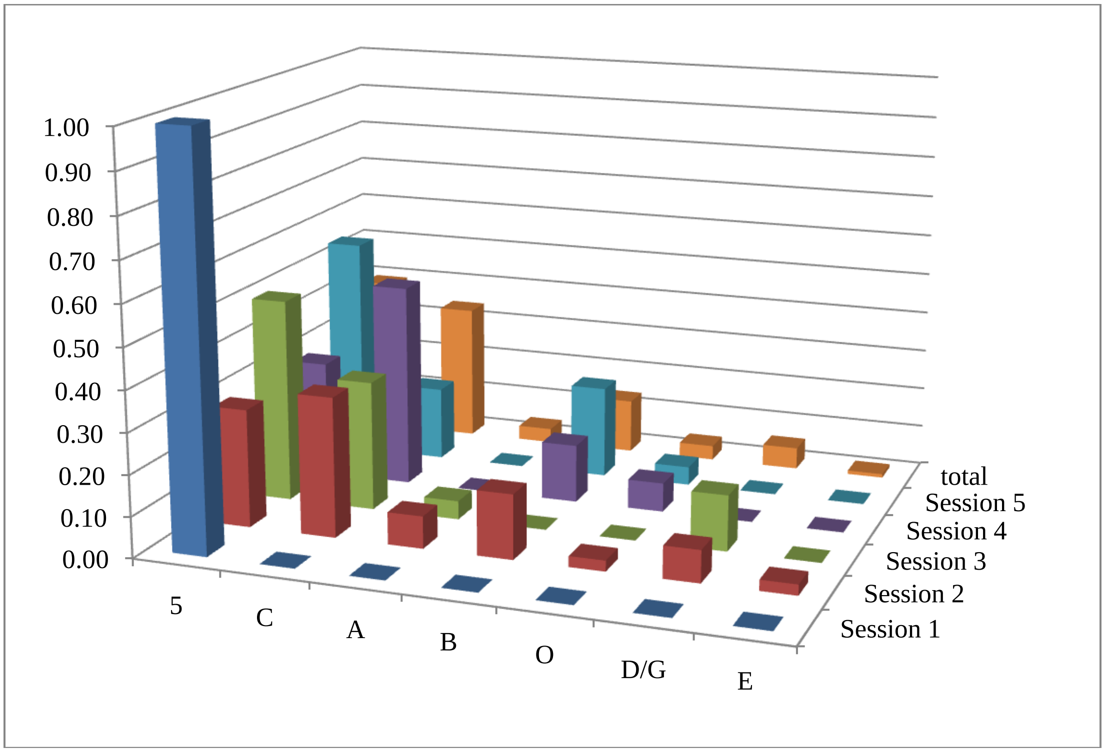

Figure 18A: Proportion of handshapes over all sessions and overall preference for Simon

