6-4-2012 12:00 AM

Altered Auditory Feedback Causing Changes in the Vowel Production of Children with Specific Language Impairment

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Recommended Citation

Holmes, Emily Michaela, "Altered Auditory Feedback Causing Changes in the Vowel Production of Children with Specific Language Impairment" (2012). *Electronic Thesis and Dissertation Repository*. 584.
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ALTERED AUDITORY FEEDBACK CAUSING CHANGES IN THE VOWEL PRODUCTION OF CHILDREN WITH SPECIFIC LANGUAGE IMPAIRMENT

(Spine title: Auditory Feedback: Children with Specific Language Impairment)

(Thesis format: Monograph)

by

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Graduate Program in Neuroscience

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science

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entitled:

Altered Auditory Feedback Causing Changes in the Vowel Production of Children with Specific Language Impairment

is accepted in partial fulfillment of the
requirements for the degree of
Master of Science

Date

Chair of the Thesis Examination Board

Abstract

Specific language impairment (SLI), an unexpected delay in the onset or development of oral language, has been hypothesized to have an underlying auditory processing component. Auditory feedback is a mechanism by which an individual controls the characteristics of their own voice, thereby assisting in the processing and production of speech. These characteristics include intensity, frequency, speed and others. The present study examined whether children with SLI make different use of auditory feedback than their typically developing (TD) peers. Participants aged 6-11 years completed a hearing screening, a frequency resolution task, vowel space task and a formant shifted auditory feedback task. Children with SLI tended to compensate more for the manipulation in the positive shift condition, and compensated similarly to TD children in the smaller, negative shift condition. These findings may indicate that children with SLI are making atypical use of auditory feedback.

Keywords: Altered auditory feedback, Vowel formant manipulation, Frequency discrimination, Specific language impairment, Language learning, Child language development.

Acknowledgments

I would first like to thank my thesis supervisors, Dr. Lisa Archibald and Dr. David Purcell for their guidance during this thesis and dedication to my development as a researcher. I have learned so much from them, both due to their extensive knowledge and their devotion to producing excellent work in the scientific community. I am incredibly grateful for their insight and considerate feedback. I am a better scientist for having worked with them.

Secondly, I would like to thank my advisory committee: Dr. Marc Joanisse, Dr. Ruth Martin and Dr. Susanne Schmid. Each of them provided exceedingly helpful suggestions to foster the improvement of this work. Thanks also to Janis Oram Cardy for her great insight into SLI and auditory measures. Their guidance and helpful commentary have truly added to this thesis.

Lastly, I would also like to express my gratitude for the people from the Language and Working Memory Lab and the Speech, Auditory Feedback and Evoked Responses Lab. In particular, many thanks to Allison, Tyler, Katherine, Areej, Jackson, Berger, Rosine and the other wonderful members of the LWM Lab, and Jong Min, Linh, Viji, Sriram, Laura and Gaby of the SAFER Lab. Each lab member has helped foster a fantastic, supportive, friendly work environment of which I have thoroughly enjoyed being a part.

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Perturbed Auditory Feedback Causing Changes in Vowel Production of Children with Specific Language Impairment

An individual’s vocal traits are determined mostly by the subconscious ability to perceive, analyze and modify the characteristics of their own voice. The ability to hear and process such vocal characteristics as speed, intensity, and frequency has long been noted as critical in maintaining coherent speech (Bernard, 1950). This mechanism, termed auditory feedback, compares predicted vocal outcome with actual vocal outcome to determine if changes are necessary, and assists in compensation should the outcome not match the prediction. When auditory feedback is decreased or lost, whether this loss occurs slowly as in the case of post-lingually deafened individuals or nearly immediately when one is wearing noise-dampening headphones, observable changes occur in vocal characteristics. Despite recognition of the importance of auditory feedback in development and maintenance of coherent speech (Bernard, 1950; Yates, 1963; Waldstein, 1990, Leonardo & Konishi, 1999), the relationship between auditory feedback and language learning remains poorly understood. This thesis explored the links between auditory feedback and language learning by examining the auditory feedback abilities of typically developing children and those with a relatively specific deficit in language learning known as specific language impairment (SLI).

Auditory feedback has analogues to other sensory modalities. When instructed to complete a reaching task after a participant’s peripheral vision was altered, participants’ trials displayed a decreased accuracy, as compared to their baseline accuracy without vision alteration (Gonzalez-Alvarez, Subramaniam & Pardhan, 2007). Further, when the target is altered near the end of a reaching motion, individuals tend to compensate for the shifted target by aiming for a position between the original location (or prediction) and the final location (or outcome) (Ma-Wyatt & McKee, 2006). Ma-Wyatt and McKee (2006) suggested that the individuals are making a "best bet" as to the true location of the target. Likewise, auditory feedback provides the necessary speech control mechanism that is required for adapting to changes in the auditory environment, as it continuously compares the prediction with the outcome. When outcome does not match predictions, changes in vocal characteristics are made to match the participant's perception of the true location of the vocal production target.

Vowels and Vowel Spaces

Vowels form the nucleus of a syllable and are crucial to speech intelligibility. Vowels are produced by a fairly open vocal tract, and are individually differentiated by the constrictions of the tongue, lips and other articulators. The ability to alter vocal characteristics is integral to forming different vowels and consonants. Changing the height of the tongue (by changing position of the jaw) and shape or position of the tongue and lips produces different vowels. The tongue position may change from being localized in the front, central to back of the oral cavity. The tongue height in the oral cavity can change from high (termed close), mid, to low (termed open). The shape of the lips can change from rounded to unrounded. Each of these three categories, tongue height, tongue position and lip shape, act as filters on the air that comes from the lungs and passes through the vocal folds. These filters alter the resonances in the oral cavity, which results in different formant frequencies (see Figure 1) recognized perceptually as different vowels. For example, when the tongue position is back, tongue height is low, and lips are unrounded, the vowel /ɔ/ (as in the word ‘bought’) is produced. The /ɔ/ vowel is represented in the bottom right quadrant of the vowel space (see Figure 1). The vowel /i/, (as in ‘see’) on the other hand, is produced with the tongue in a high, front position without lip rounding, and is represented in the top left quadrant of the vowel space. Vowels are easy to manipulate as a class, making them a valuable variable for studying the mechanisms of auditory feedback.

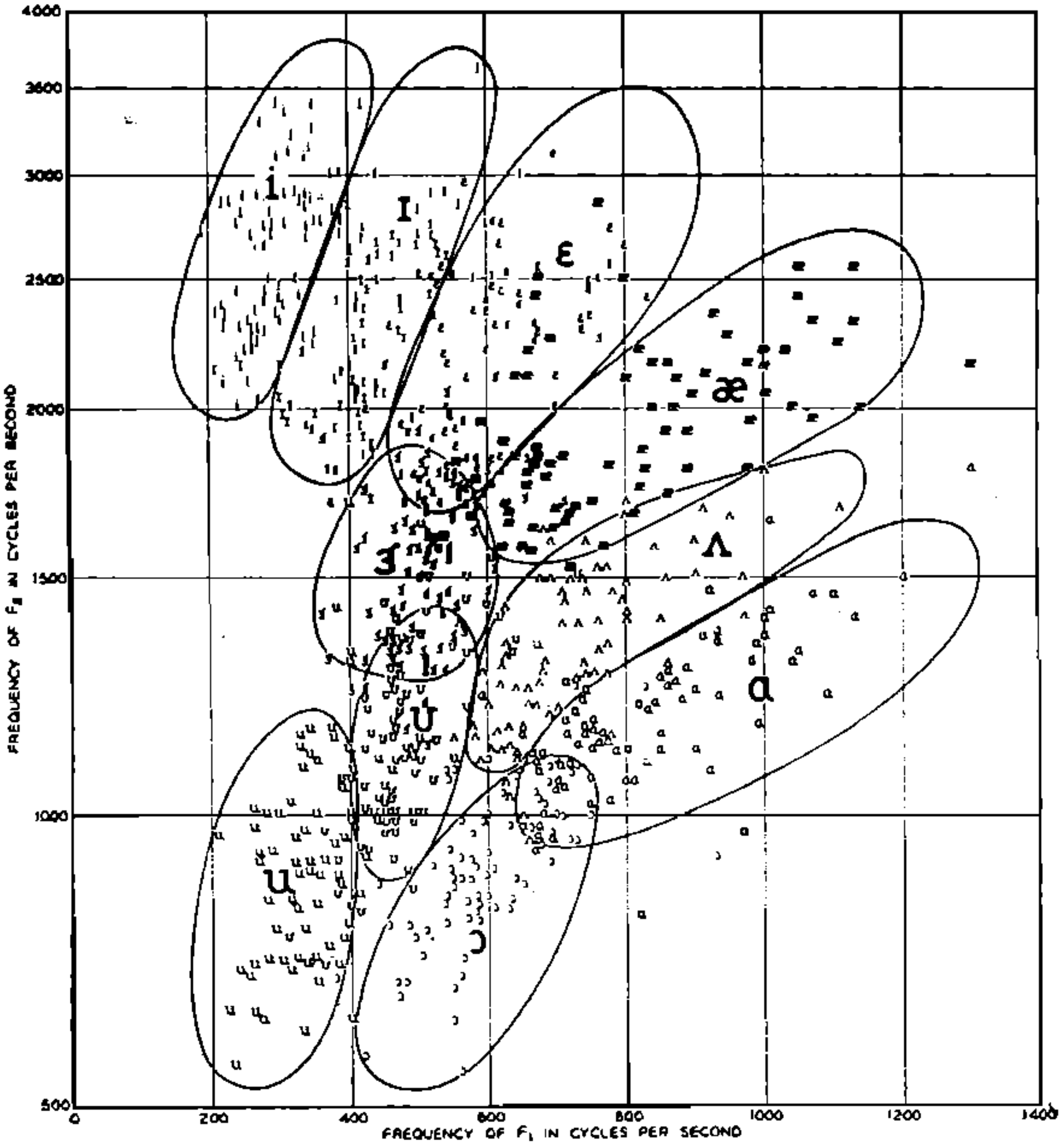


Figure 1. Sample New Jersey English vowel space averaged over 76 speakers: Second formant versus first formant, obtained from Peterson and Barney (1952). Note the top left of the graph depicts the most constriction (tongue is close to the palate and at the front of the mouth), and the bottom right of the graph depicts the least constriction (tongue is at the back of the mouth and far from the palate).

Alteration of formant frequencies changes which vowel the speaker produces. The tongue height, tongue position and lip shape affect the first formant (F1), second formant (F2) and third formant (F3) respectively. This is a useful approximation, however, in reality the positions of the tongue, jaw and lips are not perfectly independent of one another. Changing position of any of these structures may produce some changes in formants other than the main formant affected. In general, the most important formants affecting how a vowel is perceived are F1 and F2 (see Figure 2 for formants changing over time during the word “heard”). By manipulating formants, and even solely F1, researchers have the opportunity to transform one vowel to another from those that were originally recorded, without mechanical manipulations of the oral cavity. These properties of vowels form the foundation of the formant shifted auditory feedback paradigm.

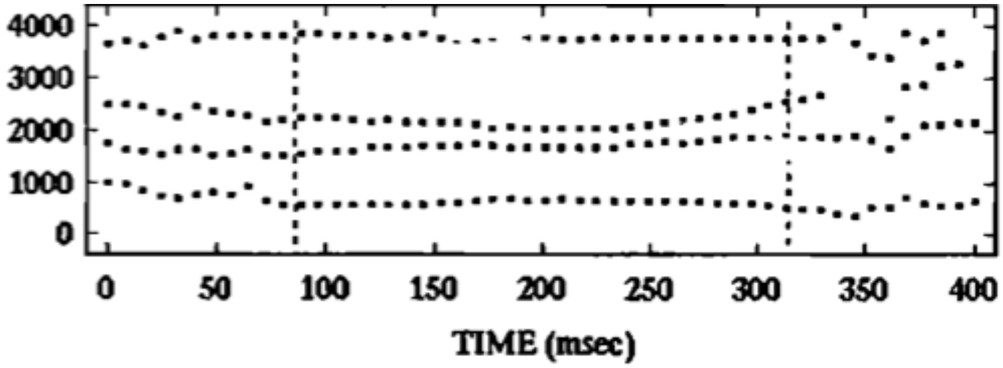


Figure 2. Linear Predictive Coding (LPC) spectra for a child saying “heard” in Midwestern American English. The y-axis depicts formant frequency (Hz). This depicts a hand-corrected spectrum, where four formants can be seen as four horizontal, semi-parallel dotted lines. The vowel nucleus boundaries are indicated by vertical dotted lines. Obtained from Hillenbrand et al., (1995).

The graphical map depicting the acoustical location and location of articulation in the oral cavity for an individual’s vowels (see Figure 1), known as an individual’s vowel space, is influenced by several factors. These factors include an individual’s age, language and dialect, as well as other less apparent components such as individual variability in vocal tract structure. Additionally, an individual’s vowel space changes throughout their development and with aging. This is most notable during adolescent years, when male and female voices can change substantially (Peterson & Barney, 1952; Lee et al., 1998; Bennett, 1980; Busby, 1994 and others). The considerable variability in vowel production both within and between individuals makes studying vowels a challenge for researchers. This variability can be reduced through careful selection of age parameters since individuals within the same developmental bracket tend to have similar vowel spaces (Lee et al., 1998). Researchers can also normalize data for gender or other differences in the case of adolescent (13 years of age or older) or adult participants. Normalization is performed by subtracting an individual's average baseline formants from the formant values for trials where manipulation is being performed (Munhall et al., 2009). In addition to normalization, individual variability is mediated by discarding the first several trials in a vowel production task when the individual is adjusting to the presence of headphones.

Methods Used to Study Auditory Feedback

Adaptation to novel information applies to several domains within language, including the speed, intensity, and phonemes used in an individual's speech. Phonemes are the smallest components of language, such as the vowels /ɪ/ (ih) as in "hid", /ɛ/ (eh) as in "head", or /æ/ as in "had". Accurate and easily understandable speech requires an ability to rapidly and reliably produce phonemes. Large variations in phoneme production can produce errors of many kinds, including those of misunderstanding. For example, the words "cat", "kit", "cot/caught", "coot", "Kate" differ mainly in one phoneme alone: /æ/, /ɪ/, /ɔ/, /u(w)/ and /e(y)/ respectively. Thus, being able to produce and categorize phonemes reliably is very important to both language and comprehension. To examine whether online changes occur in these components of language, Houde and Jordan (1998) designed a study to perturb an individual's auditory feedback. Participants wore headphones and a microphone, and were instructed to whisper Consonant-Vowel-Consonant (CVC) words ("pep", "peb", "bep" and "beb") at regular intervals as prompted by the word appearing on a computer screen (Houde & Jordan, 1998). They designed a formant altering apparatus which they used to shift participants' formant frequencies F1, F2 and F3 of the target vowel /ɛ/ either 400 Hz higher (+400 Hz) towards the vowel /a/, or lower (-400 Hz) towards the vowel /i/. As a result, the participants went from hearing “pep” to “pop” in the +400 Hz shift condition, and “pep” to “peep” in the −400 Hz condition. This shift was performed very gradually, by only a few imperceptible Hertz at a time, such that participants heard their manipulated voice over the headphones and perceived it as their own voice. Houde and Jordan (1998) recorded the participant’s productions (each speech word) and measured the formant frequency during each production. The results indicated that participants made significant compensation (moving the articulators to create different formants that opposed the formant shift) for the manipulation in both shift conditions. The researchers noted that there was much variability from one individual to another in terms of the amount of compensation for the manipulation.

Houde and Jordan (1998) employed whispered speech in their paradigm because whispered speech is not conducive to bone conduction. Bone conduction assists speakers in discerning the identity of the phonemes in their speech. It mainly assists in hearing voiced speech. The researchers reasoned that participants would be more likely to perceive the altered auditory feedback in their task as their own productions if bone conduction were minimized. That is, they wanted to reduce the chance that participants would detect the discrepancy between what they were saying and the manipulated feedback they were hearing at their headphones Later, Purcell and Munhall (2006a) demonstrated that voiced speech could also be used in the manipulated auditory feedback paradigm as long as manipulated feedback was played to participants at a comfortably loud volume such that bone conduction was overwhelmed at the cochlea.

Purcell and Munhall (2006a) designed a study to examine how adults adapted to altered auditory feedback of phonemes in their speech. In their study participants wearing headphones and a microphone were prompted by words on a computer screen to produce the word “head” (Purcell & Munhall, 2006a). Their speech entered the microphone and was played back to them through headphones in what was effectively real-time, so that in general the participants perceived the productions, even those with manipulated formants, as their own speech. Initially their productions were played back to them through their headphones without any manipulation. Over many trials the participant’s first formant of the vowel /ɛ/ in the word “head” was shifted up by an imperceptible 4 Hz per production. Over trials the vowel the participants’ heard more closely approximated the participant’s own productions of /æ/ (ae) as in “had”, which was determined at the beginning of the study [average positive vowel shift: +136Hz ± 46.2Hz (Purcell and Munhall, 2006a)]. Another set of trials introduced a manipulation in the opposite direction, so that over many trials the vowel heard by participants through their headphones was shifted down to more closely approximate their own productions of /ɪ/ as in “hid” [average negative shift: -135Hz ± 42.7Hz, (Purcell and Munhall, 2006a)].

Purcell and Munhall (2006a) found that in response to these manipulations, participants would compensate, on average, by shifting their own productions in the opposite direction of the manipulation introduced into their speech, altering the F1 of their productions approximately less than 30% of the total shift imposed in either direction. This was a partial compensation in response to the manipulation, as had been found in several other studies between which the overall magnitude of the shift differed (Houde & Jordan, 1998; Houde & Jordan, 2002; Purcell & Munhall 2006a; Purcell &

Munhall, 2006b). In another study, shifting using a gradual manipulation of about 5 Hz per production or using a step method of 50-125 Hz still produced a similar partial compensation of 25-30% of the overall manipulation (MacDonald et al., 2010). Thus, the amount of compensation due to auditory feedback does not rely on the size of the steps taken to achieve the maximum manipulation. Instead, it relies on the total magnitude of the manipulation up to a point. MacDonald et al., (2010) found that very large shift magnitudes evoked proportionately small compensation magnitudes. Thus, as shift magnitude increases, compensation magnitude also increases, but the proportion of compensation is not the same for all shift magnitudes.

