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The Effect of Visual Feedback on Vocal Compensation Abilities in Individuals With Post-Stroke Aphasia

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THE EFFECT OF VISUAL FEEDBACK ON VOCAL COMPENSATION ABILITIES IN INDIVIDUALS WITH POST-STROKE APHASIA

by

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ABSTRACT

Speech production is a complex and highly organized process comprised of various sensory and perceptual components. Post-stroke aphasia can impair speech production abilities by interrupting individuals' ability to detect and correct speech errors and produce their targeted behavior. Contemporary models of speech production aim to understand the relationship between sensory systems and the human ability to produce perceptually accurate speech. This study seeks to understand the relationship between visual feedback and vocal compensation abilities in individuals with post-stroke aphasia to determine the effectiveness of incorporating visual feedback into therapeutic expressive language intervention. It was hypothesized that that the multi-sensory experimental condition will improve vocal control ability in both experimental groups as indexed by smaller compensation magnitude of (i.e., more stabilized) responses in the presence of artificial pitch-shift perturbations. It was also hypothesized that the post-stroke aphasia group would benefit more from the audiovisual feedback experimental condition and would produce a more stable vocal output via suppressing vocal compensation responses to external pitch-shift stimuli compared with control participants. The results revealed that there are no significant effects of visual feedback on improved stabilization of vocal pitch or suppression of external altered auditory feedback stimuli on control participants. However, this experiment revealed a significant effect on the aphasia group for the downward shift in the AV Sham condition, indicating that visual feedback may benefit individuals with post-stroke aphasia. The results of this present study add to current literature to inform professionals in the field of communication sciences and disorders about the impact of multi-sensory feedback on speech productions. Additionally, the results revealed through this research uncover potential benefits of involving visual feedback into therapeutic expressive language intervention for individuals with post-stroke aphasia.

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CHAPTER 1

BACKGROUND

1.1 Sensory-Motor Integration for Speech

Findings from a large body of research studies provide supporting evidence for the important role of sensory feedback in speech production and perception. Wernike's classic model regarding neural circuitry of language identified an undeniable link between sensory and motor system's involvement in speech production and perception (Hickock, 2012). This connection is important to understand the motor system's ability to match sensory targets during a wide range of goal-directed movements. With visual-manual tasks such as picking up an object, our visual (i.e., sensory) system locates the object and assesses its geometrical and other physical properties (e.g., size, shape, texture, color, etc.). The motor system then generates an appropriate motor command to reach over and grab the object by visually guiding limb positioning in accordance with the perceived object. At the same time, kinesthetic (or somatosensory) feedback from joints and muscles fine-tunes movement trajectory for increased accuracy. Similarly, speech production involves the execution of a series of goal-directed movements in the vocal tract and articulatory structures to match sensory targets in the auditory system. However, in contrast with limb movement, sensory targets for speech are not external, and the brain uses internal targets to produce sounds based on perceptual auditory representations. In addition, somatosensory feedback from speech muscles fine-tunes motor commands for accurate production.

Supporting evidence for the role of sensory feedback mechanisms in speech has been provided by studies on online alteration of auditory and somatosensory input during overt production of isolated vowel sounds, as well as continuous words and sentences. For example, a study by Larson (1998) evaluates the influences of kinesthetic and auditory feedback for motor control and regulation of speech vowel fundamental frequency (F0) in trained versus untrained singers. This research found that online alteration of auditory feedback using pitch-shift stimuli elicits compensatory vocal motor behavior that opposes the direction of F0 changes in both groups. Another study (Sundberg, 1967) found that trained singers are able to rely on kinesthetic feedback, or proprioceptive senses of how their muscles and vocal folds should "feel" to control their vocal F0, even in the presence of distorted auditory feedback. Together, the findings of these studies support the notion that auditory and kinesthetic feedback play a significant role in voice F0 control both in trained and untrained singers.

This notion was further corroborated by other studies showing that applying online formant shifts to the auditory feedback of multisyllabic words during continuous sentence production elicits a similar pattern of compensatory behavior that adjusts the movement of articulatory muscles to oppose the direction of perceived formant shifts to achieve the targeted speech sound. The converging line of evidence from these studies suggests speech production is a high level, skilled function involving several sensory systems (Hickock, 2012). Another study by Cai et al. (2011) was the first to uncover that auditory feedback is used by the speech motor system to precisely adjust spatiotemporal measures in the articulation of multisyllabic words. This study adds to existing evidence that auditory feedback plays an important role in speech motor control, specifically for articulatory processes.

1.2 Contemporary Models of Speech Sensory-Motor Integration

Contemporary models of speech production consider various sensory inputs involved in speech production and perception including tactile, proprioceptive, and auditory feedback. These models are discussed below.

1.1.1 *Dual-Stream Model of Speech Processing*

The Dual Stream Model theorizes the cortical involvement of the auditory and motor systems in speech production and perception.

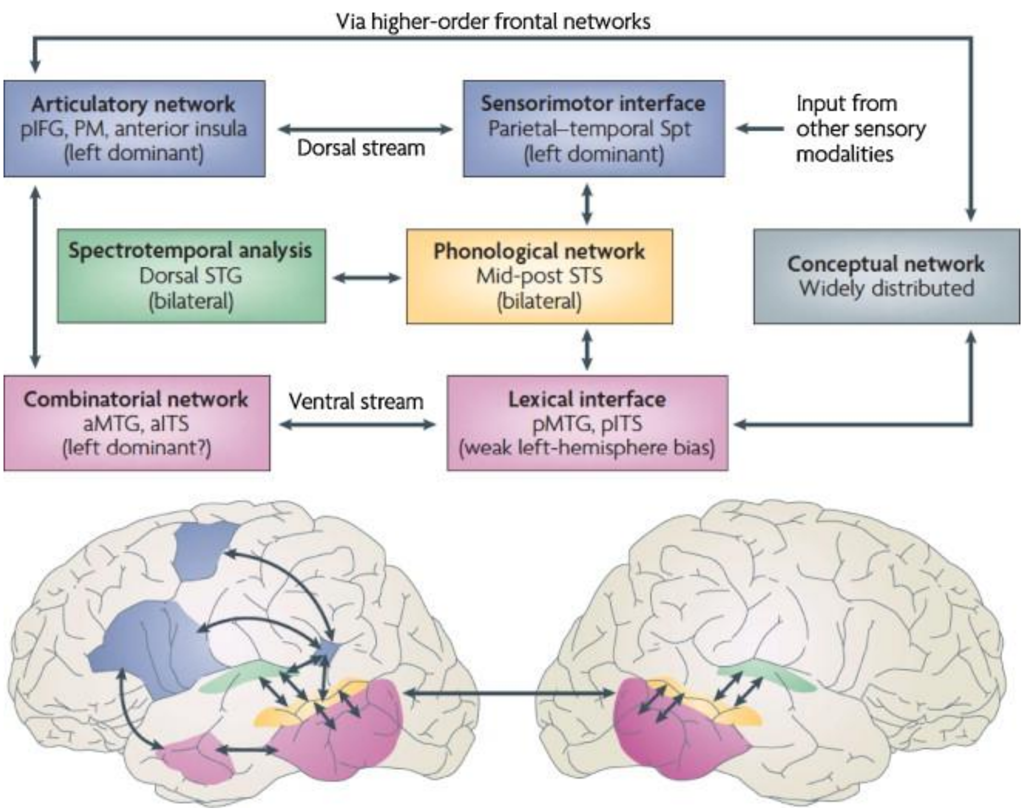

Figure 1.1 The Dual Stream Model (Hickok and Poepell 2000, 2004, 2007). This model depicts the cortical organization of speech processing, which is represented by two streams: the dorsal and ventral streams.

The Dual Stream Model by Hickock (2012) theorizes the cortical involvement of the auditory and motor systems in speech production and perception. This model is broken up into two routes: the dorsal and ventral streams. The dorsal stream is left-hemisphere dominant and involves structures residing in the posterior temporal region and the posterior frontal lobe. It controls speech production by taking acoustic speech signals and manipulating the articulatory structures to produce speech sounds. The ventral stream is bilaterally organized and involves superior and middle portions of the temporal lobe. This stream controls speech comprehension by interpreting auditory speech signals (Hickock, 2012).

1.2.2 DIVA Model

The DIVA model is comprised of feedforward and feedback control subsystems. This model aims to explain how a person uses tactile, proprioceptive, and auditory feedback signals to learn and shape their speech production abilities. The feedforward system uses auditory feedback to create articulatory movements, while the feedback system uses the auditory target and collects proprioceptive and tactile feedback from the attempt. Together, the feedforward and feedback control systems allow individuals to use auditory targets and sensory feedback for self-regulation that allows production of accurate speech sounds (Tourville & Guenther, 2010). The feedforward subsystem is proposed to begin in the left frontal operculum, then it involves the cerebellum in order to produce feedforward commands. This is then communicated to the motor cortex, which passes those commands to the articulatory musculature through subcortical nuclei. The feedback subsystem is composed of auditory and somatosensory feedback. The auditory feedback is collected via subcortical nuclei and passed onto the superior temporal cortex.

Additionally, the auditory target generated from the left frontal operculum is passed to the superior temporal cortex and together those feedback commands are passed along to the motor cortex. Simultaneously, the system receives somatosensory feedback via subcortical nuclei that is transferred to the inferior parietal cortex to be compared to the somatosensory target generated in the left frontal operculum. Any auditory or somatosensory errors detected in those regions are then communicated as feedback commands to the motor cortex. This system is what allows the human brain to produce precise and accurate articulatory movements to communicate through verbal speech (Guenther, 2006).

