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AUDITORY-MOTOR INTEGRATION INFLUENCES ON SPEECH MOTOR CONTROL AND FLUENCY: A COMPARISON OF NORMALLY FLUENT SPEAKERS AND PEOPLE WHO STUTTER

BY

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DISSERTATION

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ABSTRACT

The overall purpose of this dissertation was to identify the effects of delayed auditory feedback (DAF) on speech motor stability and speech fluency in normally fluent adults (PWNS) and to compare them with effects on adults who exhibit persistent stuttering. If the auditory processing influences differently the two groups, it might shed light on the basic role of auditory-to-motor integration in speech production. Differences in auditory feedback dependency were also expected between normally fluent individuals who are highly susceptible to DAF and normally fluent individuals who are minimally affected by DAF. Three studies were conducted to (I) subgroup 62 normally fluent males and females based on their responses to DAF during spontaneous conversational speaking and reading tasks, (II) compare responses to DAF between 15 normally fluent adults who showed high stuttering-like disfluencies (SLD) under DAF (*High-SLD* group), 15 normally fluent adults who showed low SLD under DAF (*Low-SLD* group), and 15 adults who stutter, and (III) compare the specific effects of DAF on speech motor stability and movement patterns (lower-lip movement) in 11 normally fluent adults versus 11 adults who stutter.

Study I revealed that normally fluent participants, as a group, increased the amount of SLD and speech errors (SE), and decreased articulation rate (AR) when speaking under DAF relative to speaking under amplified non-delayed condition (aNAF). Sex had a limited differential effect on other disfluencies (OD) and AR whereas task effects were seen in OD, SE, and AR. Neither sex nor task, however, did influence SLD. Three subgroups, *Low*, *Middle*, and *High Responders* were identified. There were clear differences between the *Low* and *High Responders* in that the *Low Responders* exhibited

smaller numbers of SLD and SE as well as faster AR than the *High Responders*. The *Middle Responders* revealed task dependency, showing different responses than those exhibited by the *Low* and *High Responders*.

The results of Study II showed that people who stutter did not reduce SLD counts under DAF condition, a finding that deviates from reports of previous studies. PWS also exhibited higher mean number of SLD than the normally fluent *Low-SLD* group but similar to that of normally fluent *High-SLD* group. For all groups, the number of SE was higher and AR was slower under DAF than aNAF. PWS showed larger individual variability in responses to aNAF compared to natural feedback conditions in that some PWS reduced SLD under aNAF condition.

Study III revealed significant difference between PWS and PWNS in speech kinematic stabilities, showing that PWS exhibited higher spatio-temporal index (i.e., lower speech motor stability) than PWNS across auditory feedback conditions in four utterance stimuli. PWS, however, yielded higher speech movement stability under aNAF and 25ms-DAF in longer stimuli compared to natural feedback condition. There was no group difference in movement displacement and velocity for opening-closing sequential movements but the patterns were different in each group. PWNS showed lower displacement and velocity under aNAF and DAF compared to natural feedback condition for both opening and closing movements whereas PWS showed higher displacement under DAF than aNAF condition and higher velocity under nNAF than 25ms-DAF. Normally fluent people showed shorter movement duration and faster articulation rate than PWS across auditory feedback and stimuli.

This dissertation study has demonstrated different influences of auditory feedback on speech motor control in normally fluent adults and adults who stutter. In both groups, individual variability was obvious. In normally fluent adults, diverse responses to DAF could be explained with different auditory feedback dependency for ongoing speech articulatory production. PWS were more dependent on auditory feedback for speech production, and auditory-to-motor integration under aNAF and short delay feedback conditions helped them to improve speech motor stability.

Dedicated to my mother,
이숙자 *(SukCha Lee)*

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Summary of study

Although there have been attempts to explain the developmental speech disorder called stuttering from various theoretical perspectives, one central and recurring view of stuttering is that it is a sensorimotor disorder. The sensory modality that has received the most attention is audition, changes in which have been shown to affect the occurrence of stuttering disfluencies among adults and children with this disorder. The present study is based on this view with a focus on how *altered auditory feedback* (AAF) influences speech production in adults who stutter. AAF refers to an electronic alteration of the speaker's speech output so that speakers perceive their own voice differently than the unaltered signal. AAF has been known to influence speech output over the short-term in people who stutter (PWS) as well as people who do not stutter (PWNS). Previous studies have consistently shown the behavioral effects of AAF in terms of diminishing stuttering-like disfluencies (SLD) of PWS and eliciting disfluencies, compensations, or adaptations, in the speech output of PWNS. Among the various types of AAF, delayed auditory feedback (DAF), in particular, has been shown to have potent effects on inducing disfluent speech in PWNS, but with the opposite effect of reducing the SLD frequency in PWS. However, the mechanism(s) that explain(s) why altering auditory feedback affects motor output (i.e., referred to as auditory-motor integration: the functional link between auditory feedback and speech production) in both groups, as well as the reasons underlying individual variability in responses to DAF, are unclear.

In past research, susceptibility to DAF has been compared using temporal and perceptual components, such as duration of speech and speech disruptions, respectively, but individual differences in susceptibility to DAF, as well the specific effects on speech movement control have not been clarified. The real possibility that auditory feedback influences the stability of speech-motor movement in different directions for PWS and PWNS has potential for explaining the basic role of auditory-motor integration in speech production.

Therefore, to investigate the link between altered auditory feedback and speech motor output, this research will: (1) profile individual differences in DAF susceptibility in a large sample of PWNS, (2) compare DAF susceptibility between normally fluent people who showed high SLD under DAF, normally fluent people who showed low SLD under DAF, and PWS, and (3) compare the specific effects of DAF on speech kinematic stability in PWNS versus PWS.

1. Overall view: The diversity of theories in stuttering

The cause and development of stuttering has been related to diverse and highly variable factors, including genetics, motor control, sensory processing, cognitive processing, language, environment, emotions, temperament, and others (e.g., Anderson, Pellowski, Conture, & Kelly, 2003; Bosshardt, 2006; Johnson et al., 1959; Ludlow & Loucks, 2003; Postma & Kolk, 1993; Yairi & Ambrose, 2005). This diversity of perspectives is consistent with the view that stuttering is a multifactorial disorder, arising from dynamic interaction between aforementioned factors (Smith & Kelly, 1997). This view contrasts with previous attempts to explain stuttering from a single perspective. A

brief review of pertinent one-dimensional views is provided here to allow for a contrast with the sensorimotor perspective to be emphasized here.

Psychological view A psychological influence on the cause of stuttering was suggested by Coriat (1928) who proposed that stuttering is a psychopathological disorder. This view, based on Freud's psychoanalysis theory, considered stuttering as an overt symptom of deep conflicts at the oral stage (Coriat, 1928) or the anal stage (Fenichel, 1945) of psychosexual development. Today, even though a psychopathological cause of stuttering had not been supported by controlled research, recent studies suggest that children's temperament or personality could be related to the development of stuttering (e.g., Anderson et al., 2003; Guitar, 2003).

Learning theory Behavioral perspectives on the cause of stuttering have been proposed by prominent researchers, including Johnson and colleagues (Johnson et al., 1959) and Bloodstein (1961, 1995). In 1959, Johnson and colleagues proposed that stuttering begins when parents or caregivers (listeners) diagnose their child's normal speech disfluency as "stuttering." When the parents try to correct the disfluencies, the child is thought to respond to the pressure by trying to avoid the normal disfluencies. This effect results in more tense disfluencies causing more parental pressure. As this negative cycle continues, normal disfluencies become increasingly tense and gradually develop into stuttering. Bloodstein, in his *anticipatory-struggle model* (1961, 1995), also proposed that avoidance aspects are related to stuttering onset. When children experience communication failure due to normal disfluencies or other difficulties, they anticipate negative experiences during upcoming speaking situations and end up using struggle behaviors to avoid the communication breakdown. Bloodstein suggested that the effort

would exacerbate normal disfluencies into clinically significant stuttering. Recent studies demonstrate, however, that stuttering begins not only gradually with easy repetitions that slowly increase in frequency, but also suddenly with blocking and/or prolongations or other abnormal disfluencies (Yairi & Ambrose, 2005). Therefore, the "learning" perspectives are contradicted by their documentation of the rapid onset of "advanced" stuttering symptoms in the absence of previous communication failure or excessive parental demands for fluent speech.

Linguistic view Several investigators have emphasized that linguistic processing problems underlie stuttering. Wingate (1988) suggested that stuttering emerges from functional dyssynchrony between the left and right hemispheres and subcortical structures – the areas responsible for language preparation and production. When there are problems synchronizing linguistic components in the preparation stage, stuttering occurs (Wingate, 1988). Postma and Kolk (1993) also proposed involvement of language production aspects in the form of the *covert repair hypothesis*. They suggested that the internal monitoring of language production provides a normal mechanism for correcting covert faulty speech formulation prior to production. The generation of a phonetic plan is aberrant in PWS which is detected by the internal monitor leading to repair processes that create disfluencies.

This error detection and correction view can be potentially related to findings of functional brain imaging studies showing inappropriately reduced activation in auditory cortical regions and hyperactivation in motor cortical regions of PWS (Braun et al., 1997; Fox et al., 1996). This inappropriate balance of cortical activity may be explained by a

mismatch between speech monitoring activity and speech production activity, resulting in overt correction attempts – disfluencies.

Genetic perspectives The possibility that stuttering is genetically transmitted has been studied since the 1930s. Early attempts typically looked at the presence of family history of stuttering in individuals who stutter. Yairi, Ambrose, and Cox (1996) reviewed literature and concluded that up to 74% (range: 20% - 74%) of people who stutter reported such histories compared with up to 42% (range: 1.3% - 42%) of normally speaking individuals. A second line of research looking at the incidence of stuttering among twins showed that monozygotic twins had significantly higher concordance for stuttering than dizygotic twins, adding to evidence of genetic influences (Andrews & Harris, 1964; Andrews, Morris-Yates, Howie, & Martin, 1991; Felsenfeld et al., 2000; Howie, 1981). The third direction, aggregation studies, involves analyses of the distribution of stuttering pedigrees of PWS, accounting for sex and relative class, and compared it against several possible genetic models (e.g., Ambrose, Cox, & Yairi, 1997; Ambrose, Yairi, & Cox, 1993; Andrews & Harris, 1964; Kidd, 1977, 1980; Kidd, Kidd, & Records, 1978). The last two have supported strong genetic components to stuttering. Most recently, research has shifted to linkage studies aimed at identifying specific regions on chromosomes where gene responsible for stuttering may be located (Kang et al., 2010; Riaz et al., 2005; Shugart et al., 2004; Suresh et al., 2006; Wittke-Thompson et al., 2007). Suresh et al. (2006) found evidence for chromosomes 2, 7, 9, 12, 15, and 21. Indeed, Kang and colleagues (2010) reported significant influences of mutations in GNPTAB, GNPTG, NAGPA genes on chromosome 12 genomic region. These studies

have yielded several overlapping positive findings for the genetic transmission of stuttering. What is being transmitted, however, has remained unknown.

Brain dysfunction perspectives Travis (1931) proposed the *cerebral dominance theory*, claiming that stuttering results from failure to establish hemispheric dominance. The left-hemisphere is dominant for speech and language for normally fluent people but PWS do not show such dominance, sending asynchronized neural commands to the speech musculature that result in speech blocks. A more recent view related to brain functions for stuttering, however, suggests that stuttering is caused by varied forms of central brain dysfunction. De Nil and colleagues (2000) hypothesized that PWS either had innate or compensatory brain activation patterns: essentially stuttering is proposed to result from excessive right-hemisphere activity (e.g., the right frontal operculum and the right insula) during speech production - *Excessive Right Hemisphere Activity*. This hypothesis is consistent with the general results of other brain imaging studies (Braun et al, 1997; Fox et al., 1996; Fox et al., 2000; Ingham et al., 2000). Certainly, the aberrant activation patterns in temporal auditory regions, inferior frontal regions, primary motor cortex and cerebellum, are consistent with sensorimotor integration difficulties in PWS (Brown, Ingham, Ingham, Laird, & Fox, 2005; De Nil, Kroll, Kapur, & Houle, 2000).

2. Motor and sensory differences in people who stutter

2.1. Difference in speech-motor control between PWS and PWNS

Breakdowns of ongoing speech movements are the central characteristics of stuttering which prima facie underlie attempts to explain stuttering as a motor disorder. For example, Van Riper (1971) stated that stuttering occurs when the flow of speech is

disrupted primarily due to mistiming of speech muscle movements. Perkins and colleagues (1976) proposed that stuttering represents a discoordination among respiration systems, while Zimmerman (1980) suggested that stuttering was due to a speaker's overshooting or undershooting intended articulatory targets in terms of timing or space, causing reflex response.

There have been many acoustic and kinematic studies comparing the speech motor characteristics of people who stutter and normally fluent control subjects. Acoustic studies have looked at characteristics of respiration, phonation, and articulation, such as fundamental frequency, speech rate, or duration of stuttered speech. For example, Williams (1955) used EMG techniques to study the masseter muscle. Zimmermann (1980) employed cinefluorography to study articulatory mechanisms, and Denny and Smith (2000) used EMG to study respiration. Others used indirect techniques, such as spectrographic analyses to study voice onset time (Jancke, 1994), articulation rate (Hall, Amir, & Yairi, 1999; Sawyer, Chon, & Ambrose, 2008), and other parameters. The fluent speech of people who stutter has been investigated also to test whether differences in speech motor control are pervasive in their system in general, not just during moments of stuttering.

Overall, many past studies concluded that people who stutter have limitations in speech motor control; however, the findings have been inconsistent and typically not replicated. Studies with very young children who stutter reported more subtle differences (Hall et al., 1999; Zebrowski, Conture, & Cudahy, 1985) that are yet to be replicated.

A series of studies with special relevance to the present investigation has been conducted by Smith and associates. Smith, Goffman, Zelaznik, Ying, and McGillem

(1995) proposed an index of speech motor variability called the spatiotemporal index (STI) that captures the cumulative variability of speech kinematics over time and space using a set of movement trajectories (10 - 15 trials). Their studies have shown that the STI is sensitive to differences in (1) speech production rate, (2) speech control maturation in development, and (3) speech control in PWS. In their first study, adult participants repeated a phrase 20 times in three speaking rates: habitual, fast, and slow. Lower lip (LL) movements were measured using a head-mounted strain gauge system and the STI in the three conditions were calculated. Scores were significantly higher for slow speech rates (indicating lower motor stability) than the normal and fast speaking rates.

They next studied the developmental patterns of speech motor stability in three age groups of normally fluent people: 4-year olds, 7-year olds, and young adults (Smith & Goffman, 1998). The STI along with timing measures (duration and relative timing of lower lip movement), movement displacement, and velocity of the LL were measured. There was a significant age effect with the 4 year-old group showing higher LL STI and longer LL movement time than the other two groups. There were additional timing differences between the 7-year olds and the young adults. Smith and Goffman concluded that the development of a speech motor system was "nonlinear and non-uniform" (p. 18). Maner, Smith, and Grayson (2000) investigated the effect of age and linguistic complexity on speech-motor movement in 5-year old children and young adults. Similar to Smith and Goffman (1998), the young group showed significantly higher STI than the old group. Most recently, Sadagopan and Smith (2008) measured the STI of lower lip movements across 7 age groups from age 5 through young adults. The adult group showed the most stable movement trajectories (lowest STI) compared to the other 6

younger age groups. Moreover, the linguistically complex utterances were associated with the highest movement variability in the young age groups.

To investigate speech control in PWS, Smith and Kleinow (2000) measured STI, relative timing, and kinematic features when the speech rate was altered in repeating a phrase. They employed adult PWNS and PWS divided into two subgroups: RT, those who received recent treatment, and NT, those who received no treatment or received it at a younger age. The participants repeated a stimulus sentence 20 times using a normal, fast, and slow rate of speech. No significant differences between PWS and PWNS for the three speech rate conditions were found. However, in all groups, the mean STI in the slow speech rate condition was significantly higher than in the normal speech rate condition, but not as compared to the fast speech rate condition. Kleinow and Smith (2000) then tested speech motor stability of PWS across manipulations of utterance length and complexity. They assumed that different length and/or complexity of utterances would influence the motor stability of PWS more than PWNS. Overall, PWS showed significantly higher LL STI than PWNS and this group difference increased with increasing grammatical complexity. These results support our view that PWS have less speech motor stability than PWNS and that the speech stability of PWS decreases under more complex demanding linguistic structures.

2.2. Difference in sensory function between PWS and PWNS: A sensorimotor integration framework

Audition has been known for a long time to play an important role in speech fluency. This knowledge has recently expanded by findings of deficient and/or different

brain structures and functions in auditory areas of PWS. Other consistent findings point to neural differences in anterior premotor areas which receive auditory information from auditory association areas in PWS.

Salmelin et al. (1998) compared central auditory function in PWS and PWNS using four reading tasks: reading silently, reading with mouth movements without sound, reading aloud, and reading with another person. The N100m response (measured with Magnetoencephalography or MEG) revealed group differences in the balance of auditory representation across hemispheres, particularly showing that right-hemisphere sensitivity was higher in PWS whereas left-hemisphere was higher in PWNS. The investigators suggested that this disruption of normal left hemispheric function could easily "cause abrupt non-optimal interpretation of the auditory input and, thus, disturb self-monitoring and online-adjustment of speech" (Salmelin et al., 1998, p.2229).

Positron-emission tomography (PET) that detects cerebral blood flow (CBF) was used to investigate the neural system of PWS (Braun et al, 1997; Fox et al., 1996; Fox et al., 2000; Ingham et al., 2000; Ingham et al., 2004). Fox et al. (1996) reported that PWS showed hyperactiviation in motor and premotor areas, right lateralization in primary and extraprimary motor cortices, and deactivation of auditory areas. Braun et al. (1997) found a similar pattern and suggested that when PWS stuttered, there was a dissociation between the activity of auditory perception areas (post-rolandic regions) and motor function areas (anterior forebrain regions: unreasonably activated), but the dissociation was decreased during fluency-evoking conditions (automatic speech and paced speech). In general, these results have been replicated in later functional MRI studies with the general consensus being that auditory activity decreases and motor activities increase

during speech production relative to fluent controls (Brown et al., 2005). These functional differences, found in sensorimotor speech areas, may, in turn, arise from aberrant patterns of gray matter morphology (Beal et al., 2007; Foundas, Bollich, Corey, Hurley, & Heilman, 2001), gray matter volume (Chang, Erickson, Ambrose, Hasegawa-Johnson, & Ludlow, 2008), and aberrant white matter connectivity between posterior and anterior motor areas. These particular functional differences in auditory sensory areas (suppressed activation), anterior premotor areas (increased right-lateralized activity) that receive auditory feedback, and primary motor areas (increased bilateral activation) support our hypothesis that stuttering is related to deficiency and/or differences in sensorimotor integration.

3. Auditory-to-motor integration is sensorimotor integration

3.1. Internal models: Traditional view and current perspectives as a theoretical framework

There are different concepts of internal models for motor control (Miall & Wolpert, 1996; Wolpert, Ghahramani, & Jordan, 1995). One key aspect is *the forward model* that imitates or approximates normal response of the motor system to outgoing motor commands (Miall & Wolpert, 1996). The idea is that during movement, the central nervous system (CNS) receives feedback from the organism's ongoing motor movement, compares the actual to the desired movement, and then corrects or enhances the actual one. The other concept discussed by Miall and Wolpert is *the inverse model* which prepares motor commands from the desired perceptual consequences before

initiating the actual movement (1996). The forward and inverse models have different functions but are complimentary and can be integrated within a single model.

The *Directions into velocities of articulators (DIVA)* model, a neural network model, that combines the forward and inverse internal models, was proposed by Guenther and his colleagues to identify processes in the acquisition and control of speech movements (e.g., Guenther, 2006; Guenther & Perkell, 2004; Max, Guenther, Gracco, Ghosh, & Wallace, 2004). Guenther proposes the role of auditory feedback as more critical during the babbling period (as infants learn how to produce speech sounds) because speech motor control commands (*feedforward control*: speech sound map for speech production) are not sufficiently developed. After the feedforward commands are stabilized, the speech motor systems will depend on the feedforward control more than feedback control because the motor control commands for speech production are well developed.

Based on the DIVA model, Max, Guenther, Gracco, Ghosh, and Wallace (2004) proposed that motor control commands are set up before the onset of movement but the actual movement can be corrected/modified by expected or predicted feedback from the actual motor movement. This model allows to correct for problems with forward commands by simulating the expected sensations and associated time delay of feedback from the periphery. Max et al. (2004) suggested two hypotheses for the cause of stuttering. In the first hypothesis, they theorized that the phenotypes of stuttering (i.e., part-word repetitions, audible and inaudible prolongations) are related to failure at an early age to obtain, update, or use appropriate inverse and/or forward mappings "between speech motor commands and sensory consequences" (p.113). The second hypothesis was

related to overreliance on afferent feedback because of weak feedforward commands. This could cause unbalanced speech motor control in PWS because of time lags from the feedback control. In summary, according to internal model perspectives on speech-motor control, the role of auditory feedback in monitoring and adjusting speech errors (*feedback controls*) is fundamental during the early speech acquisition period. Auditory feedback is used to compare speech output with developing neural representations of intended phonemes and words. This comparative mechanism allows for correction of intended utterances when there are differences between intended and actual output. Over time, these comparisons and corrections lead to mature or stable sensorimotor representations of phonemes and syllables. Once motor speech commands are stabilized, a shift occurs towards primary dependency on the stored speech motor representations (*feedforward commands*). At this point, the role of auditory feedback changes to maintaining the stored maps (e.g., Guenther, 2006; Max et al., 2004), which theoretically minimizes the need for continuous monitoring of auditory feedback in adults.

With the view of developmental internal model, Perkell and colleagues proposed a different role of auditory feedback in adults' mature speech production (Perkell et al., 2000). First, they consider it difficult for auditory feedback to influence ongoing articulatory movements (referred to *segmental mechanisms* because it refers to *phonemes* of the speaker's message – e.g. /s/ in Sam) because the feedback loop is too slow to influence a current speech movement. Marslen-Wilson and Tyler's investigations that ongoing speech was only recognizable after 200ms of production (1981, 1983), and several studies of postlingually-deaf participants who maintain speech intelligibility (e.g., Cowie & Douglas-Cowie, 1983; Lane & Webster, 1991) support a view that continuous

auditory monitoring is not necessary. Second, *suprasegmental mechanisms* such as pitch, sound pressure level, speech rate, and fundamental frequency (F0), which are maintained over longer periods are considered to be more amenable to auditory feedback monitoring and corrections because these features of speech involve relatively simple auditory information (Perkell et al., 2000).

We will take the DIVA model and Perkell and colleague's perspectives as our theoretical framework to explain not only motor differences between PWS and PWNS but also the role of auditory feedback in promoting or disrupting speech fluency. These ideas based on the internal models for speech production are important in interpretation of previous and current AAF studies, especially delayed auditory feedback (DAF) and frequency-shifted feedback studies. We will next review studies of AAF effects in PWNS and PWS to emphasize the role of auditory-to-motor integration on speech output.

3.2. Influence of auditory-to-motor integration on the speech-motor control of PWNS

Several electroencephalography (EEG) and magnetoencephalography (MEG), studies have examined whether speakers' auditory responses are different depending on whether they hear their own speech or an altered version of their own speech while speaking (Heinks-Maldonado, Mathalon, Gray, & Ford, 2005; Heinks-Maldonado, Nagarajan, & Houde, 2006). The investigators' hypothesis, adopted from an internal (forward) model, predicted that during self-generated speech, the efference copy of motor commands would function to predict sensory consequences (named corollary discharge). If the actual auditory feedback was matched to the predicted feedback, auditory cortical responses to the self-produced speech would be suppressed, i.e., N100 response of event-

related potential (ERP) or M100 magnetic response (MEG), relative to speech from other speakers. When producing short /a:/ sounds, the normally fluent participants received four types of auditory feedback conditions on separate trials: self-produced unaltered feedback, self-pitch shifted feedback, alien feedback (another person's pre-recorded speech), and alien-pitch shifted feedback. After the vowel production task, the participants only listened to their own speech which was recorded under the four types of feedback. The participants showed significantly damped auditory cortical responses (i.e., N100 and M100) under self-produced unaltered auditory feedback relative to other conditions during the speaking task, but there was no significant difference during the listening tasks. These results suggest that auditory responses are damped when they conform to the predicted feedback (unaltered speech) but not when the feedback is altered, and generally support the view the sensorimotor system can predict or 'model' expectations of sensory feedback; consistent with predictions from internal model approaches.

Several studies have tested Perkell and colleagues' perspectives on suprasegmental mechanisms by assessing fundamental frequency and formant frequency responses to alterations in auditory feedback. Houde and Jordan (1998, 2002) studied whether auditory feedback shifts that altered the first through third formants could influence speech production. Participants whispered CVC utterances while they were exposed to gradual but cumulative shifts in vowel formant frequencies (e.g., the vowel /ɛ/ sounds like /i/ with F1 shifted-down and F2 shifted-up feedback, and like /a/ with F1 shifted-up and F2 shifted-down feedback). The participants demonstrated both compensation and adaptation effects to the altered auditory feedback by beginning to

produce a different vowel phoneme without the awareness of their actual response and altered auditory feedback while believing they were still producing the original phoneme. This important evidence for motor compensation to a sensory alteration indicates that normal speakers can be sensitized to systematic alterations in auditory feedback. Moreover, the evidence that subjects shifted speech frequencies in the opposite directions to the alteration indicates that subjects attempt to maintain their intended motor output.

Purcell and Munhall (2006a, 2006b) similarly perturbed the first formant frequency (F1) but they used voiced stimuli in which the vowel /ɛ/ shifted upward (sounded like /æ/) and downward (sounded like / ɪ /). Immediate compensation effects to the formant frequency-shifted feedback were observed. Similar to Houde and Jordan's (1998, 2002) studies, the subjects changed their speech frequencies in the opposite direction of the shifted feedback but no significant difference was observed between the upward and downward directions. Most recently, Tourville, Reilly, and Guenther (2008) asked their participants to read CVC words containing the / ɛ / vowel (e.g., "bet") with perturbed auditory feedback in which the first formant of the vowel was shifted up (sounding like /æ/) or down (sounding like / ɪ /). The participants compensated for the unexpected and sudden auditory feedback by shifting down their actual vowel production during the up-shift auditory feedback, and by shifting up the actual vowel production during the down-shift auditory feedback. Accompanying fMRI data revealed the sensorimotor compensation was associated with increased activity in the posterior superior temporal gyrus. The authors suggest that auditory error cells in this brain region "encode the difference between actual and expected auditory feedback during vocalization" (Tourville et al., 2008).

In terms of auditory feedback influences on fundamental frequency (F_0), Burnett, Senner, and Larson (1997) first reported that participants showed rapid and involuntary compensations for unexpected F_0 pitch shifts (i.e., shifted upward and downward) by opposing or following the shifted pitch. Burnett, Freedland, Larson, and Hain (1998) then varied (1) the intensity of auditory feedback, (2) the magnitude of pitch shift, and (3) the duration of the shift, but again, the participants either opposed or followed the pitch shift in a rapid involuntary manner. Also, neither the intensity manipulation nor the amount of pitch shift influenced the participants' response latency and magnitude. There was a trend, however, for the participants to respond to lower magnitude of pitch shifts (i.e., 50 cent-shift) with opposing direction and to higher magnitude of pitch shifts (i.e., 300 cent-shift) with following direction. The results also revealed that the stimulus duration influenced response duration and magnitude in that the response duration was significantly increased at 300ms and 500ms comparing to 20ms and 50ms. The magnitude of responses was also significantly larger for 500ms shifts than 20 and 50ms shifts. Jones and Munhall (2000, 2002) also studied F_0 manipulation but they gradually increased or decreased the magnitude of pitch without participants' recognition (one cent or one semitone) to 100 cents, and then suddenly returned back to original F_0 level. The participants revealed both compensation and adaptation effects on the pitch-shifted feedback irrespective of their native languages - English (Jones & Munhall, 2000) and Mandarin Chinese (Jones & Munhall, 2002). Pitch-shift investigations showed two types of adaptation effects to the frequency perturbations. For fundamental frequency, there were *negative aftereffects*, meaning that after the adaptations to the pitch shift, the participants overshot their baseline fundamental frequency when the frequency shift was

suddenly removed (Jones & Munhall, 2000, 2002). For the first formant frequency shifts, on the other hand, there were *positive aftereffects,* meaning that after adapting to the altered first formant frequency, participants settled near their baseline frequency after the frequency perturbation was removed (Houde & Jordan, 1998; Purcell & Munhall, 2006b).

The findings of these studies, in general, support not only Perkell and colleagues' view that auditory feedback influences suprasegmental mechanisms but also that auditory feedback can work for online motor compensations that are presumably intended to maintain a certain output. Even though these studies only shifted F_0 or formant frequencies, they confirmed that online feedback changes lead to systematic compensations in vocal responses. The significant changes, however, actually appeared to affect individual phonemes as well suggesting the effects can go further than predicted by Perkell and colleagues (in particular the Houde and Jordan results). The view offered here is that altered auditory feedback influences segmental mechanisms as well as suprasegmental mechanisms. The disfluency inducing effects of delayed auditory feedback in normally fluent people show clear changes in segmental mechanisms (i.e., fluency of speech) as well as in suprasegmental mechanisms (i.e., speech rate, intensity, and pitch) (Fairbanks, 1955; Howell & Archer, 1984; Jones & Striemer, 2007; Lee, 1950a, 1950b; Mackay, 1970; Stuart, Kalinowski, Rastatter, & Lynch, 2002; Van Borsel, Sunaert, & Engelen, 2005). Therefore, this evidence for rapid effects of auditory feedback on speech motor control has overturned traditional views that regarded auditory feedback is too slow to influence ongoing speech even though there is a physiological delay. No one is advocating a return to a strict feedback perspective, but rather that the

brain apparently compares incoming information with intended responses to maintain its intended actions.

Interestingly, all of these studies also report individual variability in responses to frequency-shifted feedback (e.g., Burnett et al, 1998; Houde & Jordan, 1998, 2002; Purcell & Munhall, 2006a, 2006b) even though the investigators did not explain the variability. The variability is interpreted here as individual differences in dependency on auditory feedback (focus of Study I) and the same variability that underlies the responses to frequency shifts reported by Houde and Jordan (2002, p. 308).