Appendix B: Individual MDS and *H*` Plots

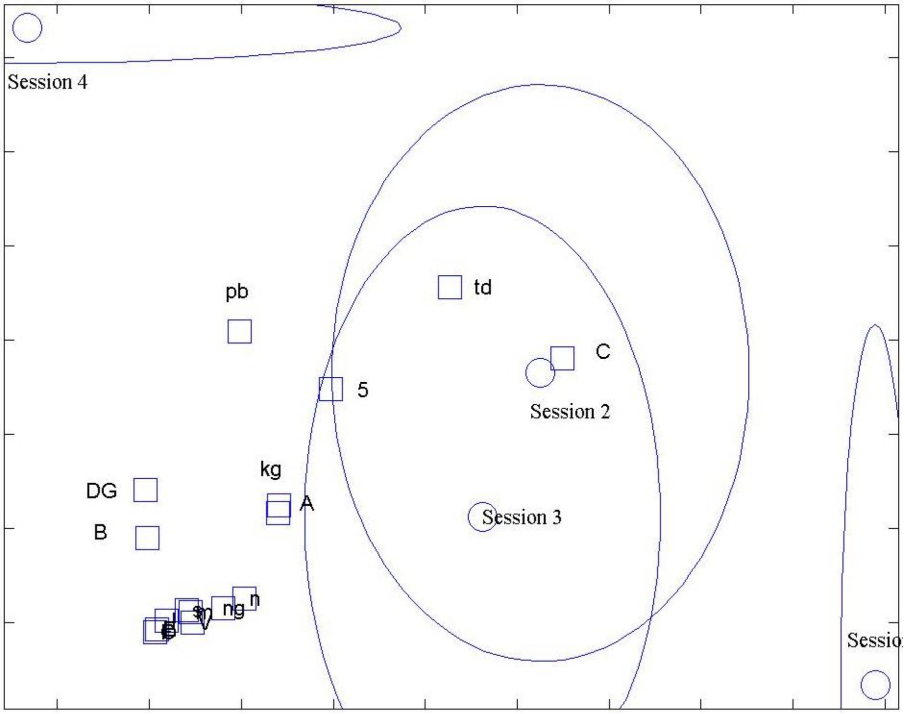

Figure 1B: MDS of consonants and handshapes combined for Beatrice

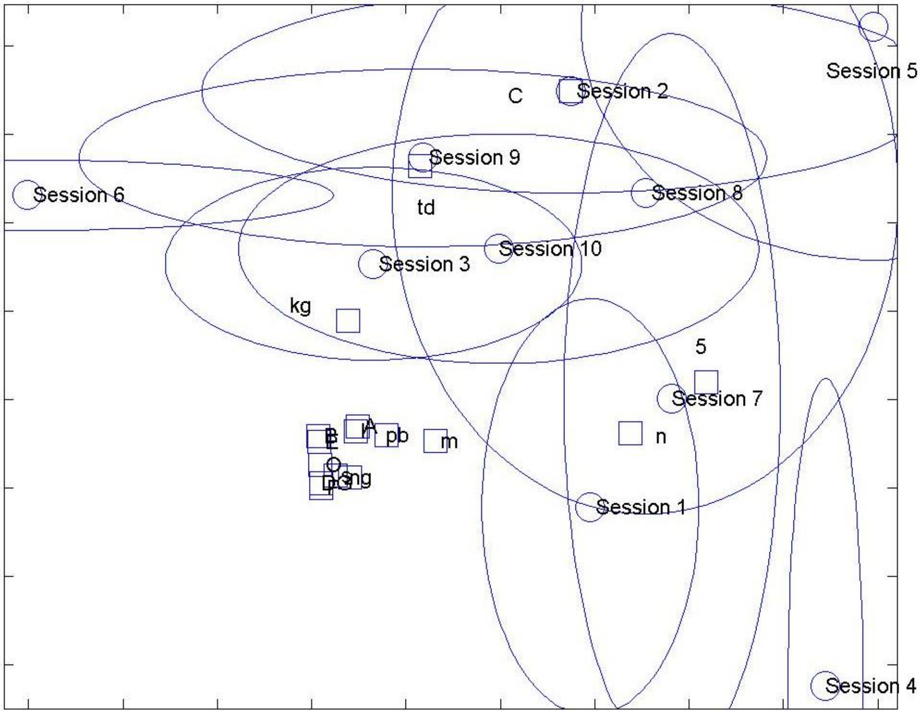