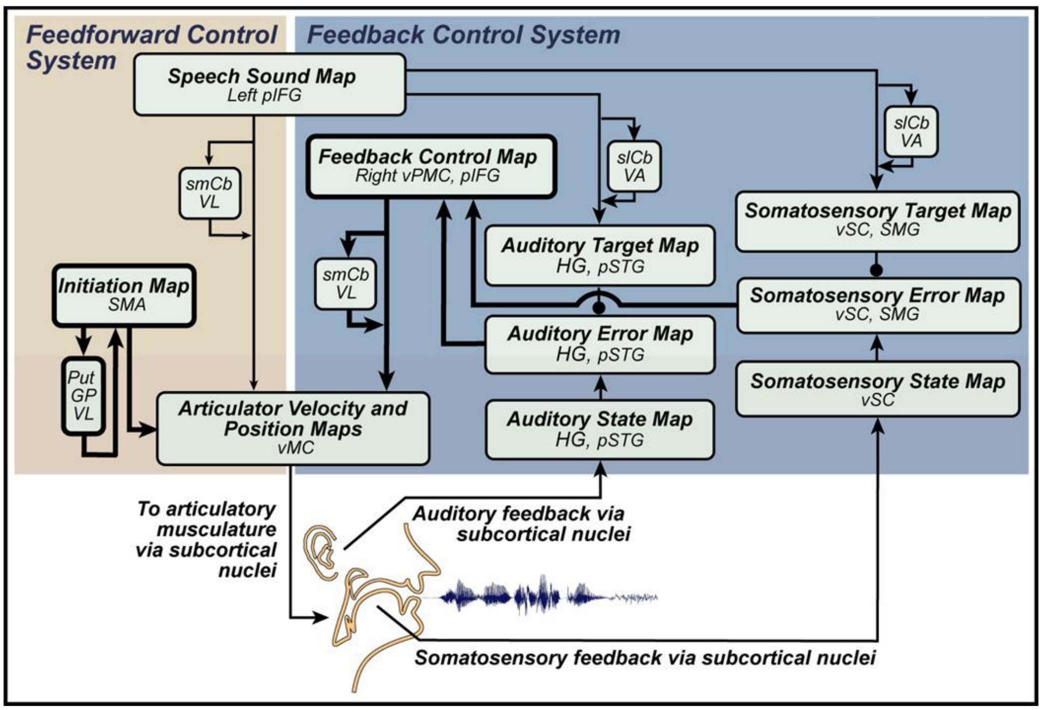

Figure 1.2 The DIVA Model. This model was proposed by Tourville and Guenther (2010) and depicts the feedforward and feedback control systems related to speech acquisition and production. This model includes auditory and somatosensory feedback and explains the hypothesized cortical organization of the related structures.

1.2.3 State Feedback Control Model

The State Feedback Control (SFC) Model aims to explain how the central nervous system (CNS) influences our body's motor outputs by estimating a part of our body's current state and creating controls based on that state. While this model has been applied to many non-speech motor movements, it is just now being studied regarding speech motor control. Like other contemporary models of speech production, the SFC model examines the way sensory feedback is generates and shapes accurate speech productions. While it is well known that the CNS is involved in motor speech production, it is less common to consider how the CNS processes auditory feedback, which is also a critical component for accurate speech production and speech learning. To produce controlled speech, our brains rely on many different types of feedback. It is known that reduced sensory feedback (i.e., hearing loss) impacts the accuracy of speech production through changes in vocal resonance, pitch, and intensity regulation, etc. Although our body does not rely solely on sensory feedback to produce speech, its influence is apparent when its disruption affects the overall quality and intelligibility (Houde & Nagarajan, 2011). It is hypothesized by Houde & Nagarajan (2011) that this model loop begins in the motor cortex (M1) where the neuromuscular controls are likely generated and applied to the vocal tract to produce speech. The end of the model loop controls feedback prediction and the processing and comparison of incoming auditory feedback and occurs in the primary auditory cortex (A1) and the somatosensory cortices (S1).

The SFC model suggests that the CNS uses auditory feedback differently during speech production compared to auditory comprehension alone. This idea of production-specific sensory processing is linked to the concept of multiple processing streams. A study by Mishkin et al. in 1983 described the dorsal stream of sensory processing, linked to the parietal cortex, as the "where" as it related to object location, and the ventral

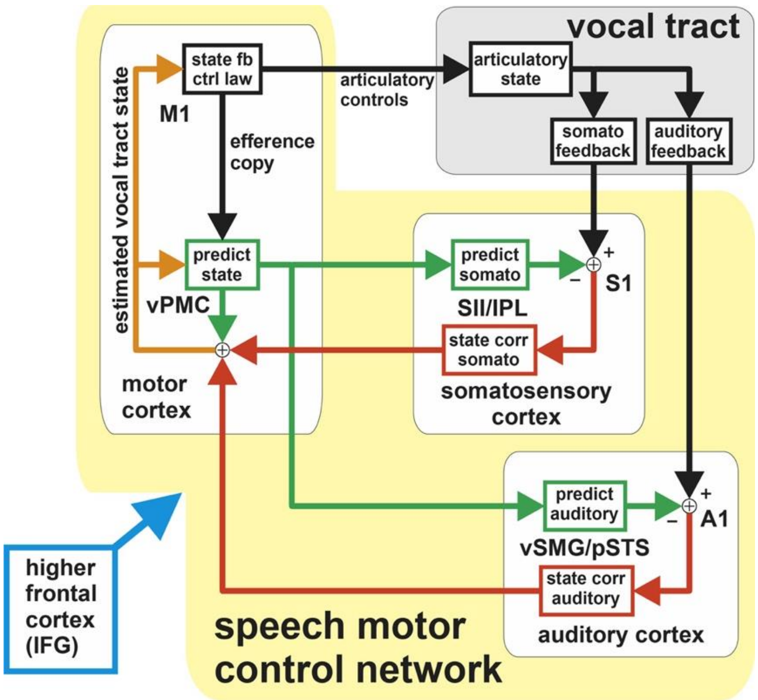

Figure 1.3 The Model of Speech Motor Control. This image is based on the SFC Model proposed by Houde & Chang (2016).

stream, linked to the temporal pole, as the "what" as it is believed to be connected to object recognition. The idea of the dorsal stream has been refined with more recent evidence and has been found to be linked to the vocal motor control system in humans, which are thought to be controlled in the posterior superior temporal gyrus and the superior parietal temporal area (Houde & Nagarajan, 2011). Houde & Nagarajan's research (2011) found a suppression of the auditory cortex during speaking with suppression not occurring in peripheral areas of the CNS. It also found that the suppression of the auditory cortex is reduced if there is a difference between the subject's auditory feedback and the subject's expectation of what the auditory feedback should have been. This information proposes the idea that there must be an existing predictive feedforward model involved within the CNS for speech production. Houde & Chang (2016) gathered that the SFC model is spread across both hemispheres of the brain. The left hemisphere is responsible for detecting mismatches in feedback predictions and the right hemisphere is involved in the process of creating corrections from the errors in feedback prediction.

1.3 The Role of Visual Feedback in Speech Production

A study by Marques et al. in 2016 proved the involvement of visual feedback on speech perception via the McGurk Illusion. While the effects of visual feedback on speech perception were revealed in this illusion, the role of visual feedback in speech production is rarely considered. Therefore, this experiment uses a novel experimental paradigm to assess whether visual feedback from vocal pitch productions influences compensatory motor responses to artificial alterations in auditory feedback in the form of pitch-shift stimuli. This phenomenon is also appreciated in a study by Ning, Loucks, and Shih (2018), which discusses the improved identification of auditory messages in noisy backgrounds with the support of visual cues via articulatory gestures, including speaker's lips and faces. These results were appreciated with the dual-modal (auditory + visual) feedback and absent in unimodal scenarios. Ning, Loucks, and Shih (2018) found significant increase in vocal stability ($F0$) and enhanced mean vocal compensation responses in native English and Mandarin speakers in the presence of artificial auditory feedback perturbation when using multisensory (auditory + visual) feedback. This finding adds to existing evidence that multisensory (auditory-visual) feedback outweighs auditory-only feedback systems and real-time visual feedback aids speakers in suppressing compensatory motor responses to pitch-shift stimuli.

A study by Bernstein and Liebenthal (2014) explores the visual perception of spoken language and its representations in the brain through the auditory speech pathways and the temporal visual speech area (TVSA). It also mentions a study by Calvert et al. (1997) which found neural activation present in the primary auditory cortex during lipreading. This suggests that visual stimuli in the form of articulatory movements may impact auditory perceptions of spoken language before auditory stimuli is processed in the auditory association cortex. Ultimately, there is strong evidence that the brain is a highly multi-sensory system; however, more research is still required to investigate the neuroanatomical organization of the visual processing of speech.

The effects of visual feedback have been proven to be beneficial for therapeutic intervention for acquired apraxia of speech, another common motor speech disorder associated with stroke. Kendall et al. (2006) found success in implementing auditory-visual modes of stimuli, via intensive phonomotor rehabilitation, to improve accuracy in speech production abilities in individuals with acquired apraxia of speech. The treatment intervention in this study includes the use of mirrors for real-time visual feedback in treatment sessions in hopes to produce fewer speech sound errors in comparison to auditory-only stimuli. The results of this study reveal increased speech accuracy in individuals who used auditory-visual feedback rather than auditory-only (Kendall et al., 2006).

1.4 Speech Entrainment

Fridriksson et al. (2015), found that the inclusion of an audiovisual speech model through their Speech Entrainment (SE) paradigm allowed some individuals with Broca’s aphasia to improve on the measures of speech fluency. The improved fluency was only observed in the presence of the audiovisual model and was absent in the presence of audio only speech models. This signifies the role of visual feedback in Speech

Entrainment and proves that the positive effects are not caused by enhanced lexical or syntactic processing, but rather the visual component. This study demonstrates that visual feedback, as used in the Speech Entrainment training, is a beneficial rehabilitative treatment for individuals with non-fluent Aphasia (Fridriksson et al., 2015). Another study conducted by Fridriksson et al. in 2012 found that treatment involving audiovisual speech perception is more successful in improving speech production abilities when compared to treatment using auditory speech stimulation alone. The article discusses the visual feedback integration that was used in this study, (visual input of the mouth of another person producing the target speech model) which allows the patient to produce increased speech output. In contrast, without visual feedback, the auditory feedback alone resulted in minimal speech production for both aphasia and normal subjects. Researchers attributed improved speech production to the fact that audiovisual model may entrain the residual left frontal speech areas in the individuals with non-fluent speech (Fridriksson et al., 2012).

It is apparent in the dual-stream model that sensory-motor control is dominated by the left hemisphere neural networks. Because aphasia is caused by damage to the neural networks of the left hemisphere, aphasia is an ideal disorder to examine to better understand the neural biological aspects associated with motor-speech deficits. Since auditory brain networks can be disrupted in individuals with post-stroke aphasia, it is important to include an intact sensory modality such as the visual system. Involving the visual system may be beneficial to consider in intervention for improving motor-speech function in this population.