3.3. Influence of auditory-to-motor integration on the speech-motor control of PWS

The previous discussion of auditory feedback effects in normally fluent speakers provides a context for predicting and understanding effects of altered auditory feedback in PWS. Although the fluency inducing effects of auditory feedback alterations have been recognized for a long time in reducing SLD frequency (e.g., Adams & Ramig, 1980; Cherry, Sayers, & Marland, 1955; Shane, 1946, 1955; Yairi, 1976) an explanation is not available. A collective term, AAF has been offered for the various types of auditory feedback (Lincoln, Packman, & Onslow, 2006) that refers to any electronic alteration such that speakers receive their own voice differently than normal feedback. It includes FAF, DAF, and masking noise, using tonal sounds or white noise. FAF and DAF can also be considered as choral speech with electronic manipulation (Saltuklaroglu, Kalinowski, & Guntupalli, 2004). Choral speech (reading or speaking with a model speaker simultaneously) substantially reduces disfluent speech in many, though not all PWS. Delayed auditory feedback and masking noise also show fluency enhancing

effects. Cherry and Sayers (1956) explain the effect by suggesting that PWS have a perceptual deficit (see the section below, 3.3.1.) while Wingate (1976) suggests that PWS improve fluency under these condition because they simply slow down their speech. The effect of frequency altered feedback (FAF), defined as auditory feedback with shifted-up or shifted-down frequency for ongoing speech, on the amelioration of stuttering was reported by Howell, El-Yaniv and Powell (1987).

3.3.1. Noise effect on stuttering

Early studies, beginning with the work of Shane (1946, 1955), tested the effects of noise on the frequency of stuttering. She reported that when the speaker's auditory feedback of own speech was interfered with binaural white noise at 90 dB, stuttering was greatly reduced. At a much lower noise level, 25 dB, no reductions in stuttering occurred. Shane presented a *psychological explanation* that stuttering results from anxiety about the person's own stuttered speech; if a person cannot hear own speech under noise, s/he cannot be critical of it and then decrease anxious and stuttering.

Cherry and associates (1955) studied noise effects on stuttering using shadowed speech, tonal noise, delivered through different auditory channels: air conduction only, and both air conduction and bone conduction. During reading, the greatest reduction in stuttering occurred under a low frequency tone (150 Hz) at high sound levels that masked both air and bone conductions. They theorized stuttering is a disorder of a *perceptual defect* in which people who stutter suffer from a defective auditory feedback loop that interferes with accurate motor speech movement. When this interference is over-ridden by the noise, stuttering disappears. This explanation suffered from a subsequent study

showing reduction in stuttering even when noise was delivered to only one ear (Yairi, 1976) because the masking is incomplete. Several portable electric noise makers have been used in treating stuttering (Dewar, Dewar, Austin, & Brash, 1979).

3.3.2. Choral speech effect on stuttering

Choral speech, or unison speech, has been considered as an altered auditory feedback condition which has the most dramatic effect on decreasing stuttering symptoms by 90 – 100 % (Andrews et al., 1983; Ingham & Packman, 1979). It has obvious therapeutic limitations (Kalinowski & Saltuklaroglu, 2003; Ward, 2006) because normal speech production cannot be produced in a choral manner.

Several studies demonstrated the effects of choral reading on stuttering. Ingham and Packman (1979) reported that their stuttering subjects reduced stuttering and increased speech rate. Andrews and colleagues (1982) also revealed that stuttering completely disappeared under choral reading condition without any rate changes. More recently, Kiefte and Armson (2008) compared several types of choral speech conditions (i.e., (a) choral reading with another person, (b) choral speech with another person's record sample which was delivered simultaneously and with 60ms delay, (c) choral reading with self recording sample with another AAF condition, combining 60ms DAF and three-semi tone or one-quarter octave shifted up FAF). Stuttering was significantly reduced under all of the choral reading and AAF conditions but the choral speech conditions were most effective.

Varied explanations for the immediate amelioration of stuttering under choral speech involve relaxation from communicative pressure, reduction of concentration for speech production, adaptation of new speech patterns such as slowing down speech rate

or increasing loudness (e.g., Barber, 1940; Eisenson & Wells, 1942; Wingate, 1976), or the activation of mirror neurons (Kalinowski & Saltuklaroglu, 2003; Saltuklaroglu et al., 2004).

3.3.3. Frequency altered feedback (FAF) effect on stuttering

Frequency altered feedback encompasses more than just the pitch-shifted feedback described earlier because FAF can be provided during ongoing speech production. Frequency altered feedback was initially introduced by Howell et al. (1987) who compared the effects of several auditory feedback conditions on stuttering reduction of 6 PWS using 50ms delayed feedback, FAF (one-octave shifted down), and masking. All three auditory feedback conditions were effective in achieving fluency relative to the nonaltered feedback condition. The greatest amelioration occurred under FAF and the least under masking. Following Howell et al.'s (1987) study, Kalinowski and his colleagues have extensively investigated the effects of FAF and the combination of AAF on fluency enhancement. Their results also confirmed that (a) AAF reduces stuttering frequency compared to non-altered feedback condition, (b) masking was less effective than FAF and DAF, and (c) the effectiveness of DAF and FAF are not significantly different. Subsequent studies using smaller frequency shifts showed that all of a range of frequency alterations have fluency inducing effects (Hargrave, Kalinowski, Stuart, Armson, & Jones, 1994; Stuart, Kalinowski, Armson, Stenstrom, & Jones, 1996).

Other studies delivered FAF to different age groups and changed experimental conditions. Howell, Sackin, and Williams (1999) delivered FAF to younger (9 - 11 years old) and older (20 – 24 years old) age groups and found the younger stuttering group showed significantly less amelioration. The investigators argued that the older groups

were more fluent under FAF because they slowed down speech and thus had extra planning time to execute speech. The younger group, they suggested, might be using another way for speech planning and execution. Stuart, Kalinowski and Rastatter (1997) compared monaural and binaural AAF, (50ms DAF and one-quarter octave shifted-up FAF) in stuttering subjects. Even though each AAF condition significantly reduced stuttering, the binaural FAF or DAF conditions were significantly more effective than the monaural condition. There was no difference between the right and left ear monaural AAF conditions

Overall, the frequency altered feedback studies report positive effects on stuttering reduction that are similar to DAF efficacy. One interesting phenomenon is that participants were able to manipulate their speech rate (normal and fast) under all FAF conditions (Hargrave et al., 1994; Kalinowski, Armson, Roland-Mieszkowski, Stuart, & Gracco, 1993; MacLeod, Kalinowski, Stuart, & Armson, 1995; Stuart et al., 1996). Similar to pitch-shifted feedback, there was also individual variation in FAF responses (Armson & Stuart, 1998; Zimmerman, Kalinowski, Stuart, & Rastatter, 1997). The possible influence of loudness level was not manipulated in these studies, but was typically maintained at 85dB SPL with the input of 75dB SPL (10dB amplification), which is considered the average conversation loudness level. Other studies used the subject's most comfortable loudness level (MCL).

4. Delayed auditory feedback (DAF) effects on PWS and PWNS

The best known form of AAF in the stuttering literature is delayed auditory feedback (DAF). The term has been defined as "temporal asynchrony between speech

production and its feedback to the auditory system" (Hashimoto & Sakai, 2003, p.22). DAF has been proven as a powerful method for reducing disfluencies in people who stutter (Armson & Stuart, 1998; Kalinowski et al., 1993; Kalinowski, Stuart, Sark, & Armson, 1996; Sparks, Grant, Millay, Walker-Baston, & Hynan, 2002; Stuart, Kalinowski, Rastatter, Saltuklaroglu, & Dayalu, 2004; Stuart et al., 1997; Van Borsel, Reunes, & Van den Bergh, 2003). In contrast, it typically induces disfluencies and decreases speech rate in normally fluent people but with individual variation (Fabbro & Darro, 1995; Jones & Striemer, 2007; Lee, 1950a, 1950b; Mackay, 1970; Stephen & Haggard, 1980; Van Borsel et al., 2005). Its disruption of fluent speech and its influence on disfluent speech is referred to as the *delayed auditory feedback (DAF) effect*. In particular, the opposing disfluency inducing effects of DAF on PWS versus PWNS are unique in that normally fluent populations do not show significant disfluencies under other types of AAF. These implications suggest that DAF effects on PWNS are pointing to a critical sensorimotor factor underlying the generation of disfluencies, potentially meaning that temporal asynchrony between feedforward commands and actual feedback can interrupt segmental mechanisms (Hashimoto & Sakai, 2003; van Lieshout, Hulstijn, & Peters, 2004). On the other hand, we can hypothesize that because PWS have relatively unstable/weak feedforward commands, they are more dependent on feedback controls for speech production. Due to this deficiency in sensorimotor integration, however, their error signal detection is aberrant, and it may itself cause stuttering. Therefore, DAF effects for PWS in reducing disfluent speech imply that the temporal asynchrony under DAF may be beneficial for PWS – perhaps allowing more time to generate accurate feedforward commands.

4.1. DAF effects on brain physiology and anatomy in PWS and PWNS

These fluency effects have long prompted interest in the underlying physiology of DAF effects. One early study conducted by Abbs and Smith (1970) assessed the impact of monaurally delayed feedback on articulation errors for PWNS in four conditions: non-delay, 100, 200, and 300ms DAF conditions. They reported greater number of errors when DAF was set at 200ms and 300ms and delivered to the right ear. A later study by Elias, Yairi, Wright, Adams, and Villescas (1977) looked more carefully at the speaking rate task. Normal feedback and 200ms DAF were directed separately to each ear in two different orders. They reported significantly longer reading time under DAF in the right ear (lateralization effect in the left hemisphere), and concluded there was a small hemispheric effect.

More recent research has utilized brain-imaging techniques. Hashimoto and Sakai (2003) investigated the neural mechanisms involved with speech processing of DAF as PWNS read aloud visually presented sentences under four conditions: NAF (NORMAL), faster speech rate under NAF (FAST), slower speech rate under NAF (SLOW), and under 200 ms DAF (DELAY). The results showed that the bilateral superior temporal gyrus (STG), supramarginal gyrus (SMG), and the middle temporal gyrus (MTG) were significantly activated under the DELAY condition compared to NORMAL, FAST and SLOW conditions. Furthermore, STG activation was directly correlated with the degree of the DAF effect for all subjects. There are two recent brain imaging studies that compared the differences in neural systems of PWS and PWNS when they were exposed to normal and altered feedback conditions (i.e., DAF and/or FAF) (Sakai, Masuda, Shimotomai, & Mori, 2009; Watkins, Smith, Davis, & Howell,

2008). Interestingly, both PWS and PWNS produced more stuttering-like disfluencies under DAF even though the stuttering frequencies were not significantly different from the normal auditory feedback condition. Similar to Hasimoto and Sakai (2003), the activation of the superior temporal cortex was increased bilaterally under AAF conditions. In general, the DAF conditions influenced cortical processes over the short-term in that DAF effects mostly showed up in auditory integration regions.

4.2. DAF effects on perceptual, temporal, and kinematic features

4.2.1. DAF and normally fluent people

The earliest investigation of DAF effects on normally fluent population was reported by Lee (1950a, 1950b, 1951) who delivered several delay times to the subjects. He reported that shorter delays, 1/15 second (approximately 67 ms), did not have specific effects on speech production. The longer delays (125 ms and 250 ms), however, showed obvious effects on speech, meaning that some subjects showed "a quavering slow speech of the type associated with cerebral palsy" (Lee, 1950a, p.640), syllable repetitions, blocking and/or monotone speech. He also reported atypical types of syllable repetitions which were observed for unstressed and non-initial syllables (Lee, 1950b, 1951). This type of repetitions is of interest because it is not common for PWS either and is only observed under DAF conditions. Lee initiated interest in DAF effects on fluency by labeling these disfluencies as "artificial stuttering" (Lee, 1950b). Fairbanks and Guttman (1958) supported these types of disfluencies in their study. Fairbanks (1955) concurrently conducted studies with several delay times (0ms, 100ms, 200 ms, 400ms, and 800ms) when subjects presented while reading. The maximum number of

articulatory errors and reductions in speech rate were observed around at 200ms delays, along with the most notable changes in vocal intensity and pitch. Fairbanks labeled the changes in articulatory errors and duration as *direct effects of DAF* while the changes of vocal intensity and fundamental frequency as being *indirect effects of DAF*. Burke (1975a) tried to separate 32 low and 32 high susceptible groups from 200 male subjects using correct syllable rate (correct syllables per second). The results revealed that the low susceptible group had significantly fewer disfluencies and shorter duration than the high susceptible group in reading.

Investigations into DAF effects were expanded by assessing the perceptual (speech disruption) and temporal (duration of speech) features. Mackay (1968) studied developmental patterns of DAF effects using a wider range of delay time (from 100 to 750ms) and showed that the younger children (age 4 – 6 years) were most susceptible to DAF. Interestingly, the most potent delay time for disrupting the speech of the younger group was longer than older children (age 7 – 9 years) and adults (i.e., 375ms vs. 200ms). Siegel, Fehst, Garber, and Pick (1980) revealed similar results to MacKay (1968) in that their youngest subjects responded to DAF the most.

Mackay (1970) also investigated the influence of language familiarity on DAF effects. German-English bilingual speakers produced speech in both languages under different delay intervals. Speech disruptions were greater in the participants' second language compared to their native language under DAF. Most recently, Van Borsel, Sunaert, and Engelen (2005) expanded MacKay's study with multi-lingual speakers. They tested whether speech disruptions and reading duration were greater in the participants' second languages (less proficient languages) than in native language under

200ms-DAF condition and whether there were sex differences. The results indicated that the two acquired languages required significantly longer reading time and had more speech disruptions under DAF conditions. Also, the number of speech disruptions and the time it took to read the passages were significantly higher for all three languages when reading a passage with nonsense words.

Other studies investigated DAF effects with using a variety of other manipulations, such as feedback amplitude, visual-auditory feedback, or speech rate. Howell and Archer (1984) presented non-delay, 100ms, 200ms, 300ms, and 400ms DAF conditions at 3 loudness levels (10, 20, and 30dB amplifications) to participants when they uttered 40 vowels. The subjects were more susceptible to DAF under louder intensities. Stuart et al. (2002) were interested in whether normally fluent people were susceptible to shorter delay times and could manipulate their speech rate under DAF. Using a similar experimental setting to their previous AAF studies for PWS, they measured the number of disfluencies and duration under 0, 25, 50, and 200ms DAF when the subjects read passages at their normal and fast rate of speech. They found that PWNS had significantly lower stuttering frequencies under no delay, 25ms and 50ms DAF conditions than under the 200ms delay. The subjects also had significantly slower speech for the 50ms delay, but no differences between the unaltered and 25ms DAF conditions. The subjects could control their rate of speech under all DAF conditions even though they had more disfluencies with faster speech.

Jones and Striemer (2007) compared DAF effects with and without real-time visual feedback while PWNS repeated 10 sentences under six speech conditions: NAF only, DAF only, NAF with visual feedback, DAF with visual feedback, NAF with

reading sentences, and DAF with reading sentences. The participants showed significantly slower sentence duration and more speech disruption under DAF conditions than under NAF conditions. Under the DAF only condition, participants showed a trend to exhibit more speech disruptions than under DAF with visual feedback. This trend, however, was not significant.

Overall, delayed auditory feedback consistently reveals effects on normally fluent people by inducing disfluencies and decreasing the rate of speech. Both age- and language familiarity significantly influence the susceptibility to DAF effects. Individual susceptibility to DAF, however, has been rarely investigated even though early studies observed individual variability in susceptibility to DAF (Burke, 1975a; Lee, 1950a, 1950b; Yates, 1963a, 1963b, 1965) and thought it may cause large variations in DAF effects. Considering these age, language proficiency, and intensity influences, it appears that *feedforward control* over speech is a relevant variable here because speech which has become "highly automatic and do(es) not require constant monitoring" (Siegel et al., 1980, p.810) is less susceptible to DAF (Fabbro & Darro, 1995: MacKay, 1968, 1970; Siegel et al., 1980). It can be interpreted that the increased DAF effects on children (as stated earlier in section 3.2), who are still learning speech and language, as well as adults, who are not native speakers of a language show these populations are more dependent on auditory feedback for ongoing speech production. Accordingly, there may also be typically fluent speakers of a given language who are more dependent than others on auditory feedback, and may be more affected by DAF.

4.2.2. DAF and people who stutter

The observation that lifted DAF from merely an interesting laboratory effect is its

potent clinical effect in reducing disfluencies in PWS. Goldiamond (1965) and Wingate (1976) reported that when PWS read under delayed auditory feedback, their speech automatically slowed down and became fluent. In addition, Curlee and Perkins (1969) were among the first to develop a prototype fluency management therapy program in which motor speech coordination was facilitated primarily by focusing on slowing speech rate control by using a DAF unit. Andrews et al. (1982) further confirmed these fluency-inducing effects among 15 experimental conditions - removing 98% of the stuttering under 250ms-DAF. Differing from these earlier perspectives, however, Kalinowski and associates believed stuttering amelioration under DAF was associated with the role of auditory function. These investigators have focused on fluency effects at delays shorter than 100ms, and reported that even 25ms delay times could significantly reduce stuttering frequency even though 50ms and 75ms delay times yielded significantly greater reduction (Kalinowski et al., 1993; Kalinowski et al., 1996; MacLeod et al., 1995). In these studies, stuttering subjects could also significantly increase their rate of speech under DAF while still showing considerable fluency, which shows that DAF effect are not simply due to slowed speech.

In AAF studies with the stuttering population, loudness levels were typically set near average conversational loudness level (e.g., gain approximately 10 – 20dB SPL with 60 – 70dB SPL input) or the most comfortable loudness level (MCL) for each participant (Armson & Kiefte, 2008; Kalinowski et al., 1993; Kalinowski et al., 1996; MacLeod et al., 1995) except one study (Burke, 1975b). Burke (1975b) set the loudness level to 100 dB SPL and reported that PWS with "severe" severity ameliorated stuttering at shorter time delay (i.e., 50 – 150ms) and increased stuttering at longer time delay (i.e., 200 –

300ms) whereas PWS with "mild" severity showed increased stuttering or no significant changes across the DAF conditions.

Overall, the clinical effects of DAF in PWS that are not affected by speaking rate suggest these effects lie in sensorimotor integration. Also, the studies showing that a 50ms delay interval seems to be most effective in both PWS and PWNS differ from the longer delays used to induce maximal disfluencies in normal speakers and to reduce disfluencies in PWS. As described earlier, we expect these differences in perceptual parameters related to opposing disfluency patterns in PWNS and PWS emerge from the different role they have on speech motor control. Until now, however, these effects on actual speech kinematics have not been investigated. We expect that PWS will show more stable speech kinematics under DAF while PWNS will show less stable kinematics – opposing effects that mirror the opposing patterns of disfluencies in these populations.

Summary and Rationale

This review of the literature provides a rationale for testing DAF effects on sensorimotor integration for speech production in people who stutter (PWS) compared to people who do not stutter (PWNS). Among several methods of AAF, the review focused on delayed auditory feedback due to its divergent effects that increase speech disfluency in normally fluent speakers but decrease it in PWS. As stated earlier, however, explanations about these mechanism underlying the disfluency inducing effects of DAF in normally fluent speakers' responses remains speculative, particularly because the individual variability of DAF responses among speaker groups are not well documented. For example, are there sub-populations of normally fluent speakers who are high or low-

responders to DAF? Also what underlies the different responses to DAF between PWNS and PWS? Furthermore, systematic investigations of the specific changes in speech motor control induced by altered feedback in either PWNS or PWS have never been conducted. Therefore, the information gathered in this study will significantly contribute to our empirically based knowledge and inform theoretical perspectives regarding how complex speech production processes are influenced by auditory feedback in normalcy and in a common fluency disorder. It will also improve the application of altered auditory feedback to stuttering theory and to the treatment of this disorder.

Objectives The objective of this dissertation is to identify the effects of delayed auditory feedback on both speech fluency and speech motor stability in normally fluent adults and to compare those effects on persons who exhibit persistent stuttering. The following three studies will test auditory-to-motor integration within and between these groups.

Study I. The objective of this study is to identify individual differences in DAF susceptibility compared to amplified non-delayed auditory feedback (aNAF) in a large group of normally fluent adults.

Study II. The objective of this study is to determine differences in DAF susceptibility as compared to aNAF among three groups: (a) normally fluent speakers who had lowest SLD under DAF (*Low-SLD* group), (b) normally fluent speakers who had highest SLD under DAF (*High-SLD* group), and (c) persons who exhibit persistent stuttering (PWS). This study also aims to determine differences in aNAF condition compared to natural auditory feedback condition (nNAF) in PWS.

Study III. The objective of this kinematic study is to identify changes in the speech-motor stability (physiological basis of speech motor control) of lower lip movements induced by DAF and aNAF compared to nNAF in normally fluent adults and adults who exhibit persistent stuttering.

Because of the scope of this research, specific research questions for each of the three studies outlined above will be presented with predictions in the following three respective chapters.

CHAPTER II

STUDY I : INDIVIDUAL VARIABILITY IN DAF EFFECTS ON SPEECH FLUENCY AND ARTICULATION RATE IN NORMALLY FLUENT SPEAKERS

In normally fluent adults, speech and nonspeech disruptions under DAF are significant because the intact speech motor system is shown to be susceptible to unexpected changes in sensory feedback. The reason for these speech disruptions, however, is not known and individual variation as well as potential influences of sex and task are not well documented. Therefore, the objective of Study I was to identify the diversity of speech perturbations under DAF in order to understand whether individual differences can account for the wide variation in response to altered auditory feedback. The theoretical rationale for the role of auditory feedback in speech motor control is provided in Chapter 1. Delayed auditory feedback was assessed in terms of its influence on speech disfluency rates, disfluency types, and articulation rate, under 250 millisecond-DAF as compared with amplified non-delayed auditory feedback condition (aNAF)[1] in a large group of normally fluent adults. It was predicted that males would show more speech disfluencies (i.e., stuttering-like disfluencies and speech errors) and slower articulation rate under DAF in general. Task differences between reading and spontaneous speech were also expected in terms of normal disfluencies (referred to "other

[1] aNAF: Because the auditory feedback was amplified, it might not be considered as "normal" or "natural," but because the feedback was not electronically manipulated or delayed, it was labeled as "amplified non-delayed" auditory feedback. Previous studies used several terms such as "non-altered auditory feedback", "no-delay", or "0ms-DAF" instead of amplified non-delayed auditory feedback (e.g., Burke, 1975b; Foundas et al., 2004; Kalinowski et al., 1996; Stuart et al., 2002). In Study I, because (a) participants were normally fluent people and they did not show significantly different speech patterns except loudness change (Foundas et al., 2004; Siegel, Schork, Pick, & Garber, 1982) under amplified non-delayed feedback condition, (b) we focused more on DAF responses and (c) we wanted to maintain equivalent experimental setting between auditory feedback conditions, natural auditory feedback (nNAF) condition was not included.

disfluencies") and speech errors as the nature of spontaneous speech and reading. Participants would produce more other disfluencies such as interjections, revisions and phrase/multisyllabic word repetitions in natural speaking condition (i.e., spontaneous conversational speech) than reading. On the other hand, speech errors such as substitutions, omissions, and additions would be observed more in reading. The main prediction was that normally fluent adults would differ markedly in their individual susceptibility to DAF. This individual variability in auditory influences on speech-motor production can be interpreted within the general framework of feedback dependency. Individuals who become highly disfluent and reduce speech rate under DAF may be more dependent on intact auditory feedback during typical speaking conditions (*High Responders*). In contrast, individuals who maintain relatively fluent speech, as well as habitual speech rate under DAF, may have highly developed speech motor skills that allow them to speak fluently when speaking conditions are adverse (*Low Responders*). Moreover, individuals who could maintain relatively fluent speech but reduce speech rate are also expected following Perkell and colleagues' suprasegmental mechanisms (2000) (*Middle Responders*).

The specific questions were:

1. What is the range of DAF-induced speech perturbations in terms of (a) disfluencies, (b) articulatory errors, and (c) articulation rate in a large group of normally fluent speakers?
2. Are there significant effects of sex and task (spontaneous speech and reading) on DAF-induced speech perturbations?

3. Are there sub-groups of people who differ in DAF susceptibility, apart from sex?

METHODS

1. Participants

The original group of participants consisted of 70 normally fluent speakers (35 males and 35 females). The criteria for participant selection were: (a) monolingual native English speaker, (b) between18 to 30 years (due to the decrease of hearing sensitivity after age 30 according to Pearson et al., 1995), (c) free of any hearing, speech-language, psychiatric or neurological disorders, (d) pass a hearing screening at 20dB HL for the frequencies of 500Hz, 1000Hz, 2000Hz, and 4000Hz, conducted with a GSI 17 audiometer (Grason-Stadler Inc), and (e) right handed via the Edinburgh Handedness Inventory (Oldfield, 1971). Of the 70 participants, seven were found to be bilingual speakers whose dominant language was English but because their heritage language was not English, they were not eligible for this study. Therefore, the final number of qualified participants for this study was 63 normally fluent speakers. The 30 males ranged in age from 18;6 to 29;7 years; months (M = 20;10), and the 33 females ranged in age from 18;6 to 22;9 years (M = 20;2). The mean handedness inventory scores were 92.41 (SD = 9.00) for males and 91.72 (SD = 12.58) for females.

2. Procedures

Each participant was seated in a sound-treated booth and fitted with headphones (Sennheiser HD280 Professional with 8Hz to 25,000Hz frequency response). A

microphone (Shure WL185 Cardioid Lavalier Microphone) connected to a preamplifier (Shure MX1BP) was placed approximately 10 centimeters (cm) from the participant's mouth. Digital audio and video recordings were used to obtain participants' reading and spontaneous speech in an amplified non-delayed auditory feedback condition, as well as in a delayed auditory feedback condition. Video recordings were obtained with a SONY digital camera (model DCR-VX2000) and concurrently burned on DVD using a Panasonic DVD Video Recorder (model DMR-T2020). An audio recording was obtained with a HHB CDR830 BurnIT CD Recorder.

In the aNAF condition, the participant's own voice was amplified and delivered through headphones similarly to previous studies (e.g., MacKay, 1970: 95dB SPL; Siegel et al., 1980: 95dB SPL; Van Borsel et al., 2005: 96dB SPL). A Brüel & Kjær sound level meter (type 2235) was used to calibrate the headphone output sound level. A calibration tone of 94dB SPL at 1000Hz was directed to the microphone placed one cm from a calibrator (Brüel & Kjær, type 4230). The tone generated a 95 dB SPL feedback level through the headphones with the sound level meter placed one cm from the right headphone cup (with A weighting). At this level of amplification, each participant was asked whether the loudness of sound they were hearing through the headphones was "loud but O.K." This rating corresponds to level 6 on the 7-point scale of Loudness Categories (Cox, Alexander, Taylor, & Gray, 1997) in which level 1 is "very soft" and level 7 is "uncomfortably loud." Previous research reported that level 6 represents a range from 70 – 100dB HL for speech of normal hearing people (Cox et al., 1997). Most participants reported the loudness level was not uncomfortable. For two participants, however, the intensity was reduced until the participants reported the level 6. After

determining the loudness level, it remained consistent throughout the session. Sound levels were identical under the DAF and aNAF conditions.

The delayed feedback was implemented using the DAF/FAF Assistant software program (version 1.1, http://www.artefactsoft.com/) at a latency of 250ms (Fairbanks, 1955; Goldiamond, 1965; Van Borsel et al., 2005). The delay time indicated in the program was 220ms but an additional 30ms-processing delay from the speaker's microphone to headphones was identified using an oscilloscope resulting in an overall delay of 250ms.

3. Tasks

Spontaneous conversational speech and oral reading tasks were performed by each participant under both DAF and aNAF conditions. During the spontaneous speech task, each participant carried on a casual conversation with an investigator on selected topics, such as the participant's study major, current classes, hobbies, plans for vacations, movies, and states or countries where s/he had visited. A speech sample of approximately 300 to 500 syllables in each feedback condition was recorded. For oral reading, the participant was asked to read one of two passages, each of 123 and 125 words, balanced for phonemes and satisfying reading level for teen ages and adults (SSI-3, Riley, 1994). The order of DAF and aNAF presentation was counterbalanced for all tasks across participants.

4. Analyses

All speech samples recorded under DAF and aNAF for each task were transcribed using the Systematic Analysis of Language Transcripts (SALT) Program (Miller & Chapman, 1996). An utterance was defined as a series of words (a) containing a communicative idea, (b) bounded by a simple intonational contour, and (c) being grammatically complete (Sawyer, Chon, & Ambrose, 2008; Walker, Archibald, Cherniak, & Fish 1992; Yaruss & Conture, 1995). Utterances that included simultalk or unintelligible speech, or utterances containing fewer than three consecutive words in spontaneous speech, were excluded.

In the spontaneous speech sample, a consecutive set of 15 utterances was selected from the transcription, disregarding the first 5 utterances. To determine whether the data from the 15 utterances of the spontaneous speech sample were representative of the entire spontaneous speech sample, 10 participants' data (15.9% of entire data) were randomly selected and the numbers of each disfluency type (SLD and OD) and speech errors (SE), which are described below, per 100 syllables and the mean articulation rate of the entire speech samples, excluding the first 5 utterances, were analyzed. These values were compared with those for 15 consecutive utterances using paired *t*-tests (at $\alpha = .05$). The two sample sets did not reveal significant differences in the numbers of SLD (aNAF: $p = .605$, DAF: $p = .357$), OD (aNAF: $p = .434$, DAF: $p = .470$) and SE (aNAF: $p = .343$, DAF: $p = .385$) or in the mean articulation rate (aNAF: $p = .321$, DAF: $p = .717$). The entire sample was used for the reading task.

4.1. Disfluencies and speech errors

Disfluencies and speech errors were analyzed for each participant. Nine types of disfluency, classified into two general categories, were identified following Ambrose and Yairi (1999): stuttering-like disfluencies (SLD) and other disfluencies (OD). The first class, SLD, includes repetitions (single-syllable word and part-word repetitions) and disrhythmic phonation (including blocks and sound prolongations). As also described by Lee (1950a, 1950b, 1951) and Fairbanks and Guttman (1958) in their DAF studies, other types of disfluencies were observed: repetition of unstressed syllable such as /aluminum-num-num/ and slow trembling speech under DAF. Typically, both types are not present in natural speech conditions. These disfluencies were labeled as part-word echo (PWE) and wavering voice (WV), and included in the above mentioned repetition and disrhythmic phonation categories respectively. They, however, were coded separately in the SALT transcripts. The second class, other disfluencies (OD), includes interjections, revision/abandoned utterances and multisyllable/phrase repetitions (see Ambrose & Yairi, 1999, p. 899). Each type of disfluency was identified, counted and the numbers of SLD and OD per 100 syllables were calculated for the spontaneous speech and reading tasks. Speech articulatory errors (SE), including omissions, substitutions, and additions were also counted and reported as the number of SE per 100 syllables for the tasks as well. Each variable was determined separately in the aNAF and DAF conditions.

