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Infant Phonotactic Learning

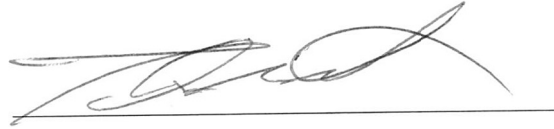
A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Linguistics

by

Victoria Anne Thatte

2011

The dissertation of Victoria Anne Thatte is approved.

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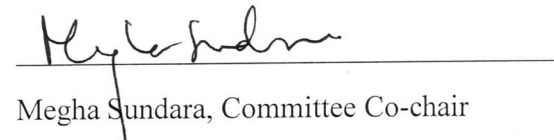
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Dedication

I would like to dedicate this dissertation to my husband, Gautam, and to my parents, Candace and Jim.

Gautam, I love you. Period. Thank you for being such a wonderful partner in life.

Mom and Dad, you have supported me in everything I've ever done. I know you love me not just for being accomplished, but for being myself. I also know I would be neither without the both of you. I am, and always will be, proud to be your daughter.

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Acknowledgments

My heartfelt thanks are due first of all to my dissertation co-chairs, Megha Sundara and Bruce Hayes, without whose unending patience and unfailingly helpful input this dissertation would be a shadow of its current self; any errors that remain exist despite their best efforts to the contrary. Second, my other committee members, Patricia Keating and Tobin Mintz, were also very generous with their help.

I could not have accomplished nearly so much, and with so little loss of sanity, without the UCLA Language Acquisition Lab managers—Chad Vicenik, Kristi Hendrickson, and Adrienne Scutellaro—and RAs. Thanks also to Henry Tehrani of the UCLA Department of Linguistics for building the hardware necessary to run the experiments, and to Professor James Morgan and the Metcalf Infant Research Lab at Brown University for sharing their procedure software.

I am also grateful to the NSF for the Dissertation Research Improvement Grant (BCS-0957956) that helped fund much of my research, and to the UCLA Department of Linguistics for providing such a supportive environment, both financially and intellectually, and such a friendly one too. Much appreciation is also due to Brook Lillehaugen and Asia Furmanska for being patient enough to record the stimuli, and to Colin Wilson of Johns Hopkins University for setting me on this research path in the first place.

Finally, none of this would have been possible at all without all the parents who so generously gave their time and energy—both in short supply when there's an infant around—to come in to the Lab and participate in the studies.

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PRESENTATIONS

- Thatte, V., and Sundara, M. (2010). 4.5-Month-Olds' Phonotactic Knowledge. Poster presented at the Acoustical Society of America 2nd Annual PanAmerican/Iberian Meeting on Acoustics, Cancun, Mexico.
- ud Dowla Khan, S., and Thatte, V. (2009). The phonetics of contrastive phonation in Gujarati. Poster presented at the Acoustical Society of American Annual Meeting, San Antonio, Texas.

ABSTRACT OF THE DISSERTATION

Infant Phonotactic Learning

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Doctor of Philosophy in Linguistics

University of California, Los Angeles, 2011

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For the past several decades, researchers have been investigating the stages infants go through on their way to acquiring their native language. Research into the question of the order in which, and time when, various facets of phonology are acquired has resulted in a basic timeline of development. Exploration of a second question, namely what learning mechanism infants rely on most heavily in acquiring the phonology

and phonotactics of their native language, has led to the emergence of two competing approaches: infants could be using statistical induction to deduce phonotactics from the ambient language, or they could be tapping in to biases motivated by pre-phonological, domain-specific knowledge of phonetic principles.

The research presented in this dissertation investigated both these questions. In the first half, an analysis of spoken corpus data confirmed that voiceless fricatives in fact appear more frequently word-initially in English than voiced fricatives, both in normal speech and in Infant-Directed Speech. Next, a series of infant experiments tested whether infants of 4.5, 6, and 8 to 10 months of age with monolingual American English language input display operative knowledge of the prevalence of voiceless fricatives in word-initial position, as evidenced by an attentional preference to the former over the latter. While no significant difference in attention time was found for the younger age groups, the 8- to 10-month-olds displayed a significant preference for the voiceless fricatives. This was interpreted as preliminary evidence in favor of the existence of either a statistical induction learning mechanism, or an *a priori* bias founded on inductive grounding (Hayes, 1999), as either learning mechanism would be predicated on knowledge gained through observation of properties of the input. Therefore, it would be reasonable for either one's effects to be more apparent slightly later in development, when the infant has had sufficient input and/or time to acquire this knowledge. Furthermore, the pooled data from all three age groups uncovered a significant preference for voiceless fricatives, indicating that infants may also have access to an *a priori* bias that is too weak to

motivate a preference on its own, and therefore further impetus from statistical learning must be present for the infants to have a significant preference.

The second half of the dissertation turned to exploring the question of which learning mechanism is dominant at the time that infants first show a strong preference for voiceless initial fricatives. This was accomplished first by exposing 8- to 10-month-old infants to only dental word-initial fricatives, of which [θ] has a higher word-initial token frequency—so that it should be preferred if the infants are using statistical induction—while [θ] is more in keeping with the principle of ease of articulation (Ohala, 1997)—so that it should be preferred if the infants are being guided by an unlearned bias. No significant preference was found in attention to either condition, a result which appeared to indicate that either (a) both an *a priori* bias and statistical learning are operative, but they exert equal influence, or (b) the statistical learning mechanism is stronger, but facts about the types of words making up the vast number of [θ]-initial tokens are weakening its effect in this case. The final experiment tested whether the knowledge demonstrated in the first series of experiments is generalized to the featural level, by investigating whether 8- to 10-month olds' preference for voiceless fricatives is generalized to Polish fricatives. No significant preference was found in the final experiment alone, nor when the data were pooled with those from the experiment testing infants' preference for either class of English fricatives, confirming that infants' statistically-gained knowledge is not generalized across segments.

Chapter 1 ♦ Introduction

1.1 Overview

For the past several decades, linguists and psychologists have been investigating the stages infants go through on their way to acquiring their native language. Research into the question of the order in which, and time when, various facets of phonology—including phonotactics—are acquired has resulted in a basic timeline of development. Exploration of a second question, namely what learning mechanism infants rely on most heavily in acquiring the phonology of their native language, has led to the emergence of two competing approaches: infants could be using statistical induction to deduce phonotactics and other phonological regularities, or they could be tapping into biases motivated by *a priori*—that is, pre-phonological—knowledge of phonetic principles.

The research program described in this dissertation was conducted with the aim of further contributing to the literature investigating both these questions. A first series of experiments was conducted with two aims. The first was to determine whether infants of 4.5, 6, and 8 to 10 months of age with monolingual American English language input display operative knowledge of the prevalence of voiceless fricatives over voiced fricatives, as evidenced by an expected listening preference in favor of voiceless fricatives. The test sounds were restricted to word-initial position, as previous research has indicated that sounds in initial position are more salient to infants than sounds in final position (Zamuner, 2006). The results from each of the separate experiments showed that though infants of 4.5 and 6 months do not yet show evidence of such knowledge, infants

of 8 to 10 months do, as evidenced by a significant listening preference in favor of voiceless fricatives. However, when the results from all three age groups were pooled, a significant preference for the voiceless fricatives on the part of all the infants together emerged, indicating that infants may have a small amount of knowledge at the younger ages as well.

The second purpose of these first three experiments was to provide preliminary information regarding the question of which learning mechanism is dominant at this stage: despite the fact that the use of either mechanism should result in an attentional preference in favor of voiceless fricatives, the age at which such a preference would be likely to emerge differs depending on the mechanism implicated.

Both mechanisms should influence infants to pay longer attention to voiceless fricatives because they are both statistically more common in English—generally and word-initially—and physically easier to produce and perceive than voiced fricatives. This latter fact is due to the oral configuration required to produce a fricative: the air pressure behind the relevant articulator must be high in order to cause the air turbulence to be perceived as frication. However, the production of voicing requires the air pressure above the glottis to be low, so that the air being pushed out of the lungs can flow through the constricted glottis at a high enough speed to produce vibration. Thus, the two components make essentially opposing demands on the physical state of the oral cavity in voiced fricatives, while voiceless fricatives involve no such conflict (Ohala, 1997). Longitudinal studies of child speech production indicate that children generally produce voiceless fricatives before their voiced counterparts, which could be due to ease of

articulation (see e.g. Stoel-Gammon, 1985), or to the greater prevalence of voiceless fricatives in English.

While infants should thus prefer voiceless word-initial fricatives in either case, the predictions regarding when such a preference should emerge differ depending on the learning mechanism. If an innate *a priori* bias is operative, younger infants should display the preference particularly clearly, as they have yet to acquire a large amount of other information about the phonology and phonotactics of their native language that could influence their attention otherwise. If, on the other hand, either statistical induction or an *a priori* bias resulting from observation of the relative difficulty of pronunciation of different segments is the learning mechanism relied upon by infants as they acquire their native phonology, one would expect that infants might not show a preference for either voicing category until they are somewhat older, and have had time to gather enough statistical information to guide their attention. Thus, infants might plausibly indicate no preference when they are 4.5 or 6 months old, as in Experiments 2 and 3, but show a preference for voiceless fricatives by the time they reach 8 to 10 months of age, as in Experiment 1, by which time experiments have shown that they have learned a good deal about native language phonotactics. Yet the significant preference for voiceless fricatives that emerged from the pooled data of all three age groups indicates that infants have some knowledge regarding the different classes of sounds at ages younger than 8 months, but that the preference the knowledge leads them to show is extremely weak. This would seem to indicate that an *a priori* bias is also at work, but that it is too weak to lead infants to prefer voiceless fricatives without added motivation from statistical learning.

The second set of experiments turned to directly exploring the question of which learning mechanism—statistical induction, or an *a priori* bias either of innate origin, or developed through direct and indirect experience regarding the relative articulatory difficulty of various sounds—is dominant at the time that infants first respond to the discrepancy between voiced and voiceless initial fricatives, and whether the resulting knowledge is codified at a segmental level or generalized to a featural level. To answer the first part of this question, 8- to 10-month-old infants were exposed to only the syllables from Experiment 1 that began with English dental fricatives. One of these, [θ], is more in accord with the principle of ease of articulation (Ohala, 1983, 1997),¹ especially in word-initial position, and is more common in word types of English. The other, [ð], is statistically much more common in adult running speech, giving it a vastly higher token frequency, according to counts based on both CELEX (Baayen, Piepenbrock, & Gulikers, 1995) and CHILDES (MacWhinney, 2000).² Thus, infants should demonstrate a preference for word-initial [θ] if they are relying on an *a priori* bias, regardless of its source, and for [ð] if statistical learning is operative. In the end, the experiment found a lack of preference on the part of 8- to 10-month-old infants for either word-initial fricative. Taken together with the outcome of the first series of experiments, these results do suggest that infants are aware of the difference in relative statistical frequency of the dentals when compared to other fricatives of English, as otherwise a

¹ An alternative account based on ease of perception rather than ease of articulation, presented in Balise & Diehl (1994), cites the fact that the aerodynamics of voicing necessarily reduce the high frequency noise that is a strong cue to sibilant fricatives. Thus, maintenance of voicing during a sibilant is undesirable because it reduces the perceptual distinction between fricatives and approximants.

² For details, see 2.3 Stimuli and Appendix E: List of CHILDES Transcripts Analyzed.

continued preference for the voiceless fricative would be expected. However, the statistical learning mechanism is not strong enough to motivate infants to show a preference for the voiced fricative, again indicating that the two mechanisms—statistical induction and an *a priori* bias—must favor the same sounds in order for infants to show a significant preference.

A final experiment utilized Polish stimuli to test whether the knowledge demonstrated in Experiment 1 seems to be operative at the segmental or featural level, by investigating whether 8- to 10-month olds' preference for voiceless fricatives is generalized to nonnative sounds, or restricted to phones that are available in the infant's input. The experiment additionally addressed the learning mechanism question. An *a priori* bias should lead infants to prefer the voiceless Polish fricatives, for the same reasons that it should motivate them to prefer voiceless English fricatives. The statistical mechanism would also drive infants to prefer voiceless Polish fricatives, if infants' statistical knowledge is implemented at the featural level and therefore easily generalized from familiar sounds to unfamiliar ones. Alternatively, statistical induction could allow for a lack of preference in either direction, if the knowledge is restricted to the segmental level, preventing them from applying it to new sounds. The results showed no preference for either voicing category of Polish stimuli, indicating that infants' statistical knowledge appears to be operative at the segmental level and providing further evidence in favor of the idea that both mechanisms must be in accord for a significant preference to emerge.

1.2 Outline of the Dissertation

The remainder of the dissertation is organized as follows. Chapter 2 explains the Headturn Preference Procedure (Kemler Nelson et al., 1995) and how it was used in conducting the experiments, as well as the criteria used to select subjects. Chapter 3 provides a review of the literature regarding infant phonotactic development. Chapter 4 through Chapter 6 describe the results of Experiments 1 through 3 respectively, which tested infants at 8 to 10, 4.5, and 6 months of age to determine whether they prefer voiced or voiceless initial fricatives. Chapter 7 analyzes the aggregate results of Experiments 1 through 3, and addresses how these results fit into the timeline of infant phonotactic development, as well as what information they provide regarding possible learning mechanism. Chapter 8 summarizes previous research related to infant language learning mechanisms, and Chapter 9 and Chapter 10 add the results of Experiments 4 and 5, which respectively asked whether a preference uncovered in the first series of experiments was due to the proposed *a priori* bias in favor of phonetic principles or to statistical learning of regularities of English, and whether the preference extends to novel segments. Chapter 10 additionally considers the implications of these experiments' results for the questions of learning mechanism and knowledge codification, and Chapter 11 summarizes the overall contributions of the results uncovered by the research program.

Chapter 2 ♦ Experimental Methods

2.1 Experimental Procedure: The HPP

All experiments described in this dissertation followed the Headturn Preference Procedure (HPP) (Kemler Nelson et al., 1995). The procedure varied between experiments only in the stimuli to which the infants were exposed.

2.1.1 Experiment Booth Layout

In the HPP method, the infant is seated on a caregiver's lap in the middle of a three-sided peg-board booth. Three lights are visible to the infant: one red light on each side, and a blue light in front. Stimuli are played from speakers located behind the red lights, and infant responses are monitored by the experimenter via a television screen connected to a video camera placed above the front blue light. The caregiver and experimenter listen to masking music via headphones to avoid influencing or misinterpreting the infant's visual orientation.