1.5 Post-Stroke Aphasia

Decreased speech production and vocal compensation abilities are common deficits present in individuals with post-stroke aphasia. Findings from research by Behroozmand, et al. in 2022 confirms the presence of impairment of feedback control mechanisms in vocal production in individuals with post-stroke aphasia. Additionally, individuals with post-stroke aphasia have been found to have significantly impaired speech error detection and decreased motor correction abilities when compared to adults without history of stroke (Sangtian et al., 2021). Speech error detection and decreased motor correction abilities, as well as overall decreased speech production and vocal compensation abilities, are all factors that lead us to believe the aphasia participants in this study may have decreased vocal compensation responses under our visual feedback paradigm, compared to healthy controls.

1.6 Research Question and Rationale

This study aims to further explore the impact of multisensory feedback on speech production and examine the effects of visual feedback for vocal compensation abilities in individuals with post-stroke aphasia versus healthy adults. As previously discussed, the role of visual feedback processing is often not considered in the contemporary models of speech sensorimotor integration. This present study will use a novel audiovisual feedback model to study sensorimotor integration mechanisms involved in speech motor control and examine the effectiveness of using the intact audiovisual networks that may present in individuals with damage to the speech production networks in the brain. It will also evaluate the magnitude of vocal compensation responses for up and down pitch shifts in three different feedback conditions between the two experimental groups. This study will additionally examine if there is a different effect of visual feedback on vocal compensation abilities in individuals with post-stroke aphasia versus healthy adults. Furthermore, this experiment aims to evaluate is there be a significant difference between unimodal and multisensory feedback in vocal compensation abilities. Another component that will be considered is whether auditory-visual feedback increase vocal compensation magnitudes when an artificial auditory perturbation is administered. To determine the effectiveness of the multisensory feedback for stabilizing vocal pitch and compensating for artificial pitch perturbations, this study will examine compensation magnitudes for individuals with post-stroke aphasia and healthy adult controls. Research has proven the influence of multisensory integration in the process of speech production, specifically visual feedback (Freidrickson et al., 2015). The current standard approaches to aphasia treatment in the field of speech language pathology do not typically include an overt form of visual feedback to assist in improved accuracy for motor speech productions. Current research, like the studies performed by Freidrickson et al. (2015), Ning, Loucks, and Shih (2018), and Cai et al. (2011), reflect that visual feedback could be an extremely helpful tool in therapeutic intervention targeting motor speech control

1.7 Hypothesis and Significance

Based on previous research, it is hypothesized that the multi-sensory experimental condition (auditory + visual feedback) will enhance sensorimotor integration and produce increased vocal compensation magnitudes in the presence of artificial pitch-shift stimuli for both experimental groups. This hypothesis is supported by the results of the study completed by Ning, Loucks, and Shih in 2018 that used a similar experimental design as the present study. Likewise, this experiment evaluated the relationship between bi-modal sensory feedback (auditory + visual) and the suppression of pitch shift responses and found that this multisensory feedback improved the stability of the healthy adult participant's vocal pitch. It is also hypothesized that participants with post-stroke aphasia will benefit most from the audiovisual feedback experimental condition as it will promote increased vocal pitch control and improved suppression of external pitch-shift stimuli. These improved abilities are due to the activation of the intact visual pathways that compensate for the damaged auditory networks which is supported by Fridriksson et al. 2015. This effect of the use of visual pathways for improved vocal compensation abilities is indexed by greater suppression of vocal compensation behaviors in response to external pitch perturbations in the aphasia group compared to the control group. This research could influence speech therapy rehabilitative techniques for individuals with post-stroke aphasia by proving the effectiveness of visual feedback and therefore incorporating it into standard practice. If this study shows significant results in the inclusion of visual feedback, it could further justify the consideration to implement visual feedback into post-stroke aphasia therapeutic intervention.

CHAPTER 2

METHODS

2.1 Participants

A total of 40 participants were included in this research study. There were 20 individuals with chronic left-hemisphere stroke and post-stroke aphasia, and 20 control adult controls with no history of neurological, speech-language, or hearing disorder. In the aphasia group, there were 12 female and 8 male participants all ranging between the ages of 43.75 and 77.08 with the mean age of 62.23 years. In the control group, there were 12 female and 8 male participants all ranging between the ages of 31 and 76 with the mean age being 56.32 years. All stroke participants included in this study were recruited through the Aphasia Lab and Center for the Study of Aphasia Recovery (C-STAR) at the University of South Carolina. The eligibility criteria for the aphasia group was as follows: the individual must be between the age of 40-80 years old, diagnosed with aphasia due to chronic (>6 months) left-hemisphere stroke, are able to provide informed written or verbal consent, and have the ability to understand study instructions and speak. All aphasia participants had been evaluated using the Western Aphasia Battery-Revised (WAB-R; Kertesz, 2007) revealing a mean Aphasia Quotient (the measure of aphasia severity on the WAB-R) was 70.55. Based on the WAB-R aphasia

Table 2.1 Aphasia Group Demographic Information WAB-R Scores.

Aphasia Participants										
ID	Age	Sex	Education (yrs.)	Aphasia Quotient	Fluency	Spontaneous Speech	Auditory Verbal Comprehension	Repetition	Naming	Type of Aphasia
A1	65.92	M	14	85.8	6	15	9.2	9.2	9.5	Anomic
A2	77.08	M	16	55.3	3	10	7.05	4.4	6.2	Broca’s
A3	66.08	M	12	52.1	4	11	4.15	7.4	3.5	Broca’s
A4	63.17	M	18	72.2	9	13	7.9	6.8	8.4	Broca’s
A5	47.58	M	16	73.9	4	13	9.75	7.2	7	Broca’s
A6	60.92	M	16	67.8	6	14	6.6	4.9	8.4	Wernicke’s
A7	46.92	M	12	44.5	2	9	6.55	2	4.7	Broca’s
A8	70.83	M	14	71.7	4	11	9.95	7.1	7.8	Broca’s
A9	58.75	F	22	99.6	10	20	10	9.8	10	Above cutoff
A10	56.42	F	14	96.4	9	19	10	9.2	10	Above cutoff
A11	65.92	F	14	69	5	14	8.3	5.4	6.8	Conduction
A12	63.42	F	14	72.5	4	12	8.95	7.7	7.6	Broca’s
A13	71.17	M	22	19.6	1	3	5.9	0.7	0.2	Broca’s
A14	64.1	F	12	76.4	8	17	8.4	8.5	4.3	Broca’s

A15	74.67	M	15	84.4	9	18	9.4	6.6	8.2	Anomic
A16	76.08	F	12	55.9	4	9	7.45	4.5	7	Broca’s
A17	43.75	M	16	93.9	9	19	9.75	8.7	9.5	Anomic
A18	54.92	F	19	92.8	-	18	9.8	9.8	8.8	Anomic
A19	67.0	M	23+	72.4	4	12	8.6	8.1	7.5	Transcortical Motor
A20	48.75	F	16	54.8	4	11	6.9	3.7	5.8	Broca’s
Mean Age = 62.23										

classification system, the distribution of aphasia subtypes was as follows: 4 Anomic, 11 Broca’s, 1 Conduction, 1 Transcortical Motor, and 1 Wernicke’s, and 2 participants that tested above the cutoff for aphasia. Control participants were recruited by posting flyers in virtual groups and local locations in Columbia, SC. The eligibility criteria for the control group required the individual to be between the age of 40 and 80 years old, a healthy individual with normal speech, language, and hearing, no history of neurological or psychiatric disorders, able to provide informed written or verbal consent, and can understand study instructions and speak. All individuals were given a hearing screening prior to participating in this study. All participants signed informed consent forms and were monetarily compensated for their participation. This research project was approved by the University of South Carolina Institutional Review Board.

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Table 2.2 Control Group Demographic Information.

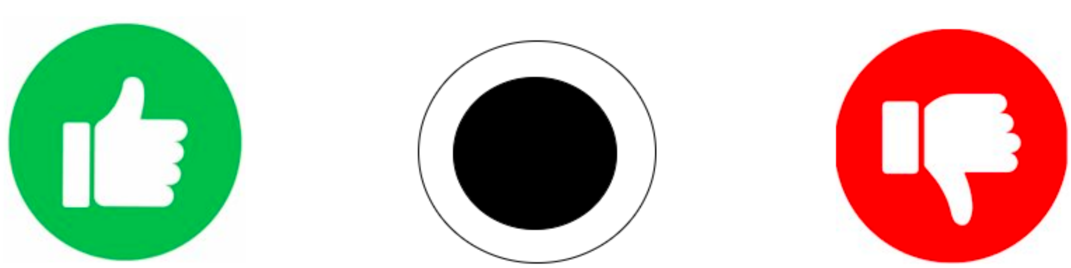
Control Participants			
ID	Age	Sex	Education (yrs.)
C1	76	M	18
C2	56.83	F	16
C3	68.25	F	18
C4	68	F	12
C5	57	F	16
C6	43.75	M	16
C7	59.08	F	19
C8	54.5	F	18
C9	31	M	18
C10	35.42	F	18
C11	67.75	F	16
C12	70.4	F	16
C13	71.5	F	16
C14	31.75	M	14
C15	58.92	F	16
C16	50.42	M	15
C17	60.67	M	14
C18	46.75	F	19
C19	57.58	M	16
C20	60.92	M	19
Mean Age = 56.32			

2.2 Experimental Procedure

Experimenters provided comprehensive training and brief practice of the speech tasks prior to the initiation of the experiment to ensure their understanding of the task and accuracy in producing vocalizations. This experiment was conducted in a sound-attenuated booth and electroencephalography (EEG) data was concurrently collected while the participant completed a speech task of vocalizing the vowel sound /a/. EEG data was collected via 64 Brainvision actiCAP active electrodes following the standard 10-10 montage with electrode impedances below 5 KΩ and a common average reference. The electrodes were placed on the participant's scalp using conductive gel to reduce impedance between the surface of the scalp the electrode to promote adequate signal quality. The BrainVision actiCAP amplifier (Brain Products GmbH, Germany) combined with Pycorder software recorded EEG signals at a 1 kHz sampling rate after applying a low-pass anti-aliasing filter at 200 Hz.