4.2. Articulation rate

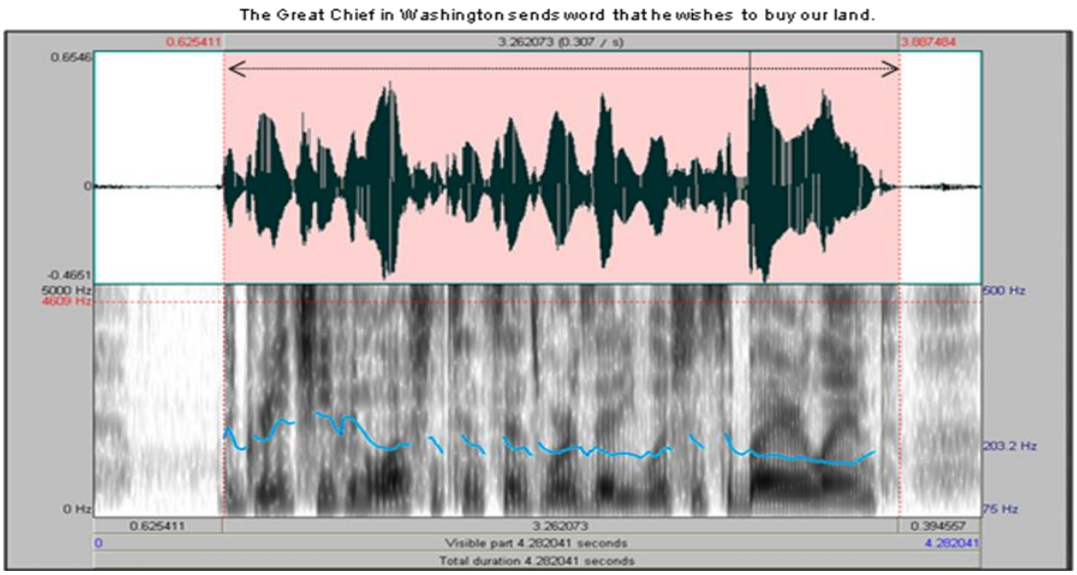
Articulation rate was defined as *the number of perceptually fluent content syllables* divided by *the duration of fluent speech in seconds* for each utterance based on the acoustic record. To determine the duration of perceptually fluent speech, the

durations of (1) disfluencies and (2) pauses following disfluencies or greater than 250ms were excluded (Andrews et al., 1982; Hall et al., 1999; Miller, Grosjean, & Lomanto, 1984). Breaks in phonation following SLDs or ODs in utterances were also excluded to control the number and duration of pauses that can influence articulation rate (Adams & Ramig, 1980; Chon, Sawyer, & Ambrose, 2007; Zellner, 1994).

Using the GoldWave software program (version 5.23, Craig, 2008), all audio-recorded speech samples were converted to wave file format at a sampling rate of 44 kHz, and each utterance was captured for the rate analysis. The Praat software program (version 5.0.13, Boersma & Weenink, 2008) was used to measure (a) the whole duration of each captured utterance, (b) the duration of each pause in the utterance to determine whether it was longer than 250ms, and (c) the duration of each disfluency and the following pause in the utterance to subtract this segment from the total duration. Speech errors were considered as fluent speech if they did not interrupt the fluency of utterances because these errors, except omissions, also contained linguistic content. For accurate measurement of duration, the onset and offset points of speech were determined from the time waveform, corresponding spectrogram and by listening to the audio signal. The onset point of speech was the initiation of acoustic energy identified on the time waveform and spectrogram and confirmed with audio signal. The offset point of speech was the end of acoustic energy of sound identified from the time waveform and spectrogram and confirmed with audio signal. The duration of pauses within the utterance was measured from the offset point of acoustic energy to the subsequent onset point of acoustic energy. An example of measuring the articulation rate is illustrated in Figure 1 below. The acoustic waveform was taken from a participant performing a

reading task under aNAF condition. Disfluencies or pauses greater than 250 ms were not observed. The overall duration of this utterance, containing 17 perceptually fluent syllables, was 3.262 seconds. Therefore, the articulation rate was 5.21 syllables per second (17/3.262 = 5.21).

Figure 1. An example of measuring articulation rate using the Praat software program.



The duration of SLDs was measured following the acoustic measurements of Throneburg and Yairi (2001) and Stuart and colleagues (2008), and durations of PWE, WV and ODs were measured similarly:

- Interjection and revision/abandoned utterances: duration from onset to offset points of disfluent sound.
- Multisyllable/phrase, single-syllable word and part-word repetitions: duration of entire disfluency with repetition units and pauses between the units.

- Prolongations, PWE and WV: duration from onset to offset points of disfluent sound.
- Blocks: duration from the onset of a tensed/abnormal hesitation identified in the video recording corresponding to the audio signal to the offset of the acoustic wave of the stuttered word. However, if the decision of onset point was not reliable, the word and the following pause adjacent to the initiation of blocks were measured together to minimize the risk of inaccurate measurement.

After calculating the duration of perceptually fluent speech and counting the number of fluent syllables in the utterance, articulation rate was calculated for each utterance. Next, the mean articulation rates of 15 utterances in the spontaneous speech and for all utterances in the reading sample were calculated for each participant.

5. Reliability

Intra- and inter-rater judge reliability analyses for (1) the types and locations of SLD, OD and SE, and (2) mean articulation rate were performed. Fifteen percent of samples (10 data sets) were randomly selected from spontaneous speech and oral reading tasks under both DAF and aNAF for each variable.

All SLD, OD, and SE were identified and re-coded using the SALT transcripts by a volunteer who has extended experiences in SALT transcripts. For the inter-rater judge reliability, the volunteer listened to 10 datasets which had been completed by another transcriber. The disfluencies (i.e., SLD, OD, and SE) were identified and coded on the SALT transcripts. For the intra-rater judge reliability, the volunteer re-listened to the 10 datasets and marked and coded all disfluencies and speech errors. To measure the intra-

and the inter-judge reliabilities, the "percent of agreement on occurrence" of each variable, calculated by the number of agreements of occurrence divided by the sum of the numbers of agreements and disagreements, was used (Baird & Nelson-Gray, 1999; Bryington, Palmer, & Watkins, 2004).

For SLD, the intra-rater judge reliabilities in aNAF and DAF were .80 and .84, respectively in spontaneous speech. The intra-rater judge reliabilities were .86 for aNAF and .82 for DAF in reading. The inter-rater judge reliabilities in aNAF and DAF were .93 and .91, respectively in spontaneous speech. The inter-rater judge reliabilities were .91 for aNAF and .81 for DAF in reading.

For OD, the intra-rater judge reliabilities in aNAF and DAF were .94 and .91, respectively in spontaneous speech. The intra-rater judge reliabilities were .94 for aNAF and .90 for DAF in reading. The inter-rater judge reliabilities in aNAF and DAF were .97 and .93, respectively in spontaneous speech. The inter-rater judge reliabilities were 1.00 for aNAF and 1.00 for DAF in reading.

For SE, the intra-rater judge reliabilities in aNAF and DAF were 1.00 and .80, respectively in spontaneous speech. The intra-rater judge reliabilities were .90 for aNAF and .76 for DAF in reading. The inter-rater judge reliabilities in aNAF and DAF were 1.00 and .97, respectively in spontaneous speech. The inter-rater judge reliabilities were 1.00 for aNAF and .86 for DAF in reading.

For the mean articulation rate, the Pearson product-moment correlation analysis was used both for the intra- and inter-rater judge reliabilities. For the intra-rater judge reliability, the 10 datasets were reanalyzed by the first author after a period of 4-5 months. For the inter-rater judge reliability, an undergraduate volunteer was trained to measure

articulation rate, analyzed one dataset with the investigator, and then analyzed 10 data sets. In spontaneous speech, the coefficients of the intra-rater judge reliability were .99 for aNAF condition and .99 for DAF condition, and the coefficients of the inter-rater judge reliability was .95 for aNAF condition and .98 for DAF condition. In reading, the coefficients of the intra-rater judge reliability was .98 for aNAF condition and .99 for DAF condition, and the coefficients of the inter-rater judge reliability was .97 for aNAF condition and .98 for DAF condition.

6. Statistical Analysis

The SPSS version 16.0 and the R 2.9.0 software programs were used for statistical analysis. For research question 1, descriptive analysis was performed to provide means and standard deviations of the four measures, (a) number of SLD per 100 syllables, (b) number of OD per 100 syllables, (c) number of SE per 100 syllables, and (d) articulation rate in two speaking tasks (spontaneous speech and reading) under two auditory feedback conditions (aNAF and DAF). For research question 2, the repeated measures analysis of variance (ANOVA) was conducted for each dependent variable with a 2 (sex) × 2 (task) × 2 (feedback condition) design. The independent samples *t*-test, the paired samples *t*-test, and the correlation analysis were also performed to test significant interactions.

For research question 3, cluster analysis was used to separate subgroups. Cluster analysis divides a set of data objects (participants) into several groups based on the combination of independent variables observed. Thus, it allows us to predict characteristics of each group because the group shares similar properties of the independent variables. In this study, the Partitioning Around Medoids (PAM) method,

one of the most commonly used method for non-hierarchical clustering, was used to assign three subgroups for the spontaneous speech and reading tasks separately under DAF condition. Previous literature reported that participants' performances between normal feedback and DAF conditions were not significantly correlated (Burke, 1975a), thus individual susceptibility to DAF could be evaluated independently. To evaluate whether the subgroup classification was meaningful (i.e., DAF condition) and whether the subgroups initially had different speech-motor production (i.e., aNAF condition), one-way ANOVA was used for SLD, SE and AR. The Scheffé post-hoc test was performed to test for significant main effects. The Least Significant Difference (LSD) post-hoc test was also used for AR under the DAF condition.

RESULTS

Of the 63 participants, there were two participants whose number of SLD per 100 syllables was 4.95 and 3.20 under the aNAF condition. The number of 3 SLD per 100 syllables or words has been regarded as an important criterion for diagnosing people as exhibiting stuttering (Manning, 2010; Yairi & Ambrose, 2005). Nevertheless, some normally fluent speakers produce more than 3 SLD per 100 syllables. Therefore, the specific types of SLD as well as the number of repetition units per instance of repetition (an indicator of disfluency length) were inspected to evaluate the features of disfluencies for these participants. One participant who exhibited 4.95 SLD per 100 syllables had disrhythmic phonation and part-word repetitions with a range of repetition unit from 1 to 2, was excluded. The other participant, with an SLD count of 3.20, had single-syllable

whole word repetitions and part-word repetitions with only 1 repetition unit. Because normally fluent people also exhibit single-syllable whole word repetitions and part-word repetitions with 1 repetition unit (Van Riper, 1982; Ambrose & Yairi, 1995), this participant was retained. Overall, data from 62 participants (33 females and 29 males) were used for statistical analyses.

1. Range of DAF-induced speech perturbations

Descriptive data for speech perturbations in terms of disfluencies (SLD and OD), speech errors, and articulation rate for both spontaneous speech and reading are summarized in Table 1. There was a substantial increase in the mean numbers of SLD and SE under DAF condition during both spontaneous speech and reading. The standard deviations of SLD and SE were quite large in the DAF condition compared to the aNAF condition. The mean numbers of OD were similar between the aNAF and DAF conditions in each task but the mean OD was higher in spontaneous speech compared to reading. The mean articulation rates decreased under DAF compared to aNAF in both tasks.

1.1. Spontaneous speech

The mean number of SLD per 100 syllables was 0.67 (SD = 0.78) under the aNAF condition, but was much greater under DAF, 7.66 (SD = 7.20). The mean number of OD per 100 syllables was 4.85 (SD = 2.62) under aNAF and 4.55 (SD = 2.68) under DAF. The mean number of SE per 100 syllables was 0.01 (SD = 0.06) under aNAF and 1.12 (SD = 0.99) under DAF. The mean articulation rate was 5.33 syllables per second (SPS) (SD = 0.55) under aNAF and 4.54 SPS (SD = 0.61) under DAF.

1.2. Reading

The mean SLD per 100 syllables was 0.55 (SD = 0.74) under aNAF and 7.70 (SD = 10.27) under DAF. The mean OD per 100 syllables were 0.91 (SD = 1.18) under aNAF and 0.57 (SD = 0.77) under DAF. The mean SE per 100 syllables was 0.34 (SD = 0.53) under aNAF and 1.37 (SD = 1.22) under DAF. The mean articulation rate was 5.33 SPS (SD = 0.48) under aNAF and 3.90 SPS (SD = 0.76) under DAF.

Table 1. Ranges, means, and standard deviations of speech perturbations under aNAF and DAF (N = 62)

Tasks	Variables	Feedback condition	Mean	SD	Minimum	Maximum
Spontaneous speech	SLD	aNAF	0.67	0.78	0.00	3.20
		DAF	7.66	7.20	0.00	32.59
	OD	aNAF	4.85	2.62	1.00	11.83
		DAF	4.55	2.68	.00	10.74
	SE	aNAF	0.01	0.06	0.00	0.33
		DAF	1.12	0.99	0.00	3.78
	AR	aNAF	5.33	0.55	3.80	6.65
		DAF	4.54	0.61	3.27	6.53
Reading	SLD	aNAF	0.55	0.74	0.00	2.63
		DAF	7.70	10.27	0.00	64.78
	OD	aNAF	0.91	1.18	0.00	5.31
		DAF	0.57	0.77	0.00	3.80
	SE	aNAF	0.34	0.53	0.00	1.88
		DAF	1.37	1.22	0.00	5.73
	AR	aNAF	5.33	0.48	4.03	6.17
		DAF	3.90	0.76	1.97	5.32

SLD = stuttering-like disfluencies; OD = other disfluencies; SE = speech errors; AR = articulation rate

2. Effects of sex and task on DAF-induced speech perturbations

2.1. Stuttering-like disfluencies

Means and standard deviations of the SLD per 100 syllables for males and females are provided in Table 2. In the spontaneous speech task, the mean SLD for both males and females was substantially higher under DAF than aNAF. A similar finding was observed in the reading task. In both tasks and both conditions, the standard deviations were large in relation to the means. The statistical results indicated the number of SLD was significantly higher under DAF compared to aNAF (F (1, 60) = 44.78, $p < .001$). Statistical differences, however, were not detected for the sex (F (1, 60) = .34, $p = .563$) and the task (F (1, 60) = .04, $p = .850$) comparisons. There was no significant interaction between independent variables (i.e., task, sex, and auditory feedback).

Table 2. Means and standard deviations (SD) of SLD in spontaneous speech and reading, according to sex and auditory feedback condition

Sex	Spontaneous speech		Reading	
	aNAF	DAF	aNAF	DAF
Male (n = 29)	1.03 (0.91)	8.54 (7.15)	0.57 (0.71)	7.80 (8.21)
Female (n = 33)	0.35 (0.46)	6.89 (7.26)	0.54 (0.77)	7.61 (11.91)

2.2. Other disfluencies

Means and standard deviations of the number of OD per 100 syllables are provided in Table 3. The descriptive data indicate that the female group showed a lower mean OD than the male group, and the spontaneous speech task yielded larger means

than the reading task regardless of auditory feedback. There were significant main effects for sex and task (F (1, 60) = 10.62, p = .002 and F (1, 60) = 223.34, p < .001, respectively). The spontaneous speech task elicited a significantly greater number of OD than the reading task.

Table 3. Means and standard deviations (SD) of OD in spontaneous speech and reading, according to sex and auditory feedback condition

Sex	Spontaneous speech		Reading	
	aNAF	DAF	aNAF	DAF
Male (n = 29)	5.85 (2.96)	5.30 (3.05)	1.13 (1.52)	0.72 (0.93)
Female (n = 33)	3.98 (1.94)	3.90 (2.16)	0.71 (0.75)	0.43 (0.58)

Figure 2. Interaction between task and sex in OD

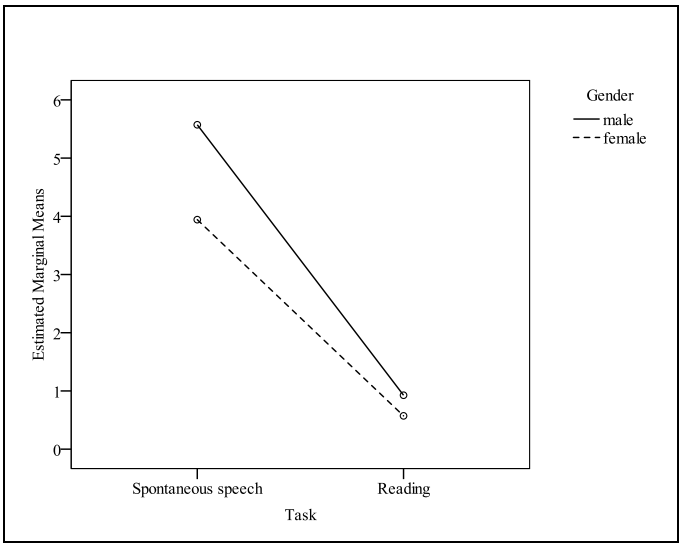


Table 4. Results of the independent two samples *t*-test with Bonferroni correction between males and females in spontaneous speech and reading for OD.

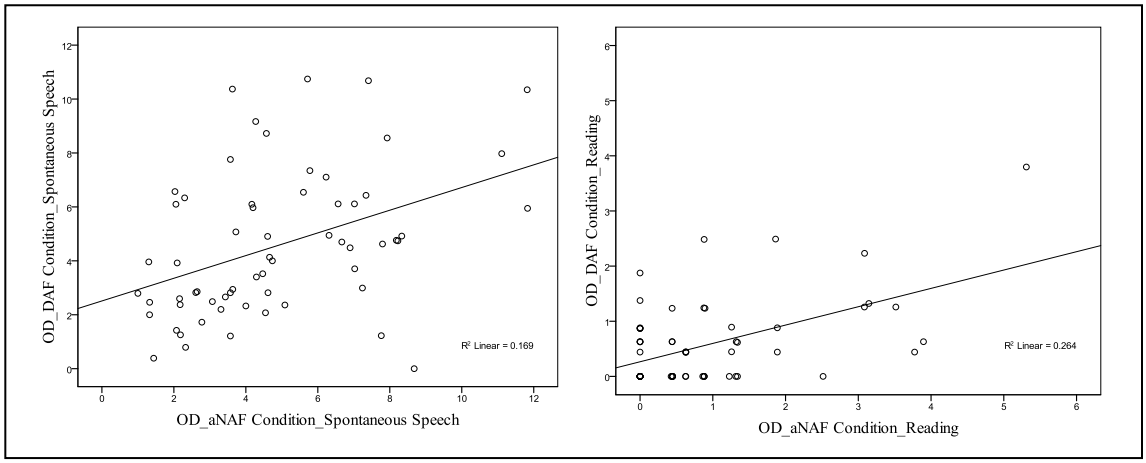
OD		*t*	df	*p*
Spontaneous Speech	aNAF	2.97	60	.004*
	DAF	2.09	60	.040
Reading	aNAF	1.42	60	.161
	DAF	1.47	60	.146

* Corrected alpha level per comparison in each task = 0.025 (Overall alpha level = 0.05)

There was a significant interaction between task and sex ($p = .021$) indicating that the difference in OD between the male and female groups in spontaneous speech was greater than in reading (see Figure 2). To test whether the differences between the sex groups in each task were significant, an independent samples *t*-test followed by Bonferroni corrections for multiple testing was performed. As described in Table 4, the results revealed that the male group had significantly more ODs than the female group in spontaneous speech under the aNAF condition (t (60) = 2.97, $p = .004$).

Auditory feedback did not significantly influence OD frequency (F (1, 60) = 2.89, $p = .095$). The scatter plots shown in Figure 3 reveal significantly positive correlations between aNAF and DAF conditions both in spontaneous speech and reading ($r = .41$, $p = .001$ and $r = .51$, $p < .001$, respectively). These results show that the means of OD were similar regardless of auditory feedback conditions within each task.

Figure 3. Scatter plots of spontaneous speech (left) and reading (right) between aNAF and DAF conditions in OD



2.3. Speech Errors

Means and standard deviations of the number of SE per 100 syllables are provided in Table 5. These descriptive data show that females had more SE than males except under DAF in spontaneous speech. Also, the reading task tended to have larger SE than that in the spontaneous speech task in both aNAF and DAF conditions.

Table 5. Means and standard deviations (SD) of SE in spontaneous speech and reading, according to sex and auditory feedback condition

Sex	Spontaneous speech		Reading	
	aNAF	DAF	aNAF	DAF
Male (n = 29)	0.01 (0.05)	1.28 (1.08)	0.29 (0.56)	1.24 (1.07)
Female (n = 33)	0.02 (0.07)	0.98 (0.88)	0.39 (0.49)	1.49 (1.34)

Significant main effects for the task and the auditory feedback (F (1, 60) = 11.51, p = .001 and F (1, 60) = 83.74, p < .001, respectively) were observed. That is, there were significantly more speech errors in reading than spontaneous speech, and under DAF than under aNAF. Sex, however, did not show a significant effect (F (1, 60) = .01, p = .919). There were no significant interactions for SE.

2.4. Articulation rate

Means and standard deviations for articulation rate (SPS: syllables per second) are provided in Table 6. The female group showed a slightly slower rate than the male group and the mean articulation rate was faster under aNAF than DAF in spontaneous speech and reading. Repeated measures ANOVA yielded significant main effects for sex (F (1, 60) = 5.29, p = .025), task (F (1, 60) = 22.34, p < .001), and auditory feedback (F (1, 60) = 496.79, p < .001).

Table 6. Means and standard deviations (SD) of articulation rate in spontaneous speech and reading, according to sex and auditory feedback condition.

Sex	Spontaneous speech		Reading	
	aNAF	DAF	aNAF	DAF
Male (n = 29)	5.48 (0.59)	4.74 (0.65)	5.35 (0.55)	4.10 (0.76)
Female (n = 33)	5.19 (0.50)	4.36 (0.51)	5.32 (0.42)	3.73 (0.72)

There were significant interactions between task and auditory feedback (p < .001), and between sex and auditory feedback (p = .034). The articulation rate in spontaneous speech was slower than in reading under the aNAF condition, but faster than in the

reading task under the DAF condition (see Figure 4). A paired samples *t*-test with Bonferroni correction for multiple testing indicated the AR in spontaneous speech was significantly faster than reading under DAF (t (61) = 6.66, $p < .001$) (see Table 7).

Figure 4. Interaction between task and auditory feedback condition in AR

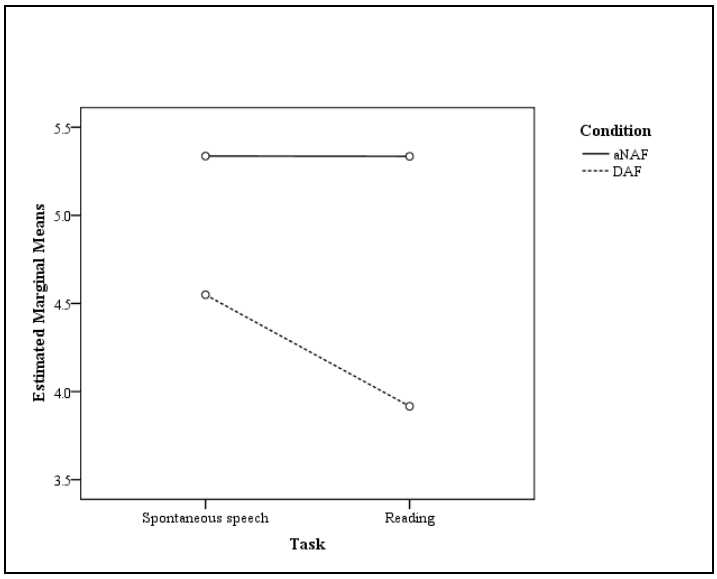


Table 7. Results of the paired samples *t*-test with Bonferroni correction between spontaneous speech and reading under aNAF and DAF for AR.

AR	*t*	df	*p*
aNAF: Spontaneous speech-Reading	-.092	61	.927
DAF: Spontaneous speech-Reading	6.66	61	.000*

* Corrected alpha level per comparison in each task = 0.025 (Overall alpha level = 0.05)

The interaction between sex and auditory feedback revealed that the male group had faster articulation rate under aNAF and DAF. The difference between the males and

females, however, was greater under DAF (see Figure 5). An independent samples *t*-test with Bonferroni correction for multiple testing showed the male group had significantly faster AR in spontaneous speech than the female group under DAF (t (60) = 2.57, p = .013).

Figure 5. Interaction between sex and auditory feedback condition in AR

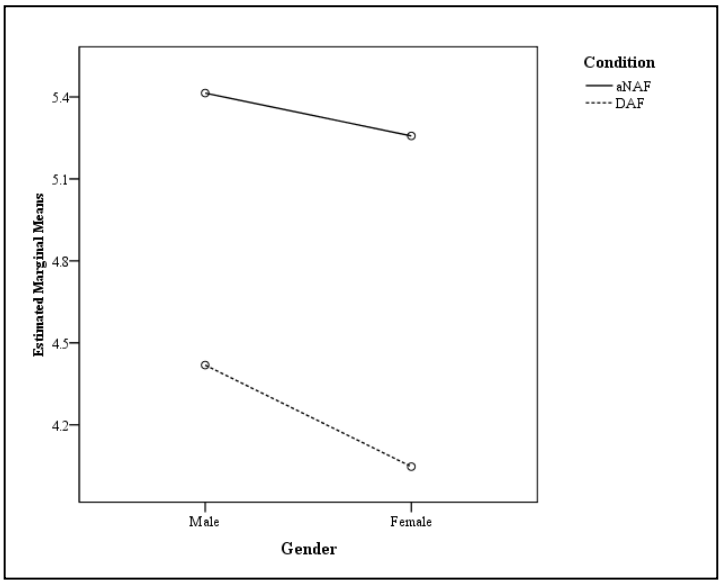


Table 8. Results of the independent two samples *t*-test with Bonferroni correction between males and females under aNAF and DAF for AR.

AR		*t*	df	*p*
aNAF	Spontaneous speech	2.09	60	.041
	Reading	.20	60	.839
DAF	Spontaneous speech	2.57	60	.013*
	Reading	1.92	60	.060

* Corrected alpha level per comparison in each feedback condition = 0.025 (Overall alpha level = 0.05)

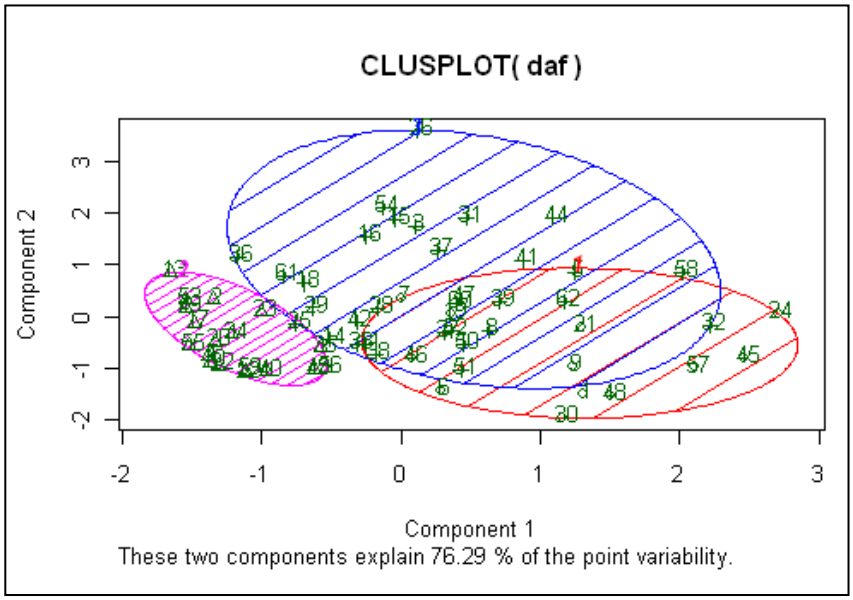
3. Individual variability: Subgroups

The numbers of SLD and SE, and mean AR under DAF for each participant were used in the cluster analysis tests for subgroups that differ in DAF susceptibility. The number of OD was excluded because OD was not influenced by auditory feedback. As provided earlier in this Chapter, the partitioning into three subgroups was preferred in response to the prediction for individual variability in auditory feedback dependency. Therefore, after categorizing the three subgroups in each task, the differences of SLD, SE, and AR among the groups were tested under aNAF and DAF separately to study (1) whether the subgroups fundamentally had different speech-motor production under aNAF condition, and (2) whether the subgroup classification was meaningful under DAF condition. The classification lists based on the PAM analysis in spontaneous speech and reading are provided in Appendices F and G.

3.1. Spontaneous speech

The results of the PAM method for spontaneous speech differentiated three subgroups (see Figure 6). The first subgroup (N = 12), labeled as *High Responders*, exhibited larger SLD and SE counts with slower AR than the other two groups (see Table 9 for descriptive results). The second subgroup (N = 18) was labeled as *Low Responders* because the SLD and SE counts were lowest and the AR was faster. The third subgroup (N = 32), labeled as *Middle Responders*, exhibited relatively few SLDs, an AR that was comparable to the *Low Responders* but had a larger SE count.

Figure 6. Cluster plot of the PAM method in the spontaneous speech task (N = 62). The lower-right side oval circle represents the subgroup 1 (*High Responders*), the lower-left oval circle represents subgroup 2 (*Low Responders*), and the top-middle oval circle represents subgroup 3 (*Middle Responders*). The numbers in each oval circle identify individual participant.



3.1.1. Stuttering-like disfluencies

After dividing the participants into their respective groups based on the cluster classification, statistical analyses were used to test whether the classification was meaningful. The data for the stuttering-like disfluencies are illustrated in Figure 7-1. Under aNAF, no significant main effect was detected for the group (F (2, 59) = 2.39, p = .101). Under DAF, there was a significant group effect (F (2, 59) = 70.69, p < .001). The *High Responders* had significantly more SLD than the other responder groups (between the *Low* and the *High Responders*: p < .001; between the *Middle* and the *High*

Responders: $p < .001$) and the *Middle Responders* had significantly more SLD than the *Low Responders* ($p = .003$).

Table 9. Means and standard deviations (in parenthesis) of SLD, SE, and AR in spontaneous speech according to subgroup and auditory feedback condition.

Auditory feedback	Subgroup	SLD	SE	AR*
aNAF	*Low Responders*	0.34 (0.45)	0.02 (0.08)	5.31 (0.62)
	Middle Responders	0.76 (0.77)	0.01 (0.05)	5.36 (0.55)
	High Responders	0.90 (1.06)	0.02 (0.08)	5.26 (0.51)
DAF	*Low Responders*	2.21 (2.10)	0.15 (0.29)	4.38 (0.43)
	Middle Responders	6.34 (3.72)	1.69 (0.88)	4.72 (0.64)
	High Responders	19.35 (6.22)	1.07 (0.76)	4.28 (0.66)

* AR was measured in syllables per second.

3.1.2. Speech errors

The data for the speech errors are illustrated in Figure 7-2. The ANOVA did not reveal a significant group effect under aNAF (F (2, 59) = .29, $p = .748$), but there was a significant group main effect (F (2, 59) = 25.36, $p < .001$) for SE under DAF. The *Middle* and *High Responders* had significantly more SE than the *Low Responders* (between the *Low* and the *Middle Responders*: $p < .001$; between the *Low* and the *High Responders*: $p = .006$).