Similar to Houde and Jordan (1998), Purcell and Munhall (2006a) found that individual variability was high: a small sample of participants either barely compensated for the manipulation or near fully compensated for the manipulation. Villacorta and colleagues (2007) also found this high degree of individual variability. They showed that greater compensation to perturbed auditory feedback was correlated with greater ability to discriminate between two instances of the same formant, for example, two F1s of slightly different tokens (words). This variable partial compensation for shifted formant frequency may be similar to the partial compensation noted by Ma-Wyatt and McKee (2006) in their reaching and grasping study. A likely explanation is that in Purcell and Munhall's altered feedback paradigm, similar to Ma-Wyatt and McKee (2006) altered reaching paradigm, participants may potentially be giving their "best bet" as to the true location of the formant frequencies. Perhaps these best bets, or how willing or able an individual is to move from an initial location to an endpoint, differ from person to person. A future study could examine this concept by means of the auditory feedback paradigm through the use of extended utterances (e.g., instructing participants to say /hɛd/ holding the /ε/ for 3 seconds), with the manipulated auditory feedback being slid upwards or downwards during the utterance itself. Compensation for this sliding formant auditory feedback could then be examined for characteristics such as change in magnitude of compensation and the final and average formant values for each trial.

In another study that examined adaptation to novel auditory feedback, Purcell and Munhall (2006b) confirmed again that once normal auditory feedback was resumed following manipulation of auditory feedback participants did not immediately return to baseline (Purcell & Munhall 2006a, 2006b). Instead, on average over many trials participants displayed a gradual return to their initial baseline that had been established at the beginning of the study.

Auditory feedback is a subconscious, rather than conscious, compensation mechanism. To test whether individuals have the ability to consciously control the auditory feedback mechanism, Munhall and colleagues (2009) followed the manipulated auditory feedback paradigm. In this study they divided their participants into three distinct groups: a group that was not told about the manipulated auditory feedback (“naïve” group), a group that was told to ignore how the headphones made their voice sound (“ignore headphones” group), and a group that was taught about the manipulation and specifically told to maintain the same pronunciation (“avoid compensation” group). Results indicated that in all three conditions there was no significant effect to being an informed or uninformed participant. This indicates that the auditory feedback process is not under conscious control for participants without extensive training. Munhall and colleagues suggested that auditory feedback likely falls into the category of “overlearned motor behaviors" (Munhall et al., 2009) such that on average even participants instructed not to compensate are sensitive to the manipulation and compensate accordingly.

The auditory feedback mechanism has also been studied using functional Magnetic Resonance Imaging (fMRI). Zheng and colleagues (2010) conducted a meta-analysis of 30 studies along with their own fMRI study to determine the origin of the auditory feedback mechanism. Following this investigation, they suggested that the focal areas involved in the auditory feedback mechanism are mainly the Superior Temporal Gyrus (STG) and Middle Temporal Gyrus (MTG) (Zheng et al., 2010). These two areas surround the primary auditory cortex. They also made the distinction that cerebral areas involved in the auditory feedback mechanism are discrete from the areas involved in simply hearing one's own voice (Zheng et al., 2010), though as could be expected, there was much overlap.

The Directions into Velocities of Articulators (DIVA) Model

The neural pathways underlying the auditory feedback mechanism are complex. Guenther and collogues, (2001), developed the Directions into Velocities of Articulators (DIVA) model, which illustrates how information may be passed through and processed in the cerebral structures involved in auditory feedback and feedforward mechanisms. The DIVA model has been supported by several studies using fMRI (Tourville et al., 2008, Guenther, 2006, Guenther et al., 2006, and others). This model is arguably one of the most prominent theories explaining speech control and online adjustment of vocal characteristics and articulators available today.

A brief and simplified overview of the DIVA model is as follows (see Figure 3). In the DIVA model (Guenther, 2001), information about the actual location of the structures of the vocal tract is sent via projections from primary somatosensory cortex [(Broadman's Area (BA) 1,2 and 3)] to the supramarginal gyrus (SMG, BA40). The premotor cortex (BA6) also has projections to BA40, through which it communicates information on the desired oral sensation targets, as well as projections onto the superior temporal gyrus (STG), through which it sends information about the desired auditory targets (Guenther, 2001). BA40 then compares the information about the actual location of the structures of the vocal tract to the desired oral sensation targets, with any difference between those being the necessary movement required in orosensory coordinates, and sends this information to the cerebellum (Guenther, 2001). BA22, which receives the auditory target information from BA6 along with actual incoming auditory information from BA41 and BA42, compares these two sets of information, with any difference between those being an error signal (Guenther, 2001). BA22 passes this error signal to the cerebellum. The cerebellum synthesizes the information from BA22 and BA40 into a "motor velocity signal" to compensate for any differences passed on by BA22 and BA40, and sends this motor velocity signal to the primary motor cortex (BA4). BA4 sends motor information to articulators that execute the motion necessary to compensate for any errors. In this way, sensory information from the orotactile and auditory environments is synthesized with predictions as to how that information should feel and sound, and the resulting error is compensated for by transforming the error into a motor signal sent to the articulators. This adjustment in the shape and position of the articulators changes the resulting speech sounds. These new speech sounds are processed in the same manner. Thus, auditory feedback and feedforward mechanisms work to consistently adjust speech to match a desired tactile and auditory outcome (Guenther, 2001).

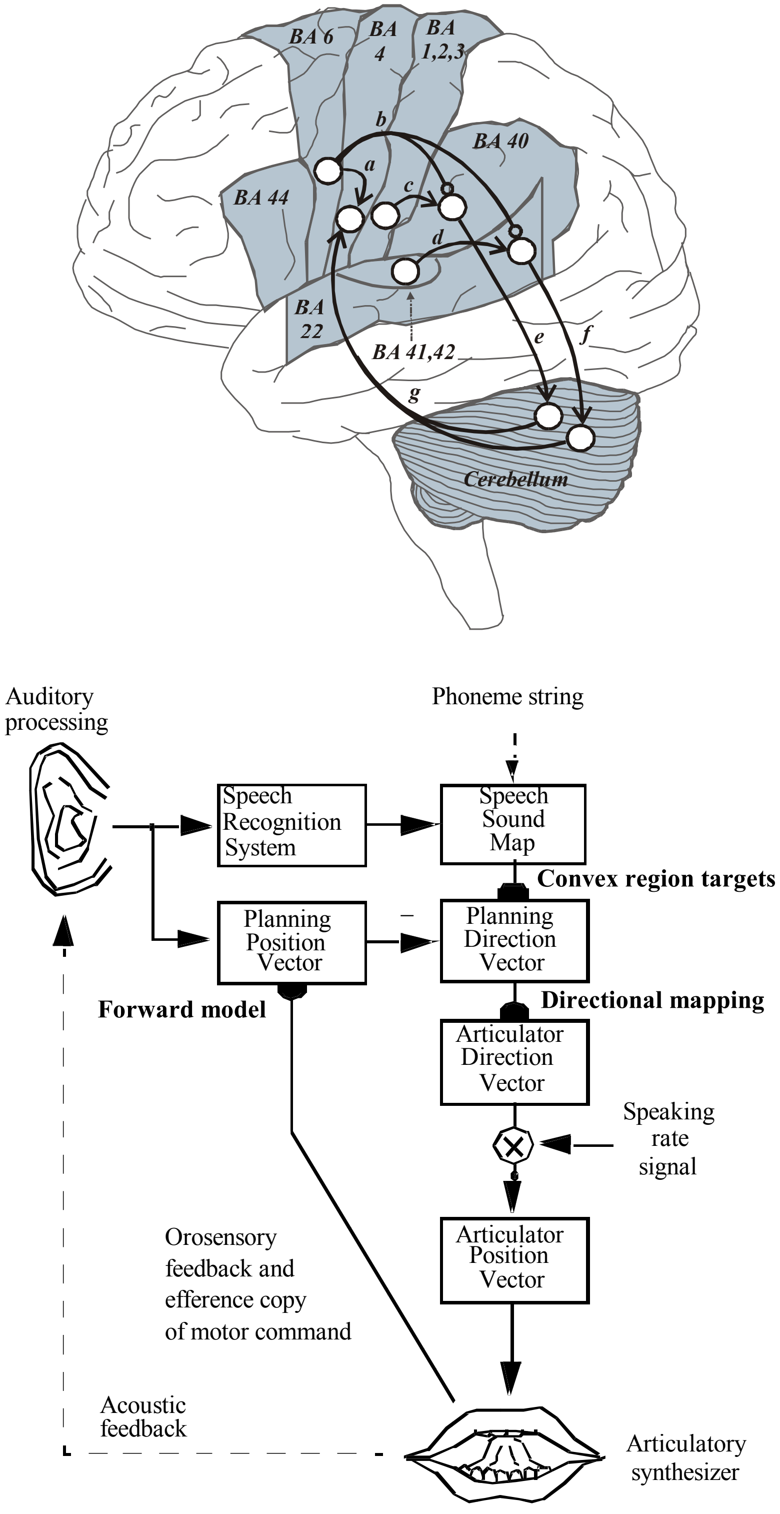


Figure 3. DIVA Model of speech production and corresponding areas. Obtained from Guenther (2001).

Tourville and colleagues (2008) performed an fMRI study examining the effects of formant shifted auditory feedback on the BOLD response. In this study, the researchers showed that during the manipulation there was greater activation of the posterior STG as well as the planum temporale than during non-manipulated, normal speech (Tourville et al., 2008). They indicated that this could possibly be due to the presence and activation of “auditory error cells” at BA22 involved in compensating for the manipulation by comparing predictions with actual auditory information and generating an error signal. This error signal would then be sent to the cerebellum and from there to the primary motor cortex, creating changes in vocal articulators and, therefore, in resulting speech sounds.

Auditory Feedback and Language Learning

Logically speaking, it makes sense that the ability to accurately monitor and modify speech production facilitates language learning. While human research is lacking, Brainard and Doupe (2000) have highlighted the integral role auditory feedback plays in the development and maintenance of vocal behaviour in another species; songbirds. Results of Brainard and Doupe’s review revealed three stages important to the development of song: a “sensory” first stage where young birds listen to the song of other birds such as parent birds to form a template, a “sensorimotor” second stage where they start mimicking and practicing song, and a third stage where the birds “finalize” their adult song. Even after these stages, adult birds still rely on auditory feedback to a certain extent however, since deafened birds will, over time, lose some qualities to their song (perhaps somewhat akin to vowel space shifting evident in humans with post-lingual deafness). Birds raised without the song of adult birds and those with lesioned Anterior Forebrain Pathways (AFP) during the template-forming “sensory” first stage fail to develop normal song (see Brainard & Doupe, 2000 for review). The human analogue to the AFP is the basal ganglia (Manaithunai et al., 2010). Brainard and Doupe (2000) as well as Fee and Scharff (2010) in their reviews of the literature have drawn connections between human and songbird auditory feedback and resultant language or song learning. These researchers, as well as the work of many others overviewed in their discussions, agree that the intact auditory feedback pathway and development of a template via listening is integral to the development of normal language or song. Nevertheless, research investigating this link in humans is very limited indeed. To the best of my knowledge, this thesis is the first to explore the relationship between language abilities and auditory feedback within typically developing children and children with a relatively specific deficit in the development of language, specific language impairment (SLI).

Specific Language Impairment

Specific language impairment (SLI) is characterized by a failure to develop language at the expected time or rate in spite of otherwise typical neurological, sensory and behavioural development and educational opportunities (Leonard, 1998). This is a relatively common impairment, affecting approximately 6-10% of the population (Tomblin et al., 1997, Bonneau et al., 2004), frequently associated with a familial history of the impairment, (Fisher et al., 1998, O'Brien et al., 2003, Bonneau et al., 2004), and about three times more common in males than in females (Bishop, 2001). Although considerable variability exists, hallmark characteristics include grammatical deficits related to verb tense and morphology, and phonological processing deficits (Leonard, 1998). Despite investigations examining associated genetic, neurological, cognitive, and social aspects of SLI, the underlying cause of SLI is not well understood.

Of particular interest to the present thesis are the auditory processing deficits in children with SLI reported by many studies (Goffman, 1999; Bishop et al., 1999; McArthur & Bishop, 2005; Miller, 2010; Ferguson, 2011). Theories arising from such findings have implicated an underlying auditory processing deficit such as a disability in frequency tracking (Basu et al., 2010), poor frequency discrimination (McArthur & Bishop, 2004) or difficulty processing swiftly changing auditory information (Tallal, & Piercy, 1975; Tallal & Stark, 1981). Related ideas link SLI to poor phonological representations or processing (Montgomery, 1995; Lahey & Edwards, 1999, Bishop et al., 1999) or poor fine motor control or neuromuscular dysfunction (Hill, 1999; Goffman, 1999; Bishop, 2001; Noterdaeme et al., 2002; Webster, 2004). The present thesis will provide a brief overview of the theories relevant to the issue of auditory feedback, although it must be noted that the present study was not designed to differentiate amongst these theories. Although additional SLI theories exist related to working memory (Archibald & Gathercole, 2006a, b), attention (Spaulding et al., 2008; Danahy Ebert & Kohnert, 2011), and statistical learning (Evans & Saffran, 2009), they will not be further addressed in the current thesis.

Frequency resolution, auditory temporal processing and SLI

One of the earliest theories of SLI was Tallal and colleagues' (1973, 1975) rapid temporal processing deficit theory. This view was based on findings that children with SLI had difficulty making judgments about two rapidly presented tones, and has sparked decades of related work. In a 1999 review of this literature, Rosen concluded that auditory processing difficulties are not apparent in all individuals with SLI despite being more common in SLI groups, and as such are not sufficient as a causal explanation of SLI. Rosen supports this hypothesis with studies that indicate that the "severity of the auditory deficit does not appear to predict the severity of the language/literacy deficit" (Rosen, 1999, p. 524) and that some people with normal language scores may display auditory processing deficits (Rosen, 1999, p. 524). It must be acknowledged, however, that many of the auditory tasks included in the studies reviewed by Rosen may not have been pure measures of auditory processing. Given the multiple demands of such tasks, the lack of consistent findings regarding SLI and auditory processing is, conceivably, unsurprising.

In addition to the tasks employed, another challenge in examining auditory processing in children is the issue of development. Potentially, adults with language impairments have “outgrown” the initial auditory processing deficits resulting in the language impairment leading to unimpaired performance on adult auditory tests. This is not surprising, since it has been suggested that SLI is caused by immature language and auditory processing systems, and even at 6-12 years of age major cortical connections in the auditory pathway are still being formed (Moore & Linthicum, 2007). Indeed, Hill, Hogben and Bishop (2005) tested typically developing (TD) children and children with SLI in two sessions almost two years apart. These researchers found that the frequency discrimination abilities of the SLI group improved during this period, but were still, on average, worse than those of TD children (Hill, Hogben & Bishop, 2005). In addition, studies using fMRI have clearly displayed reorganization and differences in activation in areas involved with language and auditory processing during typical development from childhood to adolescence, such as Broca’s area, Wernicke’s area, middle frontal, inferior parietal, and anterior cingulate regions (Schapiro et al., 2006). Auditory impairment or an immature auditory processing system observed in childhood but not in adulthood may have an impact on language development and later language abilities in spite of the initial impairment having “resolved”. Bishop and colleagues (1999) support this supposition, stating: “it is possible that a slow-maturing auditory perceptual system might leave a lasting legacy of language impairment, even after auditory discrimination has improved” (Bishop et al., 1999, p.166).

Recently, auditory processing in SLI has been investigated using event related potentials (ERPs), an electrophysiological measure of the neural response to a stimulus.

The study of ERP components or transient electrical potential shifts sensitive to early auditory processing such as the N1-P2-N2 complex (Roeser et al., 2000, p.471-497) has provided researchers with a means of examining auditory processing more directly in special groups, such as SLI, with interesting results. Results of several of these studies suggest that the auditory cortex of children with SLI is less mature, resulting in reduced ability to resolve or discriminate between frequencies (McArthur & Bishop, 2004, 2005). These studies also indicate the presence of less mature or abnormal N1-P2-N2 waveforms than those of TD individuals (Bishop & McArthur, 2005; McArthur & Bishop, 2004, 2005; Bishop et al., 2007). Even more recently, poor tracking of frequencies at the level of the brainstem has been observed (Basu et al., 2010).

Phonological processing and SLI

Many researchers have posited that SLI is related to a problem with phonological processing (Montgomery, 1995; Lahey & Edwards, 1999, Bishop et al., 1999, and others). Several possible mechanisms have been suggested including poor quality phonological representations (Sussman, 1993), reduced capacity to store phonological information in short-term memory (Gathercole, 2006; Montgomery, 1995), or difficulty with phonological segmentation or categorization (Joanisse & Seidenberg, 1998). Children with SLI have been observed to make frequent phonological errors in naming tasks (Lahey & Edwards, 1999), are less able to accurately repeat novel words (Archibald & Gathercole, 2006), and perform more poorly on phonological awareness tasks (Briscoe et al., 2001). Converging evidence comes from studies of the pars triangularis, a part of the brain involved with phonological processing, especially between words that sound alike such as those that rhyme (Poldrack et al., 2001). Gauger (1997) found that children with SLI had a smaller pars triangularis as well as an abnormal distribution of language structures, which tended to be emphasized in the right hemisphere rather than the typical left hemisphere. Gauger (1997) suggested that this abnormal brain morphology might result in the impairments in phonology observed in SLI, since the atypical brain morphology was correlated with impaired performance on language tasks. Other researchers have also noted brain abnormalities correlated with the severity and subtype of SLI, such as impairments in phonological processing (de Vasconcelos Hage, 2006; for review of the literature see Ullman & Pierpont, 2005).

Neuromotor abilities and SLI

A final theory relevant to the present thesis implicates atypical neuromotor abilities as a contributing factor in SLI (Goffman, 1999; Goffman, 2004). Goffman (1999) used a stressed and unstressed syllable task to study the oromotor abilities of seven 4-6 year old children with SLI. She found that the speech motor system of children with SLI appeared developmentally delayed as compared to that of typically developing age-matched peers, and that executing multi-movement actions showed greater variability (Goffman, 1999). Goffman (1999) suggested that this variability might make the production of phonemes (including vowels) difficult for children with SLI due to the demands for complex and well-timed oromotor movements associated with speech.