Although EEG data were collected during the experimental sessions, these data were not analyzed in the present study, and it primarily focused on examining the effects of the audio-visual processing on the behavioral measures of speech compensation in responses to pitch-shift perturbation in the auditory feedback.

The participant's vocal productions were recorded via a head-mount AKG condenser microphone (model C520), amplified by a Motu Ultralite-MK3. The participant received real-time playback of their vocalizations under the auditory feedback experimental paradigm through Etymotic earphones (model ER1-14A). Speech data was recorded throughout the entirety of the session at 44.1 kHz on a laboratory computer. The participants were asked to produce a steady vowel sound /a/ for 2-3 seconds at their typical conversational pitch and volume. Participants were prompted to initiate and finalize vocalizations with visual cues on a computer screen; an image of a thumbs up to begin vocalizing and a thumbs down to stop vocalizing.



Thumbs Up | Circle with ball | Thumbs down

Figure 2.1 Visual Feedback Paradigm Vocalization Prompts.

While they vocalized, they received real-time auditory feedback of their vocalization via headphones and visual feedback in the form of a ball and a hoop on a computer screen. The ball moved up and down on the screen in correspondence to the participant's change in vocal pitch. The goal of the task was to keep the ball centered in the hoop.

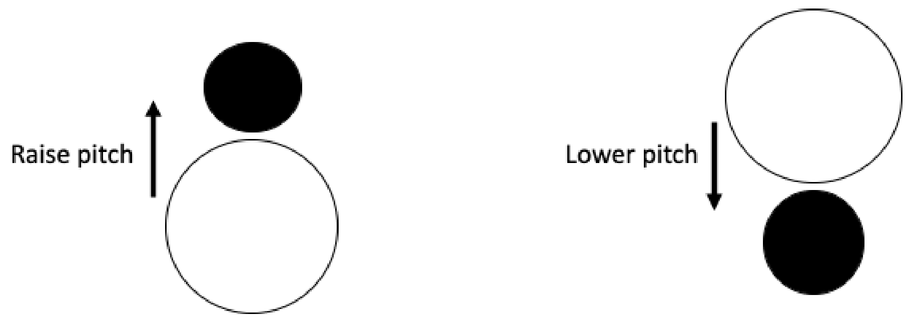


Figure 2.2 Visual Feedback Cues.

Intermittently, the participant's auditory feedback was artificially modified, or perturbed up or down in pitch (±100 cents or ±1 semitones in magnitudes) by a custom-designed program in Max/Msp (Cycling 74, v.5.0). This program controlled an Eventide Eclipse Harmonizer which was used to randomly induce the pitch shift perturbations in the vowel vocalizations. Ideally, the participant should detect the change in their pitch and automatically compensate for the speech "error." In some cases, the participant only received auditory feedback (AF) with no visual support of the ball and hoop. For other trials, the ball moved up and down based on the participant's change in pitch while they received auditory feedback (AF+VF). In other cases, the ball presented visual feedback; however, the movement of the ball was controlled by a random function instead of controlled by the participant's vocal pitch (AF+VF SHAM). These conditions were randomly presented throughout the session. The participants completed one forty-five-minute block with a range of 325-350 vocalization trials for this experiment.

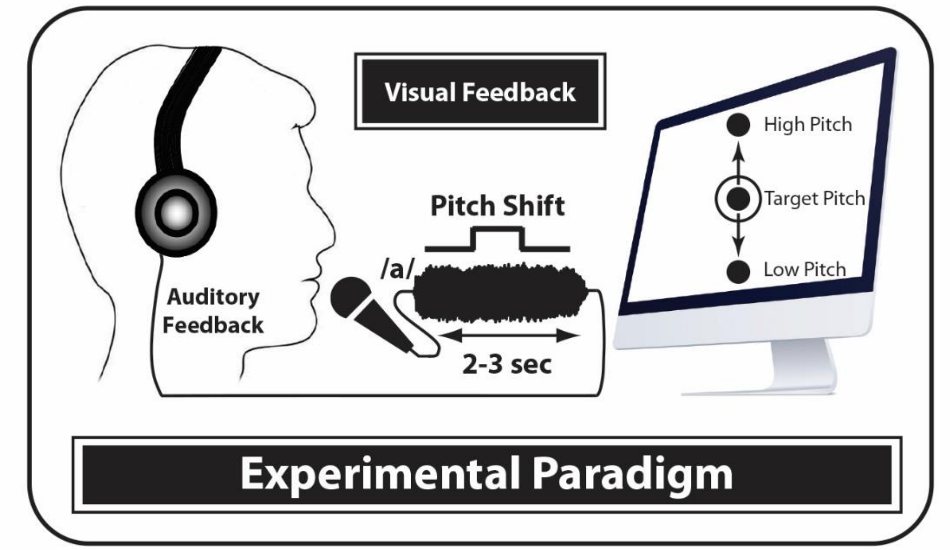


Figure 2.3 Visual Feedback Experimental Paradigm Design.

2.3 Behavioral Data Analysis

This experiment utilized MIDI software (MAX/MSP v.4.1 by Cycling 74) which controlled all parameters of the perturbed auditory feedback pitch-shift stimulus to be analyzed including: duration, magnitude and ISI. Additionally, the MIDI software generated a TTL pulse to identify the onset of each administered stimulus in order to produce a synchronized averaging of participant’s vocal responses. The vocal responses, auditory feedback, and TTL pulses were collected at 10kHz via a PowerLab A/D Converter Model (Model ML880, AD Instruments) and transferred onto a desktop computer via Chart software (AD Instruments).

For the voice response analysis, the participant’s behavioral vocal compensation responses to the artificial pitch-shift perturbations were extracted into PRAAT software utilizing the autocorrelation method and then transferred to MATLAB for additional analysis. The vocal pitch extractions were sectioned into epochs for each individual trial ranging from -100 ms to +500 ms following the stimulus onset. These pitch contours were then changed from Hz to cents using the following formula: $\text{cents} = 1200 \times \log2(F2/F1)$. In this formula, F2 represents a vector of pitch values for each trial epoch and F1 represents the mean of the pre-stimulus pitch ranging from −100 to 0 ms.

The participant's individual vocal production trials were pre-sorted into upward versus downward behavioral responses to the artificial pitch-shift stimuli. The direction of the responses was found by subtracting the mean amplitude of the voice F0 contour in a 100 ms-long pre-stimulus window (−100 to 0 ms) from a post-stimulus window (50 to 250 ms). If the participant did not produce a stable baseline pitch production, a supplemental procedure was utilized to limit data analysis to trials with minimal pre-stimulus variability. Trials with variability ±15 cents of the signal were excluded from analysis. The trials were also correlated with positive or negative values; positive for upshift and negative for down shift. These averaged responses for both stimulus direction groups were then calculated for each experimental condition. Responses that opposed the administered stimuli appeared to change in the downward direction and responses that followed the direction of the administered stimuli appeared to change in the upward direction. Response magnitudes were calculated based on the signal's greatest deviation from the response value at the initial onset of the production.

The behavioral speech data collected for this experiment was analyzed using MATLAB (The Mathworks, Inc.) software. MATLAB programming software is designed for engineers and scientists to analyze data, develop algorithms, and create visual models. The magnitude of the vocal compensation responses was quantified, averaged by group, and compared between the aphasia group and the healthy control group to determine if there is a significant difference in vocal compensation abilities.

2.4 Statistical Data Analysis

The data was also analyzed using JASP statistical data analysis software (https://jasp-stats.org/). A 2x2x3 variable mixed-measures analysis of variance (ANOVA) was used to examine the effects of group (aphasia vs. control) as a between-subject factor, and the effects of stimulus direction (up vs. down) and experimental condition (auditory only, auditory + visual, and sham condition) as within-subject factors on the magnitude of the subject's vocal responses. These factors were analyzed by three separate time windows derived from the group average data: pre-rebound and rebound windows. The pre-rebound window was selected to reflect the participant's compensatory vocal responses to pitch-shift perturbations in the auditory feedback as a behavioral measure to probe sensorimotor integration for speech motor control. The rebound time window was selected to measure the feedforward motor system's ability to re-adjust vocal pitch to baseline after pitch-shift perturbation was removed from the auditory feedback. The pre-rebound window (pitch shift down) ranged from 170-350 ms and (pitch shift up) ranged from 220-400 ms following the onset of the auditory feedback perturbation. The rebound window was derived from the period following the peak vocal compensation for each average group which ranged from 400-995 ms. Statistical significance was determined by controlling Type-I error at $\alpha < 0.05$ for all conditions. Data normality and homogeneity of variance assumptions were examined using the Shapiro-Wilk and Mauchly's sphericity tests, respectively. For data violating these assumptions, p-values were reported using Greenhouse-Geisser's correction. Partial Eta squared (η_p^2) was reported as an index of the effect size for significant main effects and post-hoc tests for significant interactions which were performed using t-tests with Bonferroni's correction.

In addition, measures of speech acoustics including Voice Pitch, Voice Intensity, Harmonic to Noise Ratio (HNR), Jitter (i.e., cycle-to-cycle pitch variability), and Shimmer (i.e., cycle-to-cycle intensity variability) were extracted and analyzed using a 2x3 variable mixed-measures ANOVA model for condition and group

CHAPTER 3

RESULTS

3.1 Behavioral Data

The figures below (3.1, 3.2, 3.3, and 3.4) depict the average vocal compensation responses to pitch-shifted auditory feedback during our experiment. It is evident that the participants elicited vocal compensation responses for both experimental groups in the opposing direction as the pitch shift in all conditions presented for the up (+100 cents) and down (-100 cents) pitch shift stimuli for all experimental conditions.