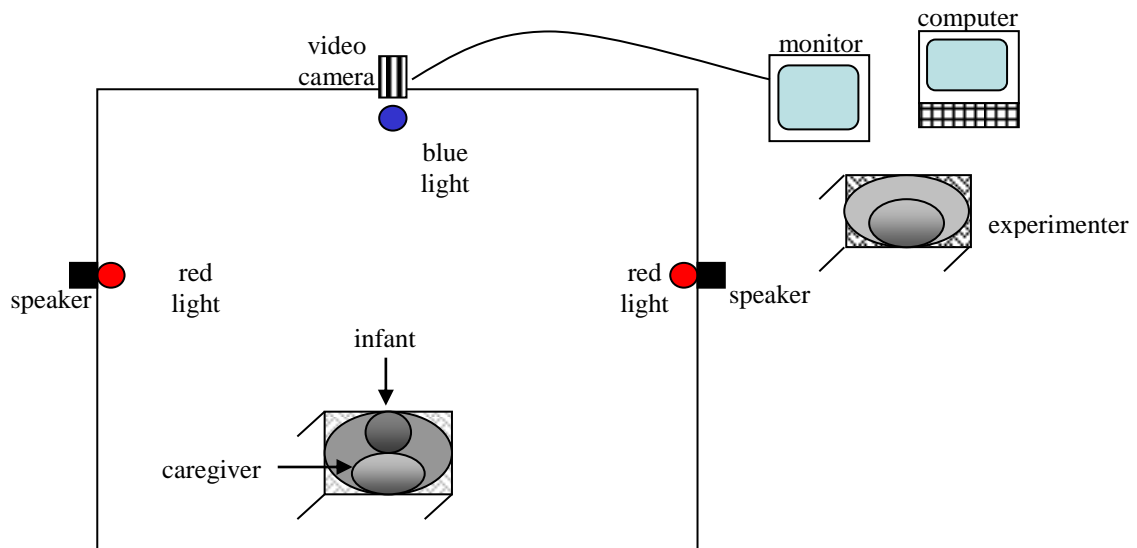


Figure 1: HPP Setup

2.1.2 HPP Procedure

An HPP experiment is most commonly organized into two phases, familiarization and testing. The two phases, with distinct purposes, differ only in the stimuli to which infants are exposed. Thus, in both phases, a trial begins when the center blue light begins flashing. It continues to do so in silence until the infant's attention is gained, immediately after which it shuts off and a randomly chosen side light begins to flash, but again without auditory stimuli. Once the infant turns approximately 30° toward the flashing side light, an auditory stimulus begins to play from the same side and the length of the infant's attention is recorded. This continues until either the maximum trial length is reached or the infant looks away for more than two seconds at a time, at which point the current trial ends and a new trial begins. Data is collected in this procedure in the form of measurements of total infant looking time to each trial.

In the canonical HPP, the familiarization phase is used to 'train' or 'familiarize' the subject on a given type of language stimulus, and the subject's learning is then tested in the following recognition phase. However, as the goal of the experiments in this research program was to investigate infants' attentional preferences for different classes of speech sounds, rather than to test their ability to learn such classes in the short term, the familiarization phase instead consisted of two 20-second-long passages of instrumental music, intended simply to accustom the infant to the procedure. This modification has been successfully used in previous preference studies to accustom the infants to the experimental setup, while still testing their preferences rather than their

learning capabilities (e.g. Jusczyk, Smolensky, & Allocco, 2002; Nazzi, Bertoncini, & Bijeljac-Babic, 2009).

The test phase followed immediately, with no change in procedure aside from the replacement of the music passages with stimulus lists. Each subject was presented with 12 test trials, six in each of the two test conditions.

2.1.3 Counterbalancing and Randomization

The computer program used to control stimulus presentation was the Headturn Preference software written by Professor James Morgan of Brown University. It counterbalanced the condition of stimulus presentation in three blocks of four trials each; during each block, two trials selected from each of the two conditions were presented. The program also randomized side of presentation, and controlled stimulus presentation within each trial by drawing randomly from the set of test stimuli in the appropriate condition. Furthermore, it monitored and recorded infant looking times as detected by the experimenter during both the familiarization and test phases.

2.1.4 Grounds for Exclusion of Data

Data from incomplete experiment sessions were excluded from analysis in all cases; such sessions were most commonly terminated due to infant fussiness. Data from completed sessions was excluded when one or more trials were compromised due to equipment malfunction or experimenter error, the latter of which was regrettably frequent due to the high degree of concentration required to record the infant's attention accurately while managing other components of the laboratory setup.

Data from infants with fricative-initial first names were furthermore excluded from the primary versions of the analyses to rule out a possible skewing of token-initial fricative frequencies in their individual language input experience due to frequent occurrences of their first name. This was identified as a possible confounding factor because parents commonly use their infant's name either in isolation (e.g., Phillips, 1973) or in a highly salient position in the sentence, even if it results in a violation of the adult grammar, (i.e., Durkin, Rutter, & Tucker, 1982) as a fairly successful attention-getter even early in the first year of life. This behavior results in 4-month-old infants learning to recognize their own first names versus other names with similar or different stress patterns (Mandel, Jusczyk, & Pisoni, 1995), and to prefer listening to passages that contain his or her name versus passages that do not at an age at which there is extremely little evidence for learning of any other word less frequent in the infant's input than "baby" (Mandel-Emer & Jusczyk, 2003).

The extremely frequent use of the infant's first name in IDS was confirmed via an analysis conducted of the CHILDES files with subjects below 1 year of age,³ which indicated that the infant's name has an extremely high number of tokens in IDS in comparison to other words. For instance, in the Joe files by Soderstrom in which the infant is less than a year old, 555 of the 43,504 tokens comprising the IDS were some version of the infant's name (*Joseph, Joseph's, Joseph P., Joe, and Jose*). This meant that the infant's name, in some form, appeared more often than all but eight words, all of

³ For a complete list of all files analyzed, and age of subject on date of recording for each file, see Appendix E: List of CHILDES Transcripts Analyzed.

which were function words (in descending order of frequency, *you, I, the, a, it, that, to,* and *and*). Due to these factors, the distribution of fricatives in the infant's linguistic input is likely to be highly skewed if his or her name begins with a fricative, and could therefore directly influence his or her attentional preference if learning at this stage is based on statistical induction.

2.2 Subject Selection

2.2.1 Recruitment

Participants were enrolled through the subject recruitment process of the UCLA Infant Language Lab. In this process, birth records are obtained from the California Department of Health and Human Services. A letter is mailed to each infant's parents inviting them to participate in infant studies at UCLA. Typically, approximately 3% of the addressees return response cards. Once parents return a response card with contact information and relevant biodata, the infant is entered into the UCLA Developmental Research Participant Pool. When an infant is the right age for an experiment, his or her parents are contacted. The study is explained to the parents before parents are asked whether they are interested in participating in it. If parents are interested and available, an appointment for a lab visit is made at their convenience. Parking is provided, and the child is offered a small gift as a token of appreciation.

2.2.2 Inclusion Criteria

Only full-term infants (born no more than 14 days early) with a birth weight greater than 5 lbs. 9 oz. were tested. The infants were also screened, based on parental report, for normal (or corrected) vision; general good health; no history of hearing,

learning, or speech disorders; a history of no more than three ear infections; and no cold or ear infection symptoms on the day of testing.

2.2.3 Language Input Requirement

To ensure that subjects were acquiring English monolingually, language background was determined via a detailed parental questionnaire based on Bosch & Sebastián-Gallés (2001); this questionnaire was used previously in Polka & Sundara (2003), Sundara, Polka, & Molnar (2008), and Sundara & Scutellaro (in press). Infants who received 90% or more of their input in English were considered English monolingual.

2.3 Stimuli

Fricatives were chosen to be the crucial word-initial segments for all experiments due to special properties of the statistical distribution of certain voiced versus voiceless fricatives in English. According to the CELEX database of spoken English (Baayen, Piepenbrock, & Gulikers, 1995), there are anywhere from 4 to 2,700 times as many tokens beginning with voiceless fricatives as tokens beginning with voiced fricatives for most places of articulation in English. Type frequencies are equally skewed in favor of voiceless fricatives, with anywhere from 5 to 343 times as many voiceless-initial types as voiced-initial types. However, the token frequencies of the dental fricatives have the opposite distribution from all other pairs: because of its presence at the beginning of many function words of English (*than, that, the, their, theirs, them, themselves, then, thence, there, therefore, these, they, this, those, though, and thus*), the voiced dental fricative [ð] is seven times more common than voiceless [θ] in word-initial position in

running speech. Table 1 gives the raw numbers for both type and token frequencies of the fricatives in initial position in CELEX.

Fricative Place and Voicing			Types	Tokens
Bilabial	Voiceless	[f]	1,474	43,891
	Voiced	[v]	356	11,002
Dental	Voiceless	[θ]	201	18,437
	Voiced	[ð]	42	132,248
Alveolar	Voiceless	[s]	3,248	82,566
	Voiced	[z]	26	487
Postalveolar	Voiceless	[ʃ]	343	8,144
	Voiced	[ʒ]	1	3

Table 1: Type and Token Frequencies for Initial English Fricatives in CELEX

An analysis of type and token frequencies in Infant-Directed Speech (IDS) was also conducted, utilizing the CHILDES database (MacWhinney, 2000). In the analysis, all transcripts of parent-child sessions with infants of less than one year of age⁴ were mined for non-infant speech using CLAN (MacWhinney, 2000). The resulting utterances were separated into individual words, and all but the fricative-initial words were eliminated. Instances of the infant's name were also excluded, as examination of the resulting word bank indicated an extremely high frequency of the infant's name in comparison to other words; thus, the statistical distribution of different phonemes in the input could be highly skewed for individual children, depending on the phones contained in their respective names. The remaining words were then annotated by hand for standard pronunciation of the initial fricative (aside from a few utterances wherein the recording was consulted for pronunciation) and subsequently organized into types using the Typizer

⁴ For a complete list of all files analyzed, and age of subject on date of recording for each file, see Appendix E: List of CHILDES Transcripts Analyzed.

computer script (Hayes, n.d.). The results of the analysis indicated that the proportions of voiceless to voiced types and tokens in speech common to infants' environments were very similar to those found in CELEX.

Fricative Place and Voicing			Types	Tokens
Bilabial	Voiceless	[f]	322	7,130
	Voiced	[v]	52	645
Dental	Voiceless	[θ]	56	2,915
	Voiced	[ð]	40	24,191
Alveolar	Voiceless	[s]	816	16,665
	Voiced	[z]	36	232
Postalveolar	Voiceless	[ʃ]	125	2,209
	Voiced	[ʒ]	0	0

Table 2: Type and Token Frequencies for Initial English Fricatives in CHILDES

In both corpora, all voiceless fricatives were more common than voiced ones in types, with the greatest disparity in the alveolar and postalveolar pairs. Labial, alveolar, and postalveolar voiceless fricatives were also more common in tokens, again with a much wider gap in the alveolar and postalveolar places of articulation. The proportions reverse in the case of voiceless versus voiced dental tokens, being vastly in favor of the voiced segment in both corpora due to the presence of [ð] at the beginning of many function words of English. While the proportions do not reverse when only types are considered, it is implausible that infants younger than 11 months have accomplished enough word learning to be able to track type frequencies: in an extensive study of infant vocabulary using the MacArthur Communicative Development Inventory, Fenson et al. (1994) found that most infants have learned less than two dozen content words by the age of 11 months.

Because of the exceptional distribution of the dental fricatives in running speech in English, this manner class of consonants is an ideal set of stimuli to be used in trying to separate out possible effects of the two learning mechanisms, discussed in detail in Chapter 8. The non-dental fricatives were used word-initially in the bulk of the stimuli for Experiments 1 through 3, so that either learning mechanism—statistical induction or an *a priori* bias—could be used by infants to generate the same preference. In contrast, Experiment 4 tested only for infant preference for the voiced versus voiceless dental fricative in word-initial position. In this case, statistical induction would favor the voiced fricative due to its high token frequency, while the *a priori* bias would favor the voiceless fricative due to its relative ease of articulation in initial position. Thus, a preference for [ð] in Experiment 4 would be interpreted as evidence for the use of statistical induction, and a preference for [θ] as evidence for an *a priori* bias.

2.3.1 Stimulus Recording

The stimuli for the English phoneme-based experiments were recorded by a female native speaker of American English in her twenties, with phonetic training but no knowledge of the purpose of the experiment. The speaker produced the stimuli in the speaking style often used in Infant-Directed Speech, which utilizes an exaggerated pitch range and vowel lengthening. The stimuli for Experiment 5 were recorded by a female bilingual speaker of American English and Polish in her twenties, again in an IDS style. The intensity of all stimulus tokens was normalized to 80 dB using a Praat script written by Chad Vicenik of the UCLA Linguistics Department.

Experiments, Part I:

Adding to the Timeline of Phonotactic Development

This part of the dissertation summarizes the literature on infant phonotactic development and describes Experiments 1 through 3, in which infants from three age groups with monolingual English input were exposed to word-initial voiceless versus voiced fricatives taken from the American English phoneme inventory. These first three experiments add to the timeline of development, in addition to addressing the question of which learning mechanism is relied upon at this stage.

Chapter 3 ♦ Previous Research

At 6 months of age, infants appear to have little knowledge about the phonotactics of their native language. They can distinguish legal words of the native language, in this case English, from legal words of a phonotactically very different language, here Norwegian (Jusczyk et al., 1993), and prefer stop-liquid onset clusters that have high or medium type frequency in English—[pɹ] [tɹ] [kɹ] and [pl] [bl] [kl] [gɹ], respectively—over stop-liquid onset clusters that have a low frequency of type occurrence, namely [bl], [dɹ], and [gl] (Archer, 2008), but no other phonotactic knowledge has yet been uncovered in this age group.

By 8 months, however, girls acquiring English monolingually are able to distinguish CVC nonwords composed of frequent versus infrequent diphones (Zamuner, 2001),⁵ whereas boys are able to do so at 9 months (Gerken, 2002). At 9 months, infants of both sexes also prefer to listen to nonword CVC monosyllables with high probability onsets, codas, and segment transitions over nonwords with low probabilities, even though 6-month-olds show no preference (Jusczyk, Luce, & Charles-Luce, 1994). Nazzi, Bertoncini, & Bijeljac-Babic (2009) demonstrated that French-learning 10-month-olds, but not 6-month-olds, prefer to listen to words with initial labial and medial coronal consonants, which are more common in French, over words with initial coronal and medial labial consonants, which are less common in French. Furthermore, Mattys et al. (1999) found that 9-month-old infants also prefer words with high-probability within-word internal consonant sequences to words with high-probability between-word sequences. Friederici & Wessels (1993) additionally discovered that infants of 9 months, but not 4.5 or 6 months, prefer to listen to nonword monosyllables beginning or ending with positionally legal clusters of English (such as /**b**ref/ and /murt**t**/) over words that switch the clusters so that they are positionally illegal in English (as in */fe**br**/ */rtum/). A further experiment showed that Dutch-learning infants exhibit the same preference when exposed to positionally legal and illegal clusters of Dutch. Additionally, Dutch-learning infants even show the same preference when test items with legal or illegal offset clusters are presented between identical CVC syllables (for example, /mig d**int**

⁵ However, Gerken (2002) notes that Zamuner (2001) does not control for individual phone frequency.

mig/ in the legal condition and /mig fe**br** mig/ in the illegal one), demonstrating that they can also apply their learned knowledge of native phonotactics in context.

With all this in mind, we now turn to the first set of experiments conducted in this research program, which assessed whether infants show a preference for voiceless fricatives over voiced ones in initial position at three ages: 4.5, 6, and 8 to 10 months.

Chapter 4 ♦ Experiment 1: 8 to 10 Months

The first experiment in Part I of the research program investigated whether infants of 8 to 10 months of age prefer voiceless initial fricatives over voiced ones, laying the groundwork for subsequent experiments testing at what age such a preference surfaces.

4.1 Subjects

23 infants were tested in Experiment 1. The results of seven were excluded from primary analysis: three due to experimenter error, one due to outside interruption, and three for having a fricative-initial first name.⁶ The remaining 16 infants (two female and 14 male⁷) ranged in age from 252 to 316 days (8.3 to 10.4 months), with a mean age of 284 days (9.3 months).

4.2 Stimuli

The stimuli used in Experiment 1 consisted of 13 CV syllables, seven of which began with phonemically voiced English fricatives, shown in (1), and six of which began with phonemically voiceless English fricatives, shown in (2).⁸ The relevant fricatives were placed in initial position because previous research has indicated that sounds in initial position are more salient to infants than sounds in final position (Zamuner, 2006).