Theories of SLI and the Altered Auditory Feedback Paradigm

The theories of SLI related to deficits in auditory processing, phonological processing, and neuromotor abilities have been reviewed above. While the altered auditory feedback paradigm was not designed to distinguish between these theories or potential contributions from these deficits, atypical responses to altered auditory feedback would be consistent with each one of them. If the findings of the present study reveal difficulty discriminating frequencies or atypical auditory feedback responses in our SLI group as compared to the TD group, it would be consistent with an SLI deficit along the auditory feedback pathway. A phonological processing deficit may make it difficult for children with SLI to use auditory feedback in making accurate comparisons between produced phonemes and their internal representations. Difficulty with fine oromotor movements may impair the ability of children with SLI to displace the articulators appropriately in order to compensate for the formant frequencies manipulated in the shifted auditory feedback paradigm. Although atypical responses to altered auditory feedback may be predicted for SLI groups based on these theories, it is unclear whether to expect overcompensation or undercompensation for the manipulation. Overcompensation may reflect a greater reliance on the altered auditory signal over internal phoneme representations, or larger than expected oromotor movements in compensation. Undercompensation, on the other hand, may indicate a lack of (subconscious) recognition of altered frequencies, or smaller than expected oromotor movements in compensation. At present, there is no basis to pose a strong directional hypothesis for an SLI deficit in auditory feedback.

Motivation for the Present Study

The motivation for the present study was to explore the relationship between auditory feedback and language by comparing performance of children with SLI and those with typical development (TD) on a perturbed auditory feedback task. We hypothesized that children with typically developing linguistic systems would display compensation similar to that of adults in studies using the shifted auditory feedback paradigm (Houde & Jordan, 1998, Purcell & Munhall, 2006a, Purcell & Munhall, 2006b, Munhall, 2009). We also hypothesized that children with SLI may have atypical responses to formant shifted auditory feedback.

The auditory system is particularly vital to language, learning and communication. Understanding dysfunctions in the auditory system is a gateway to the development of assistive therapies for those with impairments. To this end, it is useful to study SLI, a language impairment characterized by an unexpected delay in the development of language, which is commonly associated with suspected auditory processing difficulties. Perceiving and processing sound and language is a largely subconscious process that plays a large role in communication and language learning. It would be useful to determine if children with SLI perceive and process auditory stimuli in a different way than their peers. The findings will make a valuable contribution increasing general knowledge of auditory feedback across development, as well as auditory processing dysfunction in children with specific language impairment.

Methods

Participants

Participants were drawn from a pre-existing database containing descriptive profiles for children who had completed a standardized test battery of language, mathematics, and memory during the 2009/10 and 2010/11 school years as part of a previous study examining language, reading, and math in school age children. From this database, 30 children were selected for the present study, 20 typically developing (TD) children (11 boys; *M* = 9.31 years, *SD* = 1.65 years), and 10 children with specific language impairment (SLI; 7 boys; *M* = 9.95 years, *SD* = 1.15 years). None of the children had a diagnosis of ADD/ADHD, Autism Spectrum Disorder, or hearing impairment. To confirm grossly normal hearing abilities of the participants involved in the study, a pure-tone audiometric hearing assessment was performed for both ears at octave frequencies between 250 and 4000 Hz using TDH39 headphones and a Madsen Itera audiometer. Children raised their hand to indicate they had heard a given tone. All participants had hearing thresholds below 25 dB HL for all frequencies in both ears and none of the parents indicated concerns about the hearing abilities of their child.

In order to assess language abilities, each child completed the four core subtests appropriate for the child's age for the *Composite Language Score* (CLS) from the *Clinical Evaluation of Language Fundamentals IV* (CELF-IV; Semel, Wigg, & Secord, 2003) as follows. In the *Concepts and Following Directions* subtest, the child pointed to aspects of a picture following a spoken instruction. For *Recalling Sentences,* the child repeated sentences immediately after hearing them and for *Formulated Sentences* they created a sentence using a given word. Children under 9 years completed the *Word Structure* subtest involving completing a sentence with the grammatically correct word form, and those 9 years and older completed the *Word Classes 2* subtest involving identifying which two of four words had a related meaning. In order to assess nonverbal intelligence, the two subtests of the *Wechsler Abbreviated Scale of Intelligence* (WASI; Wechsler, 1999) comprising the Performance IQ (PIQ) composite were administered. In the *Block Design* subtest, the child arranged blocks to match a model. In the *Matrix Reasoning* subtest, the child chose a picture to complete a pattern.

Children with specific language impairment (SLI) had CLS scores more than one SD below the mean (<85) and typically developing (TD) children had CLS scores above one SD below the mean (>85) at the final testing. By this definition, any results from the TD group represent normal values for this age range. If the SLI group differs from the TD results, their values would be considered atypical. Every effort was made to select children who showed a stable profile across the two testing periods. As a result, none of the children in the present study showed a change of greater than 11 standard score points across testing periods. No exclusion criteria were set for PIQ. Children whose behavior was not conducive to completing the study tasks were not included in the reported matched sample (1 TD child). Participants were assigned to SLI or TD groups based on the standard CLS.

A subgroup composed of 10 children from the 20 with typical development was selected as a matched control group for comparisons with the SLI group. The SLI and matched-TD groups were matched for gender, age, linguistic variables (first and only language spoken at home was Ontario English), socioeconomic status and PIQ (*M* SLI: PIQ = 93, *SD* = 12; *M* matched-TD PIQ = 96, *SD* = 5). Participants were not included in the matched TD-group if they did not meet these criteria. The University of Western Ontario Ethics Non-Medical Research Ethics Board approved this study and informed consent was obtained for all children from their parents or legal guardians (see Appendices D, E and F). The children signed an assent form indicating their willingness to participate in the study after the nature of the study was explained to them. Table 1 describes the participant population for age, CLS scores (language abilities), PIQ scores (intelligence), and socioeconomic status. The participants in the matched groups were well matched for each of these factors: age ($t(18) = -.727, p > .05$), PIQ ($t(18) = .795, p > .05$), average education of mother ($t(18) = 1.842, p > .05$) and average education of father ($t(18) = .402, p > .05$). The two groups differed only in CLS, where $t(18) = 6.795, p < 0.0001$). For individual participant descriptive statistics and data for individual participants in all study procedures, see Appendix B.

Table 1

*Descriptive statistics for the SLI and TD groups. A statistically significant difference in group means in the SLI and TD populations is indicated by ** (p < 0.005).*

	Gender	Age (Years)		Level of Education[a]		CLS		PIQ	
Group	Boys: Girls	Mean	S.D.	Mother	Father	Mean	S.D.	Mean	S.D.
SLI	7:3	9.95	1.44	Some - Completed College	Some - Completed College	72**	7	93	12
TD Matched	7:3	9.42	1.81	Some - Completed College	Some - Completed College	106**	14	96	5
Full TD	11:9	9.31	1.65	Completed College - Some University	Completed College – Some University	105	11	102	10

[a] Level of education options were: “High school not completed, Completed High School, Some college, Completed college, Some university, Completed University”.

Procedure

Each child completed a single 60-minute session in our laboratories. Children were seated in a comfortable chair in a sound attenuated booth facing a computer monitor. Each child completed a *frequency discrimination task*, *a vowel space measurement task,* and a *perturbed auditory feedback task.*

Frequency discrimination task. To measure F1 frequency discrimination for vowels of interest in the present study (i.e., /ɛ/-like vowels), participants completed a task using an adaptive two-alternative forced choice paradigm that determined the smallest change in F1 they could detect. This was performed as follows. Three words were presented over headphones with an accompanying animation on a computer monitor. The middle word was used as a reference point and was always /hɛd/. Participants selected which of two options (the first or the last word) sounded the most similar to the reference point. Initially, the F1 frequency difference was such that the two choices were /hɛd/ and /hæd/, making it a simple task for children to match the /hɛd/ option with the /hɛd/ reference point. Following this, the difficulty increased as participants made correct choices (see Figure 4 below). A practice run of five easy trials (340 Hz difference between the two /ɛ/-like vowels) was used to allow participants time to become accustomed to the headphones and the task. These accustomization trials were not included in the analysis. This task determined the minimum F1 difference participants required to differentiate two /ɛ/-like vowels. Similar discrimination abilities would rule out explanations related to perceptual abilities that use the same auditory information as in the compensation task.

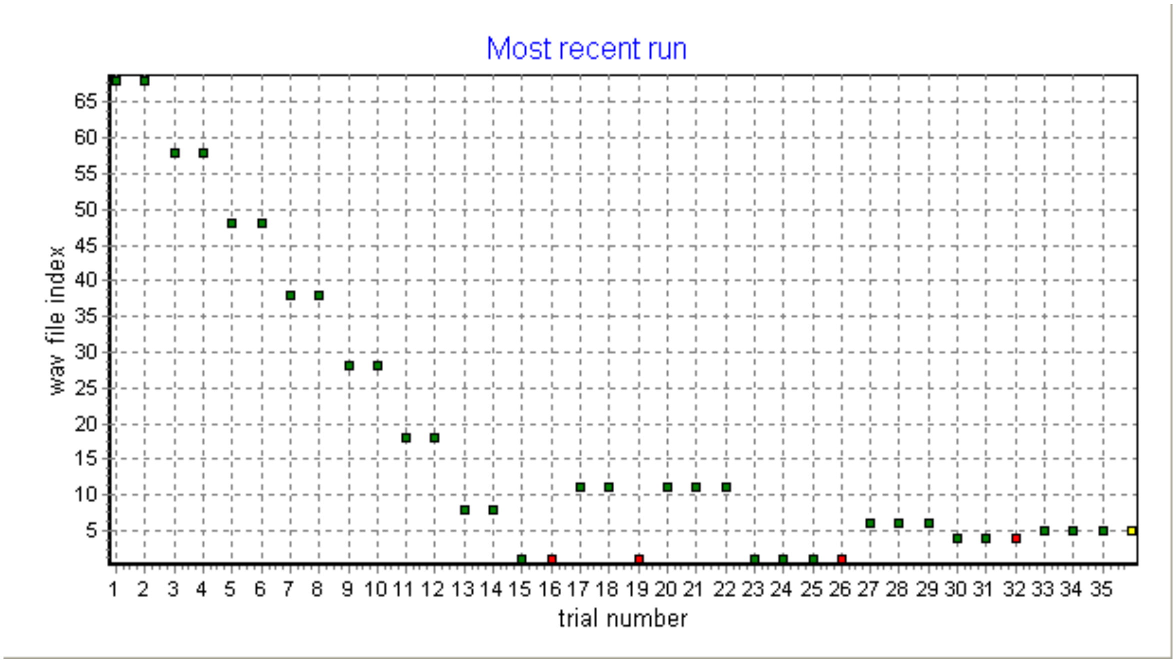


Figure 4. Example of a single participant's progression and final F1 discrimination threshold in the adaptive two-alternative forced choice paradigm F1 frequency discrimination task. Note there are four reversals (red squares) and the mean level from the fourth reversal was used to obtain the F1 discrimination threshold.

Vowel space measurement task. This task was used to determine the distribution of the children's vowel space, as well as to determine the best model order, described below, for the perturbed auditory feedback task that followed. In the vowel space measurement task, the child produced each of three vowels, /ɛ/, /æ/ and /ɪ/, six times (six tokens). This task provided data to evaluate whether the shift sizes used in the perturbed auditory feedback task were appropriate for each group's vowel space, and to evaluate whether the vowel spaces of the SLI and matched-TD groups were similar. The vowels

/ɛ/, /æ/ and /ɪ/ were chosen for recording a limited vowel space since the vowel /ɛ/ was to be manipulated during the study. More vowels were not recorded due to time constraints and in order to maintain participant attention and participation during the study. /ɛ/ has limited somatosensory feedback compared to point vowels (vowels at the extremes of the vowel space) and adults respond robustly to manipulation of its auditory feedback (Purcell & Munhall, 2006a, b; Munhall et al., 2009). The first two formants of vowels /æ/ and /ɪ/ are in close proximity to /ɛ/. The first formant in /ɛ/ can be manipulated positively or negatively such that the resultant vowel sounds to a listener like /æ/ or /ɪ/, respectively (see Figure 5). This manipulation has been performed successfully in adults and children (Purcell & Munhall, 2006a,b; MacDonald et al., 2011).

In the present study, vowels were studied in the context of a single word token /h/-vowel-/d/ or /hVd/ as in /h ɛ d/ and /h æ d/, as has been employed in many previous studies (Purcell & Munhall, 2006a, 2006b, Munhall et al., 2009, MacDonald et al., 2012). The context /hVd/ was used because /h/ is a low energy voiceless consonant created with relatively neutral articulator positions and thus co-articulation between the /h/ and the vowel is minimal. The consonant /d/, though voiced, is a stop consonant, again providing a clear indication of where the vowel ends and the /d/ begins as the spectrogram often displays a period of near silence between the vowel and the /d/. The middle 80% of the vowel is used for determining the mean formant frequencies (F1, F2 and F3) using Linear Predictive Coding (see Speech Signal Processing section), with the mean F1 value being of most importance to this study. F1 and F2 are generally considered the most important or highest information formants in distinguishing between vowels. These estimations of the vowel boundaries were marked by hand to ensure accuracy.

Six tokens for /ɛ/ were used to determine the best Linear Predictive Coding (LPC) model order to describe formants in the speech signal. The best model order was defined as that which gave the lowest standard deviations for estimates of F1 and F2. Further information is provided in the ‘Speech Signal Processing’ section below.

Perturbed auditory feedback task. In the perturbed auditory feedback task, the acoustic characteristics of participants’ vowel productions were manipulated and played back to them in real-time. The manipulation involved shifting F1 such that vowel quality changed. In auditory feedback studies involving adults (Purcell & Munhall, 2006a, 2006b), a shift of ±200 Hz has been employed. This shift was based on both the adult vowel space and the vowels of interest such that the shift resulted in a vowel quality that overlapped with a neighboring vowel. Children, however, have different vowel spaces than adults (Lee et al., 1999). If their vowel spaces were much larger than adults, a shift of 200 Hz may not be sufficient to pass a threshold point and evoke observable compensation for the manipulation. Thus, it is important to know about the distribution of the vowel space of local speakers for this task. This information was not available prior to this study. To determine an appropriate manipulation for the child population of London, Ontario, the words /hɛd/, /hæd/ and /hɪd/ were recorded six times each from 21 typically developing (TD) children aged 6-11 years in the London, Ontario school district not otherwise involved in the study (a local normative sample).

The /hVd/ utterances containing /ɛ/, /æ/ and /ɪ/ were segmented using the speech analysis program Praat (Boersma & Weenink, 2011) to obtain the vowels for each production of each child in the local normative sample. The 21 children produced 18 utterances each (six utterances of each of the three vowels) for a total of 378 utterances:

126 utterances for each vowel. Formant frequencies were determined for each vowel and the average first (F1) and second (F2) formants were calculated. The mean F1 distance /ɛ/ → /æ/ was +340 Hz and the distance /ɛ/ → /ɪ/ was −230 Hz. These manipulations were used to shift the F1 in the positive or negative direction in this study.

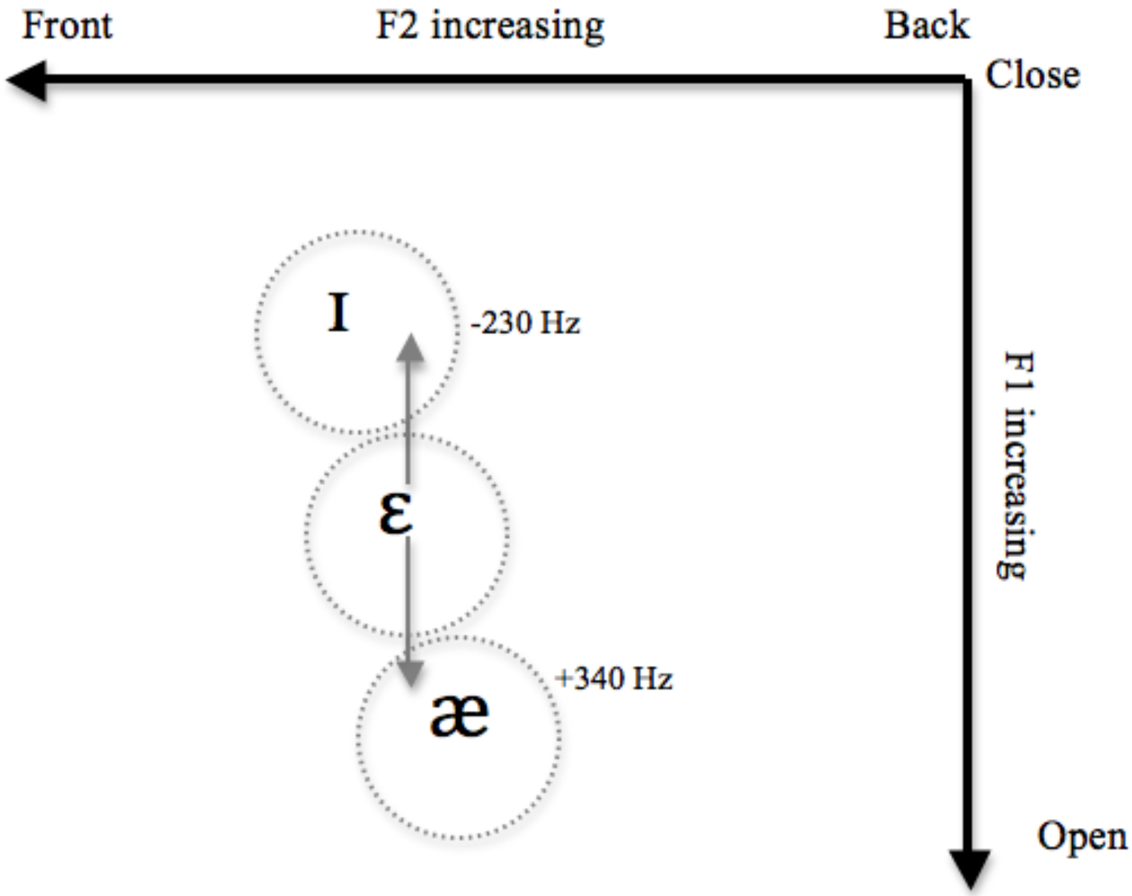


Figure 5. Formant manipulation, performed for F1 only. Axes are the first and second formants. There was a manipulation of -230 Hz between /ɛ/ → /ɪ/, and +340 Hz between /ɛ/ →/æ/.

A real-time formant filtering method was used to alter F1 that children heard over headphones in two separate conditions. In the first condition, F1 was shifted +340 Hz from baseline (/ɛ/ → /æ/) (see Figure 6). After a short break where the children were engaged in conversation, the second condition was initiated where F1 was shifted -230 Hz from baseline (/ɛ/ → /ɪ/). All participants completed both the positive and negative shift conditions, and each shift involved both a ramp phase involving incremental shifts in F1, a hold phase involving repeated presentations at the maximal shift, and an end phase where manipulation was stopped and participants heard their own unaltered voice over headphones.