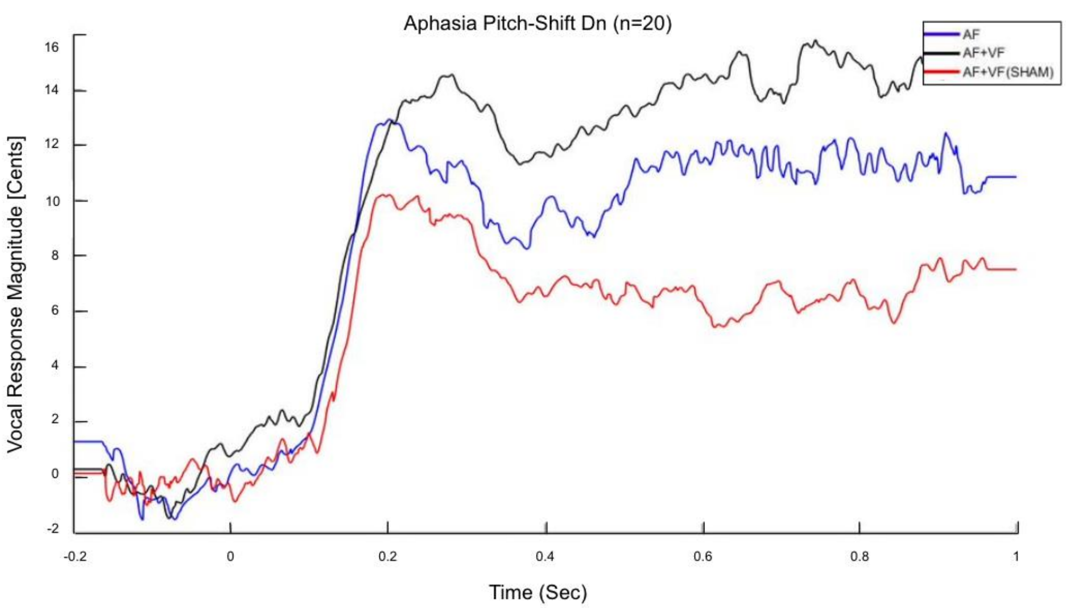


Figure 3.1 Aphasia Group Average Data for Pitch Shift Down.

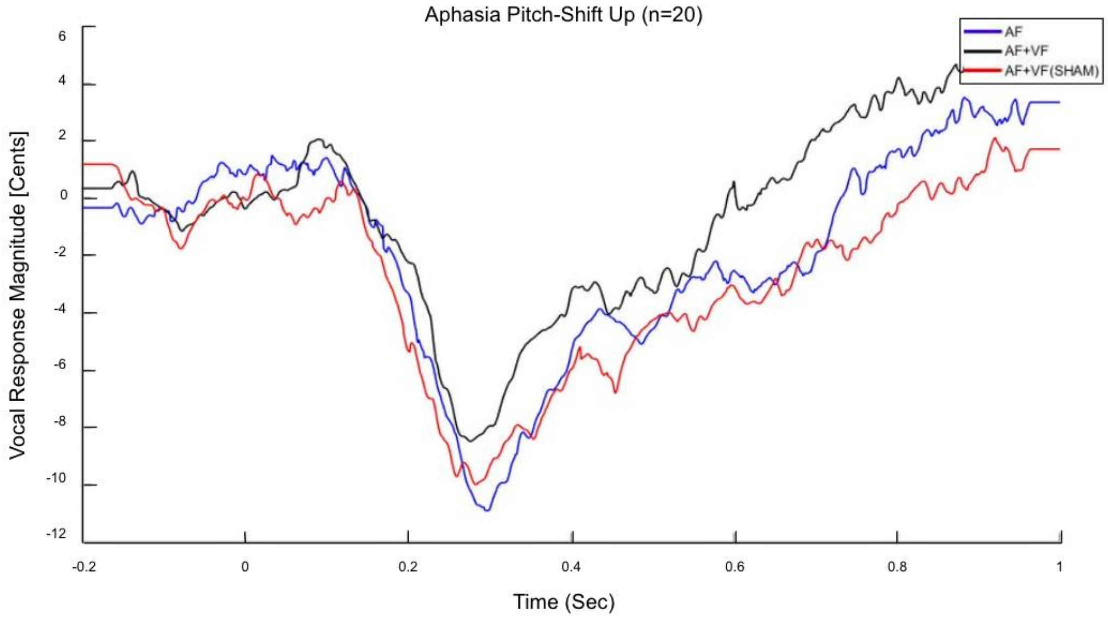


Figure 3.2 Aphasia Group Average Data for Pitch Shift Up.

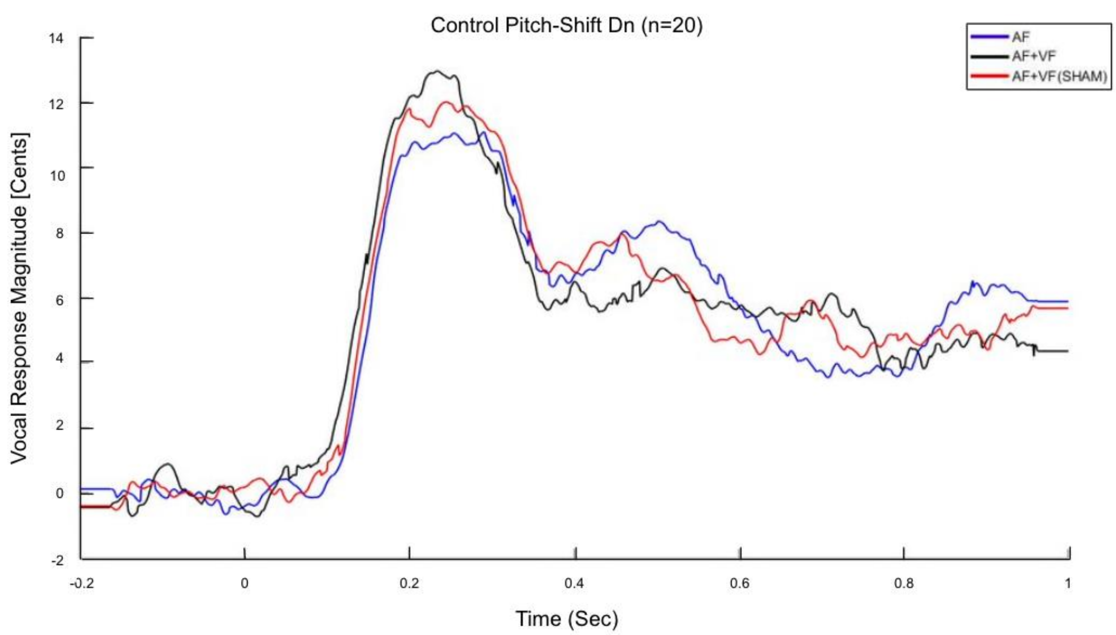


Figure 3.3 Control Group Average Data for Pitch Shift Down.

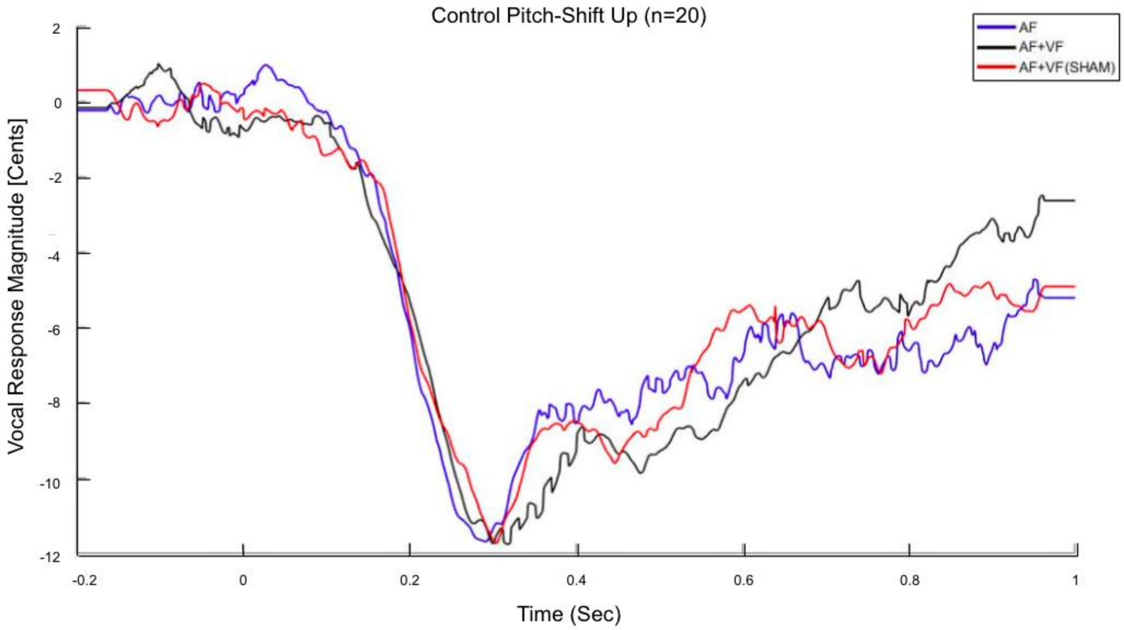


Figure 3.4 Control Group Average Data for Pitch Shift Up.

3.2 Statistical Data

A 2x2x3 variable mixed-measures ANOVA model was used to analyze vocal compensation magnitudes in two different time windows: pre-rebound and rebound. In addition, the measures of speech acoustics including Voice Pitch, Voice Intensity, HNR, Jitter, and Shimmer were analyzed using a 2x3 variable mixed-measures ANOVA model for condition and group. Results of the analysis did not reveal any significant effects for the speech acoustics. The pre-rebound time window captured the participant's vocal compensation response from when the response to the auditory perturbation was initiated until just after the peak compensation magnitude. The rebound time window captured the response following participants' peak magnitude of vocal response until the end of their cued vocalization. The data analysis revealed there were no statistically significant results for the pre-rebound window. While the results for the rebound window did not reveal statistically significant (p-value < 0.05) effects for stimulus direction or experimental condition between experimental groups, the results did show a significant difference within one of the experimental groups in one stimulus direction between two different experimental conditions for the aphasia group.

3.3 Speech Acoustics Analysis

A 2x3 variable mixed-measures ANOVA model for condition and group was run for the speech acoustics revealing for the Voice Pitch, Intensity, Harmonics to Noise Ratio, Jitter PPQ, and Shimmer ABS factors. This test revealed the following statistical results: Voice Pitch ($F(2,76) = 1.143$ $p > 0.05$), Intensity ($F(2,76) = 0.859$, $p > 0.05$), Harmonic to Noise Ratio ($F(2,76) = 0.499$, $p > 0.05$), Jitter PPQ ($F(2,76) = 0.616$, $p > 0.05$), and Shimmer ABS ($F(2,76) = 0.030$, $p < 0.05$). Although the Shimmer ABS had an F value of 0.030, the result was still insignificant because the p value was very high ($p = 0.971$). According to these results, there were no significant effects identified on the measures of speech acoustics.