⁶ See §2.1.4 Grounds for Exclusion of Data above.

⁷ In this and all experiments reported here, sex was included as a variable in the primary analysis and found to have no significant main effect or interaction, so it is not reported as a factor in the analyses.

⁸ The inclusion of a single token of [ʒu] in the voiced condition was a mistake on the part of the author, regrettably not noticed until the experiment was complete. However, to the best of the author's knowledge, this error does not affect the validity of the experiment's results.

- (1) [v^heɪ], [vu], [ð^hɑ], [ð^hu], [ʒ^heɪ], [ʒɑ], [ʒu]
- (2) [f^heɪ], [fu], [θ^hɑ], [θ^hu], [ʃ^heɪ], [ʃɑ]

In compiling the list of stimuli to be used, caution was taken to exclude all actual words of English, along with their correspondents in the opposing condition. Previous work has shown that infants may already be able to segment words from the speech stream by this time (e.g., Aslin, Saffran, & Newport, 1998; Shi et al., 2006) using frequent function words (Shi & Lepage, 2008), and a few weeks later at 11 months of age, are able not only to use frequent function words to aid segmentation (Kim & Sundara, 2010), but also to distinguish real function words versus foils (Shi, Werker, & Cutler, 2006). Furthermore, Friederich & Friederici (2005) found that 12-month-olds showed more negative responses early in processing in the frontal, lateral frontal, and temporal areas of the brain when listening to real words that either matched or did not match a picture than when listening to nonsense words, indicating that they already had some knowledge of the individual words' lexical semantics. Therefore, real words were excluded to avoid a possible confound arising if infants recognized them. In order to compensate for the consequently small number of stimulus types and avoid infants becoming too fussy to complete the experiment due to boredom, two non-word syllables beginning with dental fricatives were included in each condition of stimuli despite the fact that the relative frequency of the dental fricatives in word-initial position in English goes against the relative frequency of the other fricative pairs.

The stimuli were recorded by a female native speaker of American English in her twenties, with phonetic training but no knowledge of the purpose of the experiment. The

speaker produced the stimuli in an IDS speaking style. For a complete list of the stimuli used in Experiment 1, see Appendix A:.

4.3 Results and Discussion

The 8- to 10-month-olds looked significantly longer to the voiceless condition ($t(15) = -1.73, p = 0.05$ in a one-tailed paired t test, with an effect size of 0.27). As a group, the infants looked at the stimuli with voiced initial fricatives for 10.2 seconds (SD=3.8), and those with voiceless initial fricatives for 11.2 seconds (SD=3.2), for a mean difference of 1.0 seconds, as shown in Figure 2.

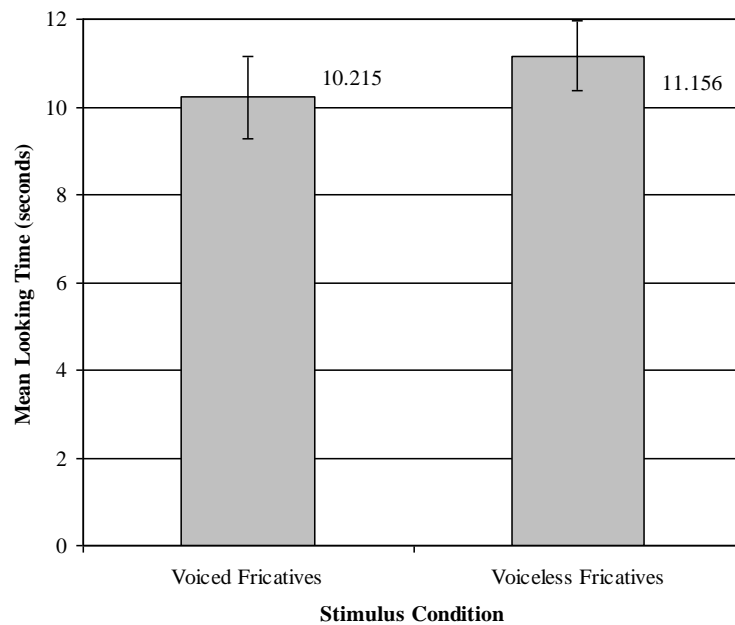


Figure 2: 8- to 10-Month-Olds' Attention to Voiced vs. Voiceless Fricatives with Standard Error Bars

Five infants listened longer to the voiced stimuli, and 11 to the voiceless stimuli, as can be seen in Table 3.

Subject Number	Preferred Condition (\pm Voice)	Mean Looking Times in Seconds	
		Voiced Condition	Voiceless Condition
1	–	13.6	17.1
2	–	10.4	13.2
3	–	12.3	12.9
4	–	6.7	10.5
5	–	4.5	8.5
6	+	15.0	13.0
7	–	6.7	9.0
8	–	7.6	8.9
9	+	9.2	8.8
10	–	14.8	15.9
11	–	10.2	10.9
12	–	5.6	5.9
13	+	8.6	6.6
14	+	14.2	14.2
15	+	16.5	13.1
16	–	7.6	10.0

Table 3: Individual Mean Looking Times in Experiment 1

Thus, a marginally significant preference on the part of 8- to 10-month-old infants was found for voiceless word-initial fricatives over voiced ones. Interestingly, if this preference arises from statistical induction, it is possible that the marginality of the significance could result from the inclusion of the dental fricatives in the stimuli. As discussed in section 2.3 above, the word-initial token frequency of [ð] is much higher in running speech than that of [θ], a distribution which is in contrast with that of the other fricative pairs, whose voiceless counterparts are more common than the voiced ones. Therefore, the conflicting information from the dentals could weaken what would otherwise be a stronger preference for the other voiceless fricatives. This possibility is examined further in Experiment 4 in Chapter 9, which examines infant attention to stimuli beginning with only the dental fricatives.

Chapter 5 ♦ Experiment 2: 4.5 Months

In order to more accurately determine at what age the preference for voiceless initial fricatives emerges, Experiment 2 turned to examining the reactions of much younger infants. The results of this experiment also serve to further probe the question of which learning mechanism drives the preference. If an innate *a priori* bias is responsible for the preference uncovered in Experiment 1, then the bias should also surface at younger ages. On the other hand, if either a bias resulting from inductive grounding or a statistical induction mechanism is the cause, very young infants might not show any preference.

4.5 months was the age group selected for testing in this experiment, as this is the youngest age at which infants can be relied upon to have the motor skills and coordination necessary to perform the head turns that are measured as indicators of attention in the HPP, yet previous research has demonstrated that infants of 4.5 months can already distinguish consonant phones on the basis of voicing (Eimas et al., 1971).

5.1 Subjects

35 infants were tested in Experiment 2. The results of 11 were excluded from the analysis: three due to fussiness, two due to equipment malfunction, three due to experimenter error, and three for having a fricative-initial first name.⁹ The remaining 21 infants (11 female and ten male) ranged in age from 107 to 150 days (3.5 to 5.0 months), with a mean age of 127 days (4.2 months).

⁹ See §2.1.4 Grounds for Exclusion of Data above.

5.2 Stimuli

The stimuli used in Experiment 2 consisted of 24 CV syllables, half of which began with phonemically voiced fricatives, shown in (3), and the other half of which began with phonemically voiceless fricatives, shown in (4). The stimuli were recorded by the same speaker and in the same style as the stimuli for Experiment 1.

(3) [vi], [veɪ], [va], [vu], [zi], [zeɪ], [za], [zu], [ʒi], [ʒeɪ], [ʒa], [ʒu]

(4) [fi], [feɪ], [fa], [fu], [si], [seɪ], [sa], [su], [ʃi], [ʃeɪ], [ʃa], [ʃu]

It was judged unnecessary to exclude real words of English from the stimuli for this experiment, as infants of this age are too young to have accomplished enough word learning for it to be plausible for them to recognize real words to a degree that would influence their looking times to one condition versus the other. Therefore, the dental fricatives were excluded from this set of stimuli entirely, in order to avoid including a possible confounding factor: if infants rely on statistical learning at this age, then the fact that dental fricatives' relative statistical frequency pattern is contrary to that of other fricatives of English could cancel out a preference for the voiceless fricatives as a group that might otherwise emerge.

5.3 Results and Discussion

The 4.5-month-old infants looked at the stimuli with voiced initial fricatives for 15.2 seconds (SD=2.9), and those with voiceless initial fricatives for 15.7 seconds (SD=3.1), for a mean difference of 0.5 seconds, as shown in Figure 3. In a paired *t* test, no significant difference in infant looking times to the two conditions was found ($t(20) = -1.01, p = 0.16$, one-tailed, with an effect size of 0.17).

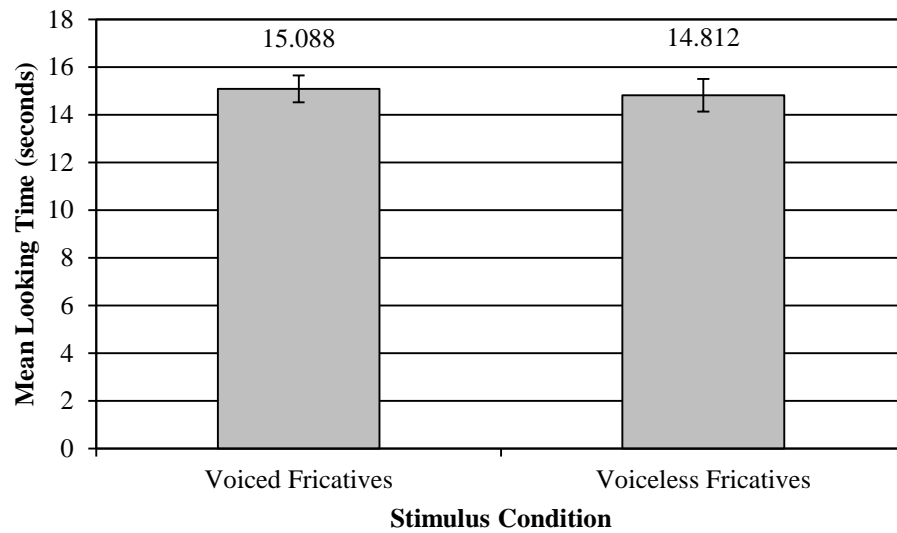


Figure 3: 4.5-Month-Olds' Attention to Voiced vs. Voiceless Fricatives with Standard Error Bars

Eight infants listened longer to the voiced stimuli, whereas 13 listened longer to the voiceless stimuli, as shown in Table 4: Individual Mean Looking Times in Experiment 2.

Subject Number	Preferred Condition (\pm Voice)	Mean Looking Times in Seconds	
		Voiced Condition	Voiceless Condition
1	–	14.3	17.5
2	–	11.4	11.9
3	–	18.6	19.4
4	–	12.5	16.9
5	+	16.9	15.5
6	–	17.7	17.8
7	+	12.4	12.2
8	–	14.0	16.5
9	+	17.7	15.8
10	–	16.0	16.3
11	+	20.1	19.6
12	+	17.3	16.1
13	+	18.8	16.1
14	–	13.5	17.1
15	+	16.1	13.3
16	–	16.9	17.6
17	–	8.4	8.9
18	–	12.4	12.6
19	+	14.1	9.2
20	–	15.1	17.5
21	–	14.2	18.6

Table 4: Individual Mean Looking Times in Experiment 2

As no significant preference for either voiced or voiceless fricatives was found on the part of the 4.5-month-olds, the results of Experiment 2 seem to give preliminary evidence that the 8- to 10-month-olds' preference for voiceless fricatives is likely either the result of statistical learning, or of an *a priori* bias based on inductive grounding, as either mechanism would require enough input, and therefore time, to gain the knowledge that would form the basis for such a preference. The following experiment addresses this question further, by testing infants at an age between 4.5 and 8 to 10 months to see whether they have yet developed a preference.

Chapter 6 ♦ Experiment 3: 6 Months

The lack of significant preference on the part of 4.5-month-olds for either fricative voicing condition in Experiment 2 could be due to many causes, including age-specific factors irrelevant to the research questions. For example, since it is not until 6 months that infants first show awareness of native language phoneme categories—and even then, only for vowels—(Kuhl et al., 1992; Polka & Werker, 1994), it is possible that the 4.5-month-olds were detecting non-phonemic differences within each stimulus category that were more salient to them than the phonemic voicing difference. Therefore, Experiment 3 tested slightly older infants on the same stimuli to determine whether they would demonstrate a preference. 6 months was chosen as the second age group to be tested since this the earliest age at which infants demonstrate any knowledge of native phoneme categories, but still have yet to develop any substantial native-language phonotactic knowledge (Jusczyk, Luce, & Charles-Luce, 1994; Nazzi, Bertoncini, & Bijeljac-Babic, 2009).

6.1 Subjects

22 infants were tested in Experiment 3. The results of six were excluded from the analysis: two due to fussiness, one due to experimenter error, one due to caretaker interference, and one for having a fricative-initial first name.¹⁰ The remaining 16 infants (six female and ten male) ranged in age from 167 to 205 days (5.5 to 6.7 months), with a mean age of 187 days (6.1 months).

¹⁰ See §2.1.4 Grounds for Exclusion of Data above.

6.2 Stimuli

The stimuli used were the same as in Experiment 2, as listed in (3) and (4) above.

6.3 Results and Discussion

As a group, the infants looked at the stimuli with voiced initial fricatives for 10.8 seconds (SD=3.5), and those with voiceless initial fricatives for 11.3 seconds (SD=3.6), for a mean difference of 0.5 seconds, as shown in Figure 4. No significant difference was found in infant looking times to either condition ($t(15) = -0.73$, $p = 0.24$ in a one-tailed paired t test, with an effect size of 0.16).

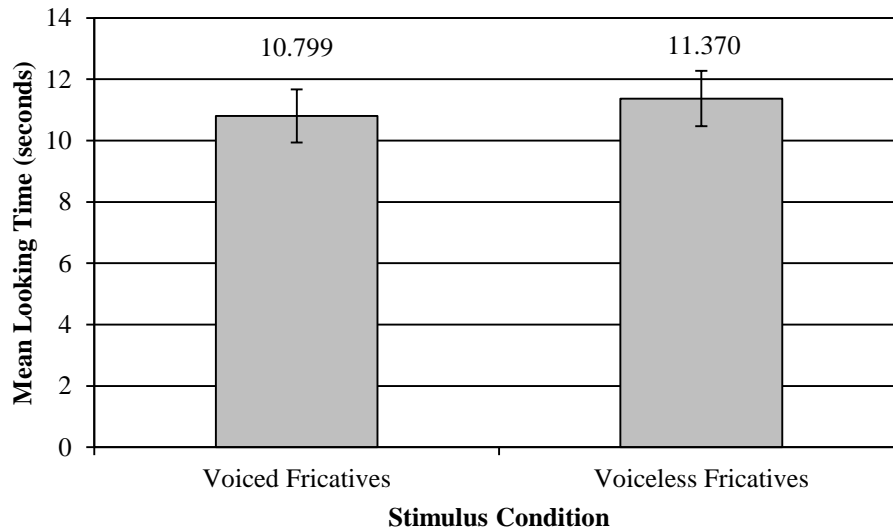


Figure 4: 6-Month-Olds' Attention to Voiced vs. Voiceless Fricatives with Standard Error Bars

Seven infants listened longer to the voiced stimuli, and nine to the voiceless stimuli, as shown in Table 5: Individual Mean Looking Times in Experiment 3.