Figure 2B: MDS of consonants and handshapes combined for Calvin

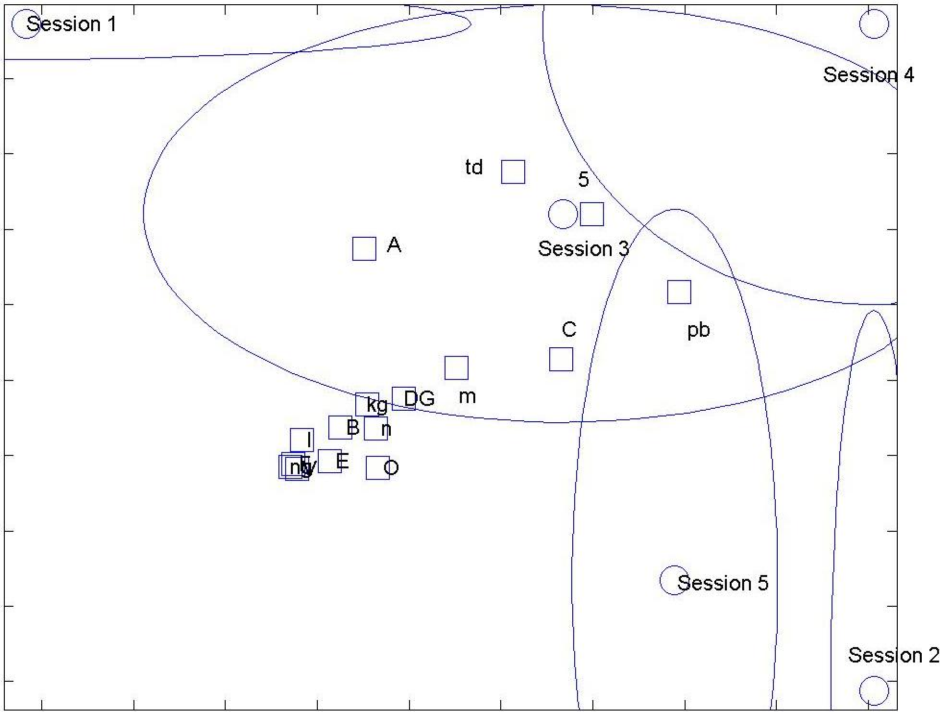

Figure 3B: MDS of consonants and handshapes combined for Henry