Figure 7. Means and standard deviations (error bar) of each independent variable (SLD, SE, AR) for *Low*, *Middle*, and *High Responders* under DAF and aNAF conditions in spontaneous speech

Figure 7-1. SLD under aNAF and DAF

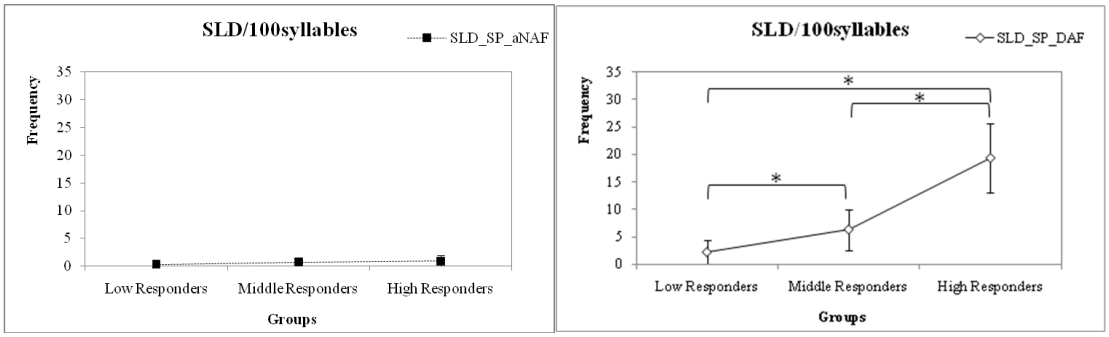


Figure 7-2. SE under aNAF and DAF

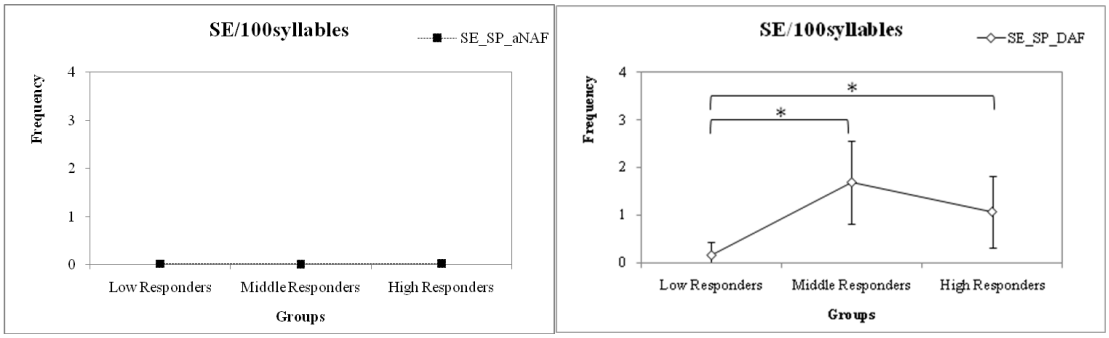
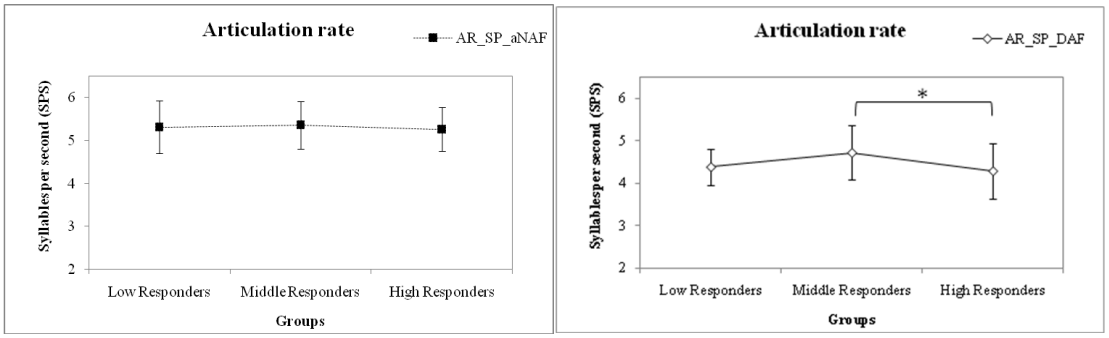


Figure 7-3. AR under aNAF and DAF



3.1.3. Articulation rate

The data for the articulation rate are illustrated in Figure 7-3. The ANOVA did not show a significant group main effect (F (2, 59) = .15, p = .857) under aNAF. There was a significant subgroup main effect (F (2, 59) = 3.35, p = .042) under DAF. The LSD post-hoc test confirmed the *Middle Responders* showed significantly faster AR than the *High Responders* (p = .031).

Table 10. Means and standard deviations (in parenthesis) of SLD, SE, and AR in reading according to subgroup and auditory feedback condition.

Auditory feedback	Subgroup	SLD	SE	AR*
aNAF	*Low Responders*	0.43 (0.66)	0.17 (0.33)	5.62 (0.32)
	Middle Responders	0.41 (0.64)	0.33 (0.62)	5.32 (0.51)
	High Responders	0.84 (0.85)	0.51 (0.53)	5.10 (0.45)
DAF	*Low Responders*	3.29 (3.02)	0.73 (0.60)	4.72 (0.35)
	Middle Responders	3.64 (3.11)	1.29 (0.91)	3.95 (0.39)
	High Responders	16.54 (14.04)	2.05 (1.60)	3.11 (0.50)

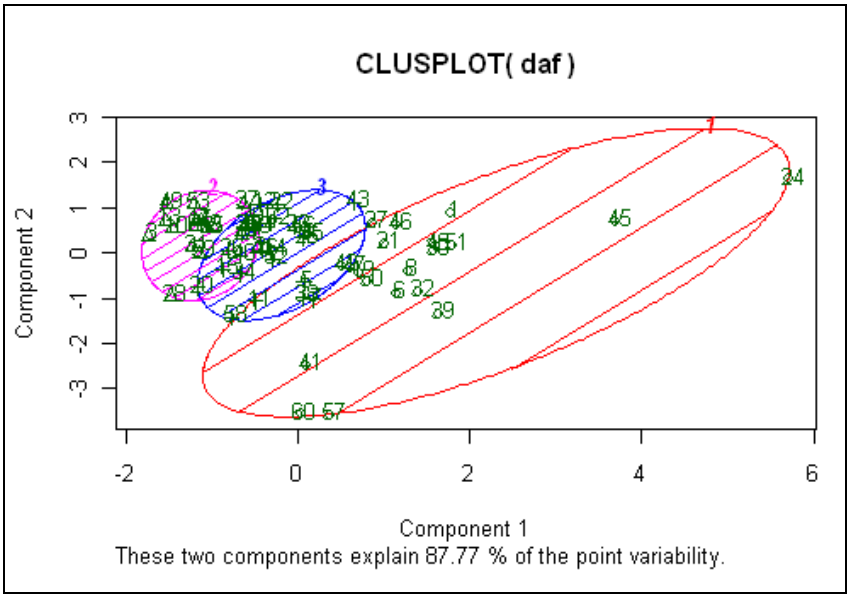
* AR was measured in syllables per second.

3.2. Reading

The results of the PAM method also differentiated three subgroups according to their SLD, SE, and AR characteristics (see Figure 8). Descriptive results are provided in Table 10. The subject distribution was different from that of the spontaneous speech task because the classification is based on the existing data which necessarily vary. The first subgroup (N = 20), labeled as *High Responders*, showed the highest SLD and SE, and slowest AR among the subgroups. The second subgroup (N = 18) labeled as *Low*

Responders showed the smallest SLD and SE counts whereas AR was the fastest among other responder groups. The third subgroup (N = 24), labeled as *Middle Responders*, showed slightly larger SLD and SE and relatively slower AR than the *Low Responders*.

Figure 8. Cluster plot of the PAM method in the reading task (N = 62). The large oval on the right shows the subgroup 1 (*High Responders*), the left oval indicates subgroup 2 (*Low Responders*), and the middle oval circle indicates subgroup 3 (*Middle Responders*). The numbers in each oval circle identify individual participant.



3.2.1. Stuttering-like disfluencies

The data for the stuttering-like disfluencies are illustrated in Figure 9-1. There was no significant group effect under aNAF (F (2, 59) = 2.32, p = .107). Under DAF, there was a significant group main effect (F (2, 59) = 16.51, p < .001). The *High Responders* had significantly more SLD than the *Low Responders* (p < .001) and the *Middle Responders* (p < .001).

Figure 9. Means and standard deviations (error bar) of each independent variable (SLD, SE, AR) for *Low*, *Middle*, and *High Responders* under DAF and aNAF conditions in reading

Figure 9-1. SLD under aNAF and DAF

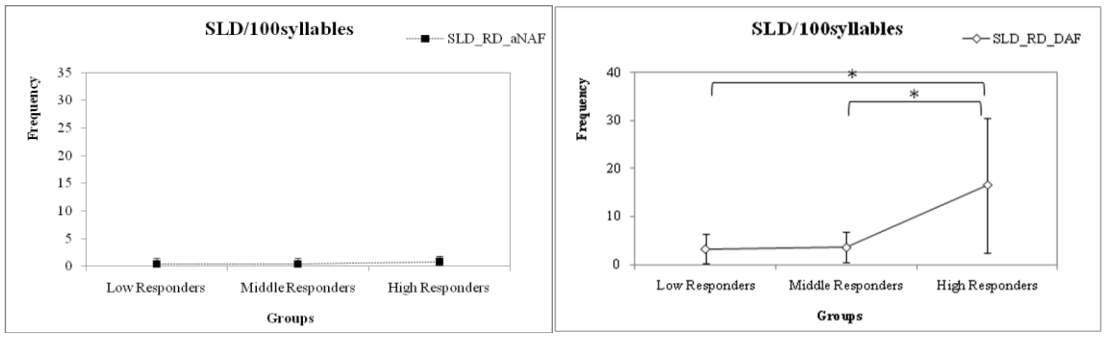


Figure 9-2. SE under aNAF and DAF

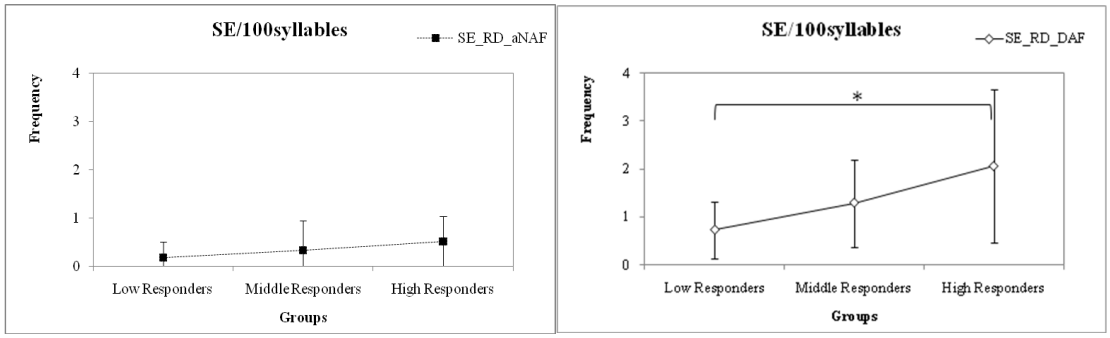
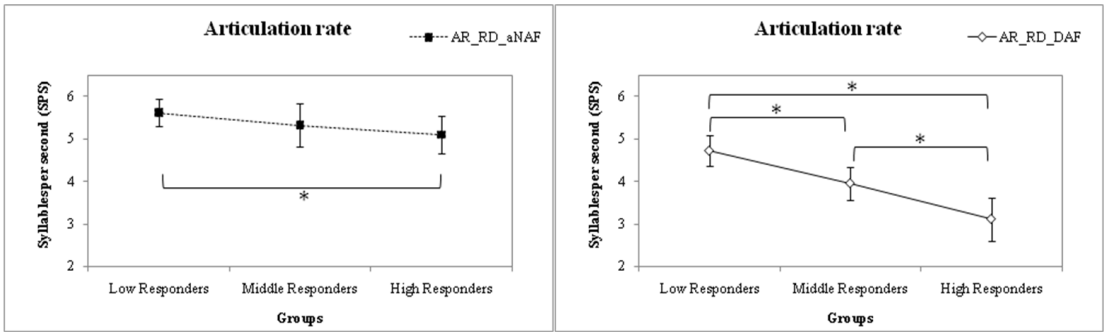


Figure 9-3. AR under aNAF and DAF



3.2.2. Speech errors

The data for the speech errors are illustrated in Figure 9-2. The ANOVA did not indicate a significant subgroup main effect under aNAF (F (2, 59) = 1.98, p = .148). A significant group main effect, however, was observed under DAF (F (2, 59) = 6.80, p = .002) with the *High Responders* showing significantly more SE than the *Low Responders* (p = .002).

3.2.3. Articulation rate

The data for articulation rate are illustrated in Figure 9-3. Under aNAF, there was a significant main effect for group (F (2, 59) = 6.67, p = .002). The *Low Responders* had significantly faster AR than the *High Responders* (p = .002). There was also a significant group effect under DAF (F (2, 59) = 68.93, p < .001) with the *Low Responders* having the significantly fastest AR among the subgroups (between the *Low* and the *Middle Responders*: p < .001, between the *Low* and the *High Responders*: p < .001). Also, the *Middle Responders* showed significantly faster AR than the *High Responders* (p < .001).

DISCUSSION

1. Summary of study

This study investigated DAF effects on speech fluency and articulation rate in a large group of normally fluent adults. The effects of spontaneous speech and reading tasks, as well as variability in individual and sex responses under these conditions were investigated. At the most general level, the results indicate that when the normal auditory feedback of normally fluent speakers' speech is disturbed by delay (DAF), they tend to

respond in rather predictable ways: (a) increment of stuttering-like disfluencies (SLD), (b) increment in speech articulatory errors (SE), and (c) decrement in articulation rate (AR). Although some past studies reported increases in disfluency and decreases in speaking/reading duration, the current findings, based on a much larger sample size (62 participants) than most, not only confirm these observations but also shed light on the wider impact of the disturbed auditory feedback on the speech production in terms of accuracy and articulatory rate. Interestingly, sex had a limited differential effect in that males exhibited more other disfluencies (OD) under aNAF and faster AR under DAF than the females in spontaneous speech. Task effects on OD, SE, and AR were also observed. SLD, however, was only influenced by DAF. OD was influenced by sex and task, but not by DAF.

An important finding was that three subgroups, *Low*, *Middle*, and *High Responders* were identified based on participants' responses to DAF. The clear differences between the the *Low* and *High Responders*, in particular, supported our predictions that *Low Responders* may have a better established feedforward control, and that *High Responders* are more dependent on auditory feedback. In addition, *Middle Responders* showed several different patterns of responses from the *Low* and *High Responders* depending on the task, that is, spontaneous speech or oral reading. An interesting question arises in this regard because people who stutter have known to have reduced SLDs under DAF (e.g., Armson & Stuart, 1998; Kalinowski et al., 1996) and the SLD in the *Low Responders* under DAF might be less different.

In summary, the results point to the significance of SLD associated with auditory feedback changes and individual variability in response to DAF that may be accounted for by differences in auditory-to-motor integration.

2. Research Questions 1 & 2. Effects of DAF on speech fluency: Stuttering-like disfluencies, speech errors and articulation rate were changed in response to DAF

The current findings are generally consistent with the published literature (e.g., Corey & Cuddapah, 2008; Mackay 1968; Stuart et al., 2002) in terms of the increase in SLD and SE and the decrease of articulation rate as compared to aNAF condition. In addition to the statistically significant DAF effects on normally fluent speakers, two other types of disfluency, part-word echo and wavering voice, which, we reasoned, should be categorized as SLD, were also observed in the participants' speech under DAF condition. These disfluencies were also observed and reported in early studies (Fairbanks & Guttman, 1958; Lee, 1950a, 1950b, 1951). The findings support our hypothesis that DAF impacts segmental production (i.e., SLD and SE) as well as suprasegmental production (i.e., articulation rate). It has been suggested that the primary role of auditory feedback in normally fluent adults is to maintain stored speech motor commands in natural speaking condition, but actually, it also keeps track of whether planned (and expected) speech output matches the actual product (i.e., feedback control).

2.1. SLD was only influenced by DAF, neither task nor sex

The increment of SLD for normally fluent people can be accounted for by auditory-motor factor underlying the generation of disfluencies. Given that people who

stutter (PWS) may have a deficiency/difference in auditory-motor integration, their error signal detection is aberrant and it may cause stuttering, we could make connection between DAF induced SLD in PWNS and SLD in PWS. The time lags (DAF) between expected speech sound produced and its actual arrival for comparison can result in unstable feedback control system in PWNS, thus the segmental features that should be dynamically produced for fast ongoing speech would be disrupted.

One of the most significant findings in current study is that SLD was not influenced by sex and task, only by auditory feedback. This is different from our initial expectations that males might produce more SLD and SE than females. There have been controversial findings regarding the sex and task factors in DAF-induced disfluencies in normally fluent speakers. As for the sex effect, two studies reported significantly more SLD in males than females under DAF (Bachrach, 1964; Corey & Cuddapah, 2008). The investigators offerred that the sex difference might be related to the known sex ratio in the stuttering population (approximate 4:1 male-to-female ratio in adults). Two other studies, however, did not report significant sex differences under DAF (Timmons & Boudreau, 1976; Van Borsel et al., 2005). As for the task effect, previous DAF studies compared reading tasks with data that showed SLD occurred significantly more often in conversational speech than in reading (e.g., Abbs & Smith, 1970; Burke, 1975a; Fairbanks, 1955; Stuart et al., 2002) except Corey and Cuddapah (2008). Lack of significant sex and task differences in SLD in current study may suggest that males and females show similar variation in DAF susceptibility, and basic auditory-to-motor integration functions are similar across these tasks. These findings suggest that among the variables employed in this study, SLD appears to be the *strongest* indicator of DAF

susceptibility because SE and AR are influenced by auditory feedback as well as task and/or sex.

2.2. SE and AR were influenced by DAF as well as task and/or sex

Speech errors refer to "unintended, non-habitual deviations from a speech plan (Postma, Kolk, & Povel, 1990, p.19)" and can be frequently observed in childhood, the learning stage of speech sounds. Increased SE under DAF and lack of difference between sex can also be considered that segmental features were interrupted by changes in auditory feedback but males and females have similar variability in DAF susceptibility which is similar to SLD. The characteristics of SE, however, may be somewhat independent or different from SLD because it does not interrupt the flow of speech by itself. The unintentional speech processing errors are shown more obviously during reading as predicted because the articulatory movements for speech production have to follow written texts.

In the current study, AR was slower under DAF, and significant AR differences also emerged between the tasks as well as sex. AR was faster in spontaneous speech than reading under DAF condition. This differs from previous findings showing faster speaking rates during reading than conversation under DAF (Corey & Cuddapah, 2008) and natural feedback conditions (Lutz & Mallard, 1986). Their methods of measuring speaking rate, however, were quite different from those employed in the current study. Previous studies measured *overall speaking rate* that includes the duration of all disfluencies and pauses in a given speech sample. This method is blind to the actual rate of the speech articulators during fluent segments, which likely explains the disparity in

findings. Additionally, Corey and Cuddapah (2008) controlled SLD frequency as a covariate when measuring overall speaking rate in conversational speech under DAF, but did not controll the number of OD (i.e., interjections). In contrast, the method employed in the current study measured *articulation rate* that reflects the temporal parameters of motor speech much more accurately (Ingham & Riley, 1998; Walker et al., 1992). The male group also showed significantly faster AR than the female group under DAF condition in spontaneous speech. This finding contradicted our prediction that males would be more susceptible to DAF in general, thus they would show slower AR than females.

Reduced articulation rate under DAF can be interpreted in two ways: First, it may be related to the characteristics of suprasegmental mechanisms as we predicted. The suprasegmental mechanisms are more amenable than segmental mechanisms because they have relatively simple auditory information. Thus, AR may be easily disrupted by unexpected changes in sensory feedback. Second, it could also be an involuntary compensatory response to overcome DAF. When interruptions are occurred between the actual speech output and its arrival for comparison due to DAF, movements of articulators may be slowed down to gain more time for the feedback control to maintain the flow of their speech production. Under DAF, the difference of AR between the tasks and sex may be explained that AR is readily more disrupted by a speech task and females are more sensitive to the sensory feedback change than in males.

2.3. Lack of difference in other disfluencies between aNAF and DAF

In other disfluencies, including interjections, revision/abandoned utterances and multisyllable/phrase repetitions, DAF effects in terms of inducing disfluencies were not presented which is similar to Sakai et al. (2009). Several investigators have shown significant changes in OD between non-altered feedback condition and DAF but they meaured OD with different methods from the ones employed in the current study. Corey and Cuddapah (2008) only looked at changes in the number of interjections in conversational speech and showed a significant decrease of interjection counts under DAF. In Van Borsel and colleague's study (2005), several types of OD were measured but mixed with SLD. For example, 'interjections' and 'revisions' were cagorized as one variable with 'prolongations,' one of stuttering-like disfluencies.

According to the current results, ODs under aNAF and DAF were positively correlated in both spontaneous speech ($r = .41$, $p = .001$) and reading ($r = .51$, $p < .001$) indicating that normally fluent individuals who have low OD under aNAF also tend to have low OD under DAF. Additionally, OD rather showed significant task and sex influences. As predicted, due to the nature of the tasks that there was decreased demand to plan "what" to produce during reading, OD was significantly lower in reading than in spontaneous speech. This finding is consistent with Lutz and Mallard (1986) study, showing that 'interjections' and 'revisions' were common among their 50 normally fluent participants during conversation but only some of the participants had few disfluencies during reading. The male group showed higher OD counts than the female group in spontaneous speech under aNAF condition. This was an unexpected finding but could serve as a hint that males have a greater susceptibility to language-formulation disruptions. Reviewing the differences between SLD and OD and related literature, Yairi

and Ambrose (2005) noted that OD is as common, at times even more common, in speech of PWNS and that the basic features are quite different from SLD. For example, Manning and Shirky (1981) considered SLD as "motoric" fluency breaks whereas OD were referred to as "formulative" fluency breaks. That is, these disfluencies appear to refelect some hesistation in the planning with linguistic components at the background. Thus it could be interpreted that OD arise from a different mechanism than SLD and SE in that OD may not be influenced as much by auditory-to-motor integration disruption. The interpretation can be supported by several experimental linguistic research studies. Some studies demonstrated that OD (or filled pause) can be a hint of utterance length and complexity. If an OD precedes a clause, the clause has a higher chance to contain more number of words as well as listeners assume the following phrase would be longer and/or complex (Cook, Smith, & Lalljee, 1974; Watanabe, Hirose, Den, & Minematsu, 2008). Also, increased syntactic complexity of utterances was possitively correlated with the number of OD, not with the number of SLD for both adolescents who stutter and normally fluent peers (Silverman & Ratner, 1997).

3. Research Question 3. Subgroups of people who differ in DAF susceptibility: Identification of three subgroups

In a large sample of participants used in the current study, it was possible to classify subgroups in response to variations in DAF susceptibility in each task. Indeed, the results agree with earlier reports that some individuals are quite fluent under DAF (low susceptible) whereas others show considerable speech disruptions (highly susceptible) (Burke, 1975a; Yates, 1963a, 1963b). Still, the current study has yielded

more comprehensive and accurate data in terms of the tasks, variables, and analysis methods. First, although Burke (1975a) recruited a larger N (200 participants) than used in the current study, intending to identify subgroups, data were collected only for reading. Second, participants were rank-ordered based on correct syllable rate under DAF. Then, the upper and lower 16% of the participants were clasified as having High or Low DAF susceptibility. Third, disfluency counts included all types (speech errors, SLD, and OD) in a single category. Fourth, the investigator measured *overall speaking rate* that included pauses, even in the reading task. In contrast, in the current study, subgroups were identified in a systematic procedure wherein data for three variables: SLD, SE, and AR that yielded significant differences between aNAF and DAF conditions. These were then used to conduct a multivariate cluster analysis to test for the presence of meaningful subgroups. In addition, the present study used SLD and SE separately, and measured *articulation rate* that excluded any disfluencies and pauses greater than 250ms.

Four clear distinctions between *Low* and *High Responders* emerged under DAF: (a) The *Low Responders* exhibited the smallest numbers of SLD and the *High Responders* exhibited the most SLD. Interestingly, the mean number of SLD for *the Low Responders* in spontaneous speech and in reading was 2.21 and 3.29 respectively. These figures are below, or close to, the criterion commonly employed for diagnosing the presence of stuttering (3 SLD per 100 syllables, Yairi & Ambrose, 2005). The mean SLDs of the *High Responders*, 19.35 in spontaneous speech and 16.54 in reading were well above the minimal criterion for stuttering. In fact, these figures would typically be regarded as rather severe stuttering. As discussed in Section 2.1, the increased number of SLD, especially, in the *High Responders* emphasizes the role of auditory-motor

integration in speech production and it could also represent why PWS produce stuttering-like disfluencies under natural feedback condition.

(b) The *Low Responders* had significantly fewer SE than the *High Responders*.

(c) The different auditory-to-motor integration functions for SLD and SE among subgroups were not detected when auditory feedback was not altered.

(d) The *Low Responders* showed faster AR than the *High Responders* under DAF, but the difference was not statistically significant in spontaneous speech. In reading, the *Low Responders* showed significantly faster AR than the *High Responders* both under aNAF and DAF.

The performances under DAF support that, in general, *Low Responders* have better speech-motor skills, enabling them to overcome the DAF influence. In other words, even though feedback control system has been weakened due to DAF, the feedforward control of the *Low Responders* could help maintain fluent speech production. In addition, they could show relatively faster AR than *High Responders*, who are more dependent on auditory feedback. As discussed in Section 2.2, the amount of decrease in AR might be a disruption by, or compensate for, DAF, depending on their auditory feedback dependency. Nonetheless, it is clear that even though the *Low Responders* showed lower SLD and SE, and faster articulation rate than the *High Responders* under DAF, their responses were not with the same as their responses under aNAF suggesting that speech motor controls are influenced by auditory feedback.

The difference between the two subgroups under aNAF in the reading task was unexpected but it might be related to the characteristics of speech rate during reading. Reading rate is characterized by interspeaker and situational variability influenced by

several factors, such as neurological capacities, social considerations, intelligence, written word comprehension, grammatical difference, phrase positions, and/or type of reading materials (Crystal & House, 1982; Gordon, 1989; Sorensen, Cooper, & Paccia, 1978; Tsao & Weismer, 1997). Furthermore, Tsao and Weismer (1997) reported habitually slow and fast reader groups that differ in both overall speaking rate and articulation rate. The groups also showed significantly different rate increment when reading a passage with their maximum reading speed. In response to the findings, the authors suggested different neuromuscular abilities, which may point to "different motor limits for producing rapid outputs (p. 864)," between the groups. Here, we might apply the results of Tsao and Weismer (1997) to our finding. The *Low Responders* might even have faster reading rate under aNAF condition because of their highly developed speech motor skills, which is probably related to higher motor limits to produce speech sounds. In addition, along with the trend of AR in aNAF, it is obvious that delayed feedback disrupted the *High Responders*' reading rate much more than that of the *Low Responders*. The amount of change in AR under DAF compared to aNAF for the *Low Responders* was 15.99 % whereas that for the *High Responders* was 38.65%.

Middle Responders' reactions to DAF were task dependent. They exhibited fewer SLD, similar SE, and faster AR than the *High Responders* regardless of tasks. In spontaneous speech, the *Middle Responders* showed more SLD and SE, but similar AR, to the *Low Responders.* In reading, however, their SLD and SE counts were similar, and their AR slower, than those of the *Low Responders.* The findings not only support our original prediction that *Middle Responders* would maintain relatively fluent speech in terms of SLD, but also demonstrate independent characteristics of SE as discussed above.

The *Middle Responders* showed higher unintentional speech processing errors under DAF than the *Low Responders*, a difference that was statistically significant in spontaneous speech under DAF. Even though there was a task influence, this result could indicate that the *Middle Responders* may have less established feedforward control, in terms of speech articulatory accuracy, than the *Low Responders*. The *Middle Responders*' AR was also reduced under DAF although to lesser degree than the *High Responders*. The result of AR was different from our prediction in that changes in AR would be similar to the *High Responders*. This finding might also support that AR changes are related to auditory feedback dependency. If feedforward control could maintain their fluent speech production with certain level under DAF, the speed of articulatory movement would be less disrupted or controlled. Thus, people may react to DAF in various ways that also vary with the mode of speech for the *Middle Responders*.

Despite differences in group membership in the two independent cluster analyses as listed in Appendices F and G, there was significant overlap in classification across the tasks. The number of participants in *Low Responders* was same in both tasks. There were more *Middle Responders* (32 participants) and fewer *High Responders* (12 participants) in spontaneous speech, while fewer *Middle Responders* (24 participants) and more *High Responders* (20 participants) were classified as such in reading. More than a half of the participants, however, overlapped across the tasks. Fifty percent (9 out of 18) of *Low Responders* in spontaneous speech were also identified as *Low Responders* in reading and vice versa. Eighty three percent (10 out of 12) of *High Responders* in spontaneous speech were also categorized in *High Responders* in reading. Participants who were not overlapped in both tasks were identified in *Middle Responders* except one

participant. The participant was classified as a *High Responder* in spontaneous speech but as a *Low Responder* in reading. Although it is not accurate to explain different classification for same subject with only one variable because the subgroups were determined using three variables, the number of SLD seems to influence the group change. The number of SLD in spontaneous speech was 19.80 and that in reading was 4.40 for this participant. Other participants, however, were not grouped from *Low* to *High Responders* or vice versa for the most part.

CHAPTER III

STUDY II : DAF EFFECTS ON SPEECH FLUENCY AND ARTICULATION RATE IN NORMALLY FLUENT PEOPLE WITH LOW- AND HIGH STUTTERING LIKE DISFLUENCIES UNDER DAF AND IN PEOPLE WHO STUTTER

Past literature has reported that, on one hand, DAF induces stuttering-like disfluencies and speech errors, as well as decreases articulation rate in normally fluent people whereas, on the other hand, it reduces stuttered speech in people who stutter. As described in Chapter 2, individual variability in DAF susceptibility was investigated in normally fluent people. From that study, two groups were identified specifically using a multifactorial cluster analysis that differed in DAF susceptibility; *Low Responders* show the smallest number of SLD in spontaneous speech and reading tasks whereas *High Responders* showed the most SLD regardless of tasks. Speech errors and articulation rates, however, did not show consistent patterns among subgroups in two tasks. It was concluded that the frequency of SLD is the most significant indicator of susceptibility to DAF. Therefore, for Study II, two groups were identified in response to the number of SLD in spontaneous speech from Study I. The 62 subjects were sorted with a hierarchical order of SLD counts under DAF, and 15 normally fluent speakers who had lowest SLD (*Low-SLD* group) and 15 normally fluent speakers who had highest SLD (*High-SLD* group) were selected.