Subject Number	Preferred Condition (\pm Voicing)	Mean Looking Times in Seconds	
		Voiced Condition	Voiceless Condition
1	–	11.8	13.0
2	+	12.9	9.1
3	+	17.2	16.4
4	–	6.4	9.3
5	+	7.2	4.9
6	+	14.7	13.2
7	+	13.2	11.1
8	+	11.1	7.7
9	–	13.6	18.2
10	–	6.9	7.8
11	+	13.8	11.5
12	–	6.9	9.5
13	–	7.7	15.2
14	–	7.7	8.7
15	–	13.4	15.2
16	–	8.2	11.2

Table 5: Individual Mean Looking Times in Experiment 3

As in the case of the 4.5-month-olds in Experiment 2, the 6-month-olds tested in Experiment 3 fail to show a preference for either voiced or voiceless fricatives, providing more evidence against an innate *a priori* bias in favor of easily articulated sounds, and for either statistical learning or an *a priori* bias based on inductive grounding.

Chapter 7 ♦ Results and Discussion for Part I

7.1 Analysis of Part I Results

First, the data from Experiments 2 and 3 were analyzed together to determine whether there was any evidence that infants younger than the established age range for demonstrated statistical learning abilities might have a preference for the voiceless fricatives that would emerge as significant with a larger group of subjects. A repeated-measures ANOVA, with looking time to each condition as the within-subjects factors and age as the between-subjects factor, found a main effect of age ($F(1,35)=19.70$, $p<.001$, one-tailed), indicating merely that the two age groups differed in their attention spans overall, but no main effect of condition ($F(1,35)=1.46$, $p=0.12$, one-tailed) and no significant interaction of age and condition ($F(1,35)=0.004$, $p=0.47$, one-tailed), indicating that the infants showed no preference for either condition, either in the separate experiments or as a combined group.

Next, the data from all three age groups were analyzed together using a repeated-measures ANOVA, with looking time to each condition as the within-subjects factors and age as the between-subjects factor. The analysis found neither a significant interaction of age and condition ($F(2,50)=0.09$, $p=0.46$, one-tailed), nor a main effect of age ($F(2,50)=0.14$, $p=0.43$, one-tailed), but did find a main effect of condition ($F(1,50)=4.78$, $p=0.02$, one-tailed).

To confirm the significance of the effect of condition, the data were examined further. The infants of all three age groups together were found to have a mean looking

time to the voiced condition of 12.4 seconds (SD=4.0), and a mean looking time to the voiceless condition of 13.0 seconds (SD=3.9), with an average difference of 0.6 seconds, as shown in Figure 5. A one-tailed paired t test showed a significant difference between looking times to the two conditions ($t(52)=1.91$, $p=0.03$, with an effect size of 0.16).

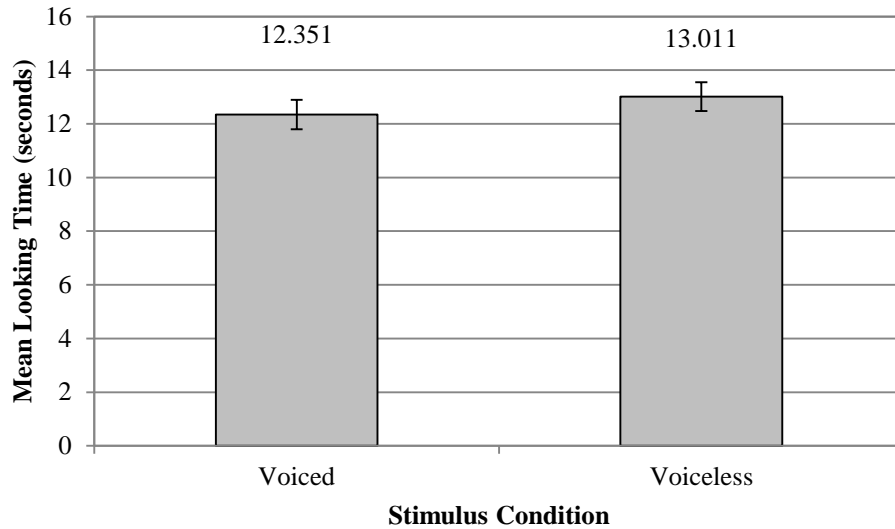


Figure 5: All Ages' Attention to Voiced vs. Voiceless Fricatives with Standard Error Bars

The appearance of a significant preference for the voiceless condition when the data from all three groups are combined appears to indicate that the younger infants could have this preference, but such a weak version of it as to be undetectable unless a large number of subjects are considered. Furthermore, the fact that both Experiment 2, with 21 subjects, and Experiments 2 and 3 combined, with 37 subjects, failed to uncover this preference suggests that the preference is very weak indeed, if it exists at the younger ages at all.

To further probe whether the three groups differed significantly in their distinction between the conditions, follow-up analyses were conducted. First, the proportion of looking times to the voiceless condition versus total looking times was calculated. To determine how many infants' listening preferences for the voiceless condition were significantly above chance, the criterion preference ratio (PR) above chance was calculated as 0.512 following Sundara, Polka, & Molnar (2008), using the formula below, wherein PR_{chance} was 0.5, the Pooled Standard Deviation was taken for all three age groups and found to be 0.058, and the effect size was small at 0.2 (Cohen, 1988):

$$(5) \quad (PR_{\text{above chance}} - PR_{\text{chance}}) / \text{Pooled Standard Deviation} = \text{Effect Size}$$

Table 6: Number of Infants with Looking Times Significantly Above Chance below gives the number of infants in each age group with above-chance looking times to the voiceless condition.

Age Group	Total # of Infants	# of Infants Above Chance
4.5 Months	21	7
6 Months	16	9
8-10 Months	16	10

Table 6: Number of Infants with Looking Times Significantly Above Chance

Figure 6 displays this information graphically, wherein the dashed line indicates the significance threshold for above chance.

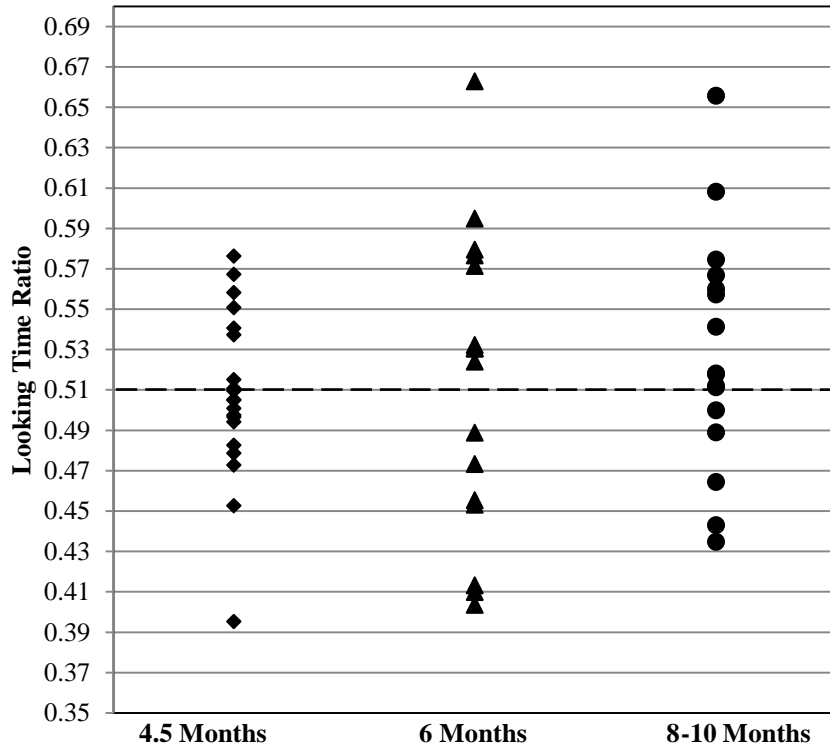


Figure 6: Ratio of Infant Looking Times to Voiceless Condition

A one-tailed χ^2 comparison of the proportions of infants looking significantly above chance was made for the three age groups, but did not show a significant effect of age ($\chi^2(2)=3.57$, n.s.).

Subsequently, the same analysis was made for each pairwise combination of age groups. No significant effect of age was found in any of the comparisons (4.5- and 6-month-olds: $\chi^2(1)=3.57$, n.s., one-tailed; 4.5- and 8- to 10-month-olds: $\chi^2(1)=3.11$, n.s., one-tailed; 6- and 8- to 10-month-olds, $\chi^2(1)=0.13$, n.s., one-tailed).

Thus, the pairwise χ^2 comparisons of the age groups provide confirmation of the ANOVA results, indicating no significant effect of age on infants' preference for the voiceless condition.

7.2 Discussion of Part I Results

Taken individually, the results of Experiments 1 through 3 in Part I appear to demonstrate that infants significantly prefer voiceless fricatives to voiced ones in word-initial position, but not until 8 to 10 months of age. These results provide preliminary evidence in favor of the dominance of either a statistical learning mechanism or an *a priori bias* based on inductive grounding, as the delay in the emergence of the preference would seem to indicate that the difference in attention is predicated on having amassed a requisite amount of input before differentiating the two groups of sounds. On the other hand, one would expect the effects of an innate *a priori* bias to be most apparent before infants have had the chance to acquire native language patterns that violate the bias. Furthermore, if the learning mechanism being used is statistical induction, the weakness of the 8- to 10-month olds' preference for voiceless fricatives could plausibly be attributed to the inclusion of dental fricatives in the stimuli for 8- to 10-month-olds, as the contradictory distribution of this pair in comparison to the other English fricatives might leave infants without a very strong preference for voiceless fricatives as a class.

Yet when the data from the three age groups are pooled, the results appear to indicate that there is some effect of condition even at the younger ages, though a very weak one. A preference for a particular condition at such young ages provides evidence in favor of the *a priori* bias hypothesis, particularly in its innate form, as it would seem implausible for a mechanism based on experience to be operative in such young infants.

Therefore, as a whole, the experiments in Part I appear to support the possibility that it is only when both the *a priori* bias and statistical learning mechanisms are

operative, and lead infants to prefer the same group of sounds, that a significant preference emerges. Because infants have not gathered enough input to make use of statistical induction until later in the first year of life, its effect is not added to that of the *a priori* bias until that time.

However, more explicit evidence is still needed to attempt to answer the question of which mechanism is dominant once both have come into effect. Experiment 4, reported in Chapter 9 below, directly probes this question by examining infants' attention to voiced versus voiceless dental fricatives only. As the voiceless dental fricative is more in line with the phonetic principles to which an *a priori* bias could reasonably refer, while the voiced dental fricative is statistically more frequent, a preference for one or the other would constitute clear evidence in favor of one learning mechanism over the other.

Experiments, Part II:

Learning Mechanism and Generalization of Knowledge

Chapter 8 ♦ Possible Learning Mechanisms

Answering the question of how infants learn their native phonology has been the motivation for much study, both theoretical and experimental. The sections below discuss the two main, and quite distinct, theoretical approaches that have emerged from this research.

8.1 Statistical Induction

The existence of a statistical induction learning mechanism has been established by several experiments demonstrating that it is used by both infants and adults in language-learning tasks (see §8.1.1 Evidence for Sensitivity to Statistical Frequency: Infant Data and §8.1.2 Evidence for Sensitivity to Statistical Frequency: Child and Adult Data below, respectively). Additional studies have further shown that this mechanism is far from being specific to human language acquisition: adult monkeys are able to exploit statistical properties of linguistic input to segment words from artificial speech (Hauser, Newport, & Aslin, 2001); human 8-month-old infants and human adults further apply statistical induction to non-linguistic tone sequences (Saffran et al., 1999); and human infants of 2, 5, and 8 months of age use the same mechanism to learn groupings of visual stimuli (Kirkham, Slemmer, & Johnson, 2002).

8.1.1 Evidence for Sensitivity to Statistical Frequency: Infant Data

Many experiments have demonstrated that infants are able to perform language-specific tasks which could only have been accomplished by tracking statistical frequency. Evidence of this ability begins to appear at 6 months of age, when infants are able to make use of statistical information to learn about their native phonology, with the result that by 8 to 9 months, infants have developed a solid foundation of knowledge regarding native phonotactics. For example, Maye, Werker, & Gerken (2002) found that 6- and 8-month-old infants are able to discriminate sounds from a phonetic continuum when trained on tokens in a bimodal distribution, but not when trained on a unimodal distribution. Following pioneering work by Werker et al. (1981) and Werker & Tees (1984), Anderson, Morgan, & White (2003) further demonstrated that at 6 months, English-learning infants are equally able to discriminate a non-native dorsal place contrast (Salish voiceless velar versus uvular ejectives) and a non-native coronal place contrast (Hindi voiceless dental versus retroflex plosives); yet by 8.5 months, they are better at distinguishing the dorsal contrast than the coronal one. The authors infer that this difference in skill is due to the fact that infants hear more coronal than velar sounds in English, and therefore have more developed native phoneme categories for coronals compared to velars, resulting in concomitant decline in the perception of non-native coronal contrasts before non-native dorsal contrasts.

Further studies have demonstrated a continued ability to use statistical induction to facilitate learning in subsequent months, when infants are able to utilize transitional probabilities to segment words. Goodsitt, Morgan, & Kuhl (1993) showed that 7-month-

olds who are trained to discriminate two specific monosyllables are subsequently able to maintain that discrimination when the syllables are embedded between two additional context syllables, but only when the resulting transitional probabilities are high between the two context syllables, but low between the context and test syllables, suggesting that the adjacent context syllables should be parsed as a word-like unit to the exclusion of the test syllables. Saffran, Aslin, & Newport (1996) and Aslin, Saffran, & Newport (1998) demonstrated that 8-month-olds are able to segment nonsense words from an artificial speech stream using only transitional probabilities, when no articulatory, acoustic, or prosodic cues to word boundaries are contained in the stimuli. Their ability is evidenced by longer listening times to non-word syllable concatenations and part-word concatenations versus trained words in test trials. Pelucchi, Hay, & Saffran (2009) extended this result by exposing English-learning infants to real, infant-directed Italian speech, revealing that infants can also segment words from fluent sentences controlled for transitional probabilities, as demonstrated by a listening preference for words contained in the familiarization phase over unfamiliar words, and a listening preference for words with high internal transitional probabilities based on the training data over words with low internal transitional probabilities. Mattys & Jusczyk (2001) also showed that 9-month-olds are able to segment words from fluent speech when cross-word-boundary consonant clusters in the training sentences have a very low probability of occurrence, and therefore are reliable phonotactic word-boundary cues, but not when they have a relatively high probability.

Infants also show evidence of using input statistics to learn phonotactic properties of their native language, as can be inferred from the experiments reviewed in Chapter 3 above: in all of these studies, infants demonstrated a preference for input with higher-probability sounds or combinations thereof over input with lower probabilities.

At 1 year of age, infants have even been shown to be able to perform a sequence of two statistical learning tasks within the same experiment. Saffran & Wilson (2003) found that, after having been familiarized with two minutes of continuous speech in which nonsense words conformed to a simple finite-state grammar, infants can discriminate between test stimuli that do and do not conform to the training grammar. This result would require the infants to first segment the nonsense words from continuous speech, and then to determine permissible orders of those words. Saffran et al. (2008) further determined—in the context of a larger study—that 12-month-old infants fail to learn an artificial grammar when statistically predictive patterns are not available as cues to the structure.