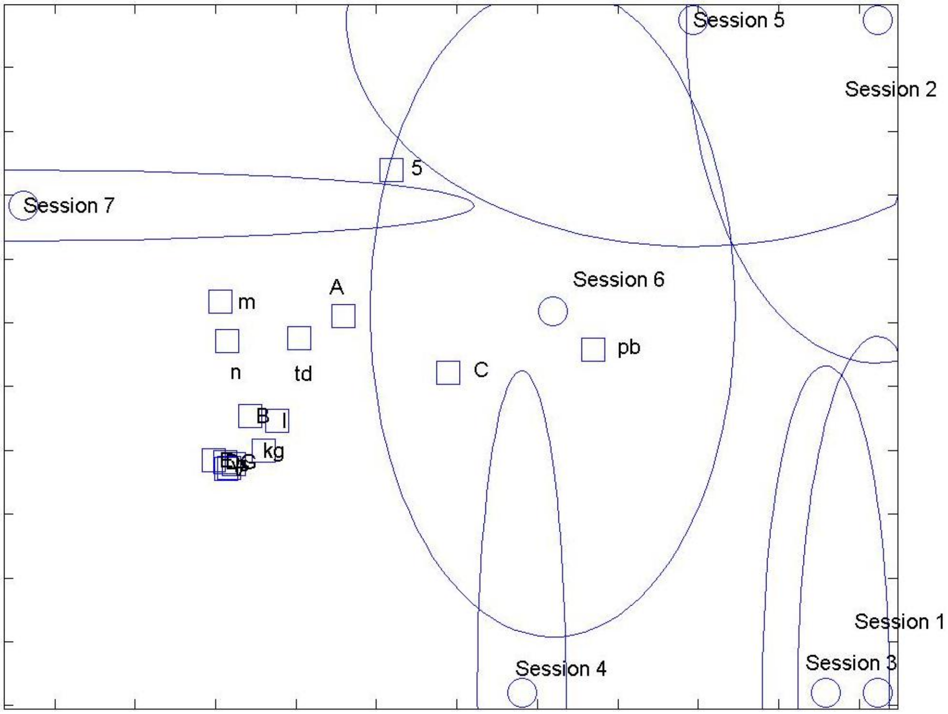

Figure 4B: MDS of consonants and handshapes combined for John

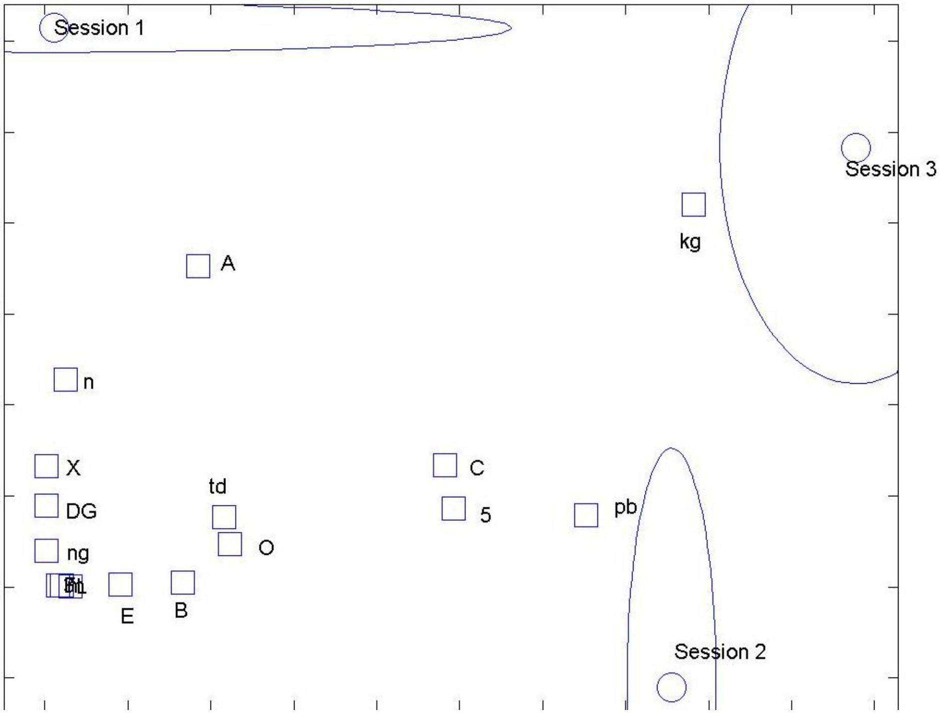

Figure 5B: MDS of consonants and handshapes combined for Leila