The findings confirm there is differential susceptibility to stuttering-like disfluencies under DAF among normally fluent individuals, which means there is variability among individuals in auditory-to-motor-integration ability for speech production. Given the hypothesis that individuals who stutter have a deficit or difference

in auditory-to-motor integration, it is important to evaluate the effects of DAF on PWS to determine how they are different from the normally fluent groups identified in Study I. DAF has been used in treatment programs to ameliorate stuttering, even though the role in auditory-to-motor integration in fluency-inducing effects remained unclear. Therefore, it is necessary to compare data from PWS with subgroups from normative data collected in Study I in order to control for stimulus characteristics and to identify DAF susceptibility among PWS. In this study, only the spontaneous speech task described in Study I was employed to evaluate responses of PWS under DAF and aNAF. The reading task was not used in order to get results from more natural speech environment. There have been only few studies that measured effects of altered auditory feedback in spontaneous conversation and/or monologue speech (Antipova, Purdy, Blakeley, & Williams, 2008; Armson, Kiefte, Mason, & De Croos, 2006; Armson & Stuart, 1998; Burke, 1975b; Ingham, Moglia, Frank, Ingham, & Cordes, 1997; Pollard, Ellis, Finan, & Ramig, 2009). Most AAF studies were designed with reading as the experimental task (e.g., Armson, Foote, Witt, Kalinowski, & Stuart, 1997; Hargrave et al., 1994; Kalinowski et al., 1993; Sparks et al., 2002; Van Borsel et al., 2003) to control for potential variables or avoidance strategies, such as substitution or circumlocusion, prior to suttering events. People who stutter, however, experience most of their speaking difficulties during daily communication and several studies have reported weaker effects of AAF in monologue/spontaneous speech compared to reading (Armson & Kiefte, 2008; Ingham et al., 1997).

Ameliorating effects of DAF on PWS have been observed with maximum comfortable listening level or average conversational SPLs (e.g., Kalinowski et al., 1993:

output of 85dB SPL with input of 75dB SPL; Zimmerman et al., 1997: most comfortable listening level) whereas the DAF effects on normally fluent people (i.e., inducing disfluencies) have been generally observed under high intensity levels to facilitate speech disruptions (e.g., MacKay, 1970: 95dB SPL; Siegel et al., 1980: 95dB SPL; Van Borsel et al., 2005: 96dB SPL). For control condition, amplified non-delayed feedback has been used because PWNS did not show significantly different speech patterns except loudness change (Foundas et al., 2004; Siegel et al., 1982) and investigators could maintain same experimental setting with DAF condition (e.g., Fukawa, Yoshioka, Ozawa, & Yoshida, 1988; Kalinowski et al., 1996; Mackay, 1970). Therefore, the first purpose of Study II was to compare DAF susceptibility in PWS with the groups of normally fluent speakers identified in Study I using the same methodology. PWS group was compared to the normally fluent *Low- and High-SLD* groups under DAF. PWS are expected to reduce their disfluencies and show relatively fluent speech that is similar to the normally fluent *Low-SLD* group.

The second purpose of this study was to determine the role of different loudness levels in auditory feedback for PWS. Previous research has reported that PWS reduce their stuttering-like disfluencies under high level noise (Cherry et al., 1955; Shane, 1946, 1955; Yairi, 1976). Simple amplification of auditory feedback but without delay can be also considered altered auditory feedback, so fluency-inducing effects would be expected in PWS. Higher loudness of auditory feedback during ongoing speech production could have an effect similar to the well-known effects on stuttering when speaking in various noise conditions. Therefore, the specific research questions of Study II are:

1. Are there significant differences among the three groups in the numbers of SLD, OD, and SE, and articulation rate under aNAF and DAF in spontaneous conversational speech?
2. Do the the numbers of SLD, OD, and SE, and articulation rate of PWS significantly differ in nNAF and aNAF conditions?

METHODS

1. Participants

The participants in the study included 15 people who stutter (11 males and 4 females) and 30 normally fluent, monolingual native English speakers: 15 *Low-SLD* group (5 males and 10 females) and 15 *High-SLD* group (7 males and 8 females) identified from the results of Study I.

The criteria for the selection of stuttering participants were: (a) monolingual native English speaker, (b) between the ages of 18 and 30 (due to the decrease of hearing sensitivity after age 30, Pearson et al., 1995); (c) previously diagnosed by a speech-language pathologist as a person who exhibits persistent stuttering; (d) exhibit at least 3 SLD per 100 syllables; (e) pass a hearing screening at 20dB HL at 500Hz, 1000Hz, 2000Hz, and 4000Hz; (f) have no known hearing, speech, language, or neurological disorders except stuttering; and (g) be right handed. All participants received a hearing screening test using a GSI 17 audiometer (Grason-Stadler Inc). Handedness scores for the participants were obtained via the Edinburgh Handedness Inventory (Oldfield, 1971).

The mean age of the stuttering participants was 23;4 years; months (SD = 4;2 years) with the age range from 18;10 to 34;3 years. All of the participants were naïve to DAF although one male participant had used a DAF software program once. There was one stuttering male participant whose age was over 30 years. However, because the participant passed the hearing screening for the wider range of frequencies (i.e., 250Hz, 500Hz, 1000Hz, 2000Hz, 4000Hz, and 8000Hz) and met other criteria, he was included. There was also one male participant who was diagnosed as stuttering and cluttering. Because he met other criteria, however, he was also included. Stuttering severity of each participant was evaluated by certified speech-language pathologists following Yairi and Ambrose (2005). The scores of stuttering severity were considered as "mild" (0 – 3), "moderate" (3 – 5), or "severe" (5 – 7). The stuttering severity of 7 PWS was mild, it was moderate for another 7 participants, and severe for 1 participant. The mean severity of stuttering was 2.9 (ranging from 0.67 to 5.32). The mean handedness inventory score was 82.76 (SD = 14.24).

The Low-SLD group ranged in age from 18;8 to 26;3 years with a mean age of 21;1 (SD = 1;10 years), and the mean handedness inventory score was 90.43 (SD = 13.04). Of the 15 participants, 11 were classified as *Low Responders* to DAF, and 4 were classified as *Middle Responders* to DAF.

The mean age of the *High-SLD* group was 19;8 years (SD = 1 year) and the age range extended from 18;6 to 21;10 years. The mean handedness inventory score was 91.52 (SD = 10.96). Of the 15 participants, 12 were classified as *High Responders* to DAF, and 3 were classified as *Middle Responders* to DAF.

2. Task and Procedures

The spontaneous conversational speech task described in Study I was conducted with each stuttering participant. Each stuttering participant participated in the spontaneous speech task without headphones for a natural auditory feedback condition (i.e., nNAF), then performed the task wearing headphones for aNAF and DAF. PWS were instructed not to use fluency enhancing techniques to produce fluent speech. The normally fluent *Low-SLD* and *High-SLD* groups did not participate in the nNAF condition.

During the spontaneous conversational speech task, each participant carried on a casual conversation with an investigator on selected topics, such as the participant's major and current classes, hobbies, plans for vacation or weekends, recent movies that the participant watched, and states or countries where s/he had been. A sample of approximately 400 - 500 syllables with at least 30 utterances was recorded in each feedback condition.

3. Analyses

The data analyses are identical to Study I.

4. Reliability

Similar procedures to those employed in Study I were used to establish reliability for the stuttering participants. Twenty percent of samples (3 PWS recorded under nNAF, aNAF and DAF) were randomly selected. For the intra-rater judge reliability, a volunteer who has extended experiences in SALT transcripts re-listened to three participants'

speech samples and re-marked all the targets. For the inter-rater judge reliability, a certified speech-language pathologist who is specialized in stuttering listened to the same samples that had been completed by another transcriber. All SLD, OD, and SE of three datasets were identified and coded on the SALT transcripts by that person. To estimate the intra- and the inter-judge reliabilities, the "percent of agreement on occurrence" of each variable was used (Baird & Nelson-Gray, 1999; Bryington et al., 2004). For SLD, the intra-rater judge reliabilities for nNAF, aNAF and DAF were .86, .89 and .85, respectively. The inter-rater judge reliabilities for nNAF, aNAF and DAF were .92, .82 and .94, respectively. For OD, the intra-rater judge reliabilities for nNAF, aNAF and DAF were .97, 1.00 and 1.00, respectively. The inter-rater judge reliabilities for nNAF, aNAF and DAF were .97, 1.00 and .93, respectively. For SE, the intra-rater judge reliabilities for nNAF, aNAF and DAF were .78, 1.00 and .89, respectively. The inter-rater judge reliabilities for nNAF, aNAF and DAF were 1.00, 1.00 and .82, respectively.

For the mean articulation rate, the Pearson product-moment correlation analysis was used both for the intra- and inter-rater judge reliabilities. For the intra-rater judge reliability, the three datasets were re-analyzed after a period of one to two months. For the inter-rater judge reliability, a graduate volunteer trained to measure articulation rate, analyzed one dataset with the investigator for practice purposes. She then analyzed three data sets independently. The coefficients of the intra-rater judge reliability were .99 for nNAF condition, .98 for aNAF condition and .99 for DAF condition, and the coefficients of the inter-rater judge reliability was .99 for nNAF condition, .96 for aNAF condition and .97 for DAF condition.

5. Statistical analysis

The SPSS version 16.0 software program was used for statistical analysis. For research question 1, the number of SLD was compared between the PWS, the *Low-SLD* group, and the *High-SLD* group across the two feedback conditions (i.e., aNAF and DAF) using a two-way ANOVA with repeated measures. The same analysis and conditions were used in separate ANOVA's to compare OD, SE and AR. The Tukey HSD post-hoc test was used to test significant main effects and interactions. For research question 2, a separate one-way ANOVA with repeated measures for each variable was used to compare the nNAF, aNAF and DAF conditions within the stuttering group. The Bonferroni pairwise comparison was used to test significant main effects.

RESULTS

1. Patterns of speech perturbations under aNAF and DAF among Low-SLD group, High-SLD group and PWS

There were no obvious differences between *Low-SLD* and *High-SLD* groups under aNAF in terms of SLD, OD, SE and AR as summarized in Table 11. PWS had more SLD, OD, and SE, as well as faster AR compared to the normally fluent groups in the aNAF condition. PWS also showed larger variability for all variables. Under DAF, the *High-SLD* group and PWS showed obvious increases in SLD compared to the *Low-SLD* group. SE increased in all the groups but the *High-SLD* group and PWS showed larger changes compared to the *Low-SLD* group. The standard deviations of SLD and SE were larger under DAF in each group. OD decreased under DAF for the *Low-SLD* and

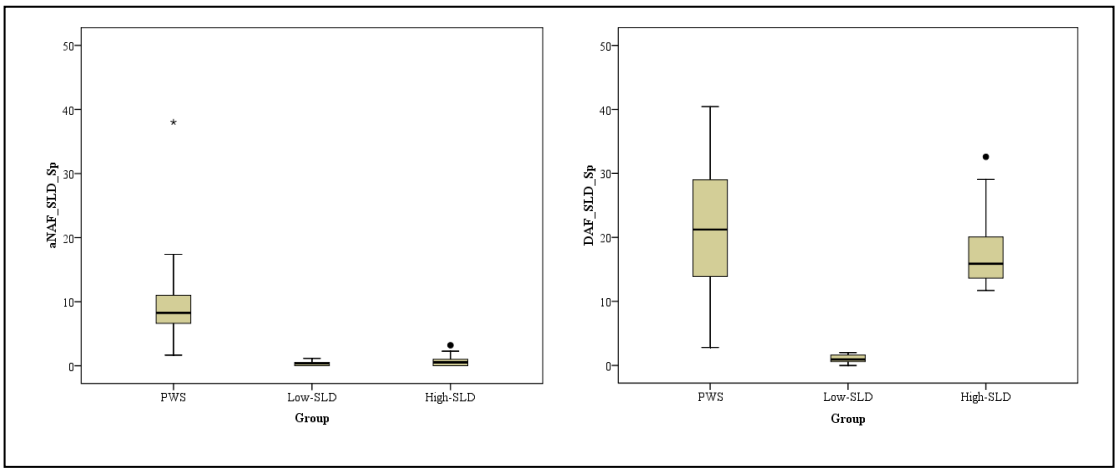
PWS groups but not for the *High-SLD* group. Each group showed a slower AR under DAF compared to aNAF.

Table 11. Means and standard deviations (in parenthesis) of speech perturbations under aNAF and DAF conditions

Group	Auditory feedback	SLD	OD	SE	AR
Low-SLD (N = 15)	aNAF	0.30 (0.35)	5.07 (2.73)	0.00 (0.00)	5.32 (0.67)
	DAF	1.00 (0.62)	4.55 (2.60)	0.45 (0.71)	4.57 (0.44)
High-SLD (N = 15)	aNAF	0.82 (0.97)	4.59 (2.81)	0.02 (0.07)	5.19 (0.48)
	DAF	17.95 (6.24)	5.21 (2.57)	1.19 (0.97)	4.32 (0.63)
PWS (N = 15)	nNAF	9.60 (5.89)	7.06 (3.68)	0.19 (0.32)	5.77 (0.54)
	aNAF	10.25 (8.59)	8.79 (6.15)	0.14 (0.26)	5.63 (0.95)
	DAF	22.05 (10.93)	7.68 (5.52)	1.33 (1.15)	5.10 (0.82)

SLD = stuttering-like disfluencies; OD = other disfluencies; SE = speech errors; AR = articulation rate measured in syllables per second (SPS)

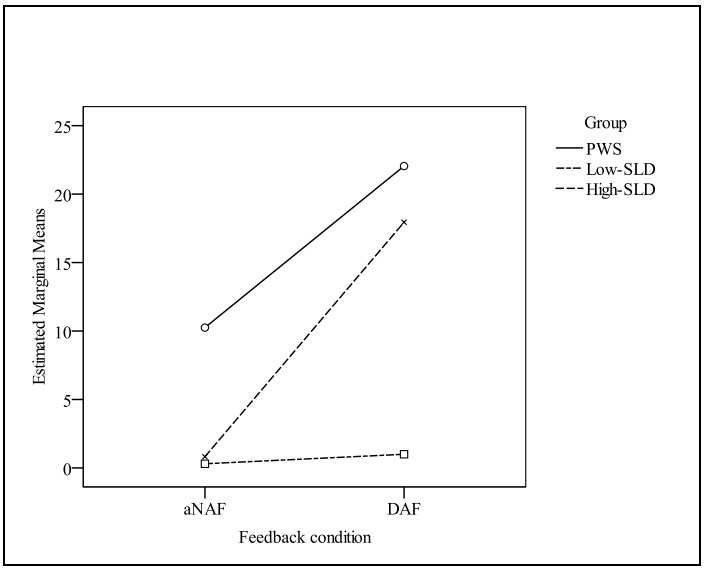
Figure 10. SLD boxplots for PWS, *Low-SLD*, and *High-SLD* groups under aNAF (left) and DAF (right) conditions



1.1. Stuttering-like disfluencies

Figure 10 illustrates the distribution of SLD in each group under aNAF and DAF conditions. Statistical test revealed significant main effects for auditory feedback (F (1, 42) = 80.37, $p < .001$) and group (F (2, 42) = 35.78, $p < .001$). Also, there was a significant interaction between the auditory feedback and group ($p < .001$) indicating that the PWS group showed significantly more SLD than the *Low-SLD* ($p < .001$) and the *High-SLD* groups ($p < .001$) under aNAF, whereas the *Low-SLD* group showed significantly fewer SLD than the *High-SLD* ($p < .001$) and the PWS groups ($p < .001$) under DAF (see Figure 11).

Figure 11. Interaction between group and auditory feedback in SLD

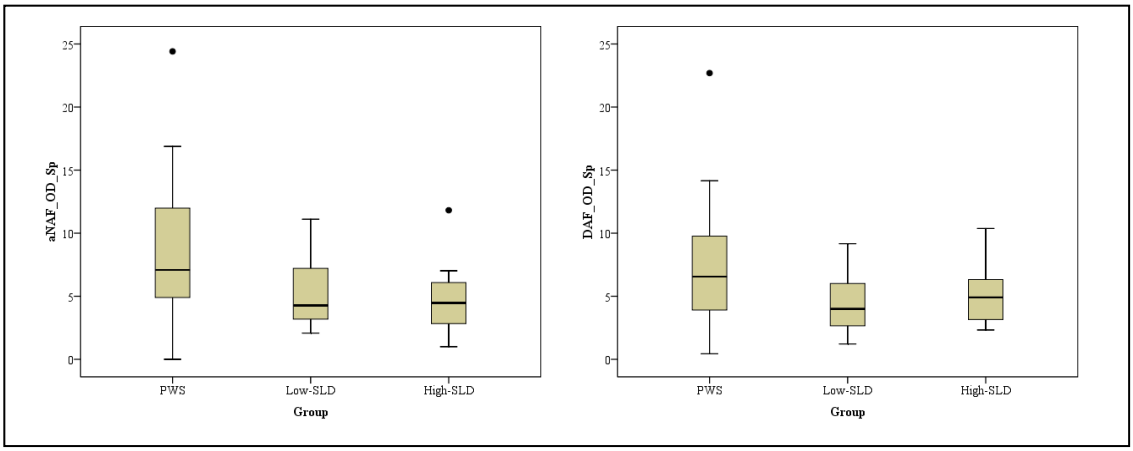


1.2. Other disfluencies

The distributions of OD in the three groups under aNAF and DAF conditions are illustrated in Figure 12. The statistical test revealed a significant main effect for group (F

(2, 42) = 4.67, p = .015) but not for auditory feedback (F (1, 42) = .32, p = .574). PWS showed significantly higher OD than *Low-SLD* (p = .028) and *High-SLD* groups (p = .033).

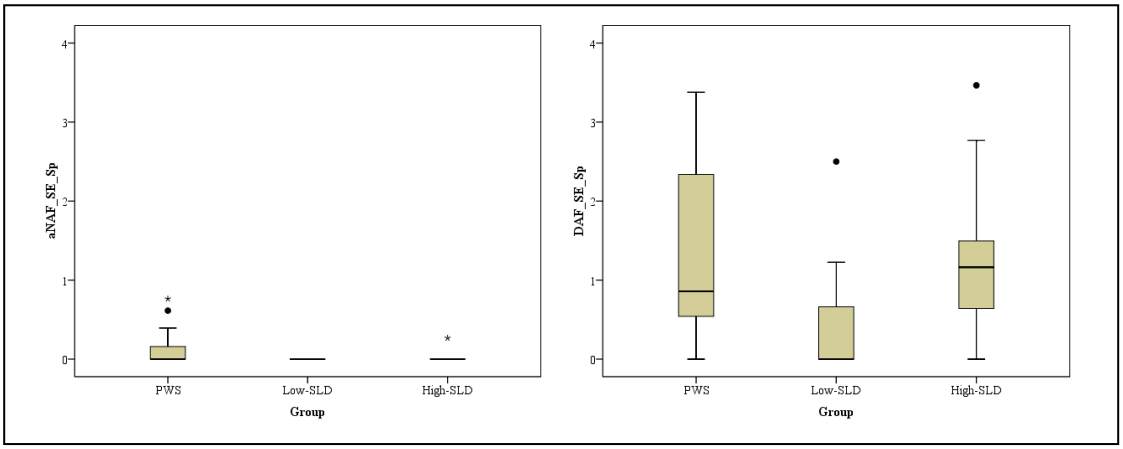
Figure 12. OD boxplots for PWS, *Low-SLD*, and *High-SLD* groups under aNAF (left) and DAF (right) conditions



1.3. Speech errors

Figure 13 shows the distribution of SE among the three groups in aNAF and DAF conditions. SE under DAF was significantly higher than that under aNAF (F (1, 42) = 38.85, p < .001). A significant main effect was also observed for group (F (2, 42) = 4.75, p = .014) indicating that PWS showed significantly more SE than *Low-SLD* group (p = .014).

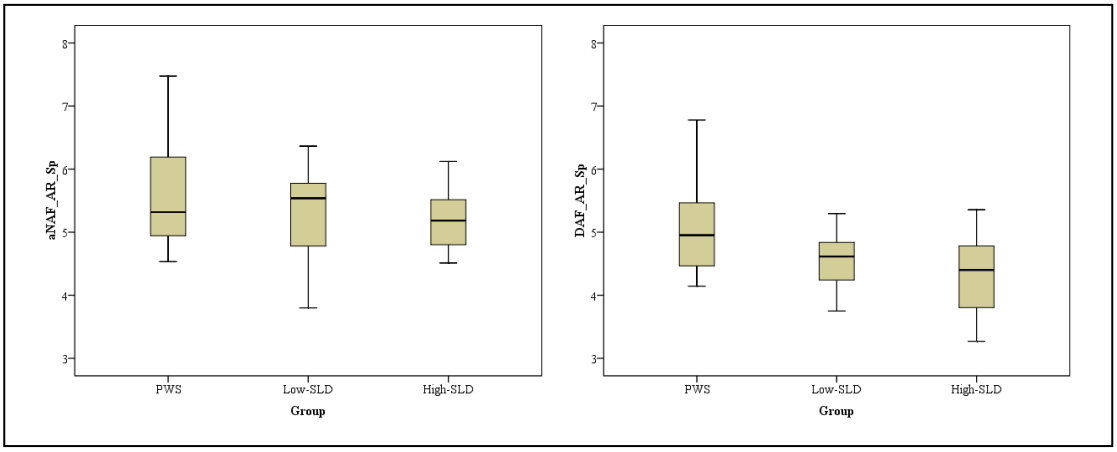
Figure 13. SE boxplots for PWS, *Low-SLD*, and *High-SLD* groups under aNAF (left) and DAF (right) conditions



1.4. Articulation rate

The data for AR are illustrated in Figure 14. Significant main effects were detected for auditory feedback (F (1, 42) = 65.71, p < .001) and group (F (2, 42) = 3.78, p = .031). AR was significantly faster under aNAF compared to DAF. In addition, PWS showed significantly faster AR than *High-SLD* group (p = .027)

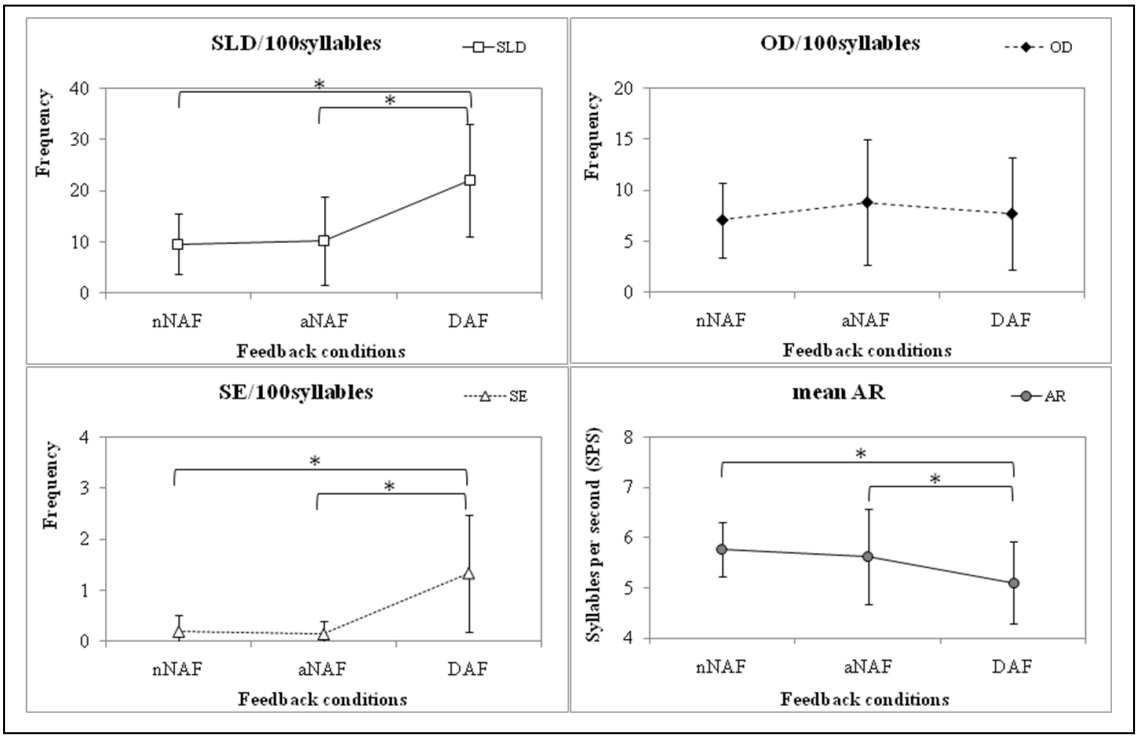
Figure 14. AR boxplots for PWS, *Low-SLD*, and *High-SLD* groups under aNAF (left) and DAF (right) conditions



2. Speech perturbations under nNAF, aNAF and DAF conditions in PWS

The performance of the PWS in the three auditory feedback conditions is illustrated in Figure 15 and descriptive data is provided in Table 9.

Figure 15. Means and standard deviations (error bar) of each independent variable (SLD, OD, SE, AR) for PWS under nNAF, aNAF and DAF conditions



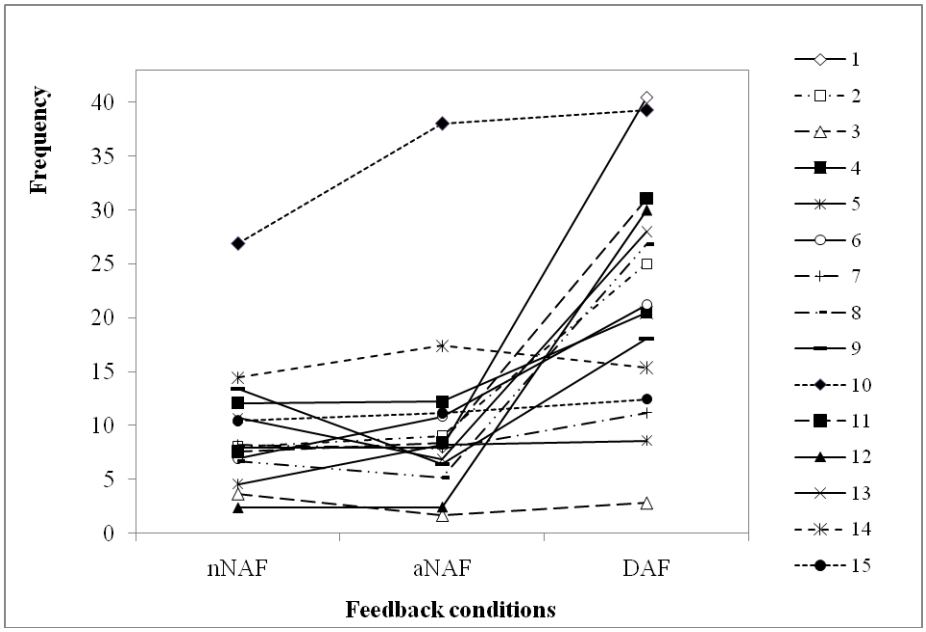
2.1. Stuttering-like disfluencies

PWS produced substantially more SLD under DAF than nNAF or aNAF, but the two non-delayed conditions showed similar findings. A significant main effect for auditory feedback (F (2, 28) = 17.76, $p < .001$) indicated the number of SLD was significantly changed; SLD was significantly higher under DAF condition compared to

both aNAF (p = .001) and nNAF (p = .003). There was no significant difference in SLD between nNAF and aNAF conditions.

The numbers of SLD of the 15 individuals who stutter are plotted in Figure 16 to inspect the SLD changes among nNAF, aNAF, and DAF. Individual variability in auditory feedback influences (i.e., aNAF and DAF) on SLD was observed. Compared to nNAF condition, 40% of PWS (i.e., 6 participants) had fewer SLD under aNAF condition even though the statistical test did not find a significant mean difference. Their SLDs were decreased with the range between 0.04% and 54.19%. Under DAF condition, however, only 6.67% of PWS (i.e., 1 participant) decreased SLD compared to nNAF condition. The number of SLD was 3.62 under nNAF condition and 2.79 under DAF condition.

Figure 16. The numbers of SLD per 100 syllables for 15 stuttering individuals under nNAF, aNAF and DAF conditions



2.2. Other disfluencies

The number of OD under aNAF condition was relatively larger than nNAF and DAF conditions. The repeated measures ANOVA, however, did not yield a statistically significant main effect (F (2, 28) = .89, p = .423).

2.3. Speech errors

There were more speech errors under DAF condition than under the other auditory feedback conditions. A statistical test confirmed the effect of auditory feedback (F (2, 28) = 12.95, p < .001) showing SE was significantly higher under DAF condition than nNAF (p = .008) and DAF (p = .008). No significant difference was observed between nNAF and aNAF conditions.

2.4. Articulation rate

The AR under DAF condition decreased relative to the other auditory feedback conditions. A significant main effect for auditory feedback (F (2, 28) = 7.26, p = .003) confirmed that AR was significantly slower under DAF than nNAF (p = .010) and aNAF (p = .015). AR was not significantly different between the non-delayed conditions.

DISCUSSION

1. Summary of study

Study II compared the effects of DAF on speech fluency and articulation rate between normally fluent adults (PWNS) who participated in Study I and a group of adults

who stutter (PWS). All measurents were taken from video- and audio recorded spontaneous speech samples. The normally fluent speakers were rank-ordered based on the number of SLD they produced under the DAF condion. Accordingly, the lower and upper 24% of the participants (15 out of 62 participants) were classified as *Low-SLD* group and *High-SLD* group, respectively. The most significant finding is that, on the average, PWS did not lower their SLD counts under DAF condition. This does not support our prediction and sharply contradicts the majority of previous reports on the ameliorating DAF effect on the SLD of PWS. Under DAF, people who stutter exhibited a larger mean numbr of SLD than the PWNS classified as *Low-SLD* group but a similar mean to those classified as *High-SLD* group. For all groups, changes in the effects on SE and AR were similar to those reported in Study I in that SE score was larger and AR was slower under DAF than aNAF. In addition, PWS exhibited more SE than the normally fluent *Low-SLD* group and faster AR than the *High-SLD* group.

Another finding of Study II is that responses to amplified non-delayed feedback (aNAF), as expressed in SLD, OD, SE and AR, did not differ from responses to natural feedback (nNAF) condition. Individual variability, however, was observed in the number of SLD in that 40% of PWS reduced thems under aNAF condition. These findings are line with our prediction and may be interpreted as supporting various suggestions (Foundas et al., 2004; Seery, Watkins, Mangelsdorf, & Shigeto, 2007; Yairi, 2007) that there are subtypes in stuttering. For some PWS, auditory feedback amplification could work as a fluency enhancing with similar amelioration effects to those of noise stimulation.