Finally, some researchers have conducted experiments using artificial language learning tasks that explicitly seek to determine whether statistical induction is sufficient to allow infants to learn patterns that lack phonetic motivation. Chambers, Onishi, & Fisher (2003) found that when trained with stimuli exhibiting syllable-position restrictions on an arbitrary group of consonants (/b/ /k/ /m/ /t/ /f/ for one group and /p/ /g/ /n/ /tʃ/ /s/ for the other), 16.5-month-olds listen significantly longer to syllables that go against the restrictions during a test phase, indicating that they are able to acquire the statistically evident restriction despite its lack of phonetic motivation. Similarly, Seidl &

Buckley (2005) showed that 9-month-olds are equally able to learn phonotactic generalizations that do not accord with phonetic principles in an experimental setting, and therefore could only be learned via statistical induction. In their first experiment, the stimuli exemplified a restriction that fricatives and affricates can occur either only word-medially (analogous to the process of spirantization, which is motivated by ease of articulation) or word-initially (apparently unattested and unmotivated). In the second experiment, the grounded pattern paired sounds according to place of articulation (labial consonants with labial vowels and alveolar consonants with front vowels) and the ungrounded pattern pairs classes of sounds arbitrarily (labial consonants with high vowels and coronals with mid vowels). In the test phases of both experiments, infants showed a significant preference for words that did not follow the trained generalization, indicating that they are able to learn both patterns based on statistical induction, regardless of phonetic motivation or lack thereof. These results would seem to indicate that infants must be relying on statistical induction, as this is the only property of the stimuli that remains the same across the two training conditions. However, Cristià & Seidl (2008) pointed out that the infants' preference could be due to the fact that some test words that violated the restriction contained novel medial segments, while the words that followed the restriction only contained segments from the familiarization phase. Therefore, the infants could simply be displaying a novelty preference that does not tap into the non-natural class-based restrictions, but merely the presence of new segments.

8.1.2 Evidence for Sensitivity to Statistical Frequency: Child and Adult Data

Natural data for the effects of statistical induction in an older child are presented in several studies by Newport and colleagues detailing the native acquisition of American Sign Language by Simon, a child of parents who are not themselves native speakers (Singleton, 1989; Ross & Newport, 1996; Newport, 1999; Singleton & Newport, 2004). Even though the adults' productions were unreliably grammatical, Simon acquired the correct version of the target structure in most cases, and generally did so at a rate comparable to the progress of other children of the same age who were receiving input from native speakers. In effect, Simon regularized his parents' irregular input, specifically by choosing the most frequent version of the grammatical structure they produced and treating that as correct. The evidence that this was Simon's (unconscious) strategy was that he showed essentially normal acquisition of morphemes that were used accurately by his parents approximately 70% of the time, but not of classifier morphemes, which his parents used correctly only 45% of the time, demonstrating that his learning clearly depended at least in part on statistical frequency.

8.2 *A Priori* Bias

8.2.1 Arguments in Favor of the *A Priori* Bias

There is much evidence that statistical learning is an operative component of infant language acquisition. However, many studies have also uncovered discrepancies in the apparent ease with which infants and adults learn phonological patterns that may be equally strong statistically, but differ in terms of whether or not the pattern itself accords with certain linguistic principles. Saffran & Thiessen (2003), for example, found that

infants are easily able to learn phonological patterns based on phonetic classes, but not arbitrary groups, of sounds. They trained 9-month-olds on CVC.CVC stimuli in citation form. In one pattern, the syllable onsets were always voiceless and the codas voiced (e.g. *todkad*), while in the other pattern, the opposite was true (e.g. *dakdot*). In the second phase of the experiment, the infants were exposed to a continuous speech stream containing two novel words following the trained pattern, and two following the opposite pattern. Finally, in the third phase, the infants were tested on their listening preferences for the words from the second phase, and the results showed that they listened significantly longer to words following the opposite pattern. However, when the syllable-position restrictions involved an arbitrary group of consonants (/p/ /d/ /k/ versus /b/ /t/ /g/), infants showed no consistent pattern of preference. In a follow-up study, Cristià & Seidl (2008) were able to train 7-month-olds to learn an artificial grammar after approximately 2 minutes of familiarization, but only if the grammatical restrictions were based on phonological classes; otherwise, the infants failed to discriminate novel stimuli that followed the familiarized pattern from novel stimuli that did not.

One plausible way to explain the variation in how easily learners are able to acquire different phonological patterns is to posit that human linguistic learning is influenced by *a priori* biases—ones which are present before phonological learning has begun—that direct the learner’s attention to specific types of input over other types (Wilson, 2006; Finley & Badecker, 2007).

The type of phonological input that researchers have primarily proposed an *a priori* bias might favor is patterns that are motivated by phonetic principles. These

principles are widely recognized as providing insight into the reasons for the universality of certain phonological alternations versus the rarity of others (see e.g. Myers, 2002) based on general criteria of gradient well-formedness. Therefore, it is plausible that the principles could also form the basis for an attentional bias in favor of patterns that are relatively well-formed, as the latter would be more likely to provide informative input regarding the language's phonological structure than patterns that are relatively ill-formed. The first of these principles, ease of perception, dictates that contrasting sounds should be made maximally distinct in order to communicate to a listener most clearly (see e.g. Flemming, 1995). This principle motivates phenomena such as the strong cross-linguistic tendency to distribute the members of vowel inventories so as to make the most use of the vowel space (e.g., Liljencrants & Lindblom, 1972), and the limiting of neutralization processes to positions in which the neutralized contrast is less or least salient (Steriade, 2001a,b).

More relevant here is the principle of ease of articulation (see e.g. Ohala, 1974; Lindblom, 1983, 1990; Westbury & Keating, 1986; Ohala & Ohala, 1993; Jun, 1995; Kirchner, 1998; Myers, 2002). This ease can be due to one or more factors, including the need for positioning of the articulators in less extreme areas of the oral cavity, to minimize articulatory distance between adjacent segments, or to minimize the need for finely-timed changes in voicing. Obedience to this principle motivates many common phonological phenomena, such as assimilation and adherence to the sonority hierarchy within syllables, which Lindblom (1983) inferred result in conservation of effort on the part of the speaker. Westbury & Keating (1986) also concluded that voicing assimilation

may reduce articulatory effort. This is so because voicing requires creating a specific amount of air pressure below the glottis, in addition to whatever movements of the articulators are required in order to produce the correct manner and place of the target segments. It is more difficult to coordinate both at once at the beginning of an utterance, or word-medially after a voiceless segment, than to simply maintain voicing that has already been initiated for an earlier segment and add in the relevant manner and place gesture. Ease of articulation also helps to motivate patterns such as the avoidance (Pater, 1995, 1996) or voicing (Hayes & Stivers, 2000) of postnasal consonants due to the effects of coarticulation. During an oral segment that immediately follows a nasal, the velum is kept at a relatively low position, a reflection of its low position in the preceding nasal (Bell-Berti, 1993). This position is often low enough that the velum does not form a complete seal, allowing air to escape through the nasal cavity during the oral segment, a result that is particularly undesirable for voiceless obstruents since it undermines the buildup of air pressure that is required to produce a stop burst (Ohala & Ohala, 1993), thereby reducing the perceptual distinction between a voiced and voiceless stop in this position. As more effortful articulation would thus be required to maintain a strong enough perceptual distinction, the solutions of simply avoiding voiceless postnasal segments, or neutralizing them with voiced ones, are favored cross-linguistically.

The idea that a bias in favor of phonetic principles—regardless of its origin—could also influence learnability is not a new one, as such a concept has been present in the literature since at least Schane, Tranel, & Lane (1974). This bias is commonly termed a ‘substantive bias,’ as it refers to properties of the phonological grammar that arise from

the vocal tract or perceptual apparatus. The bias is proposed by researchers not only to account for the fact that typologically common patterns usually conform to phonetic principles, but also to influence what types of patterns the learner attends to more closely, and therefore learns more quickly.

Researchers have also addressed the question of what the origin of this bias in favor of patterns following phonetic principles would be. The most controversial claim would of course be that the bias could be innate, essentially making it a component of Chomskian-style Universal Grammar. However, it seems highly reasonable that such a bias could instead be the result of a process such as Hayes' (1999) inductive grounding, in which a learner would develop generalizations about articulatory difficulty based on articulatory and/or perceptual exploration. For instance, Locke (1983) reviewed several studies of English-learning infants' babbling¹¹ at various points during the first two years of life, and concluded that their productions consisted largely of sounds that could be classified as English phonemes. Thus, infants appear to be gaining articulatory experience with native-language sounds at quite an early age.

Furthermore, assuming that the prevalence of English sounds in English-learning infants' babbling is due to the infants' observation of these sounds in adult speech, it seems logical to posit that infants could also be observing the relative difficulty adults appear to have in producing different sounds, as reflected in greater variability in the articulation of more difficult sounds. For example, voicing requires the maintenance of

¹¹ Irwin (1947), Fisichelli (1950), Cruttenden (1970), Pierce & Hanna (1974), Oller et al. (1976), Labov & Labov (1978), and Stockman, Woods, & Tishman (1981).

lower oral than subglottal air pressure, but in a voiced plosive, the required occlusion of the oral cavity prevents any air from escaping, resulting in a buildup of oral air pressure (see e.g., Ohala & Riordan, 1979; Westbury, 1979; Westbury & Keating, 1986). As a result, voiced plosives are difficult to articulate, and geminates even more so, given that this delicate balance of air pressure must be maintained for an even longer time span than in singletons (Hayes & Steriade, 2004). Accordingly, Kawahara (2008) demonstrated that voiced geminate plosives are optionally devoiced in Japanese when another voiced obstruent occurs elsewhere in the word,¹² and the presence of an optional phonological process of course leads to a greater variation in the phonetic realization of the target sound. Smith's (1997) analysis of native English speakers' production of /z/ similarly showed that the actual duration of voicing varied a great deal, depending largely on the phoneme's position within the utterance and word and the voicing and manner of the following segment. And while other perceptual cues separate phonemic /s/ from devoiced /z/, the elimination of voicing as a reliable cue reduces the perceptual distance between the two, effectively providing noisier information regarding how to distinguish them. Furthermore, Cristià (2011) demonstrated that infants whose caretakers produced a more extreme contrast between /s/ and /ʃ/ were better able to discriminate between instances of the two categories, suggesting that infants learn phonemic categories more easily when given more consistent input.

¹² Kawahara (2008) noted that this is only true in recent borrowings into Japanese; in native words, voiced geminates are prohibited.

Relatedly, much research—even by authors arguing against the necessity of innate linguistic knowledge in language learning—indicates that patterns—including ones in areas of the grammar outside of phonology, such as syntax—that are typologically more prevalent are also likely to be easier to learn. First, Christiansen & Devlin (1997) trained Tlearn, a software-based simulated learner (Plunkett & Elman, 1997) on a variety of grammars of various levels of recursivity. When the learner had trained on a set number of input sentences from the grammar, it was tested by being required to give predictive probabilities for possible next items to follow a sentence fragment. Its output of probabilities was then compared with the actual transitional probabilities associated with the grammar on which the learner was trained, and its accuracy assessed by comparing the mean squared error (MSE) between the learner's predictions and the grammar's empirical probabilities, for each grammar. They found that the degree of mutual recursivity (i.e., two grammatical phrase rules that each include the other as a daughter node) and inconsistency in phrase headedness was strongly correlated with the MSE, so that a high level of one predicted a high level of the other, indicating that the more recursive and/or inconsistent the grammar was, the less able the artificial learner was to acquire it. They further showed that it is exactly the kind of grammars that the learner acquires more unsuccessfully that are uncommon in natural language, and the kinds that the learner is able to acquire are those that are common. Similarly, Ellefson & Christiansen (2000) taught adult subjects one of two artificial grammars, which differed in only one respect: one that violated the subadjacency constraint—i.e., contained complex question formations that moved a too-deeply-

embedded question element to the linear front of the sentence, a pattern that is rarely attested in human language—and one that did not. After training on 30 sentences, 10 that displayed the relevant construction and 20 that conformed to the shared rules of the grammars, adults who had been taught the subadjacency-violating grammar distinguished novel strings that conformed to the trained grammar versus ones that did not with significantly less accuracy than their counterparts who had learned the non-violating grammar, indicating that they learned the former less well than the latter. Saffran (2002) presented results indicating that under the same training and testing circumstances, children between 7.5 and 9.5 years as well as adults are significantly better able to learn artificial languages in which the *presence* of one category of word perfectly predicts the presence of another category of word—like determiners and nouns in natural language—than artificial languages in which the *absence* of a category perfectly predicts the presence of another—a relationship that is unattested in natural language.

Thus, some researchers propose that the relationship between these facts is not merely correlational, but actually causal; specifically, that it is exactly their adherence to linguistic principles that make the relevant patterns easier to acquire than other possible. For phonological patterns specifically, motivation by phonetic principles is posited to be the reason why particular patterns are easier to learn than others, due to the substantive bias (Wilson, 2006).

Finally, this association between phonetic motivation and learnability is hypothesized to extend to infant learning as well, as detailed in section 8.2.4 Evidence for Sensitivity to Phonetic Principles: Infant Data below.

8.2.2 Arguments Against the *A Priori* Bias

The idea that humans may possess an *a priori* bias in favor of phonetically-motivated phonological processes does not remain uncontested, however; other researchers, such as Blevins (2004), believe that phonetic motivation does not have a measurable effect on phonological acquisition by an individual; rather, they would claim that phonetic considerations gradually influence the diachronic changes that shape a language's phonology.

Support for this view comes from the fact that many synchronic phonological patterns are only partially consistent with the principle of ease of articulation (Westbury & Keating, 1986), as in Icelandic, which typically fronts velar consonants (making them palatal) before front vowels—a process motivated by ease of articulation—yet excludes the vowels [y] and [œ] from the set of triggers of the process, an exclusion that has no phonetic basis (Anderson, 1981).

Some phonological rules even lack any apparent phonetic motivation whatsoever, earning them the name “crazy rules” (Bach & Harms, 1972), and commonly result from a series of individually motivated historical changes. For example, in the Southern Group of Pomo languages, /i/ surfaces as [u] following /n²/ in onset position, which surfaces as [d] (Oswalt, 1976), as in Kashaya (Oswalt, 1961; Buckley, 1994):

- (6) a. /çu-q'a:t-i/ → [çuq'a:ti] 'groan!'
- versus
- b. /wa-an²-i/ → [wá:du] 'come here!'
- /can²-i/ → [cadú] 'look!'
- /ma^hsan²-in/ → [mahsadún] 'while taking away'
- /ʔolo·q^wan²-in/ → [ʔolo·qodún] 'while running out from here'
- /can²-ins²/ → [cadúns²] 'I wonder if he saw it'

Note that the alternation cannot simply be attributed to vowel harmony, as shown by (6). In fact, Buckley himself stated that synchronically, “[t]here is little hope of deriving this change from a natural phonological process—in fact, there would be something suspect about any feature system which could do so” (Buckley, 1994: p. 114-115). He mentioned that Oswalt conjectured the historical explanation might be associated with the Absolutive suffix, which surfaces as [w] after vowels and [u] after [d].