Formant filtering was used during the ramp and hold phases to provide participants with the altered auditory feedback of the vowel /ɛ/ in the negative and positive study conditions. Formant filtering consists of emphasizing (increasing or creating peaks) and de-emphasizing (decreasing or creating valleys) harmonics present in speech. In the present study, during each utterance of the word /hɛd/ of the ramp phase, the shift applied to the spectral peak of F1 was changed incrementally by 10 Hz. The F1 of the final utterance of the ramp phase was altered by the maximum shift size (either +340 Hz or -230 Hz). An increment of 10 Hz is generally an imperceptible change to the human listener. This was performed 34 times, once per utterance, for the positive shift condition, and 23 times, once per utterance, for the negative shift condition. This formant shifted auditory feedback was played back to the participant over headphones in real-time. Processing of the original speech is performed in such a short time (less than 1 ms for the speech samples and less than 20 ms for the formant estimates) that participants do not detect a delay and speech heard over the headphones is perceived as their own production of /hɛd/. Manipulating F1 in this manner allows the shifted auditory feedback to encroach on a nearby vowel category. This makes it such that the produced vowel /ɛ/ at baseline would sound more like the vowel /æ/ during the hold phase of the positive shift condition (if no change in speech production occurred). Likewise, in the negative shift condition the vowel /ɛ/ at baseline sounds more like the vowel /ɪ/ during the hold phase.

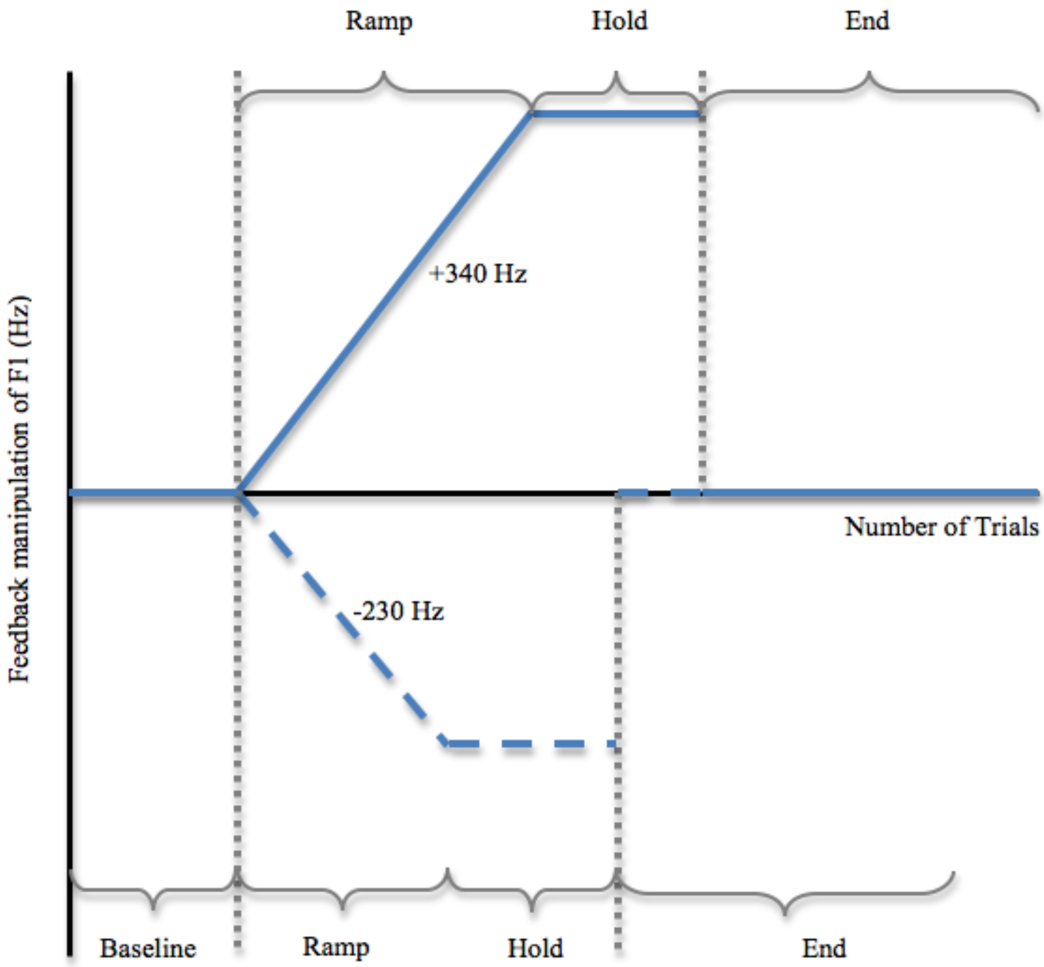


Figure 6. The phases of formant manipulation used in the present study. *Note.* The negative shift is shorter due to a smaller ramp phase (23 utterances, vs. 34 utterances in the positive shift).

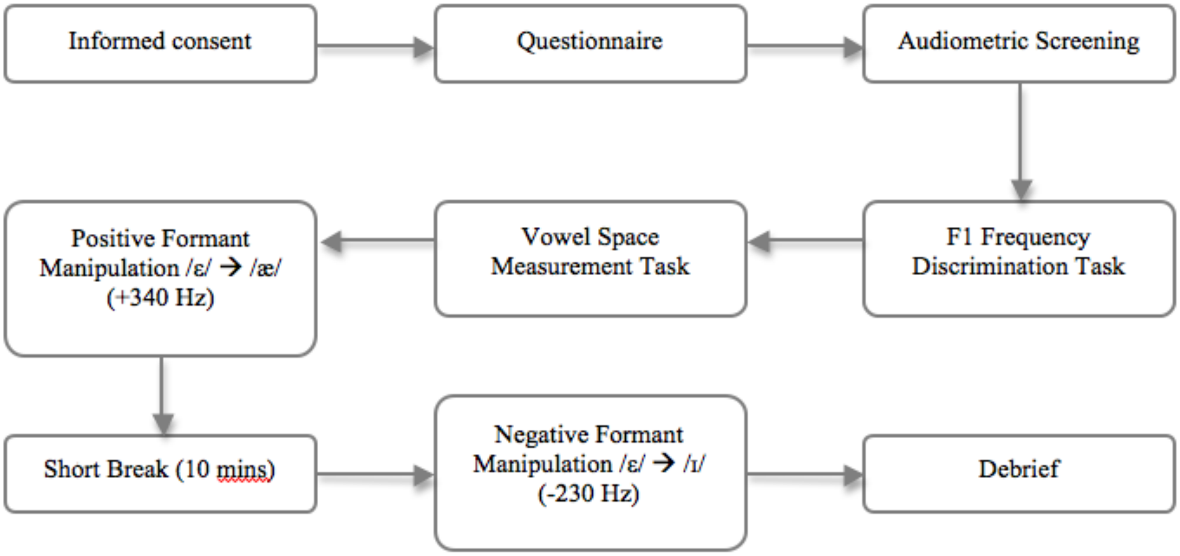


Figure 7. Summary flowchart displaying the progression of the study for one participant. Note that a short questionnaire (see Appendix C) assured that the child did not have recent ear infections or abnormalities, or expert vocal training that could have affected the results.

Speech Signal Processing. All formant shifting in the present study required an LPC model of each child's spectral envelope during production of /ɛ/. The spectral envelope gave formant estimates used to design filters to emphasize or deemphasize voice harmonics during the formant shifting procedure. Figure 8 shows an example spectral envelope for a vowel where F1 and F2 are obtained from the lowest two frequency peaks in the spectrum. The upper panel of Figure 9 shows the filters applied simultaneously to remove the produced formant and introduce the desired shifted formant. The lower panel compares the original speech spectrum from Figure 8 to the shifted spectrum. The speech is largely unchanged at higher frequencies and F1 has been shifted upwards.

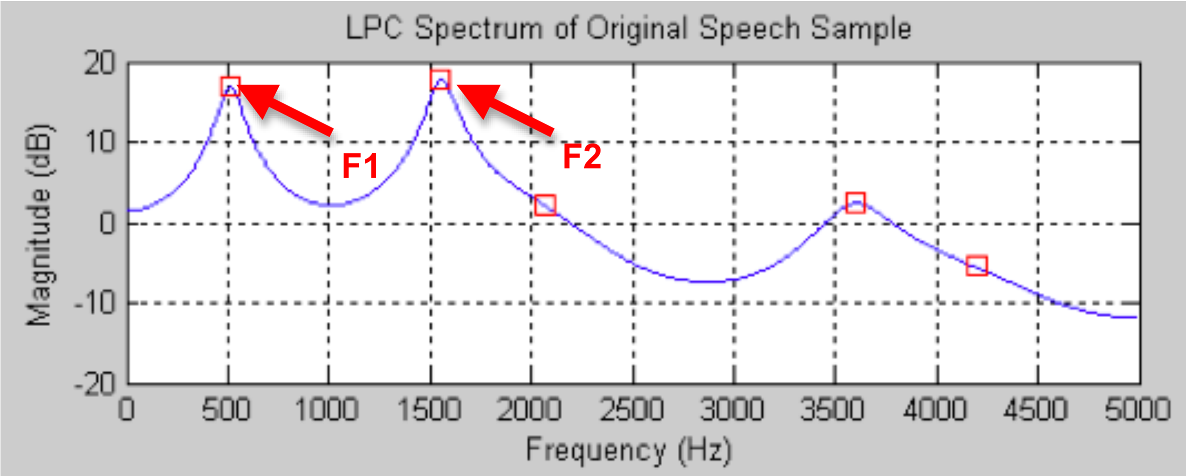


Figure 8. LPC spectrum for the vowel /ɛ/. Note the formants F1 and F2 are indicated by the boxes at the top of the first two low frequency spectral peaks.

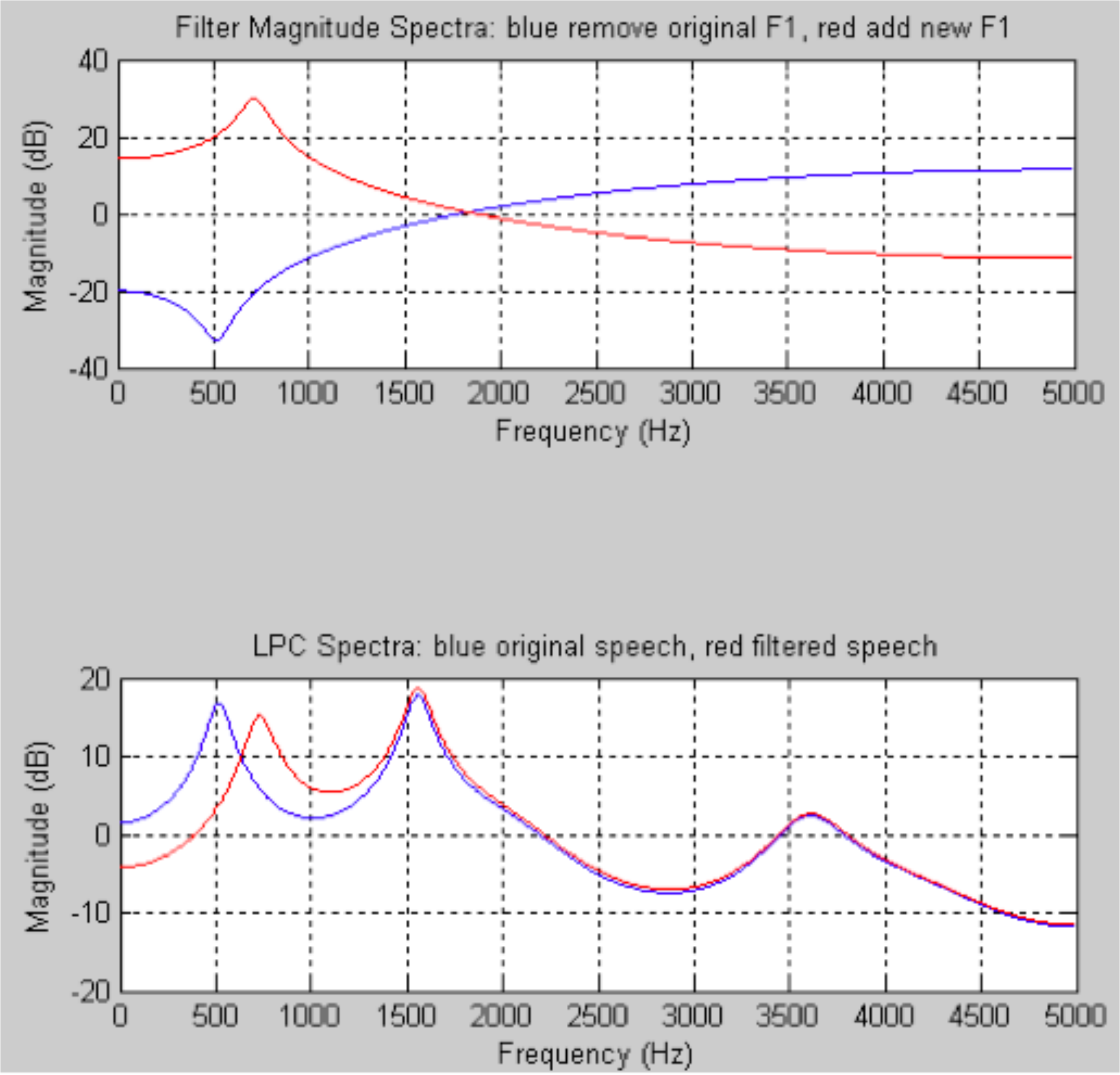
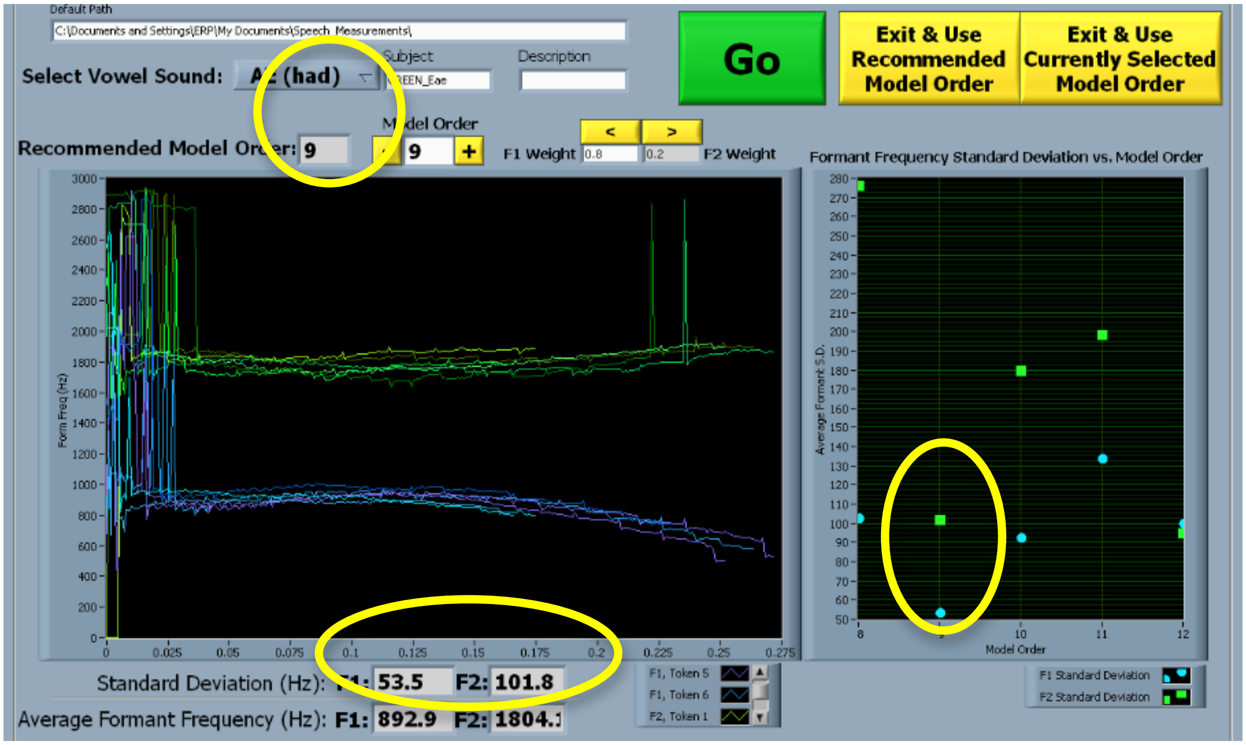


Figure 9. Formant shifting using filtering. Top graph displays the two filters used to deemphasize harmonics at the produced formant (blue) and emphasize harmonics at the new desired formant (red). Bottom graph displays the LPC spectrum before (blue) and after (red) the filters are applied.

A program was used to display the standard deviation of formant estimates for different LPC model orders. This allowed the operator to select the best model order for use during the altered auditory feedback experiment (see Figure 10).



Default Path: C:\Documents and Settings\ERP\My Documents\Speech Measurements\

Select Vowel Sound: A (had)

Subject: REEN_Eae

Description:

Recommended Model Order: 9

Model Order: 9

F1 Weight: 0.8

F2 Weight: 0.2

Standard Deviation (Hz): F1: 53.5 F2: 101.8

Average Formant Frequency (Hz): F1: 892.9 F2: 1804.1

Figure 10. Screenshot indicating the model order that gives the most stable formant estimates obtained during six tokens of /ɛ/. Note that the model order with the lowest standard deviation (in this case, model order 9) for F1 and F2 is the model order selected. The top left yellow circle indicates the best model order, bottom left yellow circle indicates the means and standard deviations for F1 and F2, and the bottom right yellow circle displays these standard deviations graphically (model order directly below the F1 and F2 standard deviation points).

Equipment. Participants wore a Shure WH20 headset microphone and Sennheiser HD 265 headphones with the formant shift being introduced in real-time by National Instruments real-time hardware and custom software (Purcell & Munhall, 2006b). The microphone signal was amplified by a TDT MA3 microphone amplifier and low-pass filtered with a cut-off frequency of 4500 Hz. After formant filtering by the National Instruments real-time hardware using a sample rate of 10 kS /s, the Itera audiometer was used to add low level speech shaped noise (40 dBA SPL) and to drive the headphones. The microphone amplifier input level was set by having the participant say the word /hɛd/ six times before vowel space collection and formant manipulation. During these six trials, the microphone input level was adjusted between 15 and 35 dB, starting at 25 dB, in 5 dB increments until the Itera's VU meter was centred on 0 dB SPL. This ensured that the speech signal would be approximately 80 dBA SPL in the headphones. Participants sat in a sound-attenuated booth (Industrial Acoustic Company, Bronx, NY) and were prompted via computer display.