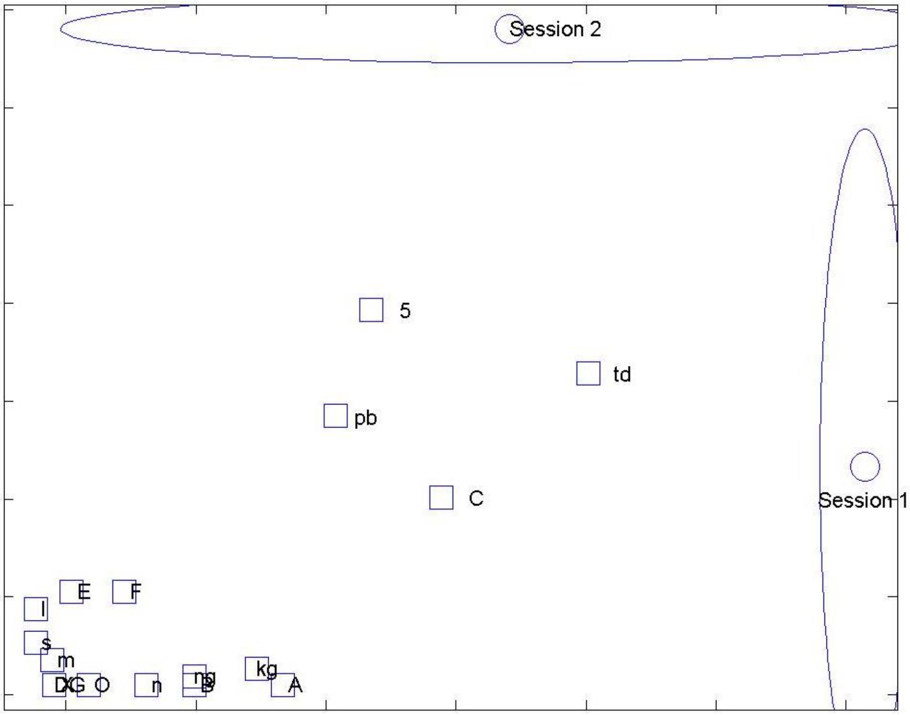

Figure 6B: MDS of consonants and handshapes combined for Rachel

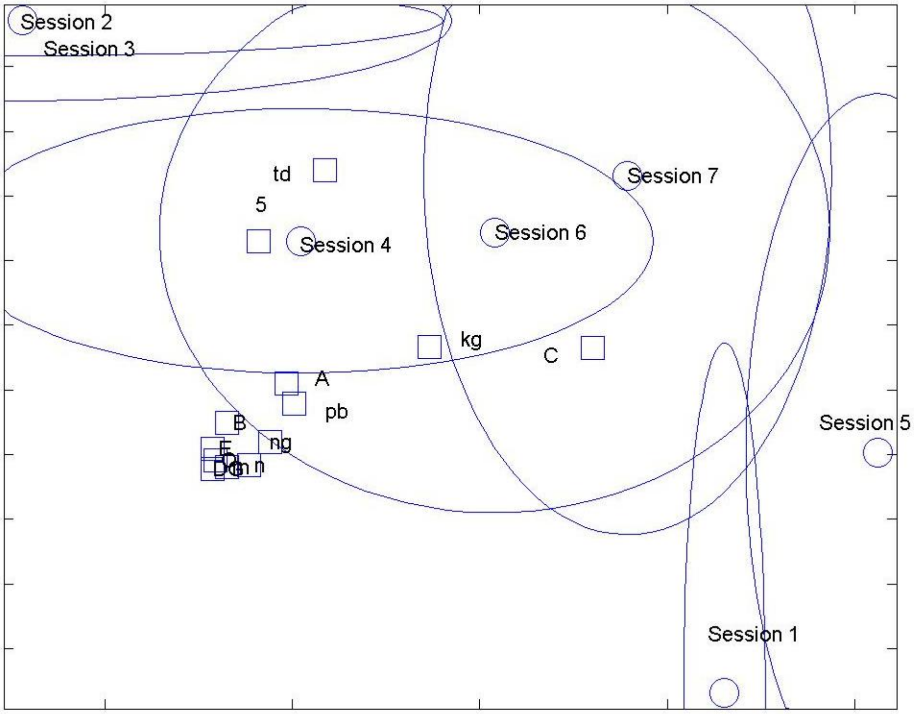