Another “crazy rule” surfaces in Eastern Ojibwa, an Algonquian language, in which a series of historical changes have resulted in a lexically-restricted alternation between [n] and [ɲ] in a synchronically incoherent set of environments (Bloomfield, 1946, 1957; Kaye, 1978; Piggott, 1980). In the verb stems affected, the underlying segment (claimed by Piggott to be abstract /l/, and by Bloomfield to be an underspecified nasal) appears as [ɲ] only before the thematic relationship suffix /-i/, and as [n] elsewhere, as shown in the examples taken from Piggott (1980) below:

- | | | | | |
|-----|-----------------|---|-------------|-----------------|
| (7) | a. ki-mi:l-i | → | [kimi:ɲ] | ‘you give me’ |
| | b. ki-mi:l-i-mi | → | [kimi:ɲimi] | ‘you give us’ |
| | c. ki-mi:l-in | → | [kimi:nin] | ‘I give you’ |
| | d. ki-mi:l-ik | → | [kimi:nik] | ‘he gives you’ |
| | e. ki-mi:l-a: | → | [kimi:na:] | ‘you give him’ |
| (8) | a. ki-na:l-i-mi | → | [kina:ɲimi] | ‘you fetch us’ |
| | b. ki-na:l-a: | → | [kina:na:] | ‘you fetch him’ |

The historical explanation given by Piggott (1980) and Kaye (1978) for this synchronic inconsistency is that in an earlier stage of the language, *i and *e merged to become modern /i/, but that the creation of [ɲ] in the stems concerned did not. Furthermore, the bizarre surfacing of an underlying segment of debatable identity as [ɲ] is a carryover from

an even earlier stage of the language, in which *θ was the underlying sound which underwent palatalization before *i, but later changed to /l/, which subsequently merged with /n/.

Yu (2004) further demonstrated that Lezgian, a North Caucasian language, voices underlyingly voiceless ejectives and unaspirated obstruents in final and preconsonantal position in some monosyllabic nouns, but not others. While the individual historical processes that cumulatively resulted in this voicing process make sense phonetically, synchronically the phenomenon is in opposition to the natural tendency to devoice obstruents in such positions as described by Westbury & Keating (1986).

8.2.3 Evidence for Sensitivity to Phonetic Principles: Adult Data

Artificial language learning experiments that test adult English speakers' success in learning various types of generalizations provide further supporting evidence for the existence of a bias in favor of patterns that have phonetic motivation. Again, though these experiments focus on whether the influence of such a bias is evident when adults attempt to learn a new generalization, rather than in their untrained (at least, in an artificial setting) responses to data, such evidence does nevertheless support the existence of a bias. First, Schane, Tranel, & Lane (1974) taught a group of English-speaking adults a set of four artificial language nouns, and then trained each subject on a series of adjective-noun combinations. Half of the subjects were trained on a pattern in which the final consonant of the adjective was deleted before consonant-initial nouns, but not before vowel-initial nouns, reflecting a natural cluster simplification process. The other half learned the complementary pattern, in which final consonant deletion occurred

before vowel-initial nouns but not consonant-initial ones—an unmotivated processes. Finally, in the testing phase, subjects were presented with 18 new nouns, nine with consonant-initial onsets and nine with vowel-initial onsets, and told to combine them with the correct form of each previously-learned adjective. The results showed that subjects trained in the motivated, pre-consonantal consonant deletion pattern made significantly fewer errors than subjects trained in the unmotivated, pre-vocalic consonant deletion pattern, indicating that adults have an easier time learning a new phonological process that conforms to principles of phonetic motivation and to typological facts than one that does not. Unfortunately, the chosen pattern does present a possible confound: the motivated pattern is also productive in English speech, as in the alternation between the two allomorphs of the indefinite article in English, ‘a’ and ‘an’, so it is possible that subjects’ knowledge of this previously-learned process was at least partially responsible for the difference in performance.

Wilson (2006) also conducted an adult artificial language learning experiment to support the proposal that an *a priori* bias in favor of phonetic principles makes phonological patterns with phonetic motivation easier to learn than those without, but avoided the confound present in Schane, Tranel, & Lane (1974). Wilson (2006) found that adults who were taught an artificial language game that palatalizes velar consonants before the mid front vowel [e] (but not the low back vowel [ɑ]) generalized the process to apply equally frequently before the untrained high front vowel [i], which accords both with the typological implication that languages in which velars are palatalized before mid-front vowels also palatalize before high front vowels (Chen, 1973; Bhat, 1978), and

with the articulatory fact that high front vowels are more physically front and have a less open constriction—making them positionally more similar to palatals and therefore a stronger trigger for this type of assimilation than mid front vowels. However, the opposite did not hold: subjects trained on a game that palatalized velars before high front [i] (but not low back [ɑ]) applied the palatalization rule significantly less often before the untrained mid-front [e] than high front [i], which aligns with the fact that velar palatalization before high front vowels does not implicate palatalization before mid-front vowels, and that mid vowels are a weaker trigger for palatalization. These results supported Wilson’s (2006) proposal that phonetically motivated processes are easier to learn than unmotivated ones.

Finley (2008) further presented a series of experiments showing that adults tend to learn vowel harmony patterns that are typologically common and/or in accord with phonetic principles better than patterns which are not. In the first experiment, subjects were trained on input-output pairs demonstrating spreading patterns that were ambiguous between directional spreading, which is typologically common, and an unattested ‘majority rules’ spreading pattern. An example training stimulus is [pidego, pidege], in which a subject could either hypothesize that left-to-right spreading was operational, or that since more underlying vowels were front and unrounded, the remaining vowel harmonized regardless of direction. A forced-choice test phase showed that, when given two input-output pairs, subjects chose the pair whose output would result from the same directional spreading pattern possible in their training data (i.e., [pumite, pumoto]), rather than the ‘majority rules’ pattern that would allow for spreading in the other direction (i.e.,

[pumite, pimate]). Experiment 2 uncovered the same results using stimuli that consisted of three separate syllables as the input for all training input-output pairs, as in [pi, de, go, pidege], supporting the connection between typologically common processes and ease of learning.

In later experiments, Finley (2008) tested whether adults generalize a backness/rounding harmony pattern from trained to novel vowel classes, and found that in general, adults generalize—thus demonstrating learning—in directions that are in accord with both typology and phonetic principles. In Experiments 7 and 8, subjects were trained on input-output pairs wherein a suffix on the output matched the backness and roundness of the identical vowels in the stem, as in [bodo, bodomu]. In Experiment 7, subjects were trained on stimuli with both stems containing two high vowels and stems containing two mid vowels, but whose suffixes contained only either the high vowels [i u] or the mid vowels [e o]. In a forced-choice task test phase, subjects from both training groups picked the harmonic output form significantly more often even when the suffix contained a vowel of the height not included in training, indicating that they were equally able to generalize to mid or high targets. On the other hand, subjects in Experiment 8 were trained on stimuli whose stems contained only either mid or high vowels, and whose suffixes could contain either a mid or high vowel. Subjects trained on mid vowel stems showed a significant effect of training, but failed to generalize the pattern to include high vowels as triggers. Furthermore, subjects trained on high vowel stems showed no significant effect of training. The results of Experiment 8 were interpreted as demonstrating that learning a rounding harmony pattern with mid triggers is an easier

task than learning a rounding harmony pattern with high triggers, which is in accord with the claim that patterns are more easily learned when they have phonetic motivation.

Though the results of Finley's Experiment 7 did not, the results of Experiment 8 did accord with Kaun's (2004) findings that high vowels are the typologically preferred targets of rounding harmony, while non-high vowels are its preferred triggers. Kaun attributed this distinction to the principle of ease of perception, as rounding is more easily perceived in high vowels, and less easily perceived in non-high vowels; thus, the feature round is best preserved when it spreads from segments wherein it may not be noticed to segments wherein it has the most perceptual salience.

A final set of experiments in Finley (2008) followed the procedure of Experiment 7 and 8, but this time explored to what extent learners generalized a height harmony pattern in accordance with typology and ease of perception. Experiment 9 trained subjects on input-output pairs with stems containing front and/or back mid and high vowels, but with suffixes that contained either only the front vowels [i e] or only the back vowels [u o]. In the test phase, only subjects trained on front vowel suffixes were significantly more likely to choose harmonic forms overall than control subjects, while subjects trained on back vowel suffixes only showed an effect of training when asked to choose between output forms containing front vowel suffixes, suggesting that adults are more easily able to learn a height harmony pattern that applies to front vowels than to back vowels, and that they generalize from back to front vowels, but not vice versa. These results again supported the connection between typology, phonetic principles, and ease of acquisition.

In a similar vein, Moreton (2008) showed that adults learn dependencies between vowel heights better than dependencies between vowel height and consonant voicing. In the vowel heights dependency condition, the two vowels in $C_1V_1C_2V_2$ nonce words were either both high or both non-high. In the height-voicing condition, high V_1 s were paired with voiced C_2 s, while non-high V_1 s were paired with voiceless C_2 s. In the experiment, subjects were trained on one of the two patterns by being asked to repeat the pronunciation of 32 distinct nonce words conforming to the relevant pattern, either height-height dependency or height-voicing dependency. Half of the training words for each subject also conformed to the other pattern, while the other half did not. In the test phase, subjects heard two nonce words per trial, and had to choose which one was part of the ‘language’ they had learned during familiarization. In this phase, one word in each pair conformed to the trained pattern, with a 50% chance of also conforming to the other pattern, and the other word did not conform to either pattern. The results showed that subjects were significantly more likely to choose the correct test item when they had been trained on the height-height dependency pattern than when trained on the height-voicing dependency pattern. This again supported the association between typological prevalence, phonetic motivation, and ease of acquisition.

Berent et al. (2007) gave further evidence in favor of this association. In the first experiment, English-speaking adults were exposed to a forced-choice task, in which they heard CCVC and CəCVC nonwords one at a time, and had to decide whether each nonword was composed of one or two syllables. Analysis showed that the subjects were significantly more likely to correctly categorize clusters of rising sonority as

monosyllables than ones with sonority plateaus, which they were more likely to categorize correctly than those with falling sonority clusters. In a subsequent experiment, subjects had to identify whether paired items were identical. Non-identical pairs only differed in that one member was monosyllabic, and the other member was the disyllable formed by inserting schwa in the consonant cluster. Subjects had significantly faster response times for non-identical pairs in which the cluster had rising sonority than a plateau, which they reacted to significantly faster than pairs with a falling sonority cluster. Their accuracy was also significantly higher for rising sonority clusters than for plateau or falling sonority clusters. Thus, the results of the experiments indicate that monolingual English-speaking adults are more likely to misperceive very highly dispreferred onset clusters—such as “lbif”—than clusters that are less highly dispreferred—like “bdif”.

To establish that such biases are language-independent, the possibility that the generalization results can be explained by learners’ sensitivity to input statistics needs to be ruled out. Experiments controlling for the possibility that during artificial language learning, speakers may (also) be relying on generalizations inferred from statistical learning of similar patterns that are actually attested in the native language, have shown more qualified support for the claim that an *a priori* bias in favor of phonetically-motivated phonological patterns is the dominant learning mechanism. Albright (2007) tested subjects on stimuli comprised of non-words with both attested and unattested initial consonant clusters by embedding them in aurally-presented English frame sentences, and asking subjects to repeat the target word aloud before rating its

acceptability as a possible word of English on a numerical scale. Unsurprisingly, subjects judged words with attested clusters to be more acceptable than words with unattested clusters; however, they also showed an ordered preference among unattested clusters, with more sonorous second members rated as more acceptable ('bw' > 'bn' > 'bd', 'bz'). Furthermore, the number of incorrect word repetitions was inversely correlated with the level of acceptability of a given form, so that less-preferred items were repeated incorrectly more frequently. Interestingly, Albright further showed that among several alternatives, the learning model that was best able to account for the native speaker data was one which incorporated *both* statistical knowledge of the relative prevalence of various types of segments as the second member of initial consonant clusters in English *and* an underlying preference for plosives to precede more sonorous segments. Thus, his results indicated that both a bias in favor of phonetically-motivated patterns and a statistical learning component are implicated in adult learning.

A similar conclusion can be drawn from a series of experiments conducted by Becker, Ketrez, & Nevins (2011), which demonstrated that adult speakers of Turkish generalize an exceptionful pattern of laryngeal alternation present in the lexicon to novel words only when the alternation is phonetically motivated, even though other conditions are equally good statistical predictors of the process' application. In Turkish, the [-continuant] segments [b d ɖ ɡ] contrast with [p^h t^h tʃ^h k^h] in onset position, but the distinction is generally neutralized in coda position,¹³ where only the voiceless aspirates

¹³ This process does not apply to the first syllable of native words, though it is productive in loan words, and also has a few lexical exceptions.

appear on the surface. In 54% of Turkish nouns, a stem-final [–continuant] segment surfaces as voiced when followed by a vowel-initial suffix that allows it to be resyllabified as an onset, while in the remaining 46%, the segment remains a voiceless aspirate. This alternation is not entirely predictable, and is therefore traditionally analyzed as arising from an underlying phonemic distinction between the two voicing classes, such that the segments that are voiced pre-vocalically are underlyingly voiced, while those that remain voiceless are underlyingly voiceless. However, word length, place of articulation, and the quality of the immediately preceding vowel and strong predictors of whether a stem-final segment will alternate or not in the relevant environment: disyllables usually show the alternation while monosyllables do not; labials, palatals, and dorsals usually alternate, while coronals do not; and segments with a preceding high vowel usually alternate, while those with a preceding non-high vowel usually do not.

In their experiment, Becker, Ketrez, & Nevins (2011) presented adult native speakers of Turkish living in the US with orthographic representations of nonce stems. Subjects then had to choose between two possible suffixed forms presented aurally, one with an alternating stem-final segment and one with a non-alternating segment. The results showed that adults extend the alternation to novel items with the same frequency as is evidenced in the lexicon based on the word length and place of articulation cues, but not the preceding vowel quality cue. In fact, of several possible models, the one that was best able to predict subjects' judgments ignored vowel quality cues entirely. These results were interpreted as providing evidence that while speakers certainly have

statistical knowledge about phonological patterns in the language, which patterns are more salient is not determined simply by statistical robustness, but rather is influenced by phonetic factors: the authors claim that initial syllables are perceptually strong and therefore relatively immune to alternation;¹⁴ furthermore, place of articulation affects the ease or difficulty with which voicing can be maintained in a given plosive¹⁵ (Ohala, 1983). On the other hand, the authors pointed out, consonant-vowel interactions are generally motivated by a shared feature—either laryngeal or supra-laryngeal—but vowel height and consonant voicing do not involve the same components of the vocal tract, and therefore do not share such features; rather, the closest association they have is a mutual correlation with tongue root position.

As a group, the results of these studies thus strongly indicate that, regardless of whether it is the only mechanism implicated in learning, there does exist a bias in favor of phonetically-motivated processes. Many questions remain to be answered, however, including (a) whether this bias is active, let alone dominant, in infant language learning, (b) whether it is innate, and (c) if it is not innate, where it comes from.

8.2.4 Evidence for Sensitivity to Phonetic Principles: Infant Data

Research conducted by Jusczyk, Smolensky, & Allocco (2002) sought to determine whether infants are predisposed to prefer sounds and sequences that follow

¹⁴ Though see Hale & Reiss (2000) for a critique of this claim, which however does not negate the relevance of Becker, Ketrez, & Nevins (2011) to this discussion.