Data Analysis. In offline analysis, the vowel portion of each production was segmented from neighbouring consonants in a semi-automated procedure using Labview (Version 8.5) and Matlab [Version 7.11.0 (R2010b)]. These vowel boundary estimates were then re-checked individually and hand corrected if necessary. From these vowel segments, averages for each of F1, F2, and F3 were determined for each utterance by averaging formant estimates taken from the middle 80% of the vowel. In this manner, single values were distilled for the first three formants of each utterance.

These F1 values were averaged across individuals in each group for each trial. These group average trials were subsequently normalized by subtracting the group's average F1 from the baseline phase. The averaged, normalized F1 trials were compared for the SLI and matched-TD groups during four separate experiment phases: the ramp trials, hold trials (where the maximum shift was employed), and the first and second halves of the end phase (20 trials each). A non-parametric Sign test was planned for these analyses due to the small sample size.

A two-tailed unequal variance *t*-test was used to determine differences in the SLI and TD groups in the F1 frequency discrimination task. This type of *t*-test does not assume equal variances and can be used in smaller sample sizes. To determine whether there was a significant difference in the vowel spaces of the matched-TD and SLI groups, a two-way mixed ANOVA was performed to examine F1 in productions of /ɛ/, /æ/ and /ɪ/ collected from each of the participants.

Results

Typical Development

Verifying manipulation with vowel space measures. Figure 11 presents the vowel spaces averaged across the full TD group in comparison to those measured for the local normative group data that determined the shift size (TDlocal). Our manipulation was based on the observation that the vowel /ɛ/ was 340 Hz below the vowel /æ/ and 230 Hz above the vowel /ɪ/ for the local normative group. As can be seen in Figure 12, there was considerable overlap between the two typical groups for the vowels /æ/ and /ɛ/, but not for /ɪ/. The local normative group had a lower F1 and higher F2 frequency for /ɪ/ and /ɛ/, and a higher F1 and F2 frequency for /æ/ than the full TD group, which resulted in a slightly larger, more distributed vowel space overall (see Figure 11). In order to ensure that this manipulation was sufficiently large for the full TD group, we completed a repeated-measures ANOVA on the F1 of the vowel space collected, with group as a between-subjects factor (full TD vs. TDlocal). The ANOVA revealed that there was no significant effect of group for vowel [$F(2, 39) = .323$, $p > .05$, $n^2_p = .008$]. The groups were, in fact, quite similar with $p > 0.20$. Furthermore, since /ɪ/ is further away from /ɛ/ in the TDlocal vowel space than in the TD vowel space, the shift chosen for this manipulation (-230 Hz) was more than sufficient to cross over into the adjacent vowel category for the full TD group in the present study. The /æ/ for both groups overlaps, indicating that the positive shift (+340 Hz) was also an appropriate manipulation. This illustrates that the shift sizes were sufficiently large to be conducive to compensation for the formant shifted auditory feedback since they adequately crossed into a neighboring vowel category.

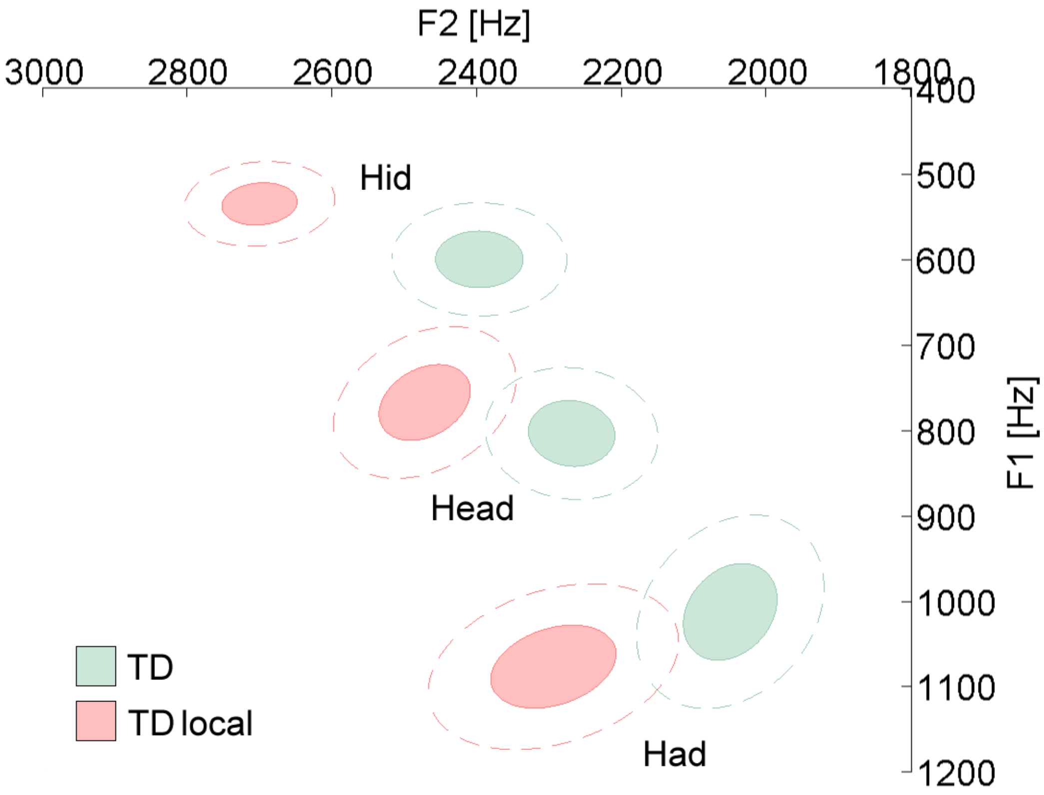


Figure 11. Vowel space data for /ɛ/, /æ/ and /ɪ/ of TD child population that determined the shift sizes (TDlocal), as well as the study TD population, $p > .20$. Center of shaded ellipses denote group mean formant frequency value, shaded ellipses denote one standard deviation from the mean, and dotted ellipses denote two standard deviations from the mean.

Frequency Discrimination. In the frequency discrimination task requiring children to detect differences between /ɛ/-like vowels, the children in the full TD group (n = 20) were able to discriminate frequency differences of 55 Hz (*SD* = 29 Hz), on average, with no single participant discriminating differences less than 23 Hz. Thus, F1 frequency discrimination thresholds were higher than the incremental shifts of 10 Hz employed in our altered feedback task for all participants, which would provide evidence of the imperceptibility of these shifts. The total shift employed in both the positive (+340 Hz) and negative (-230 Hz) shifts was much larger than the smallest F1 frequency difference that was detectable by this group. This indicated that all participants in this group would be able to perceive the shifts employed in the present study. Individuals will compensate even during small shifts, where the shift is not perceptually obvious (MacDonald et al., 2010) but a threshold point, where the auditory feedback system detects an error subconsciously, must first be crossed.

Perturbed Auditory Feedback. Figures 12 and 13 display the average normalized F1 produced by the full TD group in the +340 Hz (positive manipulation) and -230 Hz (negative manipulation) conditions of the altered auditory feedback task, respectively. The baseline phase line segment was generated by averaging all baseline formant frequency values (20 trials) for a respective group. The hold phase was similarly generated by averaging all hold formant frequency values (20 trials) for a respective group. The ramp and end phases were generated by continuity between the baseline and hold, or hold and final trial of the study respectively. In both cases, the full TD group shows the “opposing response” in which the normalized F1 frequency produced by the participant is modified in the opposite direction of the F1 frequency the participant is hearing at the headphones. On average, the children displayed a 17-20% compensation for the manipulations. This is the same response observed in adults to formant shifted auditory feedback, albeit smaller. The mean F1 values for baseline, the hold phase, compensation, and percent compensation for the two shift conditions are presented in Table 2. The percent compensation appears highly similar; as do the baselines, hold phases and the frequency difference between the two shift conditions. To examine whether the percent compensation was different for this group in the two shift conditions, a paired *t*-test was performed. This revealed no significant differences in the percent compensation between the positive and negative conditions, $t(18) = 0.676$, $p > .05$. To summarize, TD children 6-11 years of age respond similarly as adults have to formant shifted auditory feedback in that they tend to oppose the manipulation.

Table 2

Results for both manipulation conditions for formant shifted auditory feedback in the full TD group (n = 20).

	% Compensation		Baseline (Hz)		Hold (Hz)		Compensation (Hz)	
Manipulation (Hz)	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
+340	20	9.4	771	96	704	88	-52	35
-230	17	18	755	101	793	99	+38	41

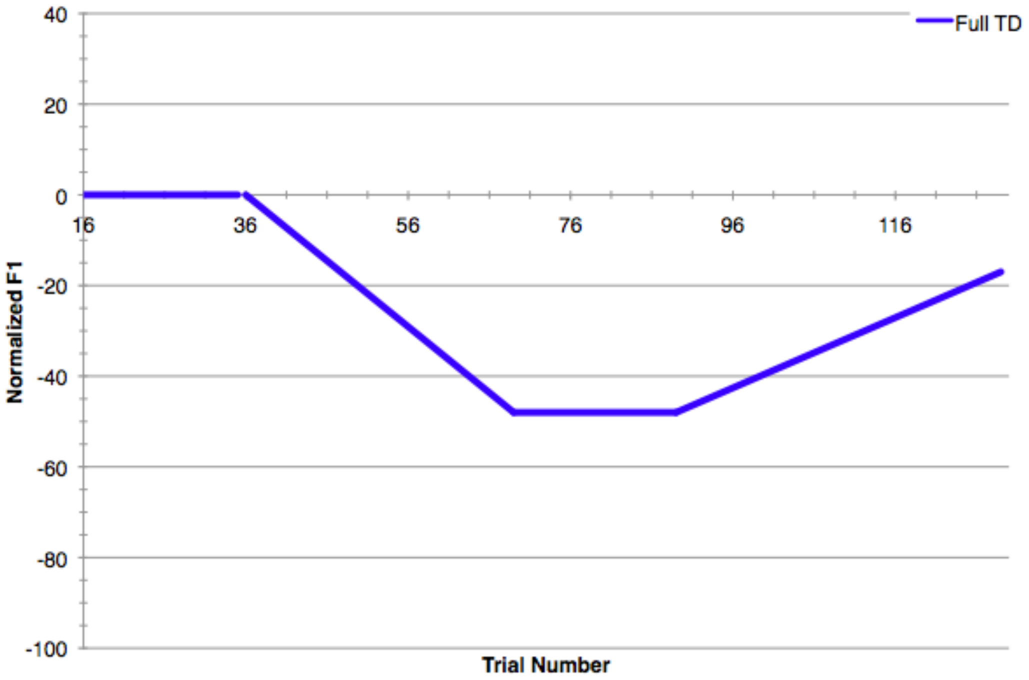


Figure 12. Response to a positive +340 Hz shift of F1 for the full TD group (n = 20) children in the present study. *Note.* See Perturbed Auditory Feedback for further detail.

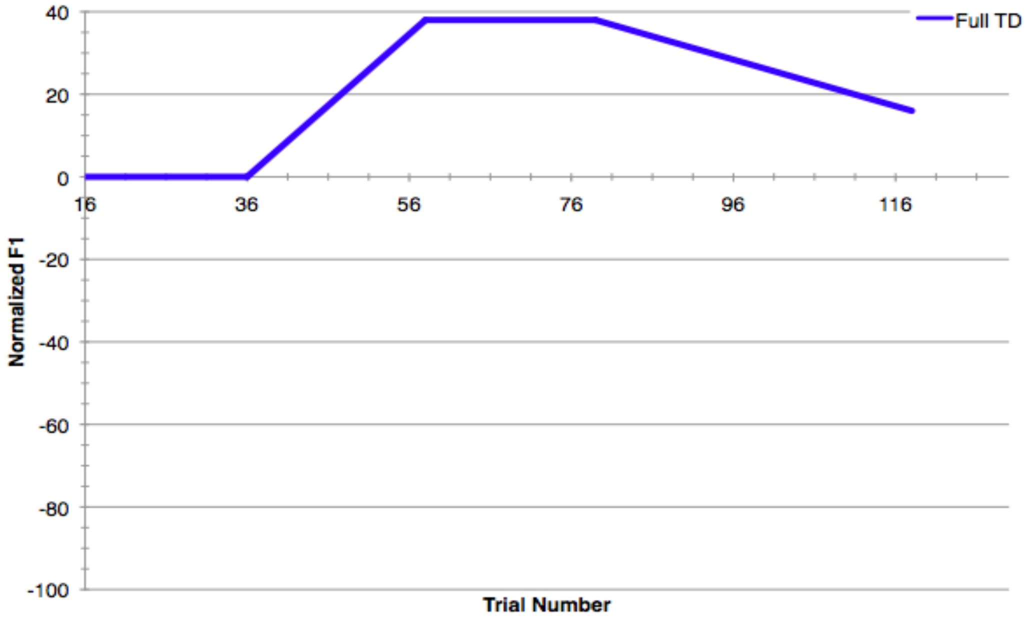


Figure 13. Response to a positive -230 Hz shift of F1 for the full TD group (n = 20) in the present study.

Matched–TD and SLI Group Comparisons

Verifying vowel space measures for TD and SLI groups. Vowel space measures for the SLI and matched-TD group are shown in Figure 14. It is evident from this vowel distribution that there was a high degree of overlap between these groups for all of the averaged formant frequencies measured (observe that the circles surrounding each vowel overlap for both groups in Figure 14). When analyzed, this similarity in vowel space of children with SLI and matched-TD was confirmed with a two-way mixed ANOVA: the SLI and TD groups did not differ significantly. The main effect of group (SLI vs. matched-TD) was not significant for vowel [$F(2, 19) = .064$, $p > .05$, $n^2_p = .004$]. The groups were quite similar with $p > 0.20$. These results indicate that the TD and SLI groups had highly similar vowel spaces. Thus, any group differences between our SLI and matched-TD groups observed in our experimental tasks were not due to group differences in vowel space.

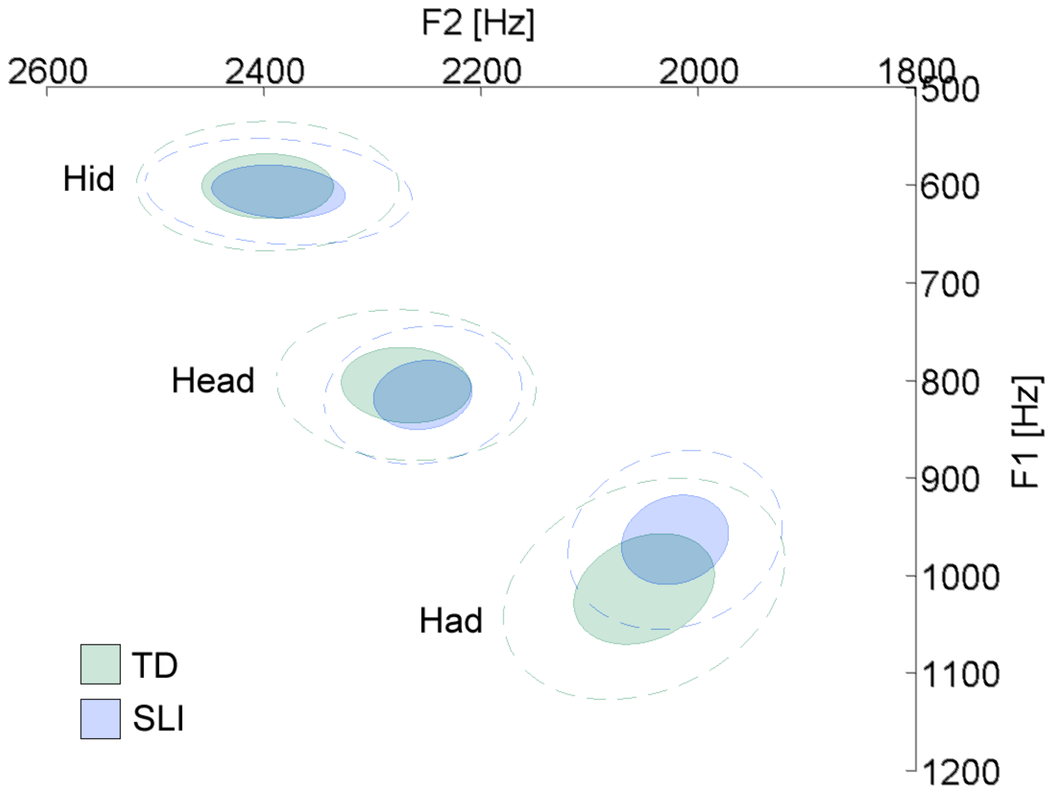


Figure 14. Vowel space data for /ɛ/, /æ/ and /ɪ/ of TD children and children with SLI, $p > .20$. Center of shaded ellipses denote group mean formant frequency value, shaded ellipses denote one standard deviation from the mean, and dotted ellipses denote two standard deviations from the mean.

Frequency Discrimination. Figure 15 displays the highly similar results of the F1 perceptual frequency discrimination task for the SLI and matched-TD groups. This indicates that children in the SLI (10 children) and matched-TD group (10 children) did not differ significantly in their ability to discriminate between F1 frequencies of /ɛ/-like vowels. Both groups exhibited a similar distribution of frequency discrimination abilities (see Appendix B for individual participant F1 frequency discrimination). Importantly, the groups did not differ in their thresholds, $t(18) = 0.195$, $p > .05$. For every participant in both groups, the step-wise shifts employed in the present study were below each child's threshold, and the total shift was easily within each child's perceptible range (Range, SLI = 20 to 140 Hz, *SD* = 38 Hz; matched-TD = 32 to 112 Hz, *SD* = 31 Hz). This made it such that differences observed in the altered auditory feedback task would not likely be due to group differences in frequency discrimination thresholds.