Table 3.1 Within Subject Effects for Voice Pitch.

Within Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
Condition	13.848 [a]	2 [a]	6.924 [a]	1.143 [a]	0.324 [a]	0.029
Condition ✻ Group	14.868 [a]	2 [a]	7.434 [a]	1.227 [a]	0.299 [a]	0.031
Residuals	460.547	76	6.060			

Note. Type III Sum of Squares
[a] Mauchly's test of sphericity indicates that the assumption of sphericity is violated ($p < .05$).

Table 3.2 Within Subject Effects for Intensity.

Within Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p

Condition	1.137 [a]	2 [a]	0.569 [a]	0.859 [a]	0.428 [a]	0.022
Condition ✻ Group	0.206 [a]	2 [a]	0.103 [a]	0.155 [a]	0.857 [a]	0.004
Residuals	50.331	76	0.662			

Note. Type III Sum of Squares
[a] Mauchly's test of sphericity indicates that the assumption of sphericity is violated ($p < .05$).

Table 3.3 Within Subject Effects for H&R.

Within Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
Condition	0.194 [a]	2 [a]	0.097 [a]	0.499 [a]	0.609 [a]	0.013
Condition ✻ Group	0.319 [a]	2 [a]	0.159 [a]	0.820 [a]	0.444 [a]	0.021
Residuals	14.769	76	0.194			

Note. Type III Sum of Squares
[a] Mauchly's test of sphericity indicates that the assumption of sphericity is violated ($p < .05$).

Table 3.4 Within Subject Effects for Jitter PPQ.

Within Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
Condition	5.018×10^{-7}	2	2.509×10^{-7}	0.616	0.543	0.016
Condition ✻ Group	6.578×10^{-7}	2	3.289×10^{-7}	0.808	0.450	0.021
Residuals	3.095×10^{-5}	76	4.073×10^{-7}			

Note. Type III Sum of Squares

Table 3.5 Within Subject Effects for Shimmer ABS.

Within Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
Condition	3.302×10^{-5}	2	1.651×10^{-5}	0.030	0.971	7.770×10^{-4}
Condition ✻ Group	2.155×10^{-4}	2	1.077×10^{-4}	0.193	0.825	0.005
Residuals	0.042	76	5.587×10^{-4}			

Note. Type III Sum of Squares

3.4 Pre-Rebound Window Analysis

For the pre-rebound time window, there were no significant values found for the within subjects effects (Table 3.6) with stimulus direction ($F(1,76) = 0.578$, $p > 0.05$) or condition ($F(2,76) = 0.459$, $p > 0.05$. The values for between subjects effects (Table 3.7) showed insignificant results for group ($F(1,38) = 0.136$, $p > 0.05$). Although many of the η^2_p display marginal significance, the overall findings for these values are insignificant due to their large, associated p values ($p > 0.05$). This reveals that the aphasia and control subjects did not show a significant change in vocal compensation magnitudes across the different stimulus directions or the experimental conditions.

Table 3.6 Within Subjects Effects for the Pre-Rebound Window.

Within Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
Stimulus Direction	292.782	1	292.782	0.587	0.448	0.015
Stimulus Direction ✻ Group	122.317	1	122.317	0.245	0.623	0.006
Residuals	18958.030	38	498.896			
Condition	17.437	2	8.718	0.459	0.633	0.012
Condition ✻ Group	17.047	2	8.523	0.449	0.640	0.012
Residuals	1442.459	76	18.980			
Stimulus Direction ✻ Condition	81.846	2	40.923	1.129	0.329	0.029
Stimulus Direction ✻ Condition ✻ Group	116.066	2	58.033	1.600	0.209	0.040
Residuals	2755.991	76	36.263			

Note. Type III Sum of Squares

Table 3.7 Between Subjects Effects for the Pre-Rebound Window.

Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
Group	48.310	1	48.310	0.163	0.689	0.004
Residuals	11254.282	38	296.165			

Note. Type III Sum of Squares

Table 3.8 Descriptive Measures for the Pre-Rebound Window.

Descriptive Measures

Stimulus Direction	Condition	Group	N	Mean	SD	SE	Coefficient of variation
UP	A	Aphasia	20	8.275	10.503	2.348	1.269
		Control	20	9.790	11.746	2.627	1.200
	AV	Aphasia	20	6.155	15.814	3.536	2.569
		Control	20	10.305	12.658	2.830	1.228
	AVSham	Aphasia	20	8.272	11.801	2.639	1.427
		Control	20	9.582	11.741	2.625	1.225
DN	A	Aphasia	20	11.250	10.763	2.407	0.957
		Control	20	10.168	9.287	2.077	0.913
	AV	Aphasia	20	13.177	14.986	3.351	1.137
		Control	20	10.942	12.474	2.789	1.140
	AVSham	Aphasia	20	9.185	11.776	2.633	1.282
		Control	20	10.910	12.430	2.779	1.139

3.5 Rebound Window Analysis

A 2x2x3 variable mixed-measures ANOVA model was used for the rebound time window. The effects revealed for the within subject effects (Table 3.9) are as follows: stimulus direction ($F(1,76) = 1.276$, $p > 0.05$), condition ($F(2,76) = 1.047$, $p > 0.05$), and group ($F(2,76) = 2.445$, $p > 0.05$). There was a marginally significant effect for Stimulus Direction * Condition * Group which was $F(2,76) = 2.445$, $p = 0.094$, $\eta^2_p = 0.060$. The analysis results for between subjects effects (Table 3.10) for group revealed $F(1,38) = 0.119$, $p > 0.05$, $\eta^2_p = 0.003$. This suggests that there was no significant effect of group or condition on the voice measures in the rebound time window.

Table 3.9 Within Subjects Effects for the Rebound Window.

Within Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
Stimulus Direction	1245.562	1	1245.562	1.276	0.266	0.032
Stimulus Direction ✻ Group	1843.713	1	1843.713	1.889	0.177	0.047
Residuals	37082.170	38	975.847			
Condition	46.514 [a]	2 [a]	23.257 [a]	1.047 [a]	0.356 [a]	0.027
Condition ✻ Group	56.466 [a]	2 [a]	28.233 [a]	1.271 [a]	0.286 [a]	0.032
Residuals	1688.058	76	22.211			
Stimulus Direction ✻ Condition	292.369 [a]	2 [a]	146.185 [a]	2.501 [a]	0.089 [a]	0.062
Stimulus Direction ✻ Condition ✻ Group	285.807 [a]	2 [a]	142.903 [a]	2.445 [a]	0.094 [a]	0.060
Residuals	4441.638	76	58.443			

Note. Type III Sum of Squares

[a] Mauchly's test of sphericity indicates that the assumption of sphericity is violated ($p < .05$).

Table 3.10 Between Subjects Effects for the Rebound Window.

Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
Group	10.084	1	10.084	0.119	0.733	0.003
Residuals	3232.774	38	85.073			

Note. Type III Sum of Squares

Table 3.11 Descriptive Measures for the Rebound Window.

Descriptive Measures

Stimulus Direction	Condition	Group	N	Mean	SD	SE	Coefficient of variation
UP	A	Aphasia	20	0.809	15.195	3.398	18.783
		Control	20	6.788	9.518	2.128	1.402
	AV	Aphasia	20	-1.195	22.756	5.088	-19.042
		Control	20	6.231	10.748	2.403	1.725
	AVSham	Aphasia	20	2.036	14.137	3.161	6.944
		Control	20	6.491	10.549	2.359	1.625
DN	A	Aphasia	20	11.024	16.227	3.629	1.472
		Control	20	5.742	8.077	1.806	1.407
	AV	Aphasia	20	14.222	22.647	5.064	1.592
		Control	20	5.304	8.418	1.882	1.587
	AVSham	Aphasia	20	6.702	13.592	3.039	2.028
		Control	20	5.502	9.024	2.018	1.640

Table 3.12 Assumption Checks for the Rebound Window.

Assumption Checks - Test for Equality of Variances (Levene's)

	F	df1	df2	p
MeanVocalResponsePssUp(A) [0.4-0.995] Sec	1.345	1	38	0.253
MeanVocalResponsePssUp(AV) [0.4-0.995] Sec	2.931	1	38	0.095
MeanVocalResponsePssUp(AVsham) [0.4-0.995] Sec	0.890	1	38	0.351
MeanVocalResponsePssDn(A) [0.4-0.995] Sec	2.939	1	38	0.095
MeanVocalResponsePssDn(AV) [0.4-0.995] Sec	3.986	1	38	0.053
MeanVocalResponsePssDn(AVsham) [0.4-0.995] Sec	1.547	1	38	0.221

Table 3.13 Test of Sphericity for the Rebound Window.

Test of Sphericity

	Mauchly's W	Approx. X²	df	p-value	Greenhouse-Geisser ε	Huynh-Feldt ε	Lower Bound ε
Condition	0.458	28.914	2	< .001	0.648	0.662	0.500
Stimulus Direction ✻ Condition	0.636	16.752	2	< .001	0.733	0.755	0.500

Table 3.14 Post Hoc Tests for the Rebound Window.