¹⁵ However, the distributions in Turkish do not seem to align with general accounts of ease of voicing according to place, as plosives made more towards the front of the vocal tract are considered easier to voice, while in Turkish, both palatals and velars are more likely to alternate with voiced segments than coronals are.

phonetic principles. In a series of several experiments, the authors showed that without training, 4.5- and 10-month-olds listen significantly longer to a pattern that is consistent with phonetically-motivated markedness principles but violates faithfulness than to a pattern that obeys the principle of faithfulness but violates markedness. First, they demonstrated that infants of both age groups are sensitive to each of the principles in isolation: when sequences were controlled for faithfulness, 4.5- and 10-month-olds listened longer to unmarked sequences such as ‘**um**, **ber**, **umber**’ than to marked sequences such as ‘**un**, **ber**, **unber**’; additionally, when listening to sequences controlled for unmarkedness, infants in both age groups also attended longer to faithful sequences like ‘**um**, **ber**, **umber**’ compared to unfaithful sequences like ‘**um**, **ber**, **ingu**’. After establishing that infants respected each of these principles separately, Jusczyk, Smolensky, and Allocco tested infants on stimuli that pitted the principles against each other, as in *faithful* but *marked* ‘**un**, **ber**, **unber**’ versus *unfaithful* but *unmarked* ‘**un**, **ber**, **umber**’. In this last set of conditions, infants listened significantly longer to the unfaithful but unmarked stimuli. Together, these results were interpreted as indicating that infants recognize both considerations of markedness and faithfulness separately, but rank the principle of markedness as motivated by ease of articulation more highly than the principle of faithfulness. However, as Seidl & Buckley (2005) point out, there are two rather major methodological issues which cloud the interpretation of the results claimed by Jusczyk, Smolensky, & Allocco (2002). First, the assumption made in the implementation of the triad paradigm, namely that infants are interpreting the first two syllables as the input and the last disyllabic element as the output of a phonological

process, has not been verified. Therefore, infants could have simply been showing a preference for the phonotactic properties of the separate triad units, and not for the process as a whole as was claimed by the authors.¹⁶ Second, and equally problematic for the theoretical claims made, is the fact that the experimenters chose nasal place assimilation as the process on which to test for infant reactions to supposedly universal principles. But because this process is productive in English, applying even across word boundaries in running speech (see e.g. Borowsky, 1986; Avery & Rice, 1989), the infant preferences could plausibly have resulted from experiential learning (particularly in the case of older infants) of properties of English phonology, rather than being motivated by the application of *a priori* linguistic knowledge. Thus, further experimental investigation is needed to provide a clear answer to the question of whether an *a priori* bias is in fact implicated in very early language acquisition.

¹⁶ This is also true of this author's master's thesis work in Thatte (2008).

Chapter 9 ♦ Experiment 4: [θ] vs. [ð]

In order to more clearly determine which learning mechanism is most active late in the first year of life, Experiment 4 tested 8- to 10-month-olds' preferences between [θ]-initial versus [ð]-initial stimuli. If the *a priori* bias is the stronger, infants should prefer initial [θ], since it is more in accord with the principle of ease of articulation (Ohala, 1983, 1997),¹⁷ especially in word-initial position. On the other hand, if statistical induction is more dominant, infants might prefer initial [ð], as it has a vastly higher token frequency in adult running speech.

However, it is also possible that an otherwise more powerful statistical learning mechanism could still lead to a lack of preference in this case, as the effects of the higher frequency of [ð] could be mitigated by certain facts about the high-frequency words that begin with it. These are all function words (*than, that, the, their, theirs, them, themselves, then, thence, there, therefore, these, they, this, those, though, thus*), which are less salient than content words since the former are generally short and not given intonational attention (Morgan, Shi, & Allopenna, 1996). They also commonly undergo unstressed-syllable reduction processes such as vowel reduction (see e.g. Fourakis, 1991; Jurafsky et al., 1998), and rarely form prosodic units of their own (Selkirk (1986) even goes so far as to contrast them with “real”—content—words). Furthermore, infants can discriminate between the two classes of words before they are 4 days old (Shi, Werker, &

¹⁷ An alternative account based on ease of perception rather than ease of articulation, presented in Balise & Diehl (1994), cites the fact that the aerodynamics of voicing necessarily reduce the high frequency noise that is a strong cue to sibilant fricatives. Thus, maintenance of voicing during a sibilant is undesirable because it reduces the perceptual distinction between fricatives and approximants.

Morgan, 1999), and by as early as 6 months, they have been shown to listen significantly longer to content words (Shi & Werker, 2001). Thus, given that function words are not only highly phonetically reduced, but also less interesting to infants than content words by 6 months of age, it is possible that the effect of the higher token frequency of [ð] could have on infants' attentional preferences via reliance on the statistical mechanism would be lessened by the tokens' low salience, leading to a lack of preference in either direction.

9.1 Subjects

19 infants were tested in Experiment 4. The results of six were excluded from primary analysis: one for equipment malfunction, two for excessive fussiness, and three for having a fricative-initial first name.¹⁸ The remaining 13 infants (six female and seven male) ranged in age from 241 to 302 days (7.9 to 10.4 months), with a mean age of 276 days (9 months).

9.2 Stimuli

The stimuli used in Experiment 4 consisted of 5 to 6 separate tokens each of the four dental-initial syllables included in the stimuli for Experiment 1, as shown in (9) and (10). The stimuli for Experiment 5 were recorded by a female bilingual speaker of American English and Polish in her twenties in a child-directed style.

(9) [ðɑ], [ðu]

(10) [θɑ], [θu]

These four syllables were the only stimuli used because out of the other syllables available in the bank of recorded stimuli, the voiced-initial member of each matched pair

¹⁸ See §2.1.4 Grounds for Exclusion of Data above.

coincided with a real word of English (specifically, [ð̥i] ‘the’ and [ð̥ei̯], ‘they’), and the speaker who had recorded the stimuli previously was unavailable for further recording.

9.3 Results and Discussion

As a group, the infants looked at the stimuli with initial [ð̥] for 10.9 seconds (SD=3.5), and those with initial [θ] for 10.7 seconds (SD=2.5), for a mean difference of 0.2 seconds, as shown in Figure 7. No significant difference was found in infant looking times to either condition ($t(12)=0.43$, $p=0.34$ in a one-tailed paired t test, with an effect size of 0.08).

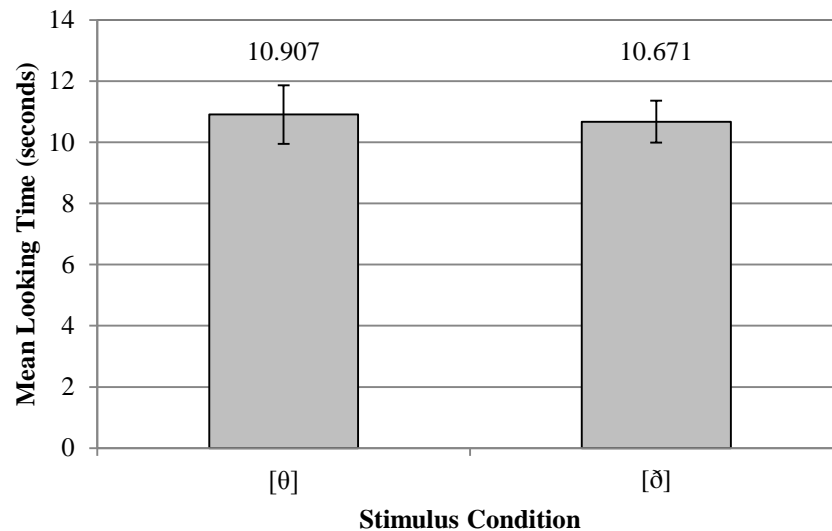


Figure 7: 8- to 10-Month-Olds' Attention to [ð̥]- vs. [θ]-Initial Stimuli with Standard Error Bars

Six infants listened longer to [ð̥]-initial stimuli, and seven to [θ]-initial stimuli, as shown in Table 7.

Subject Number	Preferred Condition (\pm Voicing)	Mean Looking Times in Seconds	
		[ð]	[θ]
1	–	8.3	8.9
2	+	19.4	15.2
3	+	7.6	6.9
4	+	10.1	8.6
5	+	13.8	11.9
6	–	9.6	10.6
7	–	9.1	9.4
8	–	12.6	13.4
9	+	7.6	6.8
10	–	10.7	12.3
11	–	7.2	10.6
12	+	14.4	11.7
13	–	11.5	12.2

Table 7: Individual Mean Looking Times in Experiment 4

The lack of preference on the part of 8- to 10-month-olds for either dental fricative thus rules out the *a priori* bias as the stronger mechanism at this age. Two possibilities remain: either the mechanisms are relied upon equally, or statistical learning is stronger, but the circumstances of the greater frequency of initial [ð] mitigate this learning mechanism's effects.

9.4 Comparison of Experiment 1 and Experiment 4 Results

In order to determine whether infant attention to the voiceless versus voiced conditions in Experiment 1, which contained all English fricatives, differed significantly from infant attention to the voiceless versus voiced dental fricative, a repeated-measures ANOVA was run with looking times to the voiced and voiceless conditions as the within-subjects factors, and experiment (all English fricatives versus only the dentals) as the between-subjects factor. The analysis found no main effect of condition ($F(1,27)=0.81$,

$p=0.19$, one-tailed) or experiment ($F(1,27)=0.01$, $p=0.46$, one-tailed), and a not-quite-significant interaction of condition and experiment ($F(1,27)=2.26$, $p=0.07$, one-tailed).

To confirm these results, a one-tailed unpaired t test was first conducted comparing the difference in looking times to the two conditions in each experiment. The level of significance was the same as that calculated by the ANOVA above ($t(27)=1.50$, $p=0.07$, with an effect size of 0.56). The average difference in looking time to the voiceless minus the voiced condition was 0.94 seconds (SD=2.2) for Experiment 1, and -0.23 seconds for Experiment 4 (SD=2.0), with an average difference of 1.2 seconds, as shown in Figure 8.

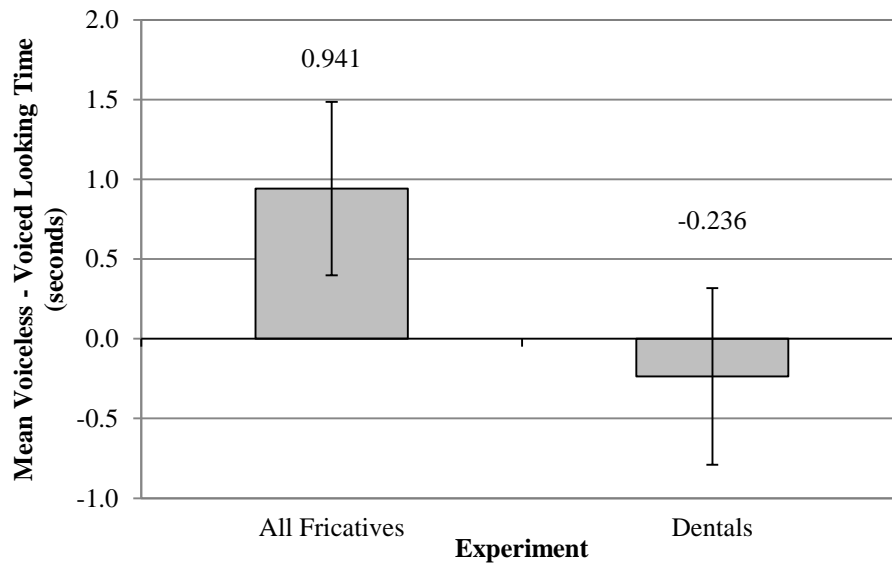


Figure 8: Comparison of Difference in Looking Times for Experiments 1 and 4 with Standard Error Bars

Furthermore, the proportion of looking times to the voiceless condition versus total looking times was calculated, and the number of infants who preferred the voiceless

condition by a greater-than-chance margin was determined. The criterion preference ratio was calculated using the method described in the equation in (5) in section 7.1 above, and found to be 0.511, with 11 out of 16 infants who heard all English fricatives and six out of 13 infants who heard only dental fricatives having an above-chance preference. A one-tailed χ^2 comparison found no significant effect of experiment ($\chi^2(1)=1.51$, n.s.).

Thus, the results of Experiments 1 and 4 considered in tandem provide further evidence for the proposal that statistical learning is operative by 8 to 10 months of age, but its effects are weakened in this instance by the nature of the [ð]-initial tokens in the input. Given that Experiment 1 found a preference on the part of infants of this age for voiceless initial fricatives, the absence of such a preference when infants are only given dental fricatives to attend to suggests that infants are aware of the single major difference between this particular pair of fricatives and the others of English: namely, that unlike the other members of its voicing class, [ð] is vastly more frequent than its voiceless counterpart. Therefore, overall, infants at this age prefer voiceless fricatives when both potential learning mechanisms—an *a priori* bias and statistical induction—would draw them to these sounds, but the preference disappears when the two mechanisms would lead them to distribute their attention in opposite directions.

Chapter 10 ♦ Experiment 5: Polish Fricatives

The final experiment tested whether the preference for voiceless fricatives demonstrated in Experiment 1 stems from segmental- or featural-level knowledge, by investigating whether the infants generalize the preference to nonnative (here, Polish) fricatives, or restrict it to phones that are available in their input. This experiment also addressed the learning mechanism question: while an *a priori* bias should motivate infants to prefer voiceless fricatives to voiced ones regardless of whether they are part of the native language phoneme inventory, a statistical learning mechanism would allow either for the knowledge gained through it to be codified at a general, featural level, leading to a preference for voiceless fricatives in Polish as well, or for a lack of preference if their knowledge is stored for individual sounds present in their input.

10.1 Subjects

23 infants were tested in Experiment 5. The results of 11 were excluded from primary analysis: four for excessive fussiness, two due to experimenter error, and five for having fricative-initial first names.¹⁹ The remaining 15 infants (eight female and seven male) ranged in age from 233 to 308 days (7.6 to 10.1 months), with a mean age of 269 days (8.8 months).

10.2 Stimuli

The stimuli for Experiment 5 consisted of one token each of 128 CVC syllables, using four Polish phonemes that are not found in English (Miękisz & Denenfeld, 1975).

¹⁹ See §2.1.4 Grounds for Exclusion of Data above.

64 items began with voiceless fricatives of Polish, as exemplified in (11), and 64 with voiced fricatives of Polish, as exemplified in (12). The stimuli for Experiment 5 were recorded by a female bilingual speaker of American English and Polish in her twenties, again in a child-directed style. A complete list of stimuli for this experiment is given in Appendix D. In each condition, half of the syllables began with an alveolo-palatal fricative and half with a retroflex fricative. The stimuli were also counterbalanced so that each condition contained as close to the same number of items with each of the six vowels and six coda consonants as possible.²⁰

(11) [zip], [zɨb], [zɛt], [zad], [zɔk], [zug], [zup], [zɛb], [zɔt], [zɨd], [zɨk], [zɔg]

(12) [ɕup], [ɕɛb], [ɕɔt], [ɕid], [ɕɨk], [ɕag], [ʂip], [ʂɨb], [ʂɛt], [ʂad], [ʂɔk], [ʂug]

The stimuli were recorded by a female bilingual speaker of American English and Polish in her twenties in a child-directed style. In order to maintain counterbalancing and variety, some syllables that would be phonotactically illegal in Polish were included in the stimuli, but only when a token was available that sounded to a non-speaker of Polish as though it had been produced as fluently as the legal syllables.

10.3 Results and Discussion

As a group, the infants looked at the stimuli with Polish voiced initial fricatives for 9.1 seconds (SD=3.3), and those with voiceless initial fricatives for 9.5 seconds (SD=3.6), for a mean difference of 0.4 seconds, as shown in Figure 9. No significant

²⁰ It should be noted that no attempt was made to ensure that all stimuli were phonotactically legal syllables of Polish; however, only tokens that were considered by the experimenter and one other trained linguist to sound natural and fluent were used as stimuli.

difference was found in infant looking time to the two conditions ($t(14)=0.51$, $p=0.31$ in a one-tailed paired t test, with an effect size of 0.12).