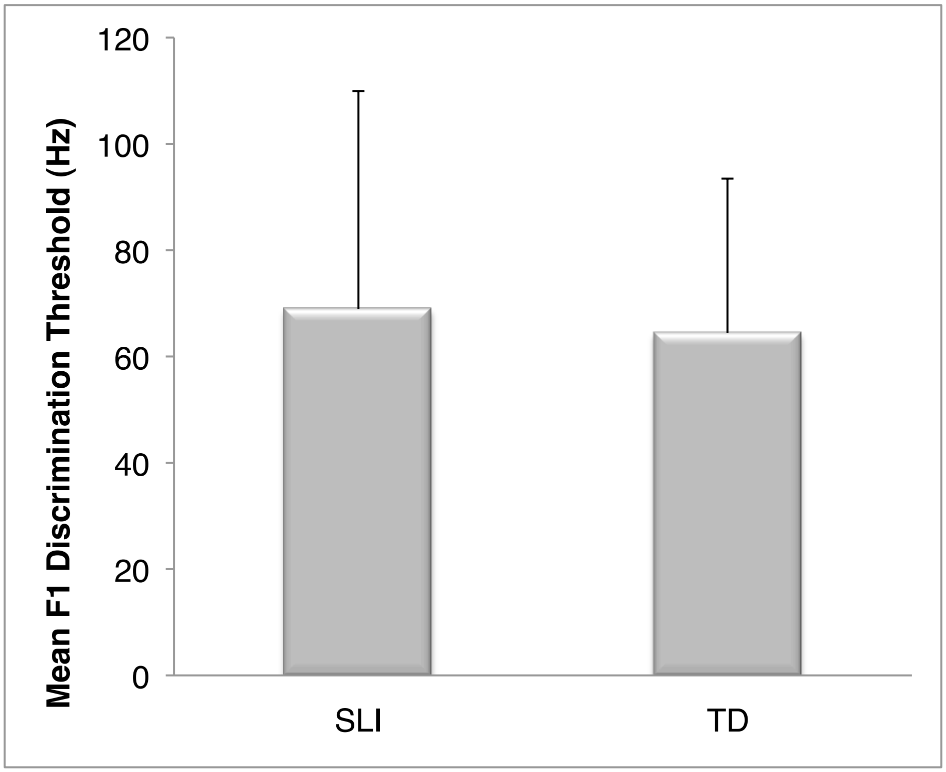


Figure 15. Frequency discrimination task. Error bars show one standard deviation.

Perturbed Auditory Feedback. Table 3 and Figures 16 and 17 display the average normalized F1 produced by the SLI and matched-TD groups in the +340 Hz (positive manipulation) and -230 Hz (negative manipulation) conditions of the altered auditory feedback task, respectively. The baseline phase line segment was generated by averaging all baseline formant frequency values (20 trials) for a respective group. The hold phase was similarly generated by averaging all hold formant frequency values (20 trials) for a respective group. The ramp and end phases were generated by continuity between the baseline and hold, or hold and final trial of the study respectively. In Figure 16, the separation of the two groups during the ramp, hold and two end phases can be observed. In Figure 17, however, the two groups appear to have overlapping group averages for each of the ramp, hold and two end phases. As observed in Figure 16, the group with SLI changed their F1 frequency from baseline by 89 Hz on average (*SD* = 51 Hz) for the positive manipulation condition (compensating 23% of the total manipulation magnitude). The matched-TD group compensated to a lesser extent at 48 Hz on average (*SD* = 33 Hz) for this condition (16% of the total manipulation magnitude). For the negative manipulation condition (see Table 3 and Figure 17), the SLI group and the matched-TD group compensated to a similar extent with the SLI group compensating 27 Hz (*SD* = 40 Hz; 12% compensation) and the matched TD group compensating 35 Hz (*SD* = 15 Hz; 15% compensation).

F1 frequency at each shift phase was compared across the SLI and matched-TD groups in separate Sign tests for each of the four phases, ramp (out of 25 utterances, from average threshold to end of ramp), hold (20 utterances) and the two end phases (20 utterances each) (see Figures 16 and 17; for average F1 for individual utterances averaged across individuals and separated by group, see Appendix A). The Sign test compares the number of times that the values from one group are larger than another and determines the likelihood that this observation would occur. For the positive shift condition, significant group differences were found with the SLI group showing a larger number of occurrences when compensation was greater than the matched-TD group in all phases: ramp, S = 20, $p < .005$, hold, S = 17, $p < .005$, early end, S = 18, $p < .0005$, and late end, S = 15, $p < .05$. No significant group differences were observed for the corresponding Sign tests for the negative shift condition: ramp, S = 4, $p > .05$, hold, S = 7, $p > .05$, early end, S = 8, $p > .05$, and late end, S = 12, $p > .05$. These results indicate that children with SLI compensated more as compared to the matched-TD group in the positive shift condition during all phases (ramp, hold, early end and late end phases). The higher F1 values for the SLI group as compared to the TD group in the end phases show that the children with SLI experienced a slower recovery from formant manipulation on average.

Table 3

Results for both manipulation conditions for formant shifted auditory feedback in the SLI group (n = 10) and matched-TD group (n = 10).

		% Compensation		Baseline (Hz)		Hold (Hz)		Compensation (Hz)	
Manipulation (Hz)	Group	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
+340	SLI	23	14	781	115	691	105	-89*	48
	TD Matched	16	8	783	87	734	86	-48*	27
-230	SLI	12	22	780	121	807	142	+21	48
	TD Matched	15	17	782	99	818	83	+36	43

* $p < .05$.

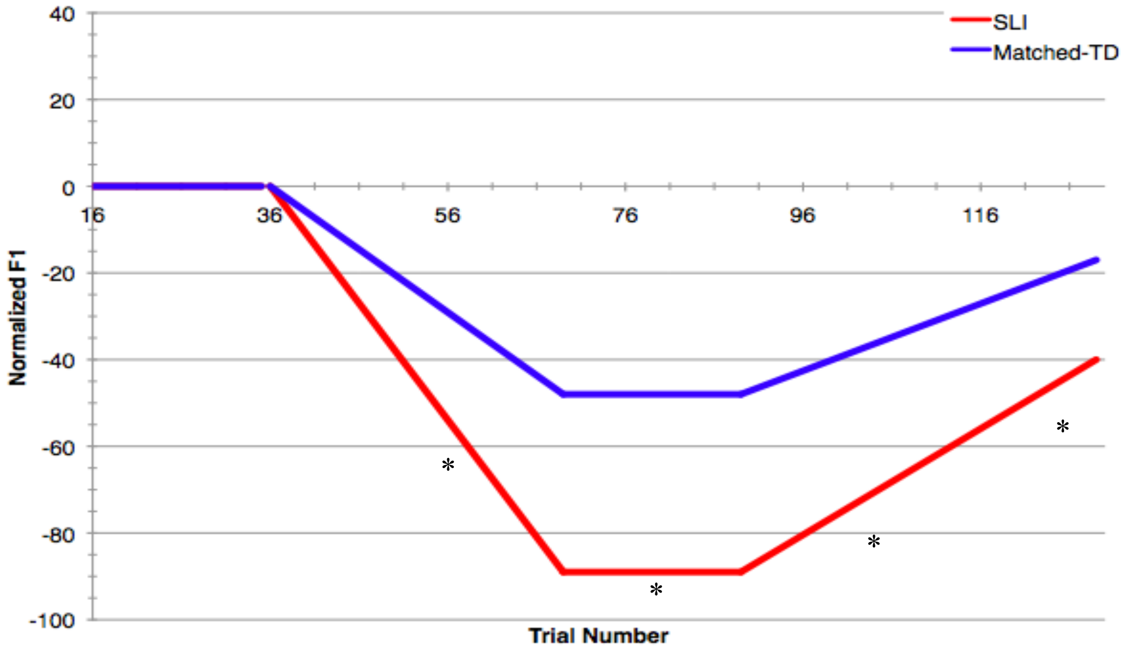


Figure 16. Response to a positive +340 Hz shift of F1. Significant difference in compensation between SLI and matched-TD groups is indicated by *. *Note.* See Perturbed Auditory Feedback for further detail.

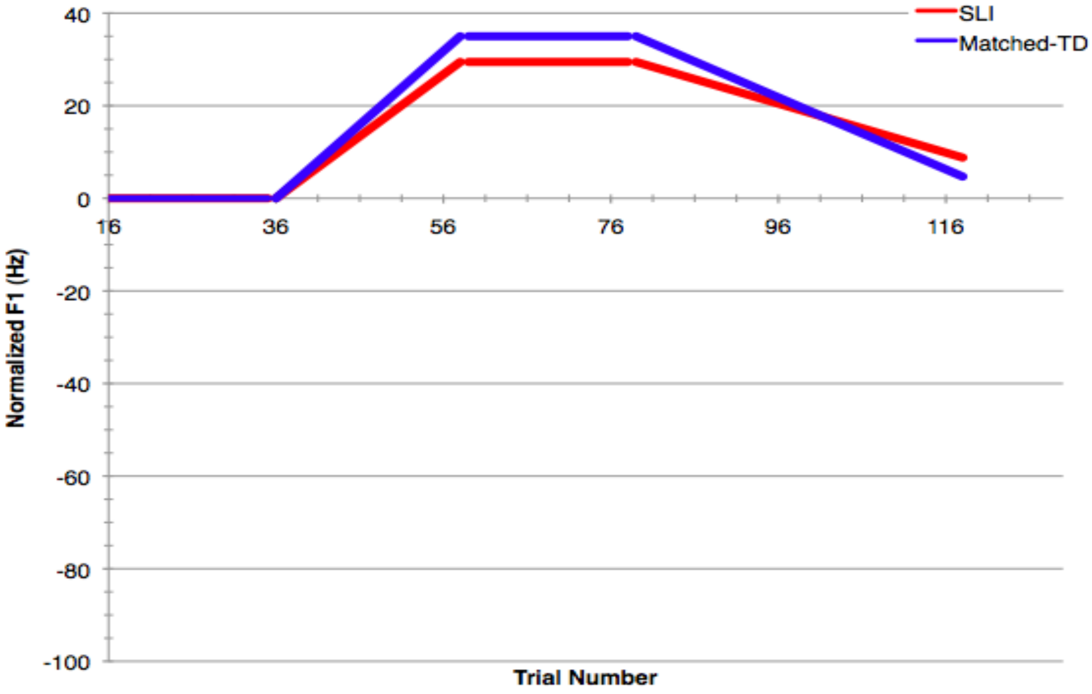


Figure 17. Response to a negative -230 Hz shift of F1 in SLI and matched-TD groups.

Discussion

The present study explored the relationship between auditory feedback and language abilities in children with either typical or impaired language development. Typically developing 6-10 year old children in the present study showed partial compensation in response to manipulated auditory feedback by making changes to the vocal tract such that changes in F1 frequency of the vowel produced opposed the manipulation. While children with specific language impairment (SLI) did not differ from a matched control group in frequency discrimination, the children with SLI did differ from the control group in their response to the auditory feedback manipulation. For the +340 Hz frequency perturbation resulting in a shift from the vowel /ɛ/ to /æ/, children with SLI tended to compensate more than their TD peers, and took longer than the control group to recover from formant manipulation. In the -230 Hz condition (/ɛ/ to /ɪ/), however, the TD and SLI groups did not significantly differ in the magnitude of their response. Neither positive shift direction nor negative direction percent was correlated with scores on a standardized language test.

Typical Development

The findings of compensation to perturbed auditory feedback in the present study build on similar results from previous studies for adults (Purcell & Munhall, 2006a,b; Munhall, 2009) and children as young as four years old (MacDonald et al., 2012). In agreement with these past findings, we noted compensation to both positive and negative manipulations from /ɛ/ to /ɪ/ and /ɛ/ to /æ/ (Purcell & Munhall, 2006; Munhall, 2009). While the percent compensation was comparable in response to both positive and negative manipulations in our typically developing group, the average magnitude of the compensation of 17-20% was lower than the rate of approximately 29% for adult groups found in other studies (Purcell & Munhall, 2006a, 2006b). A lower average percent compensation was also noted by MacDonald (2012) for his four-year-old age group, which suggests that children may compensate to a lesser extent than adults.

Specific language impairment

Results of the present study are the first to demonstrate direct links between auditory feedback and language learning abilities. Although there were no correlations between percent compensation and standardized language test scores across all participants, we did find evidence of atypical auditory feedback responses for the group with a language learning impairment, the SLI group, compared to a matched control group. We further showed that this group difference was not a result of differences in the ability to discriminate the frequency changes involved in our manipulation. Furthermore, in the positive shift condition the F1 of the children's utterances took longer to return to baseline after manipulation for the SLI than for the control group. There may be several reasons for the SLI difference in use of altered auditory feedback. The two most likely explanations for this difference are either the presence of tightly defined phonological representations, or poor fine neuromotor abilities in the SLI group. Though phonological processing and motor commands are linked along the auditory feedback pathway, they will be discussed separately here.

Phonological hypothesis

Children with SLI in the present study overcompensated relative to their age-matched peers for perturbations in auditory feedback, at least when those perturbations involved an increase in F1 frequency (positive manipulation). This compensation happened despite available kinesthetic information informing the speaker that the correct vowel was being produced. The relative overcompensation of the SLI group suggests that the SLI group relied to a greater extent on the auditory feedback they were receiving than their own internal representations of the phoneme and how it is produced. Why should children with SLI make such poor use of their internal phonological representations? One possibility is that they have poor quality phonological representations such that they do not rely on their own internal judgments about phoneme production. The notion of poor quality phonological representations in SLI would be consistent with findings by other researchers (Sussman, 1993), as would poor phonological categorization abilities (Joanisse & Seidenberg, 1998) and poor phonological awareness (Briscoe et al., 2001). Nevertheless, it is difficult to conceive of how poor quality phonological representations in SLI could account for the asymmetrical findings of overcompensation of the SLI relative to TD group in response to the positive but not negative manipulations in the current study. It is possible that children with SLI could have atypical phonological representations (an abnormal template) for certain vowels (phonemes) only. Perhaps children with SLI find some phonemes easier to process than others, or perhaps they have formed stronger representations of certain phonemes while other phonemes lag behind at this stage of development. This appears to be a relatively weak explanation for the observed differences however. All of the phonemes employed in the study are commonly used phonemes to which the children have had many, many exposures.

Alternatively, the internal phonological representations of the children with SLI may be overly constricted. As a result, their system may consider the acoustic errors introduced into their feedback as more unacceptable, leading to continued efforts/compensatory movements in an attempt to reach a position that results in a smaller acoustic and phonological error. This may, at first, sound like it should benefit a person. If, however, an individual has phonological categories that are too stringent, it would be difficult to categorize some sounds since, due to individual talker variability, not all utterances of the same phoneme may fit into atypically small phonemic categories. This would be a detriment to comprehension, since the listener would have to rely on semantic, visual or other information given the difficulties with phonemic categorization. This may be a biological mechanism where there is an "optimal range", and having higher or lower abilities does not provide benefit. In this case, perhaps there is an optimal phonemic boundary size. Perhaps once that is breached, whether it be larger or smaller than the optimal range, pathologies arise, in this case: difficulties in language learning. This may be an example of poor phonological awareness, perhaps specifically poor phonemic awareness. Other researchers have found that children with SLI tend to display poor phonological awareness (Briscoe et al., 2001).

This notion of constricted phonological representations may explain the asymmetrical SLI response of relative overcompensation to the positive but not negative manipulation in the present study. The SLI overcompensation was noted for our large (+340 Hz) but not small (-230 Hz) manipulation. If internal phonological representations are tightly defined, the SLI speaker may continue to compensate for larger manipulations making group differences easier to detect in a small study such as this one. Further research is needed to address whether it is the size of the manipulation, the vowel that is being manipulated, or both that underlies the finding of more compensation in the positive than negative shifts. Potentially, children with SLI, or a subset of children with SLI, are relying on atypically small internal vowel representations such that they are less likely to resist formant manipulation, and instead are more heavily weighting the acoustic cues in their environment.

Neuromotor hypothesis

Another possible explanation for the difference in compensation between TD children and those with SLI may be differences in oromotor abilities or in sending neuromuscular commands to articulators (Goffman, 1999). It may be that children with SLI were attempting to compensate for the manipulation in the same way as their age-matched peers, but that their poor oromotor control resulted in them ‘overshooting’ their target reflected as greater compensation in the present study. This may indicate that they may have poorer representations of motor commands that execute specific movements to create specific formants. This would result in their vocal articulators moving past the typical final articulator destination for the vowel they are hearing at the headphones. This would seem to indicate that they would be able to do equally well on a frequency discrimination task and determine that there is a difference between two sounds, as was found in the present study, but may find overshooting articulator positions from those that create one vowel to those positions that create another vowel to be an acceptable tactile incongruence, or possibly an unnoticed one, during production. This error may also include a failure to take into account, or a lower weighting of, somatosensory information about the current vocal articulator positions as compared to the new information arriving from the auditory environment. A difficulty in fine motor control or in sending information to articulators is supported in the literature. Other researchers have found that children with SLI tend to exhibit some impairment in fine-motor control (Bishop, 2001; Noterdaeme et al., 2002; for a review of the literature see Hill, 1999; or more recently Webster, 2004). These impairments have not been noted as overwhelming or as obvious as the severe motor impairments manifested in movement disorders. Rather, they are likened to an immaturity in motor development (Bishop, 2001). Motor control issues may not be the sole factor contributing to this difference in compensation. The motor control issues may be tied to issues with phonological representations or processing.

To what extent could an oromotor control problem or motor command representation problem in SLI account for the asymmetrical findings in the present study? The children with SLI overcompensated by slightly closing their mouth and pushing their tongue forward to create /ɪ/ in response to a positive frequency shift in auditory feedback. They did not show the same overcompensation (opening their mouth too much) in response to a negative frequency shift to create /æ/. At first glance, these findings might seem opposite to what might be predicted based on an oromotor control account of these difficulties. It could be argued that more kinesthetic feedback information would be expected to be available in the act of closing rather than opening the mouth: the tongue has less room when approaching the palate than the comparably large, unobstructed movement of opening the jaw. The barrier provided by the palate is contacted sooner, thus providing more kinesthetic information, than the limit of opening the mouth. From this, we would expect that opening the mouth would be more difficult (or variable) for a group with poor oromotor control abilities whereas our SLI group differed in their mouth closing but not opening gesture. Once again, these findings may be influenced by the shift sizes we imposed. It may be that the larger movements required to compensate for the +340 Hz resulted in more opportunities for measurable error to occur in the present study.