Figure 7B: MDS of consonants and handshapes combined for Rosie

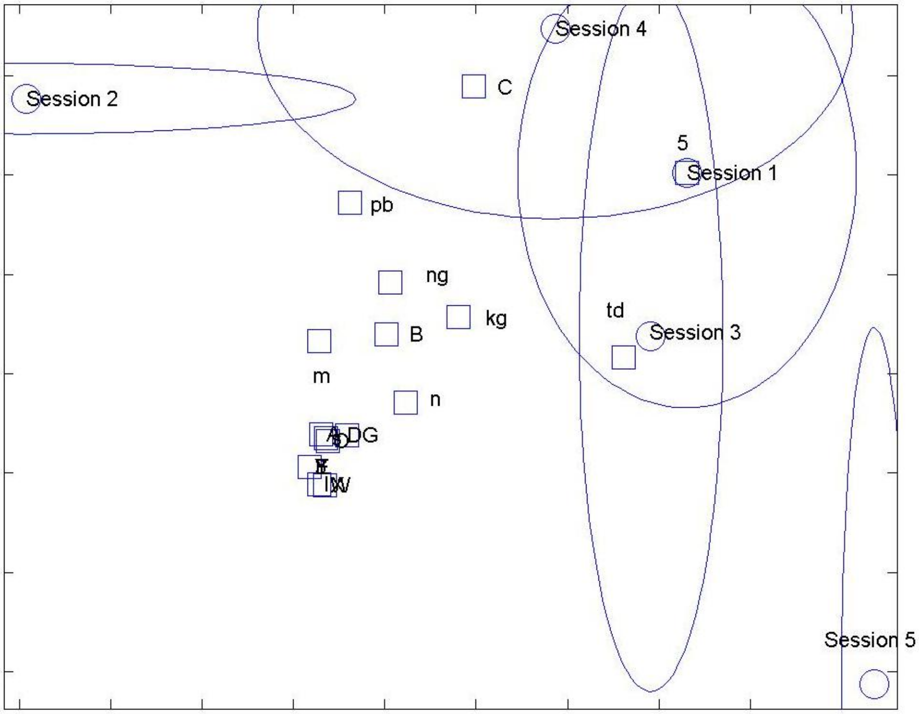

Figure 8B: MDS of consonants and handshapes combined for Simon