Post Hoc Tests

Post Hoc Comparisons - Group ✻ Stimulus Direction ✻ Condition

		Mean Difference	SE	t	p_{tukey}	p_{holm}
Aphasia, UP, A	Control, UP, A	-5.979	4.513	-1.325	0.972	1.000
	Aphasia, DN, A	-10.216	6.035	-1.693	0.863	1.000
	Control, DN, A	-4.933	4.513	-1.093	0.994	1.000
	Aphasia, UP, AV	2.004	2.008	0.998	0.998	1.000
	Control, UP, AV	-5.422	4.513	-1.201	0.987	1.000

	Aphasia, DN, AV	-13.413	5.883	-2.280	0.505	1.000
	Control, DN, AV	-4.495	4.513	-0.996	0.997	1.000
	Aphasia, UP, AVSham	-1.227	2.008	-0.611	1.000	1.000
	Control, UP, AVSham	-5.682	4.513	-1.259	0.981	1.000
	Aphasia, DN, AVSham	-5.893	5.883	-1.002	0.997	1.000
	Control, DN, AVSham	-4.693	4.513	-1.040	0.996	1.000
Control, UP, A	Aphasia, DN, A	-4.237	4.513	-0.939	0.998	1.000
	Control, DN, A	1.045	6.035	0.173	1.000	1.000
	Aphasia, UP, AV	7.983	4.513	1.769	0.828	1.000
	Control, UP, AV	0.557	2.008	0.277	1.000	1.000
	Aphasia, DN, AV	-7.434	4.513	-1.647	0.884	1.000
	Control, DN, AV	1.483	5.883	0.252	1.000	1.000
	Aphasia, UP, AVSham	4.752	4.513	1.053	0.996	1.000
	Control, UP, AVSham	0.296	2.008	0.148	1.000	1.000
	Aphasia, DN, AVSham	0.086	4.513	0.019	1.000	1.000
	Control, DN, AVSham	1.286	5.883	0.219	1.000	1.000
Aphasia, DN, A	Control, DN, A	5.282	4.513	1.170	0.989	1.000
	Aphasia, UP, AV	12.220	5.883	2.077	0.641	1.000
	Control, UP, AV	4.794	4.513	1.062	0.995	1.000
	Aphasia, DN, AV	-3.197	2.008	-1.592	0.909	1.000
	Control, DN, AV	5.720	4.513	1.267	0.980	1.000
	Aphasia, UP, AVSham	8.989	5.883	1.528	0.924	1.000
	Control, UP, AVSham	4.533	4.513	1.004	0.997	1.000
	Aphasia, DN, AVSham	4.323	2.008	2.152	0.587	1.000
	Control, DN, AVSham	5.523	4.513	1.224	0.985	1.000
Control, DN, A	Aphasia, UP, AV	6.937	4.513	1.537	0.924	1.000
	Control, UP, AV	-0.488	5.883	-0.083	1.000	1.000

	Aphasia, DN, AV	-8.480	4.513	-1.879	0.767	1.000
	Control, DN, AV	0.438	2.008	0.218	1.000	1.000
	Aphasia, UP, AVSham	3.706	4.513	0.821	1.000	1.000
	Control, UP, AVSham	-0.749	5.883	-0.127	1.000	1.000
	Aphasia, DN, AVSham	-0.960	4.513	-0.213	1.000	1.000
	Control, DN, AVSham	0.240	2.008	0.120	1.000	1.000
Aphasia, UP, AV	Control, UP, AV	-7.426	4.513	-1.645	0.885	1.000
	Aphasia, DN, AV	-15.417	6.035	-2.554	0.334	0.904
	Control, DN, AV	-6.499	4.513	-1.440	0.950	1.000
	Aphasia, UP, AVSham	-3.231	2.008	-1.609	0.903	1.000
	Control, UP, AVSham	-7.686	4.513	-1.703	0.860	1.000
	Aphasia, DN, AVSham	-7.897	5.883	-1.342	0.968	1.000
	Control, DN, AVSham	-6.697	4.513	-1.484	0.939	1.000
Control, UP, AV	Aphasia, DN, AV	-7.991	4.513	-1.771	0.827	1.000
	Control, DN, AV	0.926	6.035	0.154	1.000	1.000
	Aphasia, UP, AVSham	4.195	4.513	0.929	0.999	1.000
	Control, UP, AVSham	-0.261	2.008	-0.130	1.000	1.000
	Aphasia, DN, AVSham	-0.471	4.513	-0.104	1.000	1.000
	Control, DN, AVSham	0.729	5.883	0.124	1.000	1.000
Aphasia, DN, AV	Control, DN, AV	8.918	4.513	1.976	0.707	1.000
	Aphasia, UP, AVSham	12.186	5.883	2.071	0.644	1.000
	Control, UP, AVSham	7.731	4.513	1.713	0.855	1.000
	Aphasia, DN, AVSham	7.520	2.008	3.745	0.014	0.018
	Control, DN, AVSham	8.720	4.513	1.932	0.735	1.000

Control, DN, AV	Aphasia, UP, AVSham	3.268	4.513	0.724	1.000	1.000
	Control, UP, AVSham	-1.187	5.883	-0.202	1.000	1.000
	Aphasia, DN, AVSham	-1.398	4.513	-0.310	1.000	1.000
	Control, DN, AVSham	-0.198	2.008	-0.098	1.000	1.000
Aphasia, UP, AVSham	Control, UP, AVSham	-4.456	4.513	-0.987	0.997	1.000
	Aphasia, DN, AVSham	-4.666	6.035	-0.773	1.000	1.000
	Control, DN, AVSham	-3.466	4.513	-0.768	1.000	1.000
Control, UP, AVSham	Aphasia, DN, AVSham	-0.211	4.513	-0.047	1.000	1.000
	Control, DN, AVSham	0.989	6.035	0.164	1.000	1.000
Aphasia, DN, AVSham	Control, DN, AVSham	1.200	4.513	0.266	1.000	1.000

Note. P-value adjusted for comparing a family of 66

The post-hoc test using Tukey correction revealed the statistically significant value of T(76) = 0.014 for the aphasia group in the down shift under the AV Sham experimental condition. This indicates that there was a larger magnitude of vocal compensation in the AV Condition compared to the AV Sham condition for the aphasia group in the down shift direction. This value can be visualized in Figure 3.5.

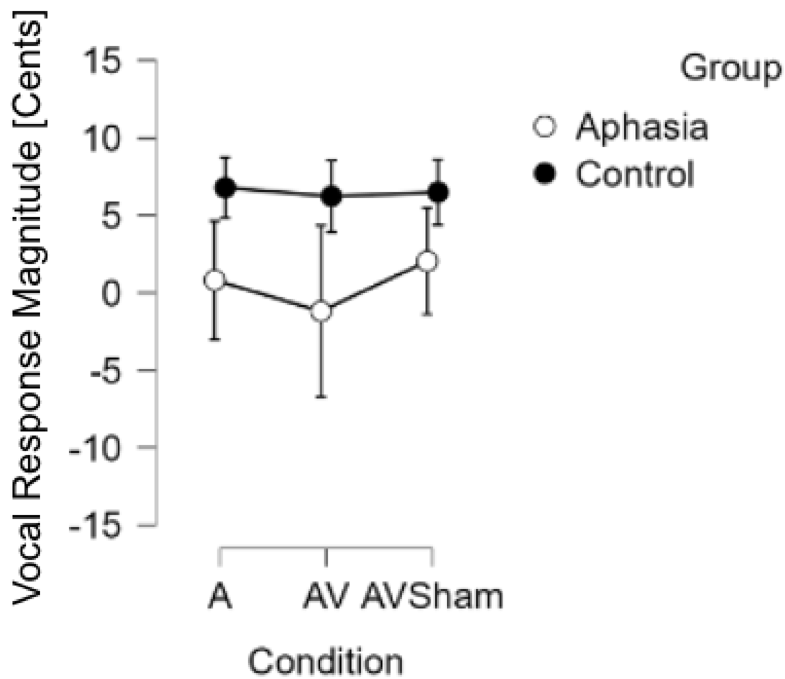


Figure 3.5 Descriptive Data Plot Pitch Shift Down.

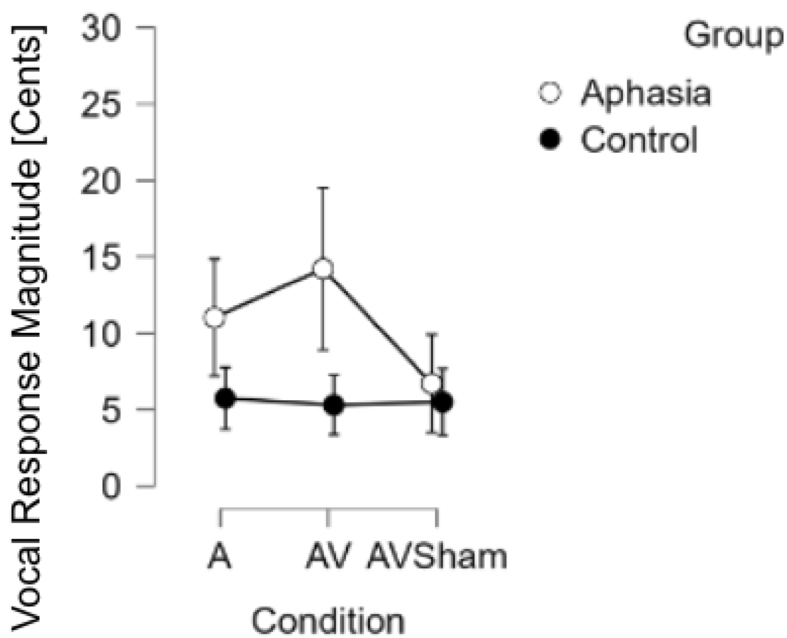


Figure 3.6 Descriptive Data Plot Pitch Shift Up.

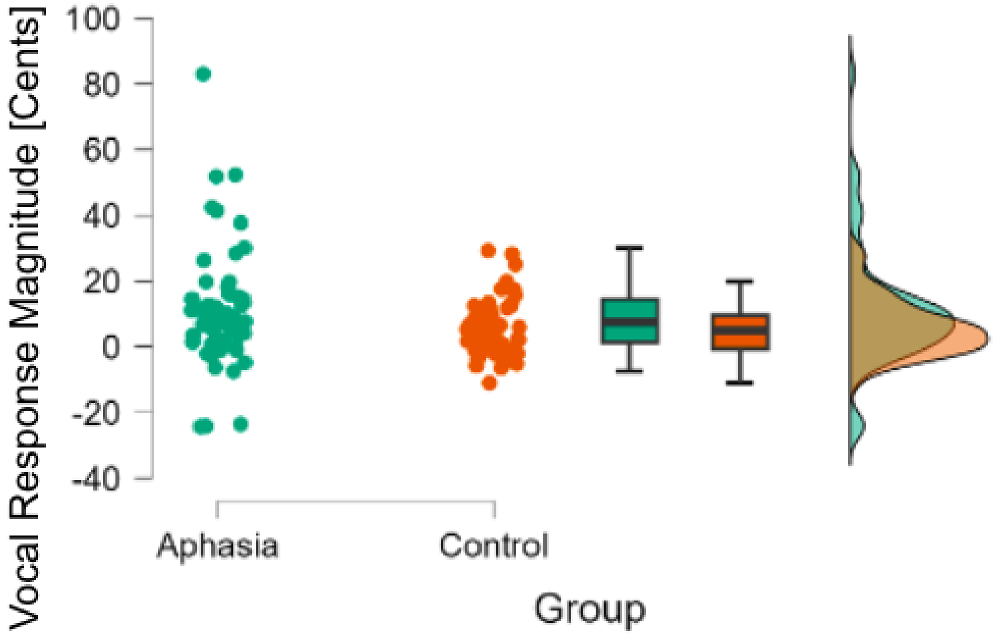


Figure 3.7 Raincloud Data Plot Pitch Shift Down.