2. Research Question 1. Effects of DAF on the three groups: Unexpected change in SLD in people who stutter

DAF has been known to reduce SLD for PWS, and the therapeutic effects have been investigated using various electronic devices and software programs (e.g., Curlee & Perkins, 1973; Craven & Ryan, 1984; Kalinowski et al., 1996; Sparks et al., 2002; Van Borsel et al., 2003; Zimmerman et al., 1997). Reduction rate in stuttering under DAF and/or FAF during monologue has been reported in the range of 30% to 67% for PWS (Antipova et al., 2008; Armson et al., 2006; Armson & Kiefte, 2008; Stuart et al., 2004). The current study, however, revealed PWS had a substantially larger number of SLD (M = 22.05) under DAF compared to aNAF (M = 10.25). It is similar to that of the normally fluent *High-SLD* group. Whereas previous studies have reported individual variability in reducing SLD under DAF for PWS, depending on subtypes, stuttering severity, or age (Burke, 1975b; Howell, Davis, & Williams, 2006; Foundas et al., 2004; Naylor, 1953), in the current study only one individual who moderately stuttered decreased his SLD (by approximately 11.74 %) under DAF compared to aNAF. An interesting observation is that the participant actually showed lower SLD counts under natural feedback (nNAF) condition compared to aNAF and DAF. More description is provided in later section. Similarly to the normally fluent groups, PWS also produced part-word echo and wavering voice that are qualitatively different types of disfluency shown in DAF.

Several explanations of this unusual finding are offerred. Although individual variability in reponses to various auditory conditions have been reported in the past, e.g., for noise (Yairi, 1976) and dichotic stimuli (Sommers, Brady, & Moore, 1975), none has reported such sharp contradictory trend. The discrepancy between current and previous

findings may be explained by the different loudness level employed. In most past studies DAF was delivered at maximum comfortable listening level, or average conversational loudness, to achieve the ameliorating effect (e.g., Kalinowski et al., 1993; Zimmerman et al., 1997) whereas in the current study amplified DAF was delivered for the identical experiment setting to the normally fluent groups (i.e., Study I: 95dB SPL output with 94dB SPL input, and then adjusted to set "loud but O.K." level). Perhaps it is possible to understand the relation between SLD counts and loudness of auditory feedback in PWS by understanding normally fluent individuals' responses to DAF. Normally fluent people show speech disruptions under DAF with individual variability (Burk, 1975a; Mackay, 1970; Stuart et al., 2002; Van Borsel et al., 2005) and the added loudness in the DAF may cause more speech disruptions (Howell & Archer, 1984; Stuart et al., 2002). For example, Stuart and colleague (2002) employed several delay times (i.e., 25ms, 50ms, and 200ms) at average conversational speech level when PWNS read a passage. At 200ms-DAF, PWNS exhibited maximum SLDs but the mean count was only 4 per 300 syllables. This is considerably lower from the mean of 7.70 per 100 syllables as reported in Study I. In addition, when presenting DAF at three different loudness levels (10, 20, and 30dB amplifications), normally fluent people showed greater susceptibility under louder DAF condition (Howell & Archer, 1984). In Study I, it was possible to classify *Low* and *High Responders* even using amplified DAF, and support the hypothesis that the *High Responders* are more dependent on auditory feedback. In Study II, PWS also exhibited high SLD counts, supporting our hypothesis that PWS are also more dependent on auditory feedback for ongoing speech production rather than feedforward control.

Another possible interpretation of higher SLD in PWS could be length of the delay time or interaction between loudness and the delay time. Early studies explored optimal delay time for reducing stuttering and reported fluency improvement with longer DAF (i.e., around 250ms) for PWS (e.g., Andrews et al., 1982; Goldiamond, 1965). The problem with earlier studies, however, is that some of them did not specify the loudness level for DAF. At the present, shorter delay is preferred for investigating treatment outcome, including speech naturalness, because at longer delay, speech rate is generally slowed down and the speech sounds unnatural. Since Kalinowski and associates (1996) reported stuttering reduction with relatively normal speech rate at shorter delay feedback, recent studies have generally used 25 – 90ms, or flexible delay time, depending on the preference of participants. There are several studies that may support our interpretations. Burke (1975b) reported changes in SLD with several delay times under amplified DAF (100 dB). Compared to non-delayed feedback, the percentage of stuttering was decreased at 50 and 100ms DAF, but with longer delay, his participants exhibited trends of reduced fluency. Watkins et al. (2008) also found SLD increament under 200ms-DAF. The loudness level, however, was not specified and the increment did not meet the statistically significant level. For stuttering treatment, Curlee and Perkins (1973) delivered 250ms delay to participants with their the maximum level of loudness. The main object for this delay time and loudness was to slow down speaking rate. They reported their participants had to produce slower rate to "avoid" speech disruption under longer time delay setting (p.400).

In the current study, all groups decreased AR under DAF. In view of previous literature, this finding is not surprising. Interestingly though, PWS showed faster AR

than *High-SLD* group. Suprasegmental mechanism was influenced by DAF but the normally fluent *High-SLD* group showed the most DAF effects. Also measured were the changes in SE and OD. DAF studies with stuttering population have generally measured changes in SLD counts and speaking rate. Both PWS and normally fluent groups yielded more SE under DAF condition, showing speech-motor controls for speech accuracy are interrupted by auditory feedback changes regardless of participants. The amount of the unintentional processing errors, however, was larger for PWS than for the *Low-SLD* group. PWS also exhibited more OD than normally fluent groups, a finding consistent with previous report (Yairi & Ambrose, 2005). As reported in Study I, however, OD was not influenced by DAF both in PWNS and PWS. In Study I, the different mechanism of OD was discussed. If we accept that OD is related to linguistic planning processes, and given that it can be observed both PWS and PWNS (Manning & Shirkey, 1981; Yairi & Ambrose, 2005), the qualitative features would differ from speech-motor execution for PWS.

The current finding regarding SLD was unexpected but can still be interpreted to support our hypothesis. In general, susceptibility to DAF is seen in SLD and SE changes in both PWS and normally fluent people with PWS showing higher SLD and SE than *Low-SLD* group. It is the opposite of our original prediction regarding the disfluencies but supports our overall hypothesis that PWS depend on auditory feedback for ongoing speech production. It also supports the assertion that auditory-to-motor integration of PWS might work similarly to that of normally fluent individuals who are highly susceptible to DAF. It is still unclear, however, how DAF influences PWS on SLD in normal level of loudness.

3. Research Question 2. Effects of amplification for PWS: Individual variability in SLD changes under DAF

As discussed above, whereas DAF significantly influenced changes in mean SLD, SE, and AR for PWS, responses under aNAF did not differ significantly from those under nNAF condition. It is interesting to note that PWS showed greater variability under aNAF for all of the measures. Especially for SLD, 40% of this group produced fewer SLD under aNAF condition with a reduction range of 0.04 – 54.19%. Also, two participants (13% of PWS) did not show obvious change in SLD showing 1% and 3% increment under aNAF. This finding is consistent with previous observations for masking auditory feedback (MAF) where PWS reduced stuttering by 52% (Andrews et al., 1982) but the ameliorating effects under MAF are less powerful than other AAF conditions (Howell et al., 1987; Kalinowski et al., 1993). Even though the mean SLD under aNAF was not statistically different from natural condition, it could support our prediction that simple feedback amplification effects stuttering reduction for some PWS. An inspection of the individual data, however, for example, of the stuttering severity or sex, has not revealed any particular characteristics that can explain the diverse responses of the participants. In the 40% of participants (N = 6) who decreased SLD under aNAF, three participants were diagnosed as "mild" stuttering and the other three as "moderate" stuttering. The sex ratio was same as well (3 males and 3 females). There were two participants who showed inconsistent responses to altered auditory feedback (i.e., aNAF and DAF). One participant increased SLD counts under AAF but more disruption was

observed in aNAF. The other participant decreased SLD in both AAF conditions but showed more reduction under aNAF.

AR also showed individual variability: nine stuttering participants decreased AR by 11.46% with the range of 2.38 – 19.82% whereas six showed faster AR. The mean rate of increament was 11.03% (range: 3.08 – 26.63%). These individual differences prevented the detection of statistical significance in mean AR between nNAF and aNAF. SE showed unreliable patterns because more than a half of participants (8 out of 15) did not exhibit SE under the non-delayed feedback conditions, showing that increased unintentional speech inaccuracy were only related to the time-delayed feedback. In the case of OD, there was no significant difference among feedback conditions but showed higher variability under aNAF and DAF. This finding also supports the notion of different mechanism of OD from SLD as discussed previously.

Overall, the current study supports our general expectation as well as individual variability in PWS. Details regarding individual variability will be discussed in Chapter 5.

CHAPTER IV

STUDY III : DIFFERENCES IN SPEECH-MOTOR STABILITY AND MOVEMENT PATTERNS BETWEEN NORMALLY FLUENT PEOPLE AND PEOPLE WHO STUTTER UNDER DAF

Susceptibility to DAF has been investigated with respect to temporal and perceptual parameters, such as duration of speech and speech disruptions, respectively (e.g., Jones & Striemer, 2007; Lee, 1951; Van Borsel et al., 2005), but not with regard to kinematic parameters. Clearly, changes in speech production occur under DAF because delays can induce disruptions of speech in normally fluent speakers (i.e., disfluencies, slower speech) on one hand, and reduce disfluencies in people who stutter on the other one. An explanation for this dissociation is predicted to involve divergent auditory-to-motor processes in normal and stuttering participants.

The current kinematic study compares changes in speech kinematic stability, movement displacement, and velocity of the lower lip movements as well as temporal parameters under two DAF (25ms-DAF, 50ms-DAF), aNAF and nNAF conditions in normally fluent people and people who exhibit persistent stuttering. Previous research reported that PWS and PWNS can maintain relatively normal speech rates under 25ms- and 50ms-DAF conditions (Kalinowski et al., 1996; Sparks et al., 2002; Stuart et al., 2002) and PWS can maintain acceptable speech naturalness under shorter amount of delay (Pollard et al., 2009). Additionally, both the 25ms and 50ms delay reduce disfluencies in PWS, and especially at 50ms delay, more stuttering reduction was observed (Kalinowski et al., 1996). For PWNS, the number of disfluencies is not different under non-delayed, 25ms-DAF, and 50ms-DAF conditions, and also speech rate

does not differ in non-delayed and 25ms-DAF conditions (Stuart et al., 2002). Interestingly, even under natural auditory feedback, slower speech rates induced greater motor instability than habitual speech rate for both PWS and PWNS (Smith et al., 1995; Smith & Kleinow, 2000). Therefore, the 25ms- and 50ms-DAF were chosen to minimize potential effects of artificially slowed speech on motor stability. It is hypothesized that spatiotemporal kinematic parameter (i.e., spatiotemporal index or STI) would vary significantly under the four auditory feedback conditions with normally fluent people showing less motor stability of lower lip under DAF conditions than under aNAF and nNAF conditions. In contrast, PWS would show lower motor stability of the lower lip under nNAF condition compared to aNAF or DAF conditions. As for the displacement and velocity, PWS would show similar or lower single sequential movements compared to PWNS under nNAF (McClean, Kroll, & Loftus, 1990; Smith & Kleinow, 2000; Zimmermann, 1980). Also, in response to a previous report that both movement displacement and velocity were influenced by the rate of speech (Smith & Kleinow, 2000), these two parameters would be expected to interact with articulation rate under altered auditory feedback conditions (AAF: 25ms-DAF, 50ms-DAF, and aNAF). The specific research questions are as follows:

1. Do PWS show <u>higher</u> speech-motor stability of lower lip under aNAF, 25ms-DAF and 50ms-DAF conditions compared to nNAF condition, while PWNS show <u>lower</u> speech-motor stability of lower lip under 25ms-DAF, 50ms-DAF conditions compared to nNAF and aNAF conditions?
2. Are the changes in speech-motor stability of the lower lip under AAF conditions similar across different linguistic contexts in each group?

3. Do PWS and PWNS differ in regard to displacement and velocity of lower lip movement under nNAF, aNAF, 25ms-DAF and 50ms-DAF conditions?
4. Do PWS and PWNS differ in regard to kinematic duration and articulation rate under nNAF, aNAF, 25ms-DAF and 50ms-DAF conditions?

METHODS

1. Participants

The participants in the study consisted of 25 monolingual native English speakers who were naïve to DAF, 11 normally fluent adults (7 males and 4 females) and 14 adults who stutter (10 males and 4 females). Of the 14 stuttering participants, 13 PWS participated in Study II. The criteria for participant selection for PWNS were identical to Study I and those for PWS followed Study II. All hearing screenings were conducted with a GSI 17 audiometer (Grason-Stadler Inc). Handedness scores for the participants were obtained via the Edinburgh Handedness Inventory (Oldfield, 1971). Language skills were assessed with the *Peabody Picture Vocabulary Test-III* (PPVT-III, Dunn & Dunn, 1997) and the *Expressive Vocabulary Test* (EVT, Williams, 1997).

The PWNS ranged in age from 21;3 to 23;2 years with a mean age of 22;2 years; months (SD = 9 months). The mean handedness score was 93.04 (SD = 12.39). Their comprehensive and expressive language abilities were within the normal limits with a mean PPVT-III score of 112.91 (SD = 8.36) and a mean EVT score of 114.36 (SD = 16.78).

The PWS ranged in age from 19;0 to 34;3 years with a mean age of 23;3 years; months (SD = 4;5 years). Of the 14 PWS, one male was 34;3 years old but because he passed hearing screening for the frequencies of 250Hz through 8000Hz and met the other inclusion criteria, he was included. Another male, who was diagnosed as exhibiting both stuttering and cluttering but met other criteria, was also included. The stuttering severity of each participant was evaluated by certified speech-language pathologists using the Yairi and Ambrose (2005) scale. The scores of stuttering severity were considered as mild (0 – 3), moderate (3 – 5), or severe (5 – 7). The stuttering severity of 7 PWS was rated as "mild," "moderate" for six participants, and "severe" for 1 participant. The stuttering severity scores ranged from 0.67 to 5.32 with a mean of 2.78 (SD = 1.46). The mean handedness score of the stuttering participants was 83.71 (SD = 15.37) and their comprehensive and expressive language abilities were within normal limits (mean PPVT-III score: 113.21 (SD = 8.89) and mean EVT score: 123.71 (SD = 19.78)). There were no significant differences in the language scores between PWS and PWNS (PPVT-III: $t(23) = .09$, $p = .931$; EVT: $t(23) = 1.25$, $p = .223$).

2. Tasks

Productions of one nonword and four different utterances that varied in length and syntactic complexity were used to sample lower lip kinematics under each feedback condition. The stimuli are listed in Table 12. The 'nonword' phrase, "pa – pa – pa – pa – pa– pa – pa – pa – pa," and the 'simple-short' structured sentence, "Buy *Bobby* a puppy," are baseline stimuli. For the nonword, the first six repetitions of /pa/ were used for analysis. The other three utterances reflect increased length as well as syntactic

complexity but the numbers of words, syllables and grammatical morphemes in the longer utterances are identical. A stimulus with increased syntactic complexity was implemented by inserting a relative clause into a simpler sentence, which follows Kleinow and Smith (2006). Kleinow and Smith (2006) employed a subject relative clause for syntactically complex utterances when they measured lip aperture (distance between the upper lip and lower lip) because previous studies reported that a relative clause (1) appears later than other syntactic structures in childhood, (2) needs more time to process, and (3) increases brain activation of language-related regions comparing to other conjoined utterances in adults (Bloom, Lahey, Hood, Lifter, & Fiess, 1980; Just, Carpenter, Keller, Eddy, & Thulborn, 1996). A syntactically wrong utterance was introduced by altering the orders of words because participants were expected to need

Table 12. Speech stimuli for the kinematic tasks (The numbers of words, syllables, and morphemes are identical in speech conditions 3 through 5)

Speech condition (Complexity)	Stimulus	Number of words	Number of syllables	Number of morphemes
1. nonword (baseline)	pa – pa – pa – pa – pa– pa – pa – pa – pa	.	9 (6)*	.
2. simple-short (baseline)	Buy *Bobby* a puppy	4	6	4
3. simple-long	Bill and *Bobby* bought big brown puppies	7	9	8
4. complex-long	Brown puppies that *Bobby* bought were big.	7	9	8
5. faulty-long	Puppies brown *Bobby* and big bought Bill	7	9	8

* The nonword phrase contains 9 syllables, but the first six repetitions of /pa/ were used for analysis (6 syllables).

more processing time for speech motor execution and relatively unstable speech motor movements due to syntactic violation. The utterances that include a subject relative clause (i.e., Brown puppies that *Bobby* bought were big) and syntactic faults (i.e., Puppies brown *Bobby* and big bought Bill) are called 'complex-long' and 'faulty-long', respectively. The utterance which contains neither a relative clause nor syntactic errors is labeled 'simple-long' (i.e., Bill and *Bobby* bought big brown puppies). A speech condition that only increased length was not included because Kleinow and Smith (2000) reported that both PWS and PWNS did not show different speech motor stability when utterance length simply increased.

3. Procedures

Each participant was seated in front of four motion sensitive cameras (Hawk Digital RealTime System, Motion Analysis Corporation) that capture movements of reflective markers in the near infrared spectrum. The participant wore 10 reflective markers on the face that are tracked by the cameras. Five reference markers were placed on the right forehead, left forehead, midline of nose, right zygomatic bone and left zygomatic bone. The other five were placed on facial points that move during speech including the midline upper lip, right lip corner, left lip corner, lower midline lip, and midline chin.

The EVa-RT software program used the digitized motion of each marker from the four cameras to assemble a virtual representation of the face. The facial motion was sampled at 100 frames per second. A behind-the-ear microphone was placed three centimeters from the participant's right corner of lip to record speech samples and was

the input to the acoustic processing software (Capybara 320 sound computation processor) that altered auditory feedback (see next paragraphs for more information). The PowerLab Data Acquisition Systems (ADInstruments, http://www.adinstruments.com) and a microphone mounted on a video camera (Canon Digital Video Camcorder, ZR800 NTSC) provided two separate acoustic records of the participant's speech.

The stimuli were presented through a computer monitor placed 1.5 meters in front the participant. Participants were asked to read each stimulus at a habitual speech rate and loudness. PWS were instructed not to use fluency enhancing techniques to produce fluent speech. During the experiment, the participants were asked to maintain a consistent loudness by monitoring a visual signal that indicated speech intensity. An analogue loudness meter (Dorrough, Model 40-A) displays speech intensity on a visual scale which was balanced to represent typical conversation loudness in the midrange of the scale. When participants saw the "+" sign between stimuli, they paused for the next stimulus. The nNAF condition with the randomized order of linguistic stimuli was presented first as an auditory control block because the other conditions required placement of the insert earphones. Then, 25ms-DAF, 50ms-DAF and aNAF conditions as well as the stimuli were presented in a randomized order after inserting the audiometric insert earphones (E-A-RTONE Gold 3A 50ohm tubephone**,** E-A-R® Auditory Systems) to minimize carry over effects.

The acoustic signal was amplified through a mixer (Behringer, Xenyx 1202) and delivered to the participant bilaterally through the earphones. A Brüel & Kjær sound level meter (type 2235) was used to calibrate the headphone output sound level. A calibration tone of 94dB SPL at 1000Hz was directed to the microphone placed

approximately 0.5cm from a calibrator (Brüel & Kjær, type 4230). The tone generated a 95dB SPL feedback through the insert earphones with the sound level meter connected to the right insert earphone tube (with A weighting). At this level of amplification, the intensity was adjusted for each participant until they reported the volume through the earphones was "loud but O.K" (level 6, Cox et al., 1997) as per Studies I and II. After setting the loudness level, the level was maintained during the experiment session. Two different delay intervals of 25 and 50ms were selected and generated by the Capybara 320 sound computation processor (Symbolic Sound Corporation, http://www.symbolicsound.com).

Each stimulus was repeated 15 times in each auditory feedback condition to provide at least 10 fluent samples for determining the Spatiotemporal Index (STI) (Smith, Johnson, McGillem, & Goffman, 2000). During the experiment, both control and experimental blocks were counterbalanced across participants.

4. Analyses

The reference markers and lower lip marker were inspected for camera tracking errors. Standard automated algorithms were used to fill in short gaps, remove occasional oscillations, and spikes occurred when the 4 images could not be assembled or markers were confused in the software through the EVa-RT software program. The corrected data (.trb file format) were then converted to ASCII files (i.e., .trc file format). The audio signals recorded from a video camera during the experiment were converted to .wav files (sampling rate of 22050Hz and 16-bit quantization) using the GoldWave software program (Version 5.23, Craig, 2008).

The acoustic data were assessed perceptually to exclude any trials with disfluencies because the STI can be measured only using perceptually fluent phrases. Thus, utterances that contained articulatory errors, disfluencies, incorrect words, and unusual speech rates were excluded following previous studies (e.g., Maner et al., 2000; Sadagopan & Smith, 2008; Smith & Goffman, 1998). There was one stuttering participant who produced an interjection /ə/ frequently at the beginning of stimulus utterances under nNAF condition. The investigator inspected the utterances, and those which did not contain any other disfluencies, articulatory errors, pauses, and/or unusual speech rates were included. If more than 10 fluent utterances were available in each set of stimulus, a data selection process was conducted in terms of excluding the first token and then the last token until 10 samples remained.

Then, the .trc files of the 10 selected samples were converted into a MatLab binary file for subsequent analysis using the MatLab 7.6 (r2008a) software program (The MathWorks, 2008). Several pre-processing steps were performed to calculate the STI, peak amplitude, and peak velocity of lower lip movement for every speech stimulus under each feedback condition. First, the audio files were inserted in the .mat file matrix containing the kinematic data. Second, the kinematic data were low-pass filtered (10Hz) in both forward and backward directions to exclude high frequency artifacts and prevent phase-shifts from filtering in only one direction. Third, velocity information was derived by differentiating the kinematic data.

4.1. Kinematic measures

4.1.1. Spatio-temporal parameter: Spatiotemporal index (STI)

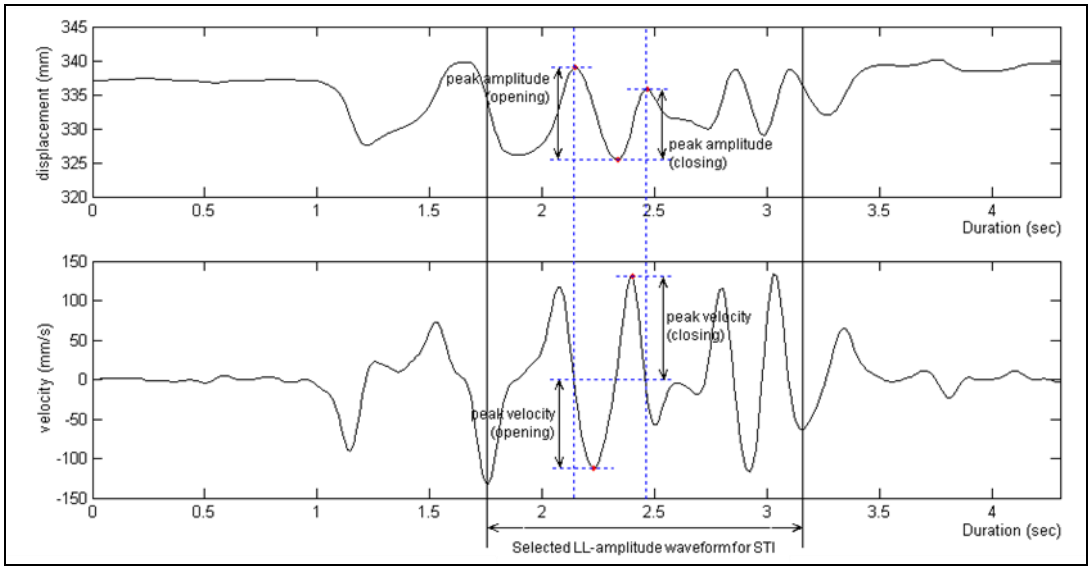
The STI measures the stability of speech movements using several repetitions of an utterance (Kleinow & Smith, 2000; Maner et al., 2000; Smith et al., 1995; Smith & Kleinow, 2000). It is typically calculated as the sum of standard deviations from multiple time points (typically 50 points: every 20th point selected from 1000 points) using amplitude- and time-normalized kinematic movement waveforms in each condition. A high STI value is thought to represent lower speech-motor stability. Moreover, STI depends on stimuli, thus STI values between different utterances cannot be directly compared for speech kinematic stability (Smith et al., 2000). In the current study, the same STI measurement with previous studies was employed: lower lip kinematic waveforms of 10 fluent repetitions in each feedback condition for each stimulus were amplitude- and time-normalized (i.e., 1000 points), and then the sum of standard deviations of the 10 movement trajectories at 50 time points (i.e., determined at every 20th point) was calculated. Hence, 20 STI values from four feedback conditions in each of five stimuli were calculated from each participant's data.

After filtering the lower lip movements and determining velocity (1^{st} derivative of displacement), the onset and offset of lower lip movements in the z-dimension (i.e., superior-inferior) were marked for each utterance. The first negative peak velocity of the lower lip movement associated with the speech onset for the first syllable and the last negative peak velocity of the lower lip movement at speech onset for the last syllable were marked as shown in Figure 17 (see "Selected LL-amplitude waveform for STI").

After cropping the data between these points, the lower lip amplitude waveforms were normalized in space and time. To normalize amplitude, the mean amplitude and standard deviation of a single trial were calculated, and the z-score for each point of the

trial was attained by subtracting the mean from each point and then dividing by the standard deviation. Due to variation within each trial, movement duration necessarily varies (see Figure 18, first row) so interpolation is required to map all kinematic waveforms onto a constant time base. To implement the linear time normalization, a trigonometric interpolation method that uses Fourier transform was used to achieve the interpolation coefficients. Each trial was then normalized to 1000 points following previous studies measuring the STI (Kleinow & Smith, 2000; Smith et al., 1995; Smith & Kleinow, 2000; Smith et al., 2000) (Figure 18, second row). Then, the STI of lower lip movements was calculated with MatLab commands as shown in the third row in Figure 18.

Figure 17. Measurement of displacement and peak velocity of phonetic syllable /bab/ (dotted vertical lines) from a simple-short structured sentence, "Buy Bobby a puppy." Selected portion (solid vertical lines) was used for measuring STI.



4.1.2. Single-movement parameters: Displacement and velocity

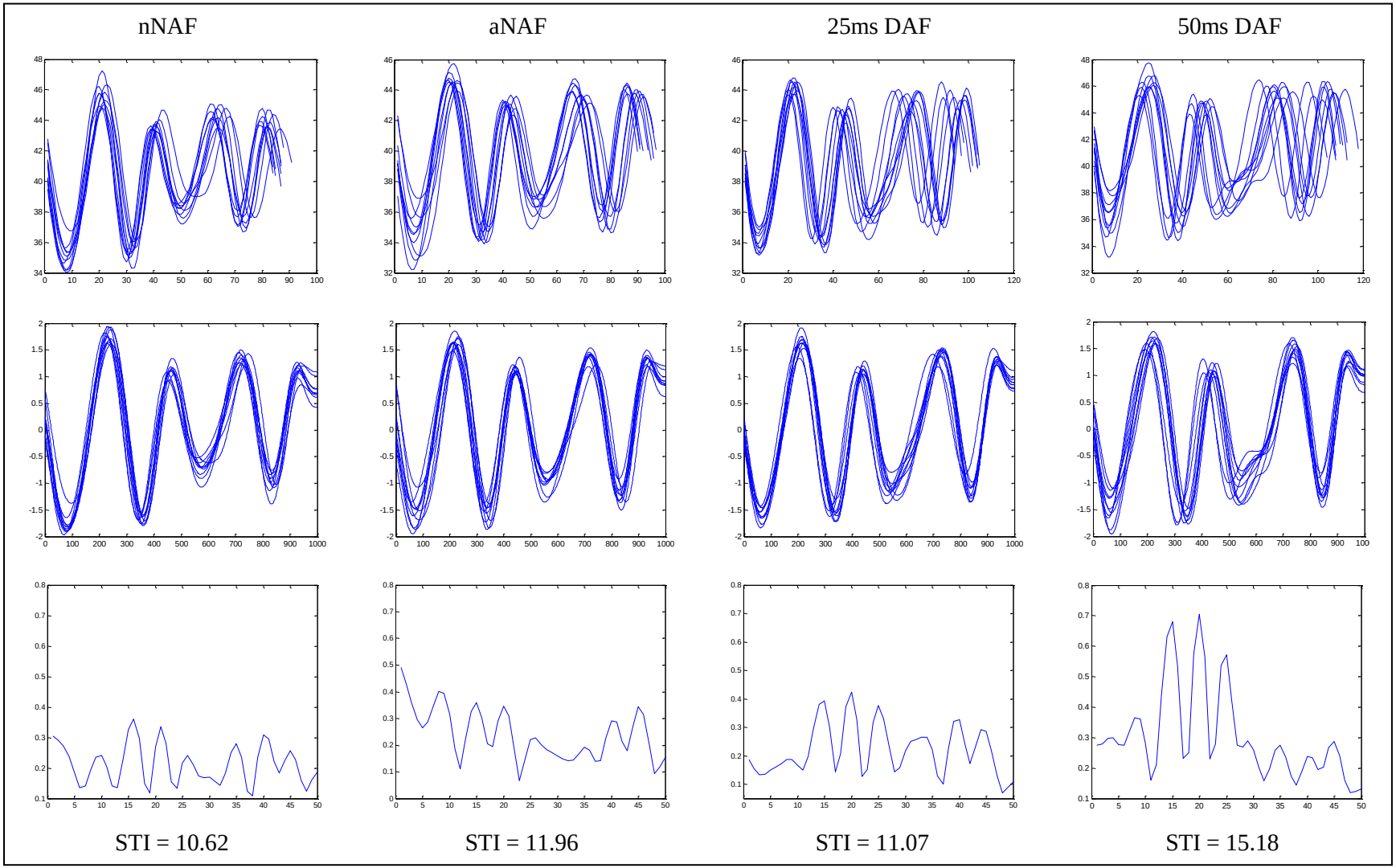
To determine whether lower lip opening and closing movement sequences were influenced by auditory feedback and linguistic complexity, displacement (mm) and peak velocity (mm/s) of the lower lip opening and closing gestures were marked for the syllable /bab/, which occurs in 4 utterance stimuli. All marking was conducted with automated MatLab routines. As shown in the first row in Figure 17, the first marked point was the onset of the lower lip opening movement for the first bilabial sound /b/ (i.e., the positive peak). The second point was the movement offset for the vowel /a/ indicated by the negative peak of the lower lip motion. The last marked point was the offset of the lower lip closing movement for the second bilabial sound /b/, which is the following positive peak in the lower lip kinematic trace. The displacement of the opening movement was determined by subtracting the second point from the first point. The displacement for the closing movement was calculated by finding the difference between the second and third points. The peak velocity (mm/s) of the opening movement (i.e., negative peak) and closing movement (i.e., positive peak) were also marked using automated routines (see the second row in Figure 17).

4.2. Temporal measures

4.2.1. Kinematic duration

The duration of each movement trajectory, which is the selected for STI, was measured using a MatLab command. The average duration was then obtained for the 10 utterances in each set of stimuli for each feedback condition.

Figure 18. Measuring STI for the simple-short utterance “Buy *Bobby* a puppy” under four auditory feedback conditions (PWNS).



4.2.2. Articulation rate

As described in studies I and II, the articulation rate of each utterance was calculated (syllables per second: SPS), and averaged across the 10 repetitions in each stimulus and auditory feedback condition.