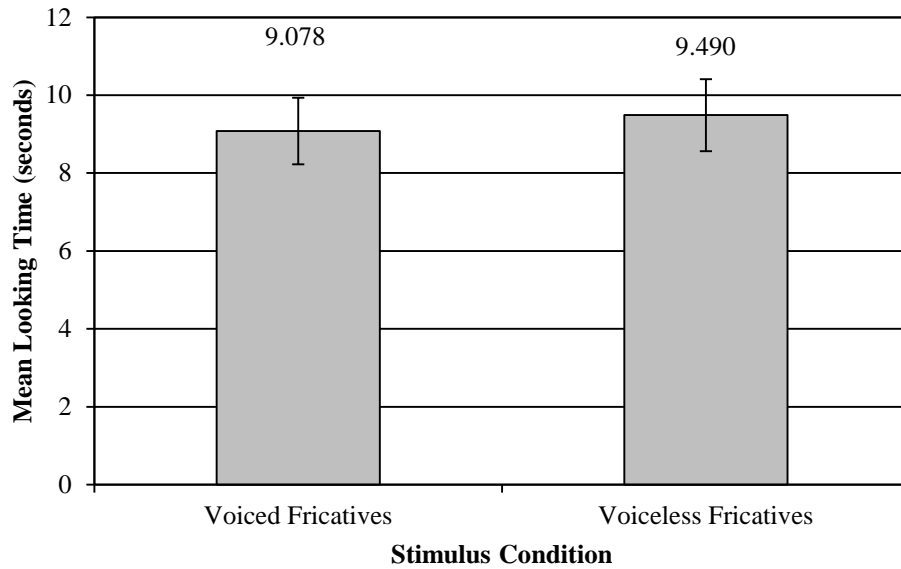


Figure 9: 8- to 10-Month-Olds' Attention to Voiced vs. Voiceless Polish Fricatives with Standard Error Bars

Seven infants listened longer to the voiced stimuli, and eight to the voiceless stimuli, as shown in Table 8.

Subject Number	Preferred Condition (\pm Voicing)	Mean Looking Times in Seconds	
		Voiced Condition	Voiceless Condition
1	–	10.0	11.8
2	+	9.2	5.3
3	–	6.4	9.1
4	+	9.4	8.8
5	–	6.2	6.4
6	+	5.1	4.2
7	–	5.8	9.5
8	–	10.7	16.4
9	–	6.1	8.0
10	+	8.0	6.6
11	–	6.1	8.3
12	+	11.2	9.7
13	–	11.3	15.3
14	+	16.3	14.3
15	+	14.3	8.5

Table 8: Individual Mean Looking Times in Experiment 5

Thus, infants do not display a significant preference for either voiced or voiceless Polish fricatives in initial position, indicating that they might not generalize their knowledge to novel segments. This can be interpreted as further evidence in favor of the proposal that both the *a priori* bias and statistical learning must favor the same group of sounds in order for infants to show an attentional preference for it.

10.4 Comparison of Experiment 1 and Experiment 5 Results

A comparison of the looking times for the two conditions in this experiment and in Experiment 1, which tested infants on English fricatives, via a repeated-measures ANOVA, failed to find any significant main effect or interaction of experiment and voicing condition (experiment: $F(1,29)=1.49$, $p=0.12$, one-tailed; condition:

$F(1,29)=1.98$, $p=0.09$, one-tailed; experiment \times condition: $F(1,29)=0.30$, $p=0.29$, one-tailed).

10.5 Discussion of Part II Results

Thus, on its own, infants' lack of a significant preference for either voiced or voiceless initial fricatives of Polish provides evidence in favor of the idea that the *a priori* bias is not strong enough to motivate a preference by itself, especially since considering a larger sample size by pooling the data from Experiment 5 with the data from Experiment 1 did not result in a significant preference for one condition over the other. These results further indicate that knowledge gained via statistical learning is not generalized across segments, as otherwise, the combination of influence from both the *a priori* bias and generalized statistical learning should impel infants to show an attentional preference for the voiceless fricatives.

Chapter 11 ♦ Conclusion

The five experiments conducted in this research program have thus addressed facets of the larger research questions discussed at the beginning of the dissertation: namely, they have added to the timeline of infant language development, and explored what learning mechanism is implicated in this specific area of their development.

In addressing the question of which learning mechanism is used by infants at this stage, two main hypotheses were considered. Under the statistical learning hypothesis, infants could be implementing statistical induction to learn about the phonotactic properties of their native language. Under the innate version of the *a priori* bias hypothesis, they could be relying on an innate bias in favor of input that accords with the principle of ease of articulation. Or, according to the learned version of the bias hypothesis, they could possess this *a priori* bias, but instead of being innate, it develops via Hayes' (1999) inductive grounding: the bias would be learned through a combination of observing the relative difficulty adults appear to have in producing different sounds (e.g., Smith, 1997) and the infant's own articulatory exploration (see Locke, 1983).

First, consider the predictions made by the statistical learning hypothesis. If it were the only learning mechanism used by infants to guide their attention, then 8- to 10-month-olds should prefer voiceless fricatives as a group over voiced fricatives, while 4.5- and 6-month-olds, who are too young to have gathered enough data from which to draw conclusions, would show no preference. When confronted with only dental fricatives, on the other hand, infants would likely prefer [ð]-initial words, given [ð]'s greater word-

initial token frequency; however, this preference could be weakened by the fact that these tokens are function words. And when exposed to novel fricatives, infants should show no preference, especially if they even fail to generalize their statistical knowledge across familiar segments, as is predicted for the dentals.

The forecasts made by the non-generalized statistical learning hypothesis are thus in accord with the individual results of the experiments in Parts I and II, but their accuracy is called into question by the significant preference for voiceless fricatives that emerges when the data from infants of 4.5, 6, and 8 to 10 months of age who heard a variety of English fricatives are considered together. This is hard to explain if statistical learning is the only mechanism infants use to gain knowledge regarding their native language's phonotactics.

Second to be examined is the *a priori* bias. Depending on the version considered, there are two possible predictions made for Part I: if the bias is innate, a preference for voiceless initial fricatives should emerge most clearly at the early stages of development, before other information can obscure its effects. If the bias develops as a result of inductive grounding, its effects might not appear until later. Regardless of its origin, the *a priori* bias would also predict that the preference for voiceless initial fricatives should apply equally well to the dental fricatives alone as to the groups of English fricatives, and should additionally extend to novel segments.

The individual results of Experiments 1 through 3 appear to rule out the innate version of the *a priori* bias hypothesis, as no preference is found until the infants are quite a bit older, though the fact that a significant preference emerges when the data is

combined indicates that the bias could still be innate, but only weakly effective. However, the results of Experiments 4 and 5 contradict the predictions of both versions of the *a priori* bias, as no preference for the voiceless fricative(s) is found in either case, so this hypothesis alone is also unable to account for the data.

Thus, in order to explain all the results of the experiments in Part I and II, it is necessary to conclude that both learning mechanisms are operative in the first year of life, but that neither is strong enough to persuade infants to show an attentional preference for a particular group of sounds without the help of the other mechanism. Moreover, it appears that the origin of the *a priori* bias may be (at least partly) innate, though many more subjects would need to be tested at the younger ages, particularly 4.5 months, in order to discover whether or not this is truly the case.

It remains to be determined whether the two mechanisms are in perfect balance, or whether the statistical learning mechanism is generally slightly stronger, and merely appears to have the same strength as the *a priori* bias because of the confounding nature of the tokens containing initial [ð]. Furthermore, additional research is also necessary to resolve the question of whether or not the information gained from statistical learning is generalized to feature classes.

Appendices

Appendix A: Stimuli from Experiment 1

Multiple tokens of each stimulus item were recorded; all tokens considered to be clear exemplars by the experimenter and one other trained phonetician were used in the experiment. Due to the fact that only five suitable tokens of [ðu] were available, an extra suitable token of [vu] was included to maintain a balance between the conditions. A total of 73 tokens were used (37 in the voiced condition²¹ and 36 in the voiceless condition).

Initial Voiced Fricatives	# of Tokens Used	Initial Voiceless Fricatives	# of Tokens Used
[v ^h eɪ]	6	[f ^h eɪ]	6
[vu]	7	[fu]	6
[ð ^h ɑ]	6	[θ ^h ɑ]	6
[ðu]	5	[θu]	6
[ʒ ^h eɪ]	6	[ʃ ^h eɪ]	6
[ʒɑ]	6	[ʃɑ]	6
[ʒu] ²¹	1		

²¹ The inclusion of a single token of [ʒu] in the voiced condition was a mistake on the part of the author, regrettably not noticed until the experiment was complete. However, to the best of the author's knowledge, this error does not affect the validity of the experiment's results.

Appendix B: Stimuli for Experiments 2-3

6 separate tokens were recorded and used for each stimulus item, for a total of 144 stimulus tokens (72 per condition).

<u>Initial Voiced Fricatives</u>			<u>Initial Voiceless Fricatives</u>		
[vi]	[zi]	[ʒi]	[fi]	[si]	[ʃi]
[veɪ]	[zeɪ]	[ʒeɪ]	[feɪ]	[seɪ]	[ʃeɪ]
[va]	[za]	[ʒa]	[fa]	[sa]	[ʃa]
[vu]	[zu]	[ʒu]	[fu]	[su]	[ʃu]

Appendix C: Stimuli for Experiment 4: [ð] vs. [θ]

<u>Initial Voiced Dental Fricative</u>	<u># of Tokens Used</u>	<u>Initial Voiceless Dental Fricative</u>	<u># of Tokens Used</u>
[ðɑ]	6	[θɑ]	6
[ðu]	5	[θu]	6

Appendix D: Stimuli for Experiment 5: Polish Fricatives

Voiced Fricatives		Voiceless Fricatives	
Alveolo-Palatal	Retroflex	Alveolo-Palatal	Retroflex
zip	ʒip	ɕip	ʃip
zib	ʒib	ɕib	ʃib
zit	ʒit		ʃit
	ʒid	ɕid	ʃid
zik	ʒik	ɕik	ʃik
zig	ʒig	ɕig	ʃig
zɨp	ʒɨp	ɕɨp	ʃɨp
zɨb	ʒɨb	ɕɨb	ʃɨb
zɨt	ʒɨt	ɕɨt	ʃɨt
	ʒɨd		ʃɨd
zɨk	ʒɨk	ɕɨk	ʃɨk
zɨg	ʒɨg	ɕɨg	ʃɨg
zɛp		ɕɛp	
zɛb	ʒɛb	ɕɛb	ʃɛb
zɛt		ɕɛt	ʃɛt
zɛd	ʒɛd	ɕɛd	ʃɛd
zɛk	ʒɛk	ɕɛk	ʃɛk
zɛg	ʒɛg	ɕɛg	ʃɛg
zap	ʒap	ɕap	ʃap
zab	ʒab		ʃab
zat	ʒat	ɕat	ʃat
zad	ʒad	ɕad	ʃad
zak		ɕak	
zag	ʒag	ɕag	ʃag
zɔp	ʒɔp	ɕɔp	ʃɔp
zɔb		ɕɔb	ʃɔb
zɔt	ʒɔt	ɕɔt	ʃɔt
zɔd	ʒɔd	ɕɔd	ʃɔd
zɔk	ʒɔk	ɕɔk	ʃɔk
	ʒɔg		ʃɔg
zup	ʒup	ɕup	ʃup
zub	ʒub	ɕub	
zut	ʒut	ɕut	ʃut
zud	ʒud	ɕud	ʃud
zuk	ʒuk	ɕuk	ʃuk
zug	ʒug	ɕug	ʃug

Appendix E: List of CHILDES Transcripts Analyzed

Average age: 9 months, 18 days

Author	Files	Age at Recording (months.+days)	Author	Files	Age at Recording (months.+days)
Brent	c1-0902	9.02	Brent	m2-1013	10.13
	c1-0917	9.17		m2-1027	10.27
	c1-0930	9.30		m2-1113	11.13
	c1-1014	10.14		q1-0900	9.00
	c1-1027	10.27		q1-0928	9.28
	c1-1129	11.29		q1-1012	10.12
	d1-0904	9.04		q1-1026	10.26
	d1-0925	9.25		q1-1109	11.09
	d1-1026	10.26		q1-1128	11.28
	d1-1106	11.06		s1-0902	9.02
	d1-1120	11.20		s1-0919	9.19
	f1-0828	8.28		s1-1001	10.01
	f1-0910	9.10		s1-1015	10.15
	f1-1003	10.03		s1-1029	10.29
	f1-1013	10.13		s1-1113	11.13
	f1-1022	10.22		s1-1126	11.26
	f1-1106	11.06		s2-0905	9.05
	f1-1120	11.20		s2-0921	9.21
	f2-0827	8.27		s2-1004	10.04
	f2-0912	9.12		s2-1018	10.18
	f2-0927	9.27		s2-1105	11.05
	f2-1010	10.10		s2-1124	11.24
	f2-1024	10.24		s3-0913	9.13
	f2-1121	11.21		s3-1028	10.28
	i1-0901	9.01		s3-1112	11.12
	i1-0914	9.14		s3-1128	11.28
	i1-0930	9.30		t1-0830	8.30
	i1-1005	10.05		t1-0918	9.18
	j1-0908	9.08		t1-0927	9.27
	j1-0922	9.22		t1-1016	10.16
	j1-1005	10.05		t1-1025	10.25
	j1-1023	10.23		t1-1108	11.08
	j1-1106	11.06		t1-1126	11.26
	j1-1115	11.15		v1-0828	8.28
	m2-0907	9.07		v1-0910	9.10
	m2-0928	9.28		v1-0924	9.24

Author	Files	Age at Recording (months.+days)
Brent	v1-1007	10.07
	v1-1024	10.24
	v1-1115	11.15
	v2-0903	9.03
	v2-1000	10.00
	v2-1014	10.14
	v2-1028	10.28
	v2-1112	11.12
	v2-1125	11.25
	w1-0913	9.13
	w1-1005	10.05
	w1-1011	10.11
	w1-1025	10.25
	w1-1123	11.23
	w3-0923	9.23
	w3-1107	11.07
	w3-1122	11.22
Higginson	may01	11.00
	may02	11.00
Soderstrom	joe01	5.30
	joe02	6.11
	joe03	7.03
	joe04	7.17
	joe05	8.01
	joe06	8.09
	joe07	8.17
	joe08	8.29
	joe09	9.01
	joe10a	9.15
	joe10b	9.15
	joe11	9.25
	the01a	6.15
	the01b	6.15
	the02a	6.23
	the02b	6.23
	the02c	6.23
	the03a	6.29

Author	Files	Age at Recording (months.+days)
Soderstrom	the03b	6.29
	the03c	6.29
	the04a	7.08
	the04b	7.08
	the05	7.12
	the08c	8.05
	the06a	7.19
	the06b	7.19
	the06c	7.19
	the06d	7.19 (assumed)
	the07a	7.26
	the07b	7.26
	the07c	7.26
	the07d	7.26
	the07e	7.30
	the08a	8.05
	the08b	8.05
	the08c	8.05
	the09a	8.09
	the09b	8.09
	the10a	8.18
	the10b	8.18
	the11a	8.23
	the11b	8.23
	the11c	8.23
	the11d	8.23
	the12	9.00
	the13a	9.09
	the13b	9.09
	the14a	9.15
	the14b	9.15
	the14c	9.15
	the14d	9.15
	the15a	10.11
	the15b	10.11
	the15c	10.11

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