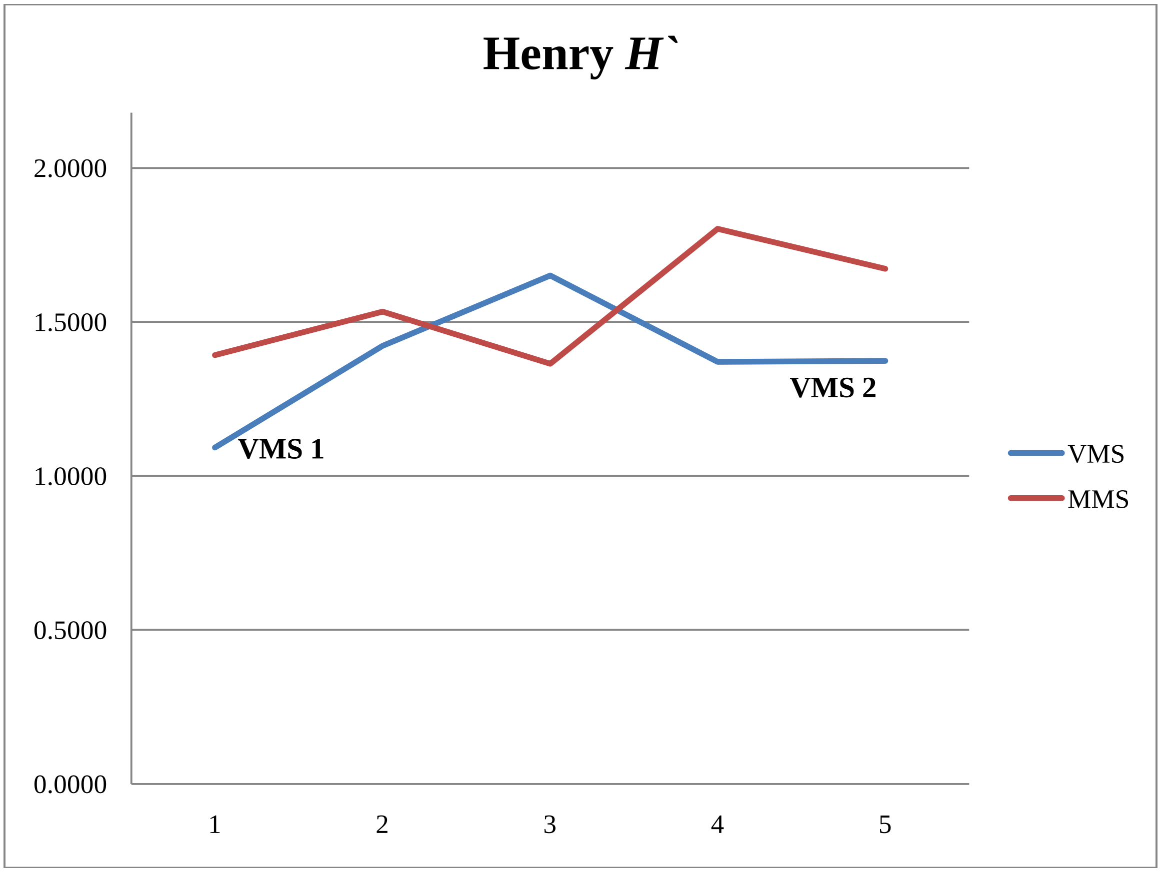

Figure 9B: Henry *H’*

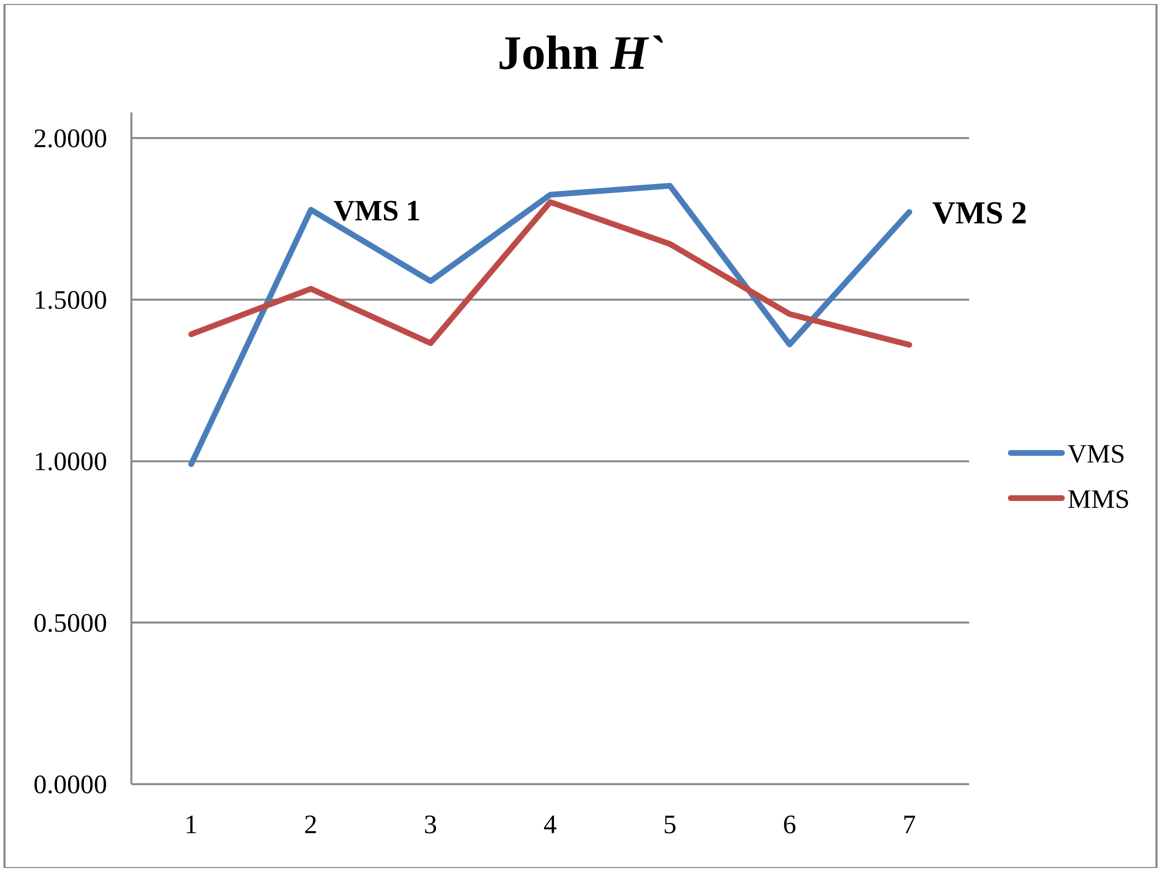

Figure 10 B: John *H*`

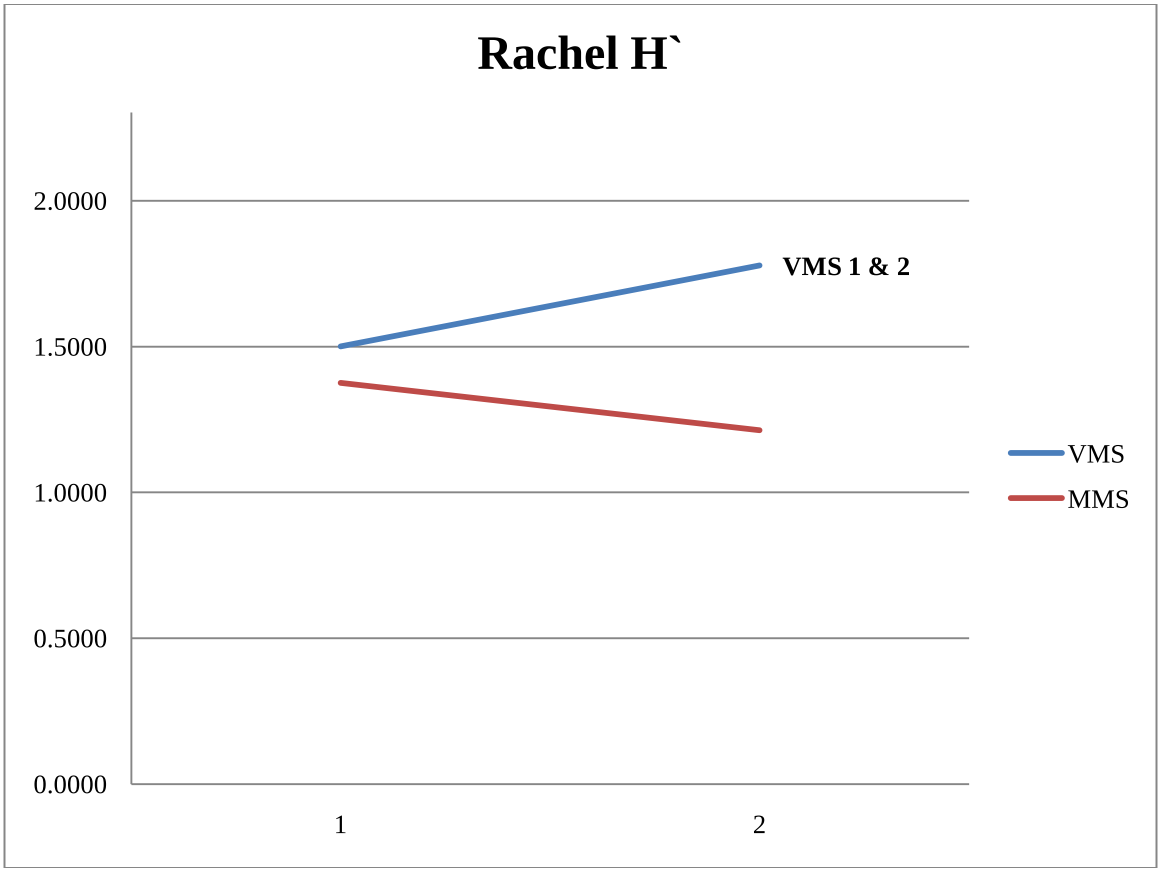

Figure 11 B: Rachel *H*`