5. Reliability

For the mean articulation rate, the Pearson product-moment correlation analysis was used both for the intra- and inter-rater judge reliabilities. For the intra-rater judge reliability, 3 datasets (12% of overall 25 datasets) were randomly selected and reanalyzed. For the inter-rater judge reliability, an undergraduate volunteer was trained to measure articulation rate, analyzed one dataset with the investigator, and then analyzed randomly selected 3 data sets.

The coefficients of the intra-rater judge reliability were .98 for nNAF condition, .98 for aNAF condition, .99 for 25ms-DAF condition and .99 for 50ms-DAF condition. The coefficients of the inter-rater judge reliability were .93 for nNAF condition, .95 for aNAF condition, .93 for 25ms-DAF condition and .95 for 50ms-DAF condition.

6. Statistical analysis

The STI, displacement, velocity, kinematic duration, and articulation rate were derived for each participant in each condition. The SPSS version 16.0 software program was used for statistical analysis. For research questions 1 and 2 that tested STI, a 2 (group) × 4 (auditory feedback) ANOVA with repeated measures was performed to test

significant main effects and post-hoc tests with a Bonferroni pairwise comparison were used to investigate each significant main effect. To test the within group differences, separate one-way ANOVAs with the Least Significant Difference (LSD) post-hoc test were performed in each speech stimulus for each group. To test research question 3 based on kinematic displacement and velocity, a 2 (group) × 4 (speech stimulus) × 4 (auditory feedback) ANOVA with repeated measures was applied to test for overall significant differences among the three parameters (group, stimuli and auditory feedback). Separate ANOVAs with repeated measures were followed to test significant interactions. The Bonferroni pairwise comparison and the Least Significant Difference (LSD) were used to test significant main effects. For research question 4, based on kinematic duration and articulation rate, a 2 (group) × 5 (speech stimulus) × 4 (auditory feedback) ANOVA with repeated measures was applied to test for significant differences among the means for kinematic duration and among the means for articulation rate, followed by the post-hoc Bonferroni pairwise comparison test.

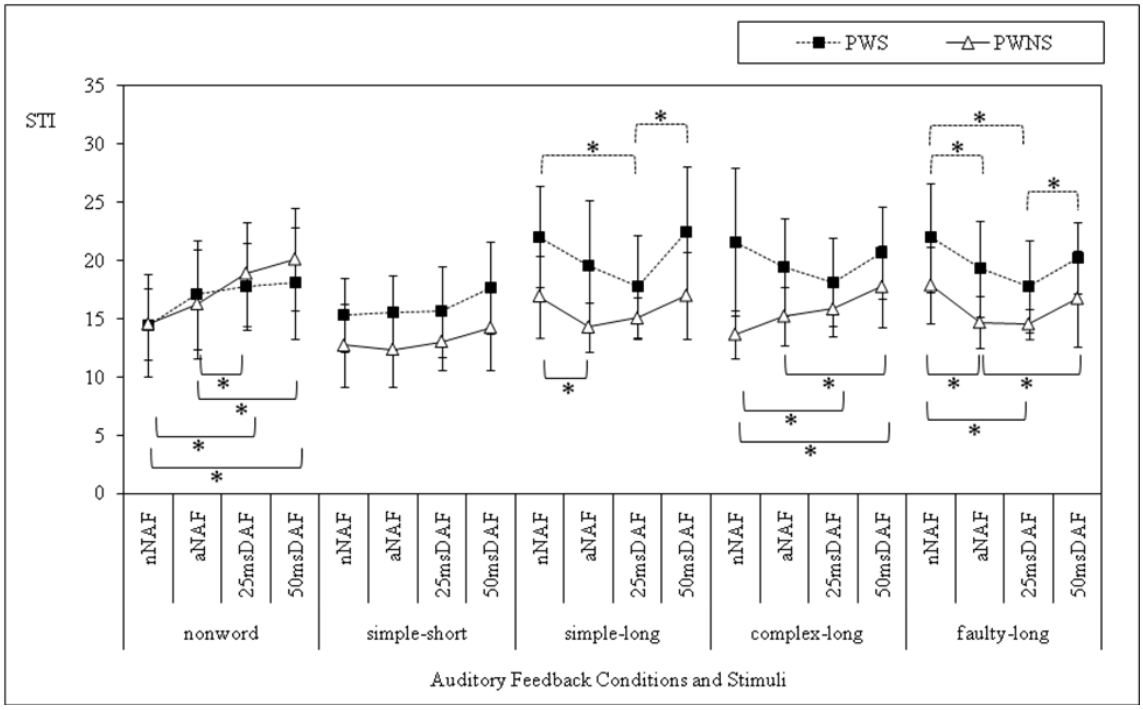
RESULTS

Of the 14 PWS, the data sets of three male participants were unusable due to stuttering. Therefore, data from 11 PWS (7 males and 4 females) and 11 PWNS (7 males and 4 females) were included for analysis.

1. Speech-motor stability: Spatiotemporal index (STI)

The STI data under nNAF, aNAF, 25ms-DAF, and 50ms-DAF conditions across stimuli are illustrated in Figure 19. Because it is impossible to directly compare STI values across stimuli (Smith et al., 2000), the patterns of STI in each stimulus were evaluated.

Figure 19. Means and standard deviations (error bar) of STI under nNAF, aNAF, 25ms-DAF and 50ms-DAF conditions across 5 stimuli. Asterisks indicate significant differences between feedback conditions in each group. Dashed brackets are for PWS and solid brackets are for PWNS.



1.1. Nonword stimulus (baseline): “pa – pa – pa – pa – pa– pa”

Descriptive data for STI between PWS and PWNS for the first six repetitions of /pa/ in nonword stimulus under four auditory feedback conditions are summarized in

Table 13. There was a substantial increase for mean STI in the aNAF, 25ms-DAF and 50ms-DAF conditions compared to the nNAF condition in both groups. Also, PWNS showed higher STI than PWS except in the aNAF condition.

The statistical tests revealed a significant main effect for auditory feedback (F (3, 60) = 10.20, $p < .001$) and the post-hoc test demonstrated that STI under the nNAF condition was significantly lower than under the 25ms-DAF ($p = .002$) and 50ms-DAF ($p = .004$) conditions. Statistical differences were not detected for the group (F (1, 20) = .18, $p = .679$). No interactions were observed.

Table 13. Means and standard deviations (SD) of STI in nonword stimulus according to group and auditory feedback condition

Group	nNAF	aNAF	25ms-DAF	50ms-DAF
PWS (N = 11)	14.41 (4.41)	17.04 (4.71)	17.77 (3.75)	18.07 (4.80)
PWNS (N = 11)	14.54 (3.02)	16.26 (4.62)	18.86 (4.45)	20.09 (4.38)

Within group differences were tested. In the PWS group, there was no significant main effect for auditory feedback (F (3, 30) = 2.77, $p = .059$), whereas a significant main effect for auditory feedback was shown in the PWNS group (F (3, 30) = 9.95, $p < .001$). In PWNS, STI values under nNAF and aNAF conditions were significantly lower than under 25ms-DAF ($p < .001$ and $p = .007$, respectively) and 50ms-DAF conditions ($p = .002$ and $p = .012$, respectively) (See Figure 19).

1.2. Simple-short stimulus (baseline): “Buy Bobby a puppy”

Means and standard deviations for STI for the PWS and PWNS for the simple-short stimulus in the four feedback conditions are provided in Table 14. In general, STI increased under DAF conditions compared to non-delayed feedback conditions with PWNS showing lower STI on average than PWS.

Table 14. Means and standard deviations (SD) of STI in simple-short stimulus according to group and auditory feedback condition

Group	nNAF	aNAF	25ms-DAF	50ms-DAF
PWS (N = 11)	15.31 (3.22)	15.54 (3.15)	15.62 (3.88)	17.68 (3.96)
PWNS (N = 11)	12.71 (3.56)	12.35 (3.24)	13.02 (2.43)	14.22 (3.61)

PWS showed significantly higher STI overall compared to PWNS (F (1, 20) = 6.88, p = .016) and there was also a significant main effect for auditory feedback (F (3, 60) = 3.16, p = .031). Post-hoc tests confirmed that STI under the aNAF condition was significantly lower than under the 50ms-DAF (p = .041). No interactions were observed. Statistical results in each group, however, did not show significant main effect for auditory feedback for both PWS (F (3, 30) = 1.92, p = .148) and PWNS (F (3, 30) = 1.34, p = .281).

1.3. Simple-long stimulus: “Bill and Bobby bought big brown puppies”

Descriptive data for STI between PWS and PWNS for the simple-long stimulus under the four auditory feedback conditions are provided in Table 15. The mean STI values were similar for the nNAF and 50ms-DAF conditions, and lower under aNAF and

25ms-DAF conditions compared to nNAF condition. There was greater variance under the 50ms-DAF condition.

Again, the STI of the stuttering group was significantly higher than the control group (F (1, 20) = 10.65, p = .004). A significant main effect for auditory feedback was detected (F (3, 60) = 8.07, p < .001). Based on the post-hoc tests, STI under 25ms-DAF condition was significantly lower than nNAF (p = .005) and 50ms-DAF conditions (p = .002). There was no interaction between variables.

Table 15. Means and standard deviations (SD) of STI in simple-long stimulus according to group and auditory feedback condition

Group	nNAF	aNAF	25ms-DAF	50ms-DAF
PWS (N = 11)	22.01 (4.34)	19.55 (5.58)	17.76 (4.39)	22.38 (5.69)
PWNS (N = 11)	16.92 (3.51)	14.27 (2.08)	15.04 (1.79)	16.97 (3.77)

Within each group, as shown in Figure 19, significant main effects for auditory feedback were detected for PWS (F (3, 30) = 5.19, p = .005) and PWNS (F (3, 30) = 3.58, p = .025). PWS showed significantly lower STI under 25ms-DAF than nNAF (p = .005) and 50ms-DAF (p < .001) conditions. For PWNS, the STI was significantly lower under aNAF condition compared to nNAF condition (p = .030).

1.4. Complex-long stimulus: “Brown puppies that Bobby bought were big”

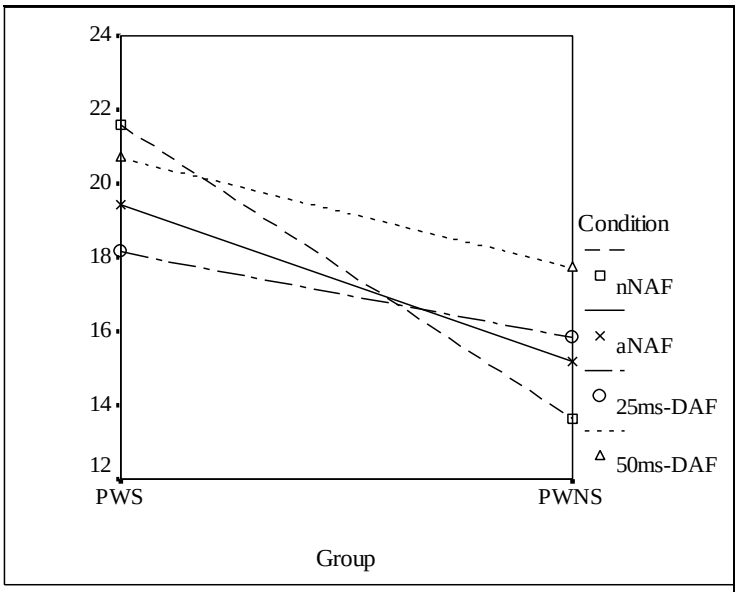
Descriptive data for STI between PWS and PWNS for the complex-long stimulus under the four auditory feedback conditions are summarized in Table 16. The mean STI was lower under nNAF than the other feedback conditions for PWNS whereas PWS

showed the highest STI, on average, under nNAF condition and the lowest STI under 25ms-DAF condition. PWS showed greater variability across feedback conditions than PWNS.

Table 16. Means and standard deviations (SD) of STI in complex-long stimulus according to group and auditory feedback condition

Group	nNAF	aNAF	25ms-DAF	50ms-DAF
PWS (N = 11)	21.59 (6.35)	19.41 (4.19)	18.14 (3.75)	20.69 (3.93)
PWNS (N = 11)	13.64 (2.11)	15.19 (2.54)	15.82 (2.33)	17.72 (3.50)

Figure 20. Interaction between group and auditory feedback condition in complex-long stimulus



Overall, PWS showed significantly higher STI than PWNS (F (1, 20) = 12.20, p = .002), but a statistically significant difference was not detected for auditory feedback (F

(3, 60) = 2.71, p = .053). There was a significant interaction between group and auditory feedback (p = .007). As seen in Figure 20, PWS and PWNS showed different STI patterns under auditory feedback conditions. Separate ANOVAs in each group revealed a significant main effect for auditory feedback in PWNS (F (3, 30) = 8.84, p <.001), but not in PWS (F (3, 30) = 2.03, p = .131). PWNS showed significantly lower STI under nNAF than under 25ms-DAF (p = .019) and 50ms-DAF (p = .002), and the STI under aNAF was also significantly lower than under 50ms-DAF condition (p = .013) (See Figure 19).

1.5. Faulty-long stimulus: "Puppies brown Bobby and big bought Bill"

Descriptive data for STI between PWS and PWNS for the faulty-long stimulus under four auditory feedback conditions are provided in Table 17. STI was higher under nNAF, and lower under 25ms-DAF, on average, than the other feedback conditions in both groups. In general, PWS showed higher STI and greater variability across the feedback conditions.

Table 17. Means and standard deviations (SD) of STI in faulty-long stimulus according to group and auditory feedback condition

Group	nNAF	aNAF	25ms-DAF	50ms-DAF
PWS (N = 11)	21.96 (4.70)	19.27 (4.12)	17.74 (3.94)	20.20 (3.02)
PWNS (N = 11)	17.87 (3.25)	14.67 (2.22)	14.53 (1.28)	16.73 (4.10)

The statistical test results indicated that PWS show significantly higher STI than PWNS (F (1, 20) = 12.17, p = .002). There was a significant main effect for auditory

feedback (F (3, 60) = 8.33, p < .001) in that STI under the nNAF condition was significantly higher than that under the aNAF (p = .007) and 25ms-DAF (p = .005) conditions. Also, STI under the 50ms-DAF condition was significantly higher than the 25ms-DAF condition (p = .010). There was no interaction between variables.

Tests of within group difference showed a significant main effect for auditory feedback in PWS (F (3, 30) = 4.68, p = .008). PWS showed significantly lower STI under 25ms-DAF than nNAF (p = .022) and 50ms-DAF (p = .005) conditions. The STI under aNAF was also significantly lower than nNAF condition (p = .020) (see Figure 19). PWNS also showed a significant main effect for auditory feedback (F (3, 30) = 3.95, p = .017) showing significantly higher STI under nNAF than under aNAF (p = .026) and 25ms-DAF (p = .016) conditions, and significantly higher STI under 50ms-DAF than aNAF condition (p = .033).

1.6. Individual variability of STI in responses to AAF

The percentage of participants who showed lower STI under AAF than that under nNAF is described in Table 18. Similar to Study II and previous studies, PWS showed individual variability in responses to AAF. Less than a half of stuttering participants showed lower STI under AAF compared to nNAF condition in the baseline stimuli. Longer utterances showed more AAF effects on changes in speech-motor stability for PWS indicating that greater percentage of PWS showed lower STI under AAF than nNAF condition. Interestingly, some PWNS also showed lower STI under AAF, especially, in ‘faulty-long’ utterance.

Table 18. The percentage of participants in each group (N = 11) who decreased STI (i.e., increased speech-motor stability) under AAF compared to nNAF condition

Group & Condition / Stimuli	PWS			PWNS		
	aNAF	25ms-DAF	50ms-DAF	aNAF	25ms-DAF	50ms-DAF
nonword	27.27	18.18	18.18	27.27	0.00	9.09
simple-short	45.45	36.36	9.09	45.45	27.27	27.27
simple-long	81.82	90.91	54.55	63.64	54.55	45.45
complex-long	63.64	72.73	72.73	27.27	9.09	18.18
faulty-long	81.82	72.73	63.64	81.82	81.82	63.64

2. Single-movement parameters: Displacement and velocity

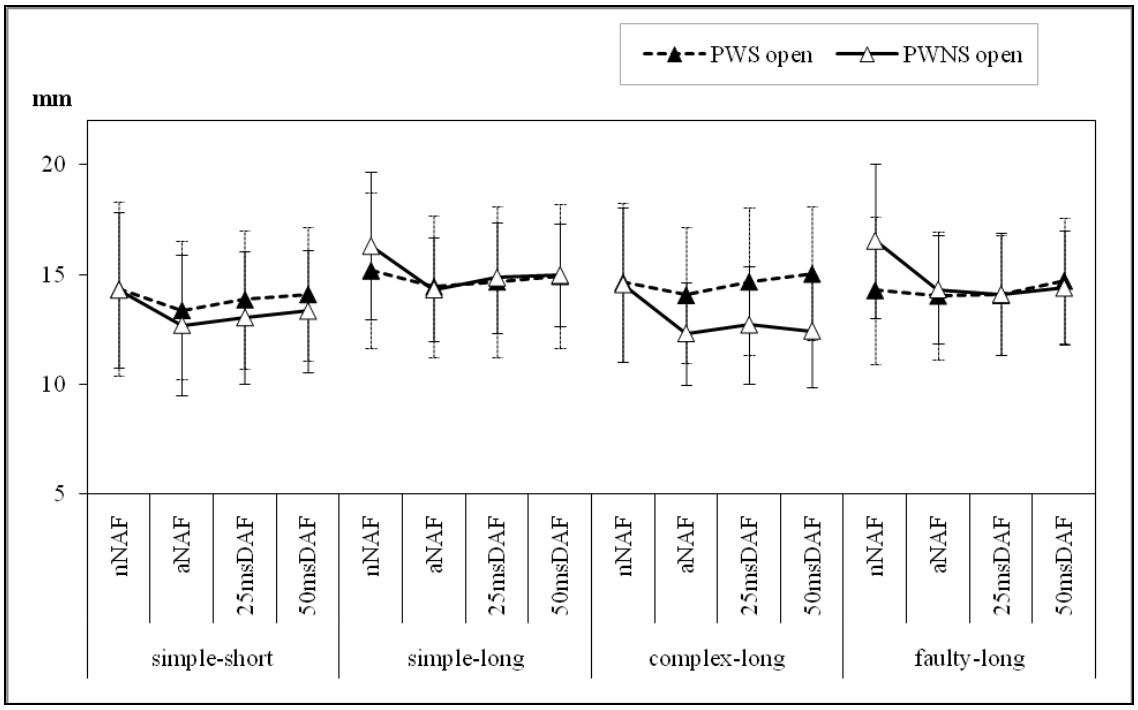
Using two sequential movements, opening and closing movements of lower lip for a syllable /bab/, displacements and movement velocities under each auditory feedback condition across four stimuli, were measured. For the opening movement, the values of peak velocities were negative, but they were plotted as positive values to compare them to the overall results.

2.1. Movement displacement

2.1.1. Opening movement

Figure 21 illustrates the means and standard deviations of displacement (mm) of lower lip opening. There was considerable overlap between PWS and PWNS in movement displacement. The patterns of displacements, however, were different between the groups. PWS did not show an obvious increase or decrease under altered auditory feedback (i.e., aNAF, 25m-DAF, and 50ms-DAF) whereas PWNS showed an apparent decrease in displacement under altered auditory feedback conditions regardless of the stimulus.

Figure 21. Means and standard deviations (error bar) of displacement for the single opening-movement for /bab/ under nNAF, aNAF, 25ms-DAF and 50ms-DAF conditions across four stimuli



An ANOVA with repeated measures failed to detect a significant group difference in displacement (F (1, 20) = .07, p = .790), but main effects for stimuli (F (3, 60) = 19.15, p < .001) and auditory feedback (F (3, 60) = 14.75, p < .001) were detected. There were also significant interaction effects between stimuli and group (p < .001), between auditory feedback and group (p < .001), and between stimuli, auditory feedback, and group (p = .034). Thus, separate ANOVAs in each group were conducted to test the interactions. For PWS, the results showed a significant main effect for stimuli (F (3, 30) = 4.40, p = .011) but not for auditory feedback (F (3, 30) = 2.87, p = .053). The movement displacement in simple-short stimulus was significantly lower than that in the

simple-long stimulus (p = .014). For PWNS, on the other hand, significant main effects were revealed for stimuli (F (3, 30) = 23.42, p < .001) and auditory feedback as well (F (3, 30) = 16.61, p < .001). There was a significant interaction between stimuli and auditory feedback (p = .022). Post-hot tests demonstrated that simple-long and faulty-long stimuli involved significantly higher movement displacements than simple-short (p = .002 and p = .015, respectively) and complex-long (p < .001 and p = .002, respectively) stimuli. In addition, movement distance under nNAF was significantly more than aNAF (p = .006), 25ms-DAF (p = .013), and 50ms-DAF (p = .024) conditions. The aNAF condition showed lower displacement than the 50ms-DAF condition (p = .009).

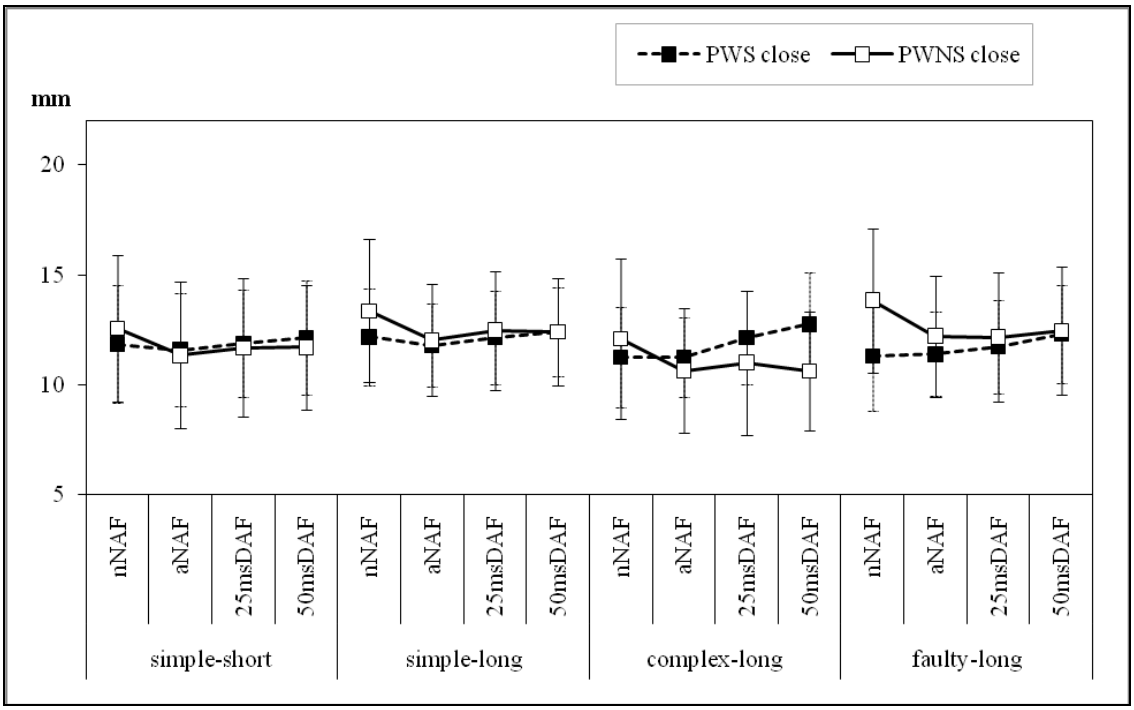
2.1.2. Closing movement

Figure 22 illustrates the means and the standard deviations of displacement of lower lip closing movements. Similar to opening movements, the movement displacements showed substantial overlap between PWS and PWNS, but more subtle group differences were apparent that depends on the auditory feedback condition.

There were significant main effects for stimuli (F (3, 60) = 7.29, p < .001) and auditory feedback (F (3, 60) = 5.31, p = .003), but no significant group difference (F (1, 20) = .02, p = .885). There were also significant interactions between stimuli and group (p = .001), between auditory feedback and group (p < .001), and between stimuli, auditory feedback, and group (p = .033).

Separate ANOVAs for each group were conducted to test the interactions. For PWS, the results only showed a significant main effect for auditory feedback (F (3, 30) = 5.50, p = .004). Under aNAF condition, PWS showed less movement displacement

Figure 22. Means and standard deviations (error bar) of displacement for the single closing-movement for /bab/ under nNAF, aNAF, 25ms-DAF and 50ms-DAF conditions across four stimuli



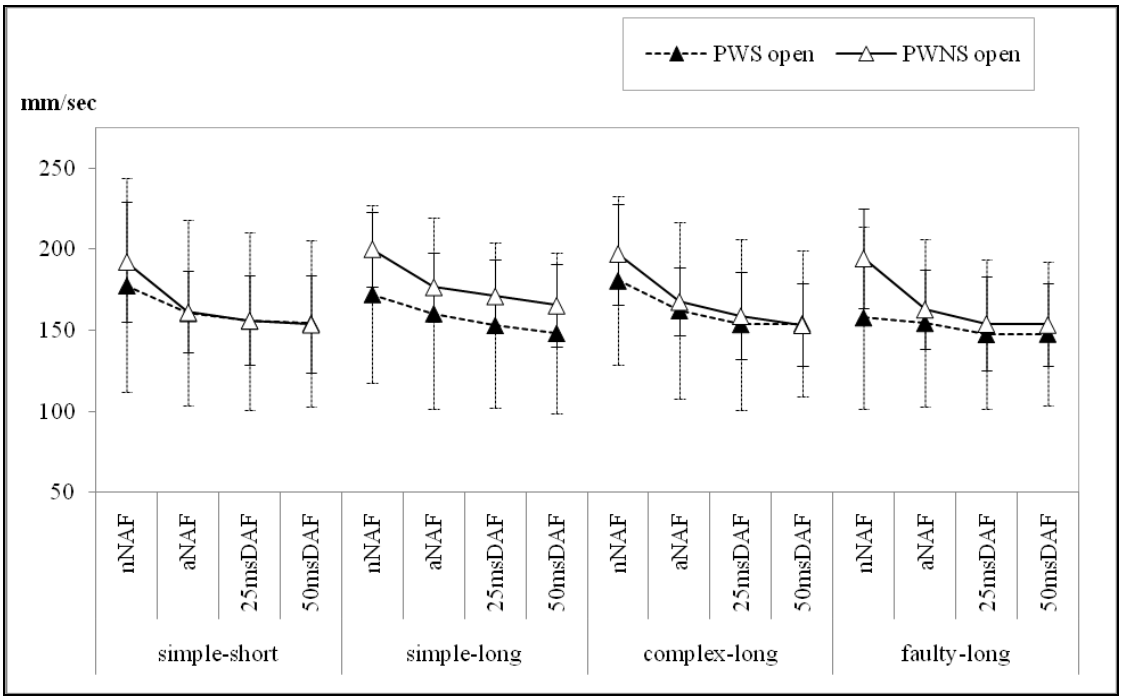
compared to the 25ms-DAF (p = .002) and 50ms-DAF (p = .003) conditions. For PWNS, significant main effects were shown for stimuli (F (3, 30) = 12.18, p < .001) and auditory feedback (F (3, 30) = 7.48, p = .001) as well. Simple-long and faulty-long stimuli showed significantly higher movement displacements than complex-long stimulus (p = .004 and p = .004, respectively), and the faulty-long stimulus also showed higher displacement than simple-short stimulus (p = .017). In addition, displacement under nNAF was significantly larger than under aNAF (p = .011), 25ms-DAF (p = .023), and 50ms-DAF (p = .031) conditions. The aNAF condition also showed higher displacement than the 25ms-DAF (p = .011) and 50ms-DAF (p = .031) conditions.

2.2. Movement velocity

2.2.1. Opening movement

Figure 23 illustrates the means and standard deviations of peak velocity (mm/s) of lower lip opening. Similar to displacement, there was considerable overlap between PWS and PWNS in velocity. Both PWS and PWNS showed higher movement velocity under nNAF than the other feedback conditions across stimuli, but PWS showed greater variability.

Figure 23. Means and standard deviations (error bar) of peak velocity for the single opening-movement for /bab/ under nNAF, aNAF, 25ms-DAF and 50ms-DAF conditions across four stimuli



There was no significant group difference (F (1, 20) = .433, p = .518), but significant main effects for stimuli (F (3, 60) = 2.99, p = .038) and auditory feedback (F

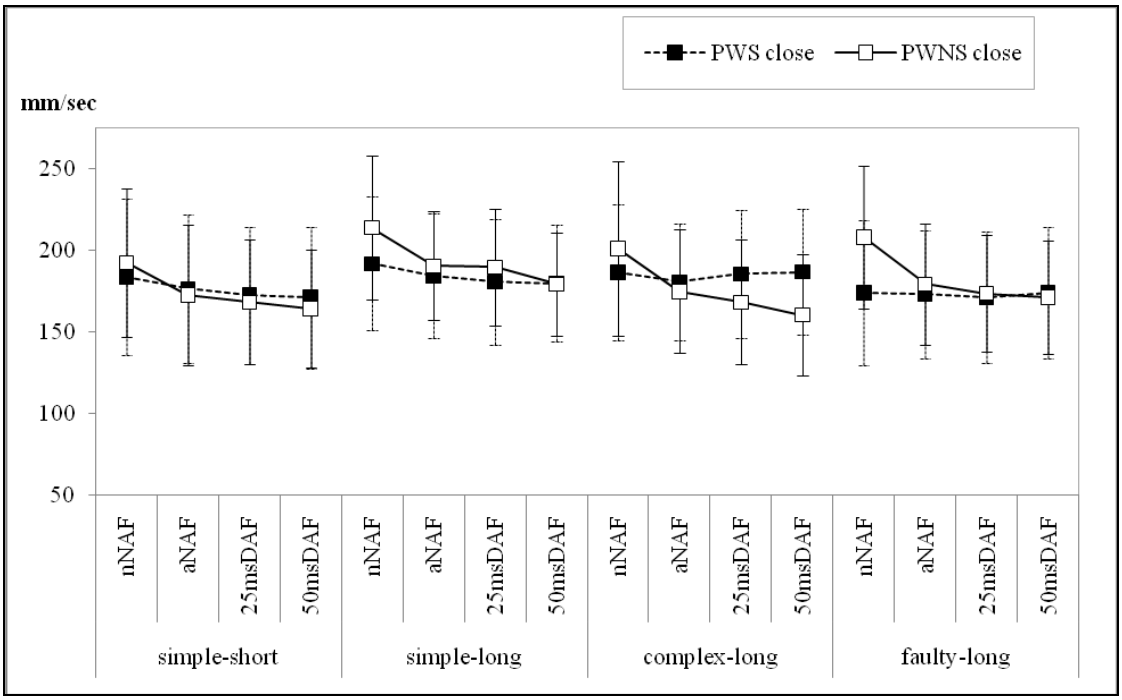
(3, 60) = 36.54, $p < .001$) were found. The peak velocity of simple-long stimulus was significantly higher than that of faulty-long stimulus ($p = .017$). There was a significant interaction between group and auditory feedback ($p = .021$). Separate ANOVAs revealed that PWS showed significantly different peak velocities according to auditory feedback (F (3, 30) = 8.79, $p < .001$). Post-hoc tests indicated their peak velocity was significantly higher under nNAF condition than 25ms-DAF condition ($p = .029$). For PWNS, there were significant main effects for stimuli (F (3, 30) = 3.64, $p = .024$) as well as auditory feedback (F (3, 30) = 31.81, $p < .001$). PWNS showed significantly higher peak velocity in simple-long than simple-short ($p = .020$), complex-long ($p = .026$) and faulty-long ($p = .009$) stimuli. The peak velocity of the PWNS was also significantly higher under nNAF condition compared to aNAF ($p = .005$), 25ms-DAF ($p = .001$), and 50ms-DAF ($p < .001$) conditions, and that under aNAF was significantly higher than 25ms-DAF ($p = .024$) and 50ms-DAF ($p = .002$) conditions.