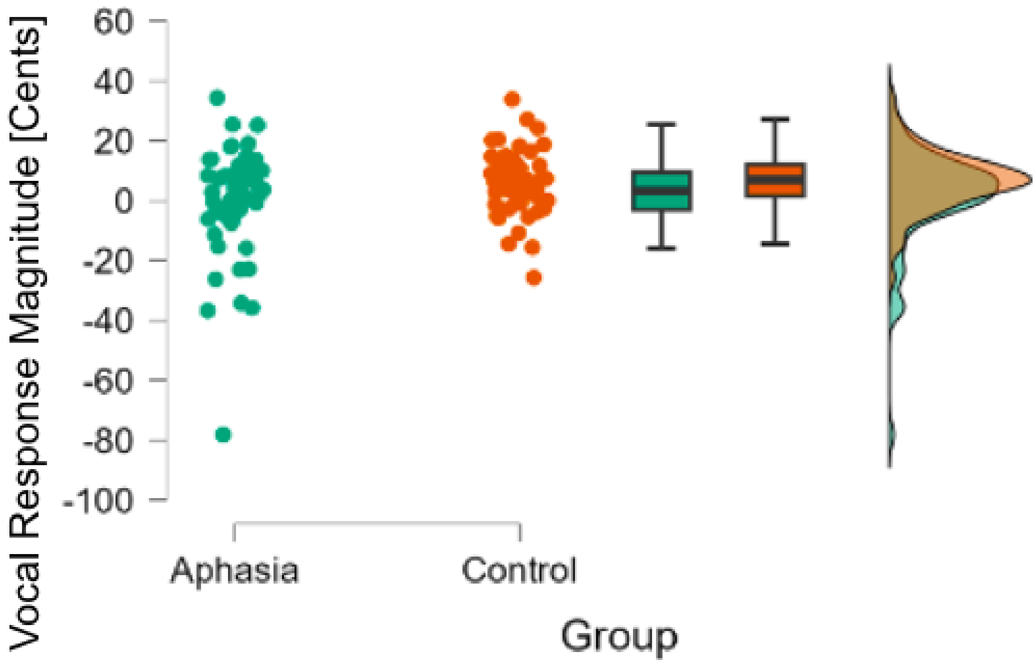


Figure 3.8 Descriptive Data Plot Pitch Shift Up.

CHAPTER 4

DISCUSSION

This study aimed to evaluate the effects of muti-sensory feedback, specifically visual feedback, on an individual's ability to compensate for errors in vocal pitch. The study examined two experimental groups including persons with post-stroke aphasia and healthy adult controls. The experiment considered three different experimental conditions including auditory feedback only, a combination of auditory and visual feedback, and a sham/control condition which paired randomized visual representations to the subject's real-time auditory feedback. It was hypothesized that visual feedback improves vocal control stability and aids in the suppression of artificial auditory feedback perturbations among both aphasia and healthy control participants when artificial auditory feedback perturbations were administered. A study utilizing the Speech Entrainment paradigm supports this hypothesis, as it discovered improved speech fluency in individuals with Broca's aphasia with the inclusion of visual feedback in expressive language therapeutic intervention (Fridriksson et al., 2015). An additional study showed improved speech production abilities with the inclusion of visual + auditory speech stimulation in comparison to auditory speech stimulation alone (Fridriksson et al., 2012).

The present experiment hoped to reveal whether visual feedback could be a useful tool in therapeutic intervention for individuals with post-stroke aphasia. If so, this experiment could help justify the implementation of multi-sensory feedback, specifically the inclusion of visual feedback, as an effective tool in expressive language therapy for post-stroke aphasia patients in the future. It was also hypothesized that the aphasia participants would demonstrate the improved vocal control and show the greatest suppression of artificial pitch-shift stimuli in the auditory + visual feedback experimental condition. This hypothesis was supported by a study which found participants with non-fluent aphasia to have significantly improved speech fluency with the use of auditory + visual input (Fridriksson et al., 2015).

Although the initial ANOVA tests did not reveal significant effects between group, stimulus direction, or experimental condition for the pre-rebound or rebound time windows, the post-hoc test revealed a significant value for the aphasia group in the down shift for the AV Sham condition during the rebound window. This significant value indicates that the post-stroke aphasia group displayed enhanced vocal control abilities when an artificial pitch-shift was administered when provided with auditory and visual feedback. The hypothesis that both experimental groups would benefit from auditory + visual feedback and display increased suppression of artificial perturbations was rejected because no significant effects were shown for the control group between the different experimental conditions. However, the alternate hypothesis that the aphasia group would show increased vocal control with auditory + visual feedback was partially accepted because the aphasia group demonstrated some degree of benefit from multisensory (auditory + visual) feedback with improved suppression of (i.e., more stable) vocal motor responses to the administered pitch-shift stimuli.

Additionally, the results that were uncovered for the rebound time window in this experiment reflect the power and responsiveness of the feedforward motor system of speech production proposed in the DIVA Model (Tourville & Guenther, 2010). The quick initiation and magnitude of the compensatory responses shown in this study were a perfect example of the brain's ability to re-calibrate the motor system to produce an adjusted vocal output to rebound to the pre-stimulus baseline pitch following the pitch-shift perturbation. The feedforward system is impressive in its ability to use sensory feedback to detect and accommodate for speech "errors" to produce a more accurate vocal target.

It was evident in the behavioral data analysis that all experimental conditions in both pitch shift directions across aphasia and control groups produced a compensatory vocal response in the opposing direction compared to the administered auditory feedback perturbations. This is reflective of the feedback and feedforward systems proposed in the DIVA Model of Speech Production (Tourville & Guenther, 2010). It was apparent that the participant's vocal productions were influenced by their real-time auditory feedback evidenced by their production of compensatory responses to the perceived vocal "errors." Existing research has proved that the visual system can influence speech production abilities (Ning, Loucks, and Shih, 2018).

Furthermore, one study by uncovered that multisensory (auditory + visual) feedback improved vocal compensation abilities in the presence of auditory feedback perturbation; however, the present experiment did not reveal visual feedback to have a major influence on vocal control across groups, pitch-shift direction, or experimental conditions (Ning, Loucks, and Shih, 2018). These results may suggest that the auditory feedback alone had a major influence on vocal compensation abilities. This idea was supported by existing the research, which found artificial alterations in pitch elicited compensatory vocal motor behaviors in the opposing direction of the pitch-shift stimuli in trained versus untrained singers (Larson, 1998). Additionally, a different study revealed that auditory feedback alone plays an undeniable role in speech motor control, specifically in the articulatory process of producing multisyllabic words (Cai et al., 2011). This knowledge of the influence that auditory feedback has on speech production supports the idea that the auditory-only feedback condition in this experiment may have been sufficient in eliciting strong compensatory vocal responses so much that the visual feedback did not have an additional impact on the participant performance.

One of the main findings of this experiment was that the aphasia group slightly benefitted from the auditory + visual feedback condition for vocal responses to downward pitch shifts. This reveals directional sensitivity to the effect which means that the visual feedback was effective in helping this group increase their vocal stability in the presence of auditory feedback perturbations. The fact that the aphasia group showed some benefit to the inclusion of visual sensory feedback and the control group did not indicates that visual feedback may be an effective route to compensate for deficits in the feedforward mechanism of vocal control for individuals who have post-stroke aphasia. This idea is heavily supported by the research which revealed that treatment for individuals with post-stroke aphasia that included audiovisual speech perception elicits improved speech production abilities when compared to treatment that utilizes auditory speech stimulation alone (Fridriksson et al., 2012). The present study indicates that auditory + visual feedback could still be a beneficial tool in expressive language therapy for individuals with post-stroke aphasia due to its ability to improve speech production and vocal stability measures.

Because this study revealed that visual feedback influences speech production and vocal stabilization abilities, visual feedback should be considered in future models of speech production. This factor is especially important to consider when studying impaired feedback and feedforward systems like those present in individuals with post-stroke aphasia. While auditory and somatosensory feedback have undeniable roles in human's ability to produce accurate speech targets, it is quite possible that the visual pathways in the brain may have a greater influence on the feedforward mechanism of speech than is currently acknowledged.

One existing limitation to this study is the sample size. It is likely that there would be less variability in the data with a larger sample size and would therefore reveal more statistically significant results between experimental conditions and the aphasia and control groups. Another limitation that should be considered is that this experiment used a variety of aphasia types. It is apparent that each aphasia subtype is associated with its own unique features and challenges. Current research has uncovered that current data indicates that the effects of speech entrainment have primarily shown benefits for one type of aphasia: Broca's (Fridriksson et al., 2015). Because SE is a therapeutic model that incorporates visual feedback as an aid in improving accurate speech production, it can be inferred that visual feedback may be most beneficial for improved speech production accuracy for individuals with post stroke aphasia. In the future, it would be interesting to use this experimental paradigm while exclusively examining individuals with Broca's aphasia, as opposed to of a variety of aphasia subtypes, to examine if that group yields a significant difference in vocal compensation magnitudes or the suppression of artificial auditory pitch-shifts with the aid of visual feedback.

Overall, this study aimed to examine the effects of multisensory feedback, specifically auditory + visual, on vocal compensation magnitudes and artificial auditory pitch-shift stimuli suppression abilities among participants with post-stroke aphasia versus healthy adult controls. Although it was hypothesized that both experimental groups would show increased vocal control and improved abilities to suppress artificial perturbations of vocal pitch via auditory feedback, there were no significant effects shown across conditions for the control group. However, the post-hoc test revealed that the aphasia group shows a significant effect under the AV Sham condition for the downward shift in the rebound window. This result indicates that the inclusion of visual feedback may compensate for damage to the feedforward mechanism of vocal control in individuals with post-stroke aphasia. Further studies using this experimental paradigm could be beneficial in adding to current research evaluating the effects of visual feedback on speech production abilities and its potential influence on therapeutic interventions targeting speech production abilities in individuals with post-stroke aphasia.

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