Links between language learning and auditory feedback

Issues in phonology. The findings of the present study speak to several possibilities underlying the delayed development of language in children with specific language impairment. In terms of the phonological hypothesis, the development of constricted phonological categories would lead to much difficulty in language learning and ongoing comprehension. This difficulty would stem from the variability present in speech. Different individuals, when asked to repeat the same phoneme several times, will use slightly different formant values in each utterance. This variability is greatly increased when one considers the different talkers that an individual encounters on a daily basis, even those within the same language, location, age group, and gender. If an individual has a small phonological category for a specific phoneme, they would be overwhelmed by the different productions of each phoneme. Different formant values may seem to indicate an entirely different phonemic identity to such an individual. Such individuals would struggle to link phonemes with an internal representation if the phonemes did not match their internal representations sufficiently. A system that is already overtaxed with the variability of speech may find the load of learning grammatical rules far more difficult. Perhaps, across development and with experience, these phonological categories are either sufficiently expanded so as to facilitate comprehension, or, individuals with SLI are exposed to grammatical rules a sufficient number of times to facilitate learning the correct rules.

Problems along the auditory feedback pathway. In terms of the neuromotor control hypothesis, delayed language learning could be explained by the DIVA model (Guenther, 2001), with difficulties in phonology and fine oromotor control arising from several different locations along the auditory feedback pathway. To review, there are several areas involved in sending and analyzing information about the location of oromotor structures. One of these, the supramarginal gyrus (SMG, BA40), compares the information about the actual location of the structures of the vocal tract coming from the primary somatosensory cortex (BA 1, 2, and 3) to the desired oral sensation targets sent by the premotor cortex (BA6), with any difference between these being the necessary movement required in orosensory coordinates (Guenther, 2001). The cerebellum is also involved, synthesizing the information from BA22 (which sends auditory error information) and BA40 (which sends motor error information) into a "motor velocity signal", sending this compensation information to the primary motor cortex (BA4). BA4 sends the information to articulators to direct motor compensation for errors.

There could be errors in several locations in the auditory feedback system. Perhaps SMG makes erroneous comparisons between the information about current motor coordinates from the primary somatosensory cortex BA 1, 2, 3 and information about the desired oral sensation targets premotor cortex (BA6). In addition to this, or instead of it, the cerebellum may be weighting the auditory information from BA22 as more important than the motor information from the SMG (BA40). Additionally, BA40, which projects the desired auditory targets to the superior temporal gyrus (STG), may not be communicating these auditory targets correctly, particularly if the desired auditory targets more highly specific than those of typically developing children. Any of these dysfunctions could explain the overcompensation observed in the SLI group for the positive shift condition.

Limitations of the present study

The results of the present study cannot address whether the difference in compensation noted in the larger magnitude, positive shift condition, is due to the magnitude or direction of the formant shift, since both were altered. To differentiate whether it is the magnitude of the shift or the direction of the shift that causes this difference in compensation between the SLI and TD groups, a future study may repeat these manipulations but reduce the magnitude of the positive shift to +230 Hz, and increase the magnitude of the negative shift to -340 Hz. This would determine whether it is the shift magnitude or the shift direction that is causing the difference between the two groups. Additionally, the shift of -230 Hz may have been too small to sufficiently tease apart the two groups. Perhaps having a shift of -340 Hz, which would have matched the positive shift in magnitude, would have been sufficiently large to observe the difference between the SLI and TD subjects.

The main theories underlying the overcompensation observed in the positive shift condition involve children with SLI having either poor phonological or poor motor abilities. Ultimately, addressing which of these suggestions forms the basis for the difference between the two groups was not the purpose of the study. At present, this is also beyond the scope of the results of this study. Using this paradigm with the addition of several other tasks together with a larger sample size, however, may allow differentiation between these two hypotheses.

Conclusions

In summary, results of the present study indicate that children with SLI respond differently to formant shifted auditory feedback in certain stimulus conditions than their typically developing peers matched for age, nonverbal intelligence, and socioeconomic status. Children with SLI compensated more for formant shifted auditory feedback when using large formant shifts than did typically developing children. This study suggests that the relationship between SLI and auditory tasks is complex and reliant on many different processes, and adds to the body of literature that suggests that children with SLI may have difficulties with auditory tasks, attention, fine motor abilities and phonological processing. The present study may assist researchers in designing sufficiently large shifts for manipulated auditory feedback stimuli for children 6-11 years of age. Future research protocols would benefit from incorporation of not only the frequency threshold task used in this study, but also phonemic categorization tasks and vowel boundary tasks. These would assist researchers in determining whether the various differences found between TD children and those with SLI are due to phonemic categorization or boundaries, auditory attention problems, frequency tracking, or poor fine motor control. If internal phonemic representation problems continue to surface as a characteristic of SLI, future intervention protocols for young children may benefit from incorporation of phonemic boundary and categorization tasks. Future research examining the nature of this compensation may reveal how the greater compensation observed for manipulated auditory feedback in these speech conditions is related to the development of language in children with SLI. If auditory and phonological problems appear to be a root cause in SLI, incorporating training in these areas may assist intervention in becoming increasingly successful.

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Appendix A

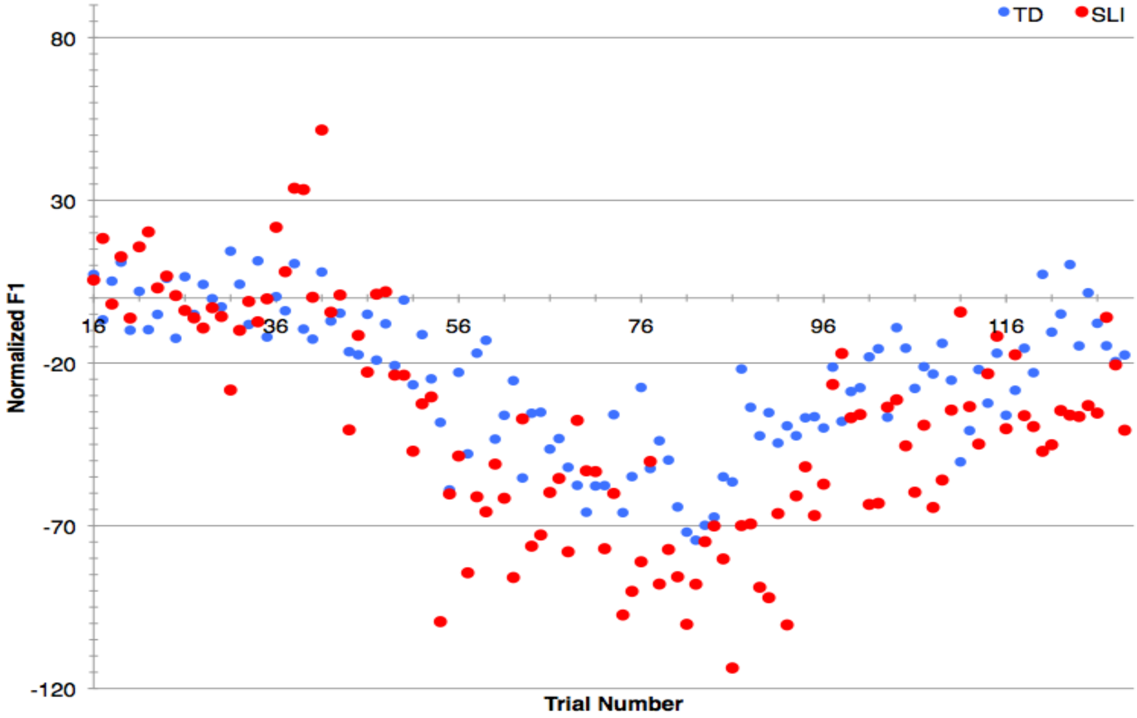


Figure 20. Scatter plot of response to a positive +340 Hz shift of

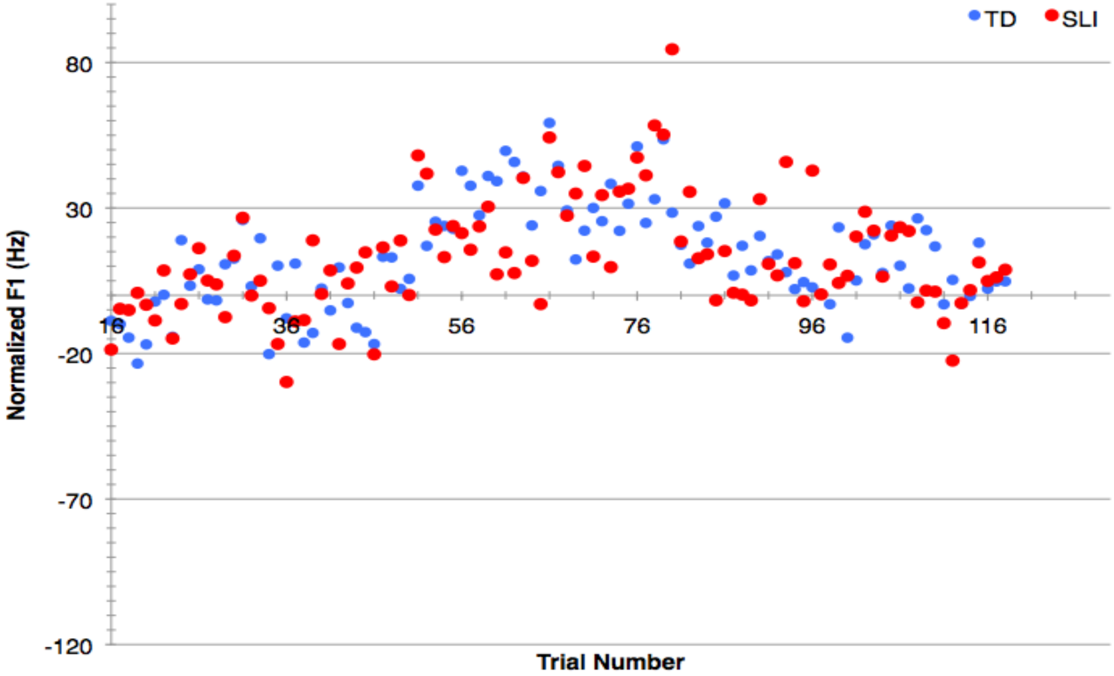


Figure 21. Scatter plot of response to a negative -230 Hz shift of F1.

Appendix B

Table 4

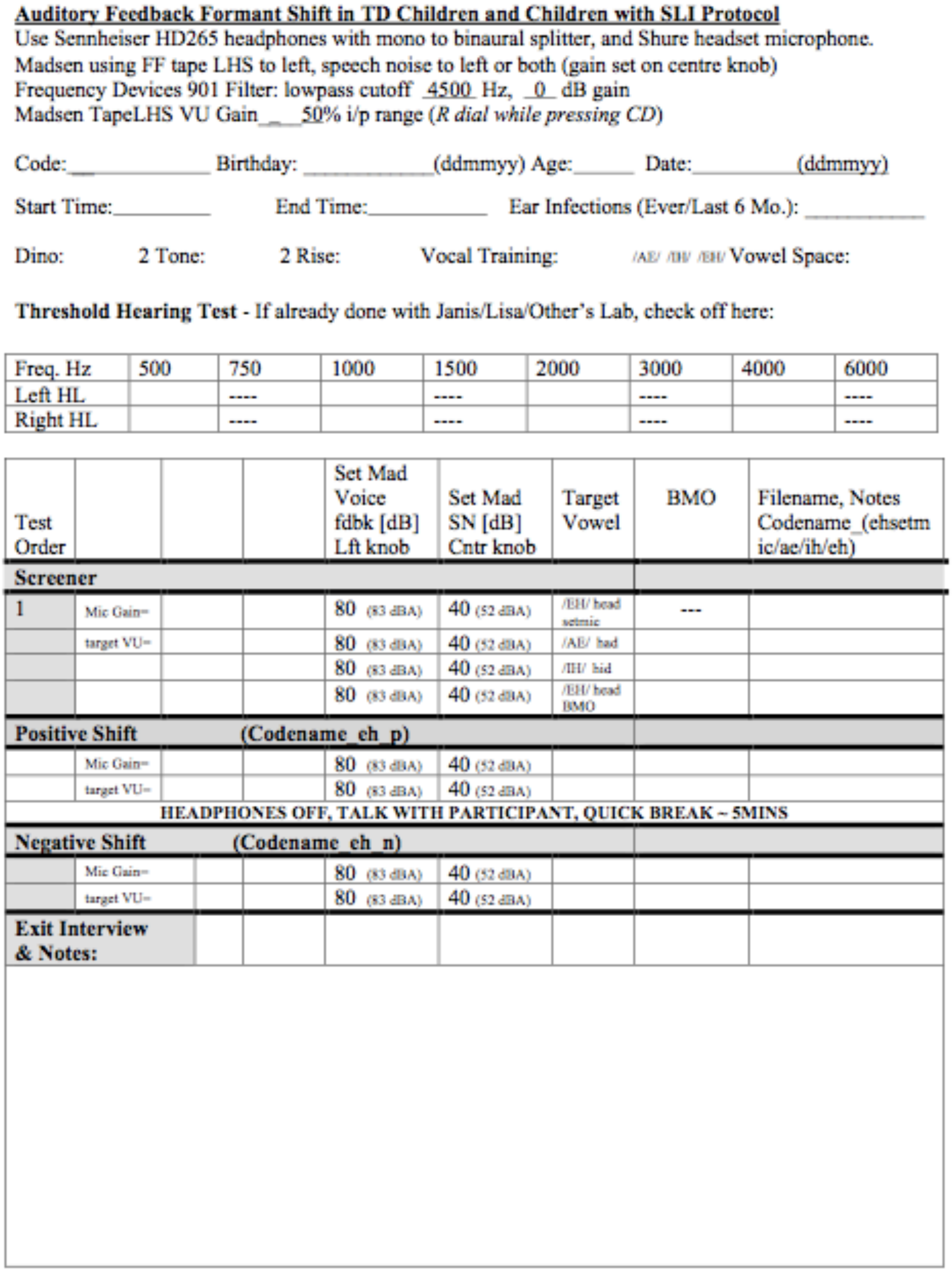
Cumulative data for all participant groups for all conditions in the study.

Group	Code	Gender	Age (Years)	CLS	PIQ	% + Comp	% - Com	F1D[a] (Hz)	F1D *SD* (Hz)	Avg. Ed. Mother	Avg. Ed. Father
SLI	kanga	F	11.6	64	88	20	40	83	44	3	5
	chip	M	10.1	76	99	31	8	24	20	3	1
	eeyore	M	10.9	82	92	33	27	25	20	4	2
	goofy	M	7.8	81	95	17	8	63	18	2	5
	lucky	M	10.3	62	61	35	27	72	58	6	
	rapunzel	F	11.1	66	105	31	18	92	21	2	4
	robin	M	11.9	75	102	3	32	42	21		
	jafar	M	8.5	78	99	40	40	37	39	4	2
	toby	M	9.2	72	95	26	30	105	29	2	5
	nana	F	8.2	67	89	4	40	140	141	1	2
	M	3F, 7M	9.95	72.3	92.5	23.20	13.0	68.30	41.10	3.00	3.25
	SD		1.44	7.20	12.3	14.31	12.2	37.74		1.50	1.67
TD Matched	aladdin	M	7.2	104	98	18	2	78	59	5	6
	basil	M	8.3	98	95	18	25	54	23	4	3
	minnie	F	9.2	123	98	26	8	98	37	6	6
	flower	F	11.7	109	97	16	8	104	23	3	3
	hercules	M	11.5	96	95	14	1	32	21	6	6
	merlin	M	6.8	133	99	12	40	112	18	6	5
	stitch	M	11.6	87	88	4	12	62	18	2	2
	percy	M	9.3	97	99	5	46	45	31	2	1
	wilbur	M	8.4	99	88	15	0	33	26	4	2
	alice	F	10.4	112	101	29	0	35	32	5	2
	M	3F, 7M	9.42	105.	95.8	15.70	15.0	65.30	28.80	4.30	3.60
	SD		1.81	13.8	4.49	7.90	7.90	30.79		1.57	1.96
TD Other	patch	M	9.2	98	104	3	6	37	39	6	4
	tigger	M	11.2	108	105	15	8	72	57	6	6
	tarzan	M	8.2	118	109	9	30	29	18	6	6
	timon	M	11.6	106	115	29	26	23	20	6	3
	nala	F	10.3	100	98	41	22	53	41	6	6
	cleo	F	6.9	102	93	43	16	97	52	6	
	aurora	F	9.4	96	106	22	20	47	31	4	2
	jasmine	F	8.2	111	126	38	15	30	35	2	3
	belle	F	7.3	108	104	21	1	27	18	4	3
	fauna	F	9.8	94	121	12	51	35	40	3	5
	M	6F, 4M	9.20	104.	108.	23.30	19.5	45.00	35.10	4.90	4.22
	SD		1.58	7.46	10.0	14.02	14.3	23.46	13.62	1.52	1.56

Note. % Compensation for negative and positive F1 manipulations (% + Comp and % - Comp) are absolute values.

[a] F1D indicates F1 frequency discrimination task abilities. Higher values indicate lower frequency discrimination abilities.