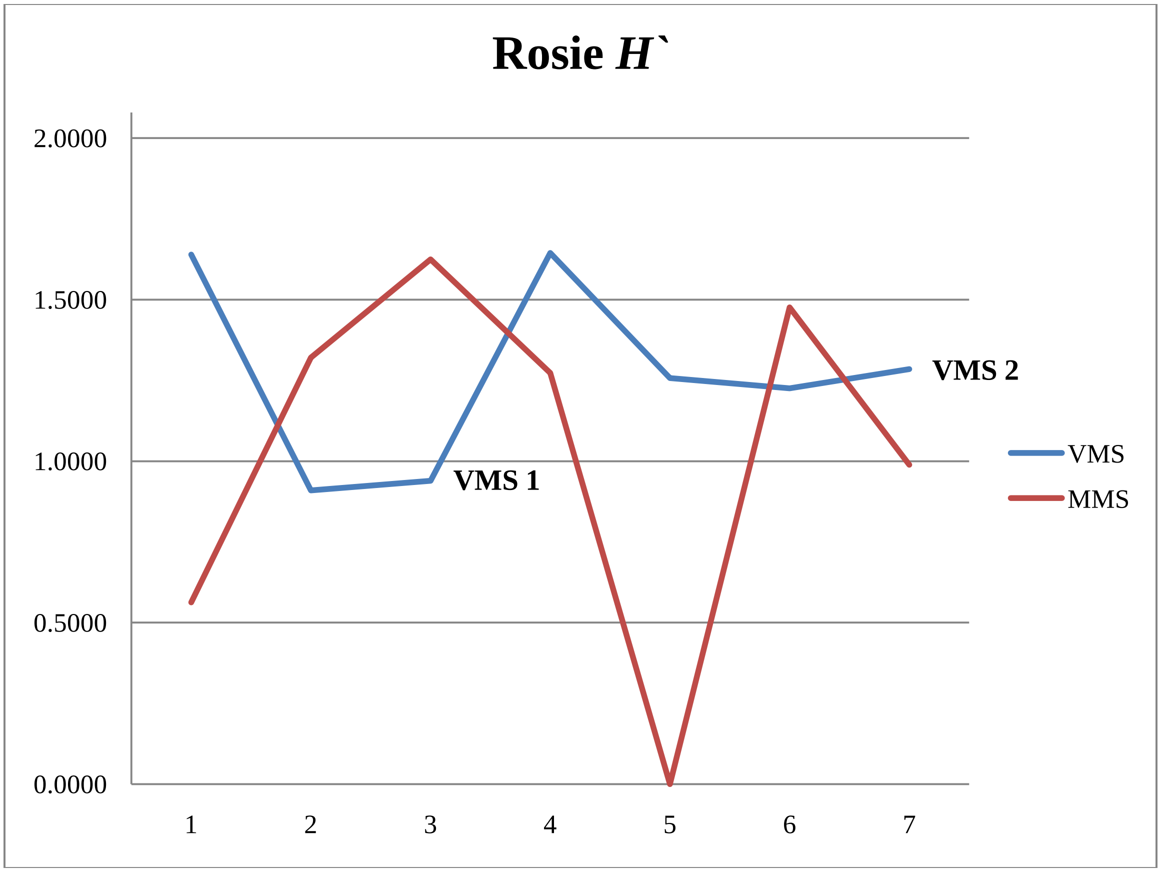

Figure 12 B: Rosie *H*`

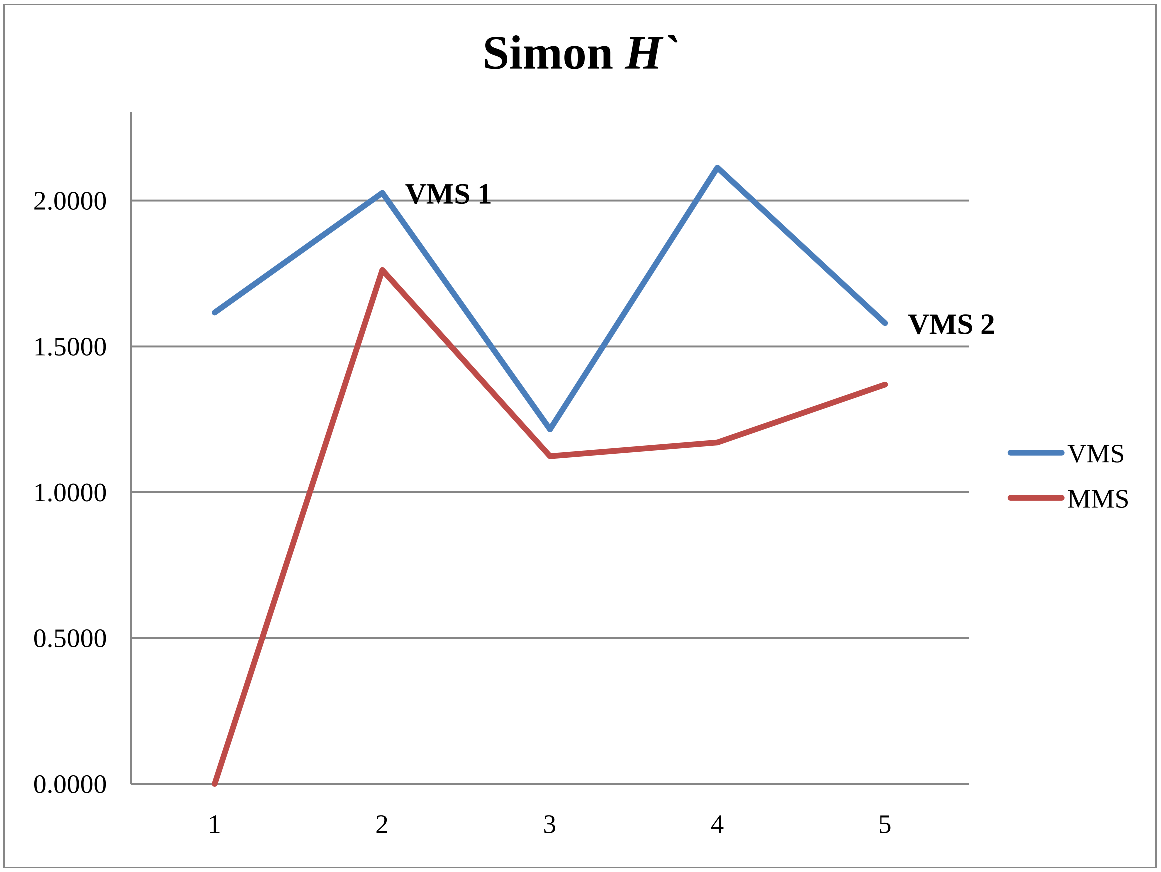

Figure 13 B: Simon *H*`

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