Appendix C



Auditory Feedback Formant Shift in TD Children and Children with SLI Protocol
Use Sennheiser HD265 headphones with mono to binaural splitter, and Shure headset microphone.
Madsen using FF tape LHS to left, speech noise to left or both (gain set on centre knob)
Frequency Devices 901 Filter: lowpass cutoff 4500 Hz, 0 dB gain
Madsen TapeLHS VU Gain____50% i/p range (*R dial while pressing CD*)

Code:_____________ Birthday: ____________(ddmmyy) Age:______ Date:__________(ddmmyy)

Start Time:_________ End Time:___________ Ear Infections (Ever/Last 6 Mo.): ___________

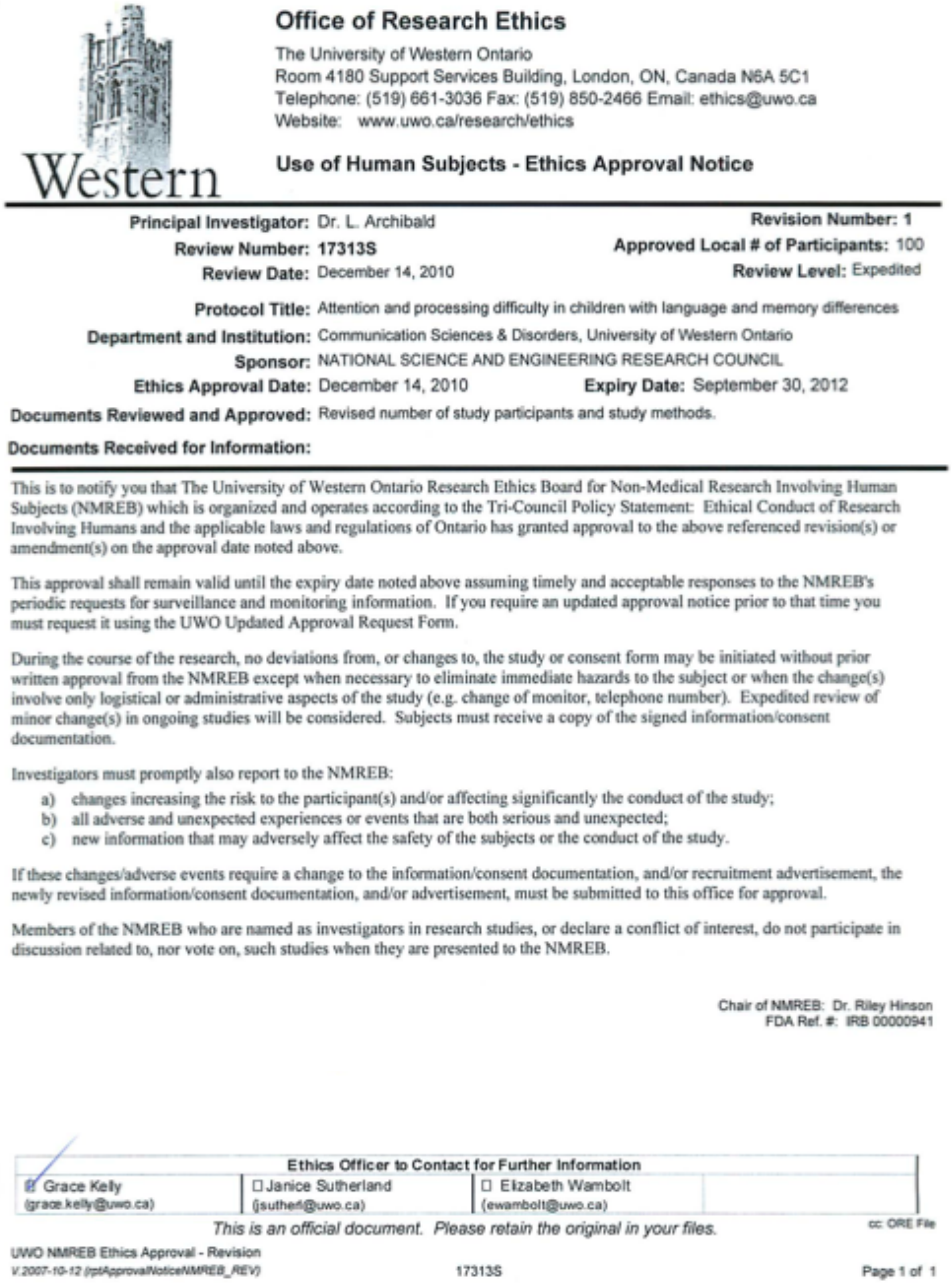
Dino: 2 Tone: 2 Rise: Vocal Training: /AE/ /IH/ /EH/ Vowel Space:

Threshold Hearing Test - If already done with Janis/Lisa/Other's Lab, check off here:

Freq. Hz	500	750	1000	1500	2000	3000	4000	6000
Left HL		----		----		----		----
Right HL		----		----		----		----

Test Order				Set Mad Voice fdbk [dB] Lft knob	Set Mad SN [dB] Cntr knob	Target Vowel	BMO	Filename, Notes Codename_(ehsetmic/ae/ih/eh)
Screener								
1	Mic Gain=			80 (83 dBA)	40 (52 dBA)	/EH/ head setmic	---	
	target VU=			80 (83 dBA)	40 (52 dBA)	/AE/ had		
				80 (83 dBA)	40 (52 dBA)	/IH/ hid		
				80 (83 dBA)	40 (52 dBA)	/EH/ head BMO		
Positive Shift			**(Codename_eh_p)**					
	Mic Gain=			80 (83 dBA)	40 (52 dBA)			
	target VU=			80 (83 dBA)	40 (52 dBA)			
	HEADPHONES OFF, TALK WITH PARTICIPANT, QUICK BREAK ~ 5MINS							
Negative Shift			**(Codename_eh_n)**					
	Mic Gain=			80 (83 dBA)	40 (52 dBA)			
	target VU=			80 (83 dBA)	40 (52 dBA)			
Exit Interview & Notes:								

Appendix D



Office of Research Ethics

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Room 4180 Support Services Building, London, ON, Canada N6A 5C1
Telephone: (519) 661-3036 Fax: (519) 850-2466 Email: ethics@uwo.ca
Website: www.uwo.ca/research/ethics

Western

Use of Human Subjects - Ethics Approval Notice

Principal Investigator: Dr. L. Archibald
Revision Number: 1
Review Number: 17313S
Approved Local # of Participants: 100
Review Date: December 14, 2010
Review Level: Expedited

Protocol Title: Attention and processing difficulty in children with language and memory differences
Department and Institution: Communication Sciences & Disorders, University of Western Ontario
Sponsor: NATIONAL SCIENCE AND ENGINEERING RESEARCH COUNCIL
Ethics Approval Date: December 14, 2010
Expiry Date: September 30, 2012
Documents Reviewed and Approved: Revised number of study participants and study methods.
Documents Received for Information:

This is to notify you that The University of Western Ontario Research Ethics Board for Non-Medical Research Involving Human Subjects (NMREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the applicable laws and regulations of Ontario has granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above.

This approval shall remain valid until the expiry date noted above assuming timely and acceptable responses to the NMREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the UWO Updated Approval Request Form.

During the course of the research, no deviations from, or changes to, the study or consent form may be initiated without prior written approval from the NMREB except when necessary to eliminate immediate hazards to the subject or when the change(s) involve only logistical or administrative aspects of the study (e.g. change of monitor, telephone number). Expedited review of minor change(s) in ongoing studies will be considered. Subjects must receive a copy of the signed information/consent documentation.

Investigators must promptly also report to the NMREB:

a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
b) all adverse and unexpected experiences or events that are both serious and unexpected;
c) new information that may adversely affect the safety of the subjects or the conduct of the study.

If these changes/adverse events require a change to the information/consent documentation, and/or recruitment advertisement, the newly revised information/consent documentation, and/or advertisement, must be submitted to this office for approval.

Members of the NMREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the NMREB.

Chair of NMREB: Dr. Riley Hinson
FDA Ref. #: IRB 00000941

Ethics Officer to Contact for Further Information			
☑ Grace Kelly (grace.kelly@uwo.ca)	☐ Janice Sutherland (jsutherl@uwo.ca)	☐ Elizabeth Wambolt (ewambolt@uwo.ca)	

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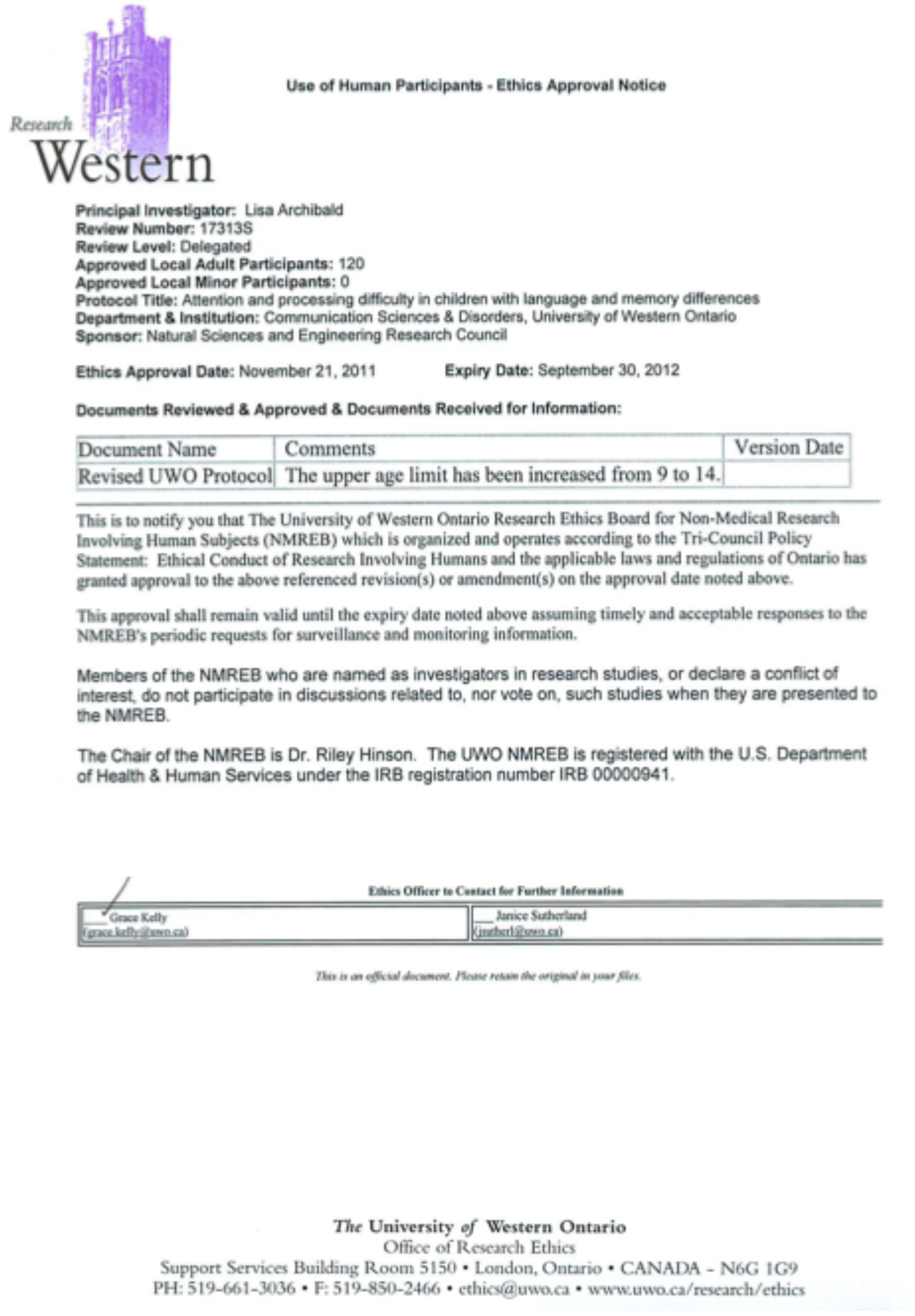
cc: ORE File

UWO NMREB Ethics Approval - Revision
V.2007-10-12 (rptApprovalNoticeNMREB_REV)

17313S

Page 1 of 1

Appendix E



Research Western

Use of Human Participants - Ethics Approval Notice

Principal Investigator: Lisa Archibald
Review Number: 17313S
Review Level: Delegated
Approved Local Adult Participants: 120
Approved Local Minor Participants: 0
Protocol Title: Attention and processing difficulty in children with language and memory differences
Department & Institution: Communication Sciences & Disorders, University of Western Ontario
Sponsor: Natural Sciences and Engineering Research Council

Ethics Approval Date: November 21, 2011 **Expiry Date:** September 30, 2012

Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Revised UWO Protocol	The upper age limit has been increased from 9 to 14.	

This is to notify you that The University of Western Ontario Research Ethics Board for Non-Medical Research Involving Human Subjects (NMREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the applicable laws and regulations of Ontario has granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above.

This approval shall remain valid until the expiry date noted above assuming timely and acceptable responses to the NMREB's periodic requests for surveillance and monitoring information.

Members of the NMREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussions related to, nor vote on, such studies when they are presented to the NMREB.

The Chair of the NMREB is Dr. Riley Hinson. The UWO NMREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000941.

Ethics Officer to Contact for Further Information

[✓ Grace Kelly] (grace.kelly@uwo.ca)	___ Janice Sutherland (jsutherl@uwo.ca)

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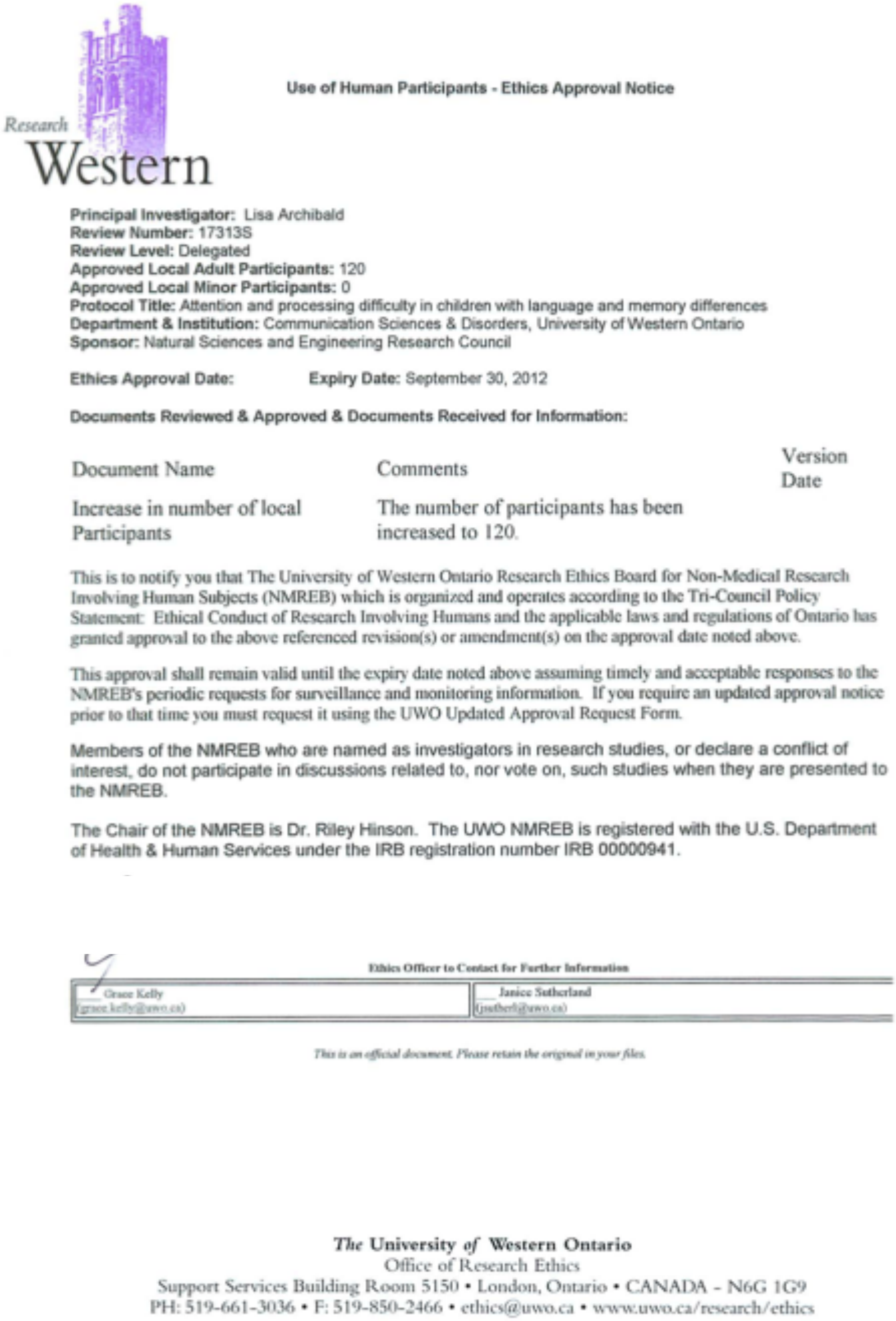
Appendix F



Research Western

Use of Human Participants - Ethics Approval Notice

Principal Investigator: Lisa Archibald
Review Number: 17313S
Review Level: Delegated
Approved Local Adult Participants: 120
Approved Local Minor Participants: 0
Protocol Title: Attention and processing difficulty in children with language and memory differences
Department & Institution: Communication Sciences & Disorders, University of Western Ontario
Sponsor: Natural Sciences and Engineering Research Council

Ethics Approval Date: **Expiry Date:** September 30, 2012

Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Increase in number of local Participants	The number of participants has been increased to 120.	

This is to notify you that The University of Western Ontario Research Ethics Board for Non-Medical Research Involving Human Subjects (NMREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the applicable laws and regulations of Ontario has granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above.

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Members of the NMREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussions related to, nor vote on, such studies when they are presented to the NMREB.

The Chair of the NMREB is Dr. Riley Hinson. The UWO NMREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000941.

Ethics Officer to Contact for Further Information

Grace Kelly (grace.kelly@uwo.ca)	Janice Sutherland (jsutherl@uwo.ca)

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Curriculum Vitae

Name: Emily Michaela Hamel

Education

2010-2012	The University of Western Ontario M.Sc. Neuroscience
2006-2010	Trinity Western University B.Sc. Biology with Distinction

Awards

2010-2012	Western Graduate Research Scholarship
2011	Great Ideas for Teaching Award
2006-2010	Dean’s List Certificate of Achievement
2006-2010	Dean’s Scholarship for Academic Excellence
2006-2007	Provincial Scholarship Award

Related Work Experience

2010-2011	Teaching Assistant The University of Western Ontario
2010-2011	Society of Graduate Students Neuroscience Councillor The University of Western Ontario
2009	Research Intern Trinity Western University and Infogenetica Bioinformatics
2006-2008	Research Assistant Trinity Western University

Conference Presentations

Hamel, E.M., Purcell, D.W., & Archibald, L. (2012). Manipulated auditory feedback causing changes in the vowel production of children. 4th Annual Western International Interdisciplinary Student Symposium on Language Research (WISSLR), Western University, London, Ontario.

Hamel, E.M., Purcell, D.W., Archibald, L. (2012). Perturbed auditory feedback causing changes in the production of vowels in children with Specific Language Impairment. Symposium on Research in Child Language Disorders (SRCLD), University of Wisconsin-Madison, Madison, Wisconsin.

Hamel, E.M., Archibald, L., & Purcell, D.W. (2012). Compensation for manipulated auditory feedback in children with Specific Language Impairment. The Listening Talker: An interdisciplinary workshop on natural and synthetic modification of speech in response to listening conditions (LISTA), University of Edinburgh, Edinburgh, Scotland.

Hamel, E.M., Archibald, L. & Purcell, D.W. (2012). Vocal responses of children with Specific Language Impairment to altered auditory feedback. Faculty of Health Sciences Research Day, Western University, London, Ontario.

Oram Cardy, J., **Hamel, E.M.,** Purcell, D.W., Joanisse, M., Archibald, L. (2012). Neural markers of auditory integration in children with Specific Language Impairment. Symposium on Research in Child Language Disorders (SRCLD), University of Wisconsin-Madison, Madison, Wisconsin.