2.2.2. Closing movement

Figure 24 illustrate the means and standard deviations of peak velocity of lower lip closing (mm/s). Similar to opening movement, the movement velocities showed substantial overlap between PWS and PWNS, but more subtle group differences are apparent that depend on the auditory feedback condition.

Again, group difference was not detected (F (1, 20) = .02, $p = .893$), but there were significant main effects for stimuli (F (3, 60) = 7.31, $p < .001$) and auditory feedback (F (3, 60) = 18.22, $p < .001$). There were also significant interactions between group and stimuli ($p = .008$), group and auditory feedback ($p < .001$), and between stimuli, auditory feedback, and group ($p = .031$). Separate ANOVAs were conducted for

Figure 24. Means and standard deviations (error bar) of peak velocity for the single closing-movement for /bab/ under nNAF, aNAF, 25ms-DAF and 50ms-DAF conditions across four stimuli



each group to test the interaction effects. For PWS, a significant main effect was yielded for stimuli (F (3, 30) = 3.64, p = .024) showing peak velocity was significantly higher in complex-long stimulus compared to faulty-long stimulus (p = .016). For PWNS, there were significant main effects for stimuli (F (3, 30) = 8.02, p < .001) and auditory feedback (F (3, 30) = 16.16, p < .001). Post-hoc tests indicated that PWNS showed significantly higher peak velocity in simple-long than in simple-short (p = .022) and complex-long (p = .025) stimuli. Faulty-long stimulus also showed significantly higher peak velocity than the simple-short stimulus (p = .031). Besides, the peak velocity was significantly higher under nNAF compared to aNAF (p = .041), 25ms-DAF (p = .016), and 50ms-DAF (p = .004) conditions.

3. Temporal parameters

3.1. Kinematic duration

Descriptive data for kinematic duration between PWS and PWNS under four auditory feedback conditions across five stimuli are summarized in Table 19. The durations in baseline stimuli (nonword and simple-short) were shorter than the other three stimuli because the baseline stimuli contain six syllables but the other three stimuli have nine syllables in the utterance. PWS showed longer kinematic duration, on average, and greater variability than PWNS.

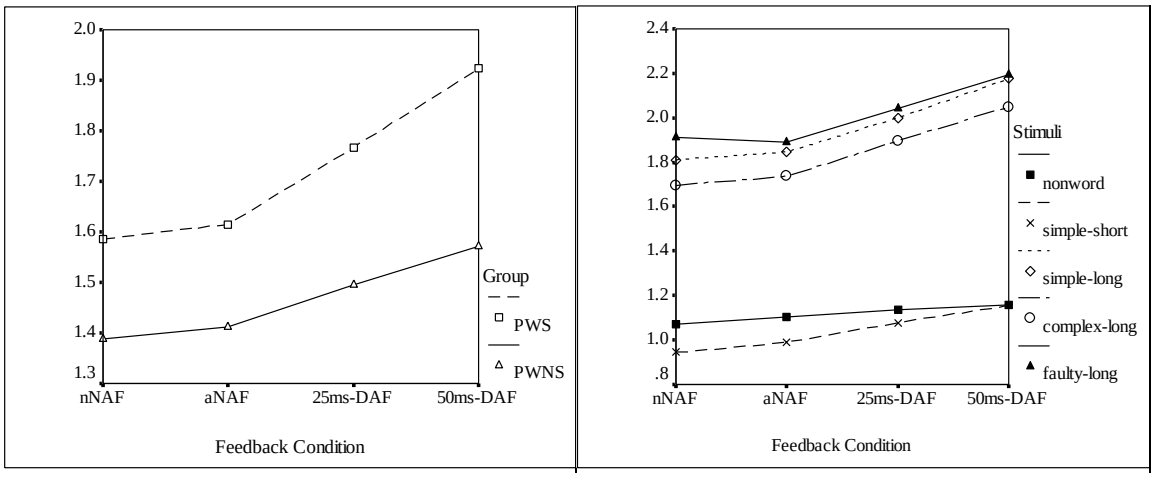
Table 19. Means and standard deviations (SD) of kinematic duration measured in seconds according to groups and auditory feedback conditions across five stimuli

Stimulus	Condition / Group	nNAF	aNAF	25ms-DAF	50ms-DAF
nonword	PWS	1.18 (0.27)	1.23 (0.37)	1.27 (0.42)	1.31 (0.46)
	PWNS	0.96 (0.18)	0.98 (0.19)	1.01 (0.21)	1.01 (0.22)
simple-short	PWS	1.00 (0.10)	1.04 (0.13)	1.16 (0.21)	1.26 (0.25)
	PWNS	0.89 (0.70)	0.94 (0.10)	0.99 (0.10)	1.05 (0.09)
simple-long	PWS	1.90 (0.19)	1.96 (0.29)	2.16 (0.37)	2.39 (0.46)
	PWNS	1.72 (0.15)	1.73 (0.13)	1.84 (0.13)	1.96 (0.19)
complex-long	PWS	1.82 (0.17)	1.85 (0.19)	2.05 (0.25)	2.26 (0.29)
	PWNS	1.57 (0.12)	1.62 (0.12)	1.74 (0.15)	1.84 (0.15)
faulty-long	PWS	2.04 (0.20)	2.00 (0.25)	2.19 (0.29)	2.39 (0.35)
	PWNS	1.78 (0.15)	1.79 (0.15)	1.89 (0.16)	1.99 (0.15)

Statistical results indicated a main effect for group: PWNS had significantly shorter movement duration of lower lip than PWS (F (1, 20) = 11.49, p = .003). Moreover, there were significant main effects for stimuli (F (4, 80) = 265.94, p < .001)

and auditory feedback (F (3, 60) = 37.19, $p < .001$). Significant interactions were observed between group and auditory feedback ($p = .023$) and between stimuli and auditory feedback ($p < .001$). The differences of kinematic duration between PWS and PWNS were greater under 25ms-DAF and 50ms-DAF conditions as compared to under nNAF and aNAF conditions (see Figure 25, left graph). The patterns of slope in kinematic duration among feedback conditions were different in nonword and faulty-long stimuli. All stimuli showed higher kinematic duration in aNAF than nNAF conditions except the faulty-long stimulus. Less increment in kinematic duration was observed in the nonword stimulus across altered auditory feedback (see Figure 25, right graph).

Figure 25. Interaction between group and auditory feedback (left) and between stimuli and auditory feedback (right) for kinematic duration



Post-hoc tests indicated, not surprisingly, baseline stimuli (i.e., nonword and simple-short) had significantly shorter durations than did longer stimuli (i.e., simple-long, complex-long, and faulty-long) ($p < .001$ for each pair). The duration in the complex-long stimulus was shorter than that in the simple-long stimulus ($p = .001$) and the faulty-

long stimulus ($p < .001$). In addition, the durations under nNAF and aNAF conditions were lower than under 25ms-DAF ($p = .002$ and $p < .001$, respectively) and 50ms-DAF ($p < .001$ and $p < .001$, respectively) conditions. The duration under the 25ms-DAF condition was shorter than under the 50ms-DAF condition as well ($p < .001$).

3.2. Articulation rate (AR)

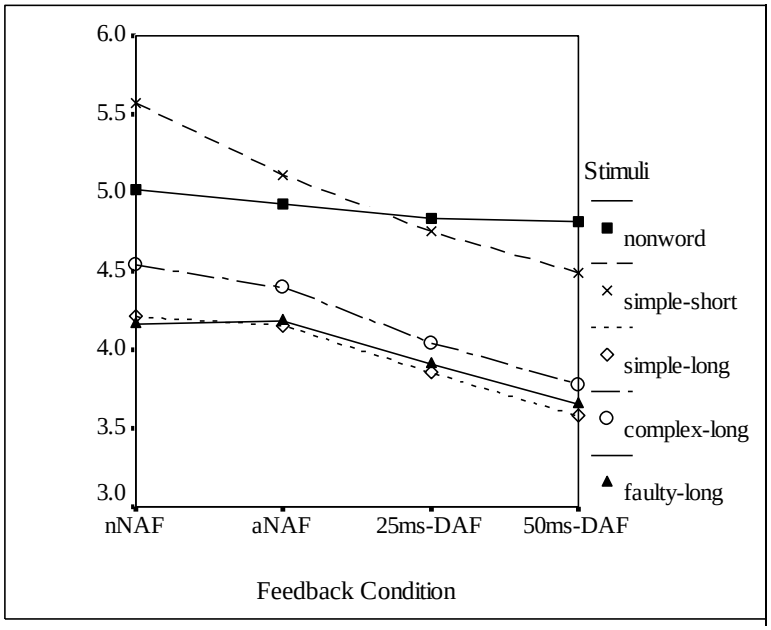
Descriptive data for mean AR measured in syllables per second between PWS and PWNS under four auditory feedback conditions across five stimuli are summarized in Table 20 and illustrated in Figure 27. Both groups showed faster articulatory movements with higher variability in baseline stimuli (nonword and simple-short) than longer stimuli. PWS showed slower AR than PWNS. AR was slower in DAF conditions compared to non-delayed feedback conditions.

Table 20. Means and standard deviations (SD) of mean articulation rate (syllables per second) according to groups and auditory feedback conditions across five stimuli

Stimulus	Condition / Group	nNAF	aNAF	25ms-DAF	50ms-DAF
nonword	PWS	4.56 (0.89)	4.44 (1.02)	4.37 (1.09)	4.29 (1.26)
	PWNS	5.48 (1.04)	5.43 (1.05)	5.31 (1.15)	5.35 (1.20)
simple-short	PWS	5.20 (0.57)	4.84 (0.53)	4.39 (0.62)	4.13 (0.62)
	PWNS	5.95 (1.00)	5.39 (0.59)	5.12 (0.64)	4.86 (0.51)
simple-long	PWS	4.00 (0.39)	3.95 (0.50)	3.59 (0.52)	3.28 (0.57)
	PWNS	4.42 (0.35)	4.36 (0.31)	4.12 (0.32)	3.88 (0.36)
complex-long	PWS	4.20 (0.45)	4.16 (0.49)	3.74 (0.46)	3.44 (0.44)
	PWNS	4.87 (0.40)	4.64 (0.47)	4.36 (0.42)	4.12 (0.39)
faulty-long	PWS	3.84 (0.42)	3.98 (0.49)	3.61 (0.50)	3.34 (0.49)
	PWNS	4.48 (0.38)	4.39 (0.40)	4.20 (0.45)	3.97 (0.31)

Significant main effects were observed for group (F (1, 20) = 11.57, p = .003), stimuli (F (4, 80) = 26.57, p < .001), and auditory feedback (F (3, 60) = 42.68, p < .001). PWNS showed faster AR than PWS. There was a significant interaction effect between stimuli and auditory feedback (p < .001). The slope of AR in nonword stimulus in altered feedback conditions was gentler than other stimuli. Also, AR increased under aNAF compared to nNAF in faulty-long stimulus whereas other stimuli showed decreased AR under aNAF (see Figure 26).

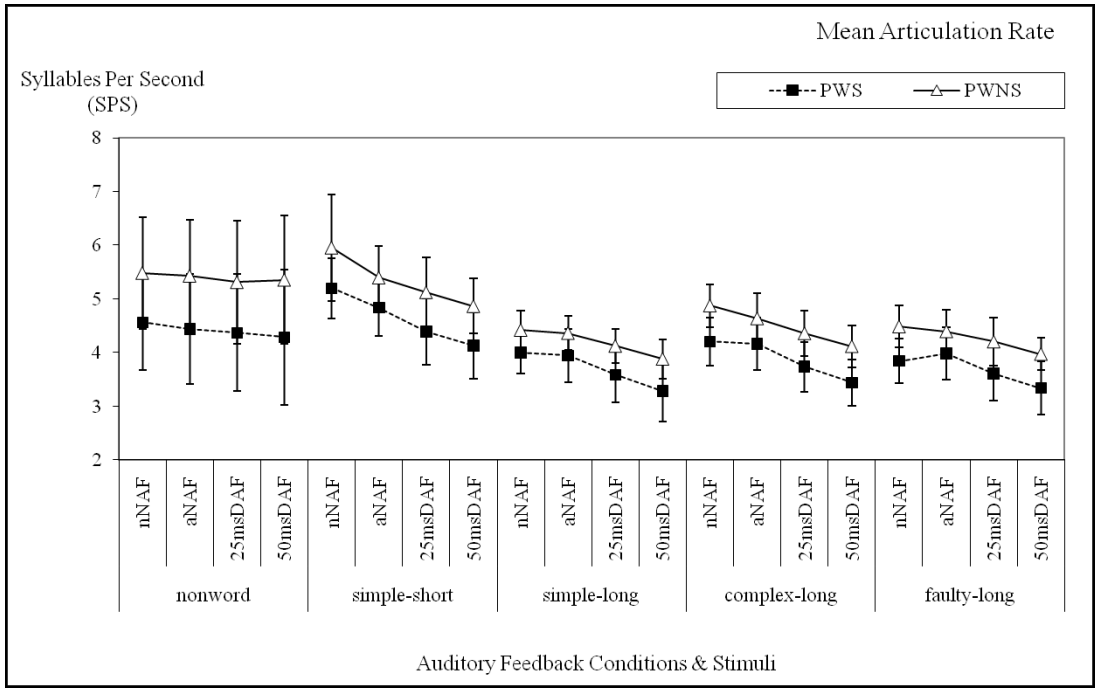
Figure 26. Interaction between stimuli and auditory feedback for articulation rate



Post-hoc test showed that nonword showed significantly faster AR than simple-long (p = .002), complex-long (p = .034), and faulty-long (p = .003) stimuli. Simple-short stimulus also showed faster AR than the longer stimuli (p < .001 for each pair). Also, AR in the complex-long stimulus was significantly faster than the simple-long (p < .001) and the faulty-long (p < .001) stimuli.

Among four auditory feedback conditions, nNAF and aNAF showed significantly faster AR than 25ms- and 50ms-DAF conditions ($p < .001$ for each pair). The AR under the 25ms-DAF condition was faster than under the 50ms-DAF condition as well ($p < .001$).

Figure 27. Means and standard deviations (error bar) of mean articulation rate under nNAF, aNAF, 25ms-DAF and 50ms-DAF conditions across five stimuli.



DISCUSSION

1. Summary of study

Study III investigated differences in speech kinematics between PWS and PWNS under non-delayed feedback and DAF conditions:

(a) PWS had a *higher* spatio-temporal index (STI) or *lower* speech motor stability than PWNS across auditory feedback conditions and four distinct utterances.

(b) The PWS showed lower STI under aNAF and 25ms-DAF in longer stimuli (i.e., simple-long, complex-long, and faulty-long utterances) than nNAF and 50ms-DAF. PWS, however, did not reveal significant variation in STI across the various feedback conditions for the baseline stimuli (i.e., nonword and simple-short utterance).

(c) PWNS showed variable patterns under altered feedback but in general, their STI was higher under 50ms-DAF than the nNAF and aNAF conditions.

(d) There was no group differences in displacement and velocity for opening-closing sequential movements of the lower lip for the syllable /bab/. The movement characters within each group, however, was different. PWNS showed lower displacement as well as velocity under altered feedback conditions compared to nNAF for both opening and closing movements. Auditory feedback also effected displacement during closing movement for PWS but, instead, they showed larger movements under DAF than under aNAF. People who stutter exhibited higher velocity under nNAF than in 25ms-DAF.

(e) In general, PWS showed longer durations and slower articulatory movement than PWNS across auditory feedback and stimuli.

2. Research Questions 1 & 2. Influence of DAF on speech articulatory stability: PWS showed <u>higher</u> speech-motor stability under AAF conditions, and linguistic contexts influenced the stability.

2.1. Between groups

Overall, PWS had higher STI than PWNS across the utterance stimuli with that interacted with auditory feedback for the more linguistically complex utterances. The significant group difference under nNAF follows previous findings that STI values for PWS would be higher and more sensitive to linguistic complexity (Kleinow & Smith, 2000). It is interesting the differences between PWS and PWNS under AAF was clearer in longer utterances.

The diverse STI patterns across the stimuli under altered feedback conditions could be related to differential processing demands for speech motor execution. Both PWS and PWNS simply repeated a syllable /pa/ nine times in the nonword, which was not sensitive to group differences. Had we used more complex nonword stimuli, such as combination of different syllables, the results might have been different. A recent study compared the influence of phonological complexity on inter-articulator movements (lip aperture: coordinating upper lip, lower lip and jaw movements) between PWS and PWNS using nonword stimuli (Smith, Sadagopan, Walsh, & Weber-Fox, 2010, in press). The study found PWS exhibited less consistent speech motor movement patterns than PWNS, with the greater differences in longer and complex nonword stimuli.

The influence of altered auditory feedback on speech motor execution differed depending on the linguistic demands. In the other baseline stimulus, "Buy bobby a puppy," an effect of AAF was not detected in either group. AAF did affect the longer utterances likely due to their increased length and syntactic complexity that presumably require more time to process in the speech motor system. PWS have shown higher speech motor variability for more complex utterances under natural feedback condition (Kleinow & Smith, 2000). Altered auditory feedback, especially aNAF and 25ms-DAF,

however, helped PWS achieve higher movement stability while PWNS showed higher variability. This provides evidence that auditory feedback functions differently in PWS and PWNS. Perhaps, the speech-motor control of PWS is less influenced by AAF in short stimuli than longer utterances due to minimum required processing time to compensate for, or adapt to, auditory feedback alteration.

Interestingly, PWNS showed similar STI patterns to those of PWS in the faulty-long utterance. Due to syntactic violation, the movement patterns for speech production could be unusually inconsistent or unstable resulting in higher STI values. Here, auditory feedback alteration might also help PWNS to achieve more stable patterns of movement. It is also suggested that aNAF and shorter delays could help the speech motor system perform in a more stable manner when processing unpredictable linguistic stimuli.

2.2. Individual variability in PWS

As reported in Table 18, a large percentage of PWS showed lower STI under aNAF and DAF conditions than nNAF. Thus, individual data support our hypothesis that PWS would show higher motor stability of the lower lip under aNAF and DAF conditions compared to nNAF condition.

It is important to note that 10 out of the 11 PWS in Study III also participated in Study II. Loudness level was identical for the two studies. In Study II, 40% of PWS reduced SLD under aNAF but showed greater SLD under 250ms-DAF. Thus, the reduced STI under aNAF in this study may support the hypothesis that some stuttering participants' speech-motor stability was enhanced, resulting in stuttering reduction. The relation between the length of the time delay and the STI may be at background. At

50ms-DAF, relatively smaller percentage of stuttering participants showed reduced STI compared to aNAF and 25ms-DAF. In addition, during our pilot experiment for Study III, it was not possible to measure STI at 250ms-DAF because more than a half of utterances contained SLD whereas measurements had to be done with fluent utterance only. Thus, even though delay times were not identical in Studies II and III, it might be possible that the effects of DAF for PWS depend on delay time when auditory feedback is amplified. With the shorter delay, PWS may be more fluent because the delayed feedback allows their speech-motor system to achieve higher stability. The speech of PWS may be disrupted with the longer delay, however, because they are unable to maintain speech motor stability. This explanation appears to be supported by an early study using amplified feedback (Burke, 1975b, 100dB SPL). Burke reported that stuttering participants showed similar or decreased SLD under 50, 100, or 150ms-DAF conditions, but showed more SLD with longer delay times (200, 250, and 300ms-DAF).

Some PWNS also showed reduced STI under AAF (see Table 18). As mentioned earlier, more than 60% of PWNS showed lower STI under AAF than nNAF in the faulty-long utterance. The individual variability in STI changes may be related to different auditory feedback dependency of normally fluent people as proven in Study I. As reported in Study I, some normally fluent people showed increased SLD under 250ms-DAF condition and were regarded as more dependent on auditory feedback. Similar to PWS, auditory feedback with simple amplification and shorter delay might help them improve their speech-motor stability but disrupt their speech outputs under longer delayed feedback condition.

3. Research Question 3. Influence of AAF on single-articulatory movement patterns: No group difference, but obvious different movement patterns within group in response to AAF

Overall, there were no group differences for opening and closing movements. PWNS showed relatively larger movement displacement across stimuli but there were considerable overlap with PWS under nNAF condition which are similar to previous studies (McClean et al., 1990; Smith & Kleinow, 2000). However, both groups showed different movement patterns under AAF. PWS did not show considerable changes in response to AAF during opening movements but revealed increased movements under 25ms- and 50ms-DAF conditions during closing movements. Opposite patterns were observed for PWNS who showed larger movements in nNAF than in AAF conditions during both opening and closing movements. PWNS also showed stimulus dependency for both opening and closing sequential movements.

Similar to displacement, no significant group differences were found for velocity but there were different trends between PWS and PWNS. Under AAF, both PWS and PWNS reduced velocity to reach the target sound. It was predicted that velocitiy in producing speech sounds would be related to the speed of articulatory movements (Smith & Kleinow, 2000) but the changes in response to the articulation rate were minimal in PWS. Auditory feedback only influenced the opening movement in PWS showing reduced velocity under 25ms-DAF compared to nNAF condition. PWNS showed their highest velocity under nNAF condition and decreased speed to reach the spatial target across AAF conditions during both opening and closing movements. PWNS also showed

stimulus effects for the sequential movements but it was only observed during closing movement for PWS.

The findings in displacement and velocity could be interpreted in two ways: First, PWNS may manage their lower lip sequential movements more flexibly, or more efficiently, to reach phonetic targets by compensating for changes in feedback than PWS (Smith & Kleinow, 2000; Tasko & McClean, 2004). Thus, lower displacements with lower velocities in PWNS might be compensatory responses to AAF, showing their auditory-motor integration functions react to unexpected feedback changes. Second, altered auditory feedback may interact with speech-motor system of PWS (i.e., auditory-to-motor integration) and beneficially modify their speech kinematics. Thus, they could maintain the movement distance with similar velocity as a response to AAF, of which the patterns are similar to those using fluency enhancing technique (slowing down speech rate: Smith & Kleinow, 2000).

4. Research Question 4. Effects of AAF on temperal parameters: Significant influence of DAF as well as obvious group difference

PWS showed longer movement duration than PWNS across the stimuli, and the differences between two groups were even greater under DAF conditions. The nonword stimulus did not show a statistical change in duration across auditory feedback, whereas the duration increased under DAF for the other stimuli. Kinematic duration differences, however, do not account for the STI differences as per Kleinow and Smith (2000). When inspecting within group patterns, PWS showed longer duration but similar or lower STI

under AAF conditions. PWNS also yielded higher duration under AAF, but their STI patterns were inconsistent depending on stimuli.

Previous studies have revealed inconclusive differences between PWS and PWNS in articulation rate (Howell, Au-Yeung, & Pilgrim, 1999; Logan & Conture, 1995; Sawyer et al., 2008). In this Study, PWS showed slower articulation rates than PWNS which is different from Study II. There were no group differences in articulation rate between PWS and the normally fluent *Low-SLD* group, but PWS had a faster AR than the normally fluent *High-SLD* group. The differences can be interpreted with the sample selection and task condition. The articulation rate in Study II was measured in spontaneous speech, and disfluent utterances were included whereas the current study only used perceptually fluent utterances collected during repeated reading. Thus, from the current study, we suggest that PWNS showed better articulatory movement skills or motor transition ability when repeating utterances. The influence of utterance length and complexity was noticeable in that the three longer and complex stimuli showed significantly slower articulation rate than baseline stimuli as suggested in previous studies (e.g., Abbeduto, 1985; Sadagopan & Smith, 2008). In addition, there were interactions between linguistic complexity and auditory feedback , indicating that the nonword stimulus yielded similar articulation rate across feedback condition whereas other uttarances yielded decreased AR under AAF conditions.

Both groups showed slower articulation rate under DAF conditions compared to non-delayed conditions which is different from previous findings (Kalinowski et al., 1996; Sparks et al., 2002; Stuart et al., 2002). The discrepancy between the current results and previous findings might be related to loundess differences because maximum

comfortable loudness level has been generally used with short delay time, and even though PWS could maintain normal speaking rate under 25ms- and 50ms-DAF, they showed relatively slower rate than non-altered condition. This result supports our general hypothesis that suprasegmental mechanism may be more easily disrupted by auditory feedback alteration than segmental mechanism. Also, as discussed in Study I, the changes in the speed of articulatory movements could represent compensation in response to unexpected sensory feedback to gain more time for the feedback control for the flow of fluent speech production.

CHAPTER V

CONCLUSION

This series of studies investigated the effects of DAF on speech fluency and speech motor control in an attempt to study auditory-to-motor integration differences in normally fluent speakers and people who stutter. For normally fluent adults, it was hypothesized that they vary substantially in their dependency on auditory feedback during speech production, therefore DAF could be used to identify distinct subgroups based on susceptibility to auditory perturbations. Those who are more dependent on auditory feedback would show more DAF-induced disfluencies whereas those who have highly developed speech motor skills would be able to compensate for the auditory perturbation and maintain fluent speech. For people who stutter, the scientific literature has reported that stuttering is associated with a deficiency and/or a difference in auditory-to-motor integration that renders their speech motor system less stable than that of normally fluent people. Therefore, two related hypotheses were proposed here: (1) the less stable motor control system of PWS would lead to weakened feedforward commands, prompting them to be more dependent on auditory feedback for ongoing speech production, and (2) a temporal asynchrony effected by DAF probably allows PWS some extra time to generate accurate feedforward commands, leading to higher speech kinematic stability (i.e., lower STI) when speaking under short delays that reduce the probability of stuttering-like disfluencies.

The results of Studies I, II, and III generally supported our hypotheses. It was possible to classify normally fluent adults into three subgroups based on variations in

susceptibility to DAF. Normally fluent participants who could maintain fluent speech, and those who showed maximal speech disruption under DAF, were particularly distinct. Further, we provide evidence that PWS are dependent on auditory feedback to maintain fluency. PWS showed lower level of speech motor stability than PWNS, but their stability increased under aNAF and 25ms-DAF, implying that amplified and/or shorter delay feedback may actually help them achieve more stable and/or accurate feedforward commands. An equally important finding was that the majority of PWS showed substantial reductions in fluency under 250ms-DAF, implying that their auditory system is more sensitive to feedback effects than normally fluent speakers.

According to the findings of Studies I and II, SLD was the most important variable measured under DAF both for PWS and PWNS. Even though previous studies with normally fluent people have reported significant increases in disfluencies, they did not clearly separate or define the specific disfluency elements (e.g., part-word repetition) or the more general disfluency categories (e.g., SLD, OD and/or SE). Both PWS and PWNS in the present studies exhibited "artificial stuttering" (Lee, 1950b) that was only observed under DAF and categorized as SLD. Inconsistent previous reports regarding sex influence under DAF might be also related to such unspecified characteristics of disfluent speech discussed above. Furthermore, data for SLD (and SE) have also led to the rejection of the notion that males are more susceptible to DAF than females. Across studies, articulation rate was decreased under DAF regardless of group, indicating that suprasegmental features were more vulnerable to auditory feedback changes than segmental ones, or could be managed to maintain segmental features as discussed in Chapter 2.

Important findings have emerged from Studies II and III. First, amplified and/or delayed auditory feedback could positively, as well as negatively, influence PWS. For a long time it has been known that PWNS show higher susceptibility to DAF with amplified loudness (Howell & Archer, 1984) and long delays, such as 200 to 250ms (Fairbanks, 1955; Lee, 1950a; Van Borsel et al., 2005) whereas PWS show improved fluency. According to the current study, however, there could be two types of DAF effects for PWS: one that supports the possibility of SLD reduction with improved motor stability during a shorter delay (e.g., 25ms) regardless of loudness, and the other reflected in SLD increment during a longer delay (e.g., 250ms) with feedback amplification. These opposite effects may suggest that there is a threshold for PWS at which the DAF effects turn to be negative. Additionally, the effects of DAF seen in the kinematic study, namely that amplified non-delayed feedback and DAF at 25ms and 50ms improve the speech motor stability of PWS, support previous reports that 25ms-and 50ms-DAF can improve speech fluency of PWS without significant rate change (e.g., Kalinowski et al., 1996). The mechanism underlying the stuttering amelioration might be inferred from the current study.

THEORETICAL IMPLICATIONS

1. Role of auditory feedback in speech motor control

In general, the current findings are in line with a theoretical framework in which the role of auditory feedback for speech motor control in adults involves maintaining and updating internal models. Individual variability in PWNS under DAF suggests different

roles of auditory feedback in speech articulatory production. According to the DIVA model, as discussed in Chapter 1, the role of auditory feedback is more essential when learning speech motor control in childhood. In adults, however, the role shifts to maintaining the developed motor control but it is not needed to directly monitor ongoing speech sounds. This is, presumably, because the speech sound map that transforms auditory representations to motor commands in adults has achieved accuracy and stability during the developmental period (Guenther, Ghosh, & Tourville, 2006; Guenther & Perkell, 2004). The varied contribution of auditory feedback to speech production has been broadly confirmed in the adults who lost hearing after learning language (post-lingual deafness: see Perkell et al., 2000 for review), as well as with bilingual speakers and children speaking under DAF. Children show more speech disruptions than adults under DAF, supporting the idea that because children are more dependent on feedback control, temporal asynchrony between speech output and auditory feedback would interrupt their speech execution more. Also in the case of second language learners, there is more DAF-induced disfluencies when using their second language compared to their first language, presumably because of lower language familiarity. That is, even in adulthood, if people do not have accurate/stable speech sound map, they may be more dependent on auditory feedback to compare expected speech to actual speech motor output. Despite the substantial reduction in dependency in adults, Study I shows that even some adult speakers, using native English, are more susceptible to auditory perturbations and, in turn, are likely more dependent on intact auditory feedback to maintain fluency. Auditory perturbations potentially reveal whether their feedforward commands are more unstable even though this characteristic is veiled in natural feedback

or non-delayed feedback condition. When feedback is manipulated, it becomes apparent in disturbed segmental production as well as suprasegmental modulation. The phenomenon of segmental disruption under DAF, including SLD, is important because it suggests that SLD, in general, is related to auditory-to-motor integration error at the segmental level. Normally fluent speakers who have higher auditory feedback dependency may have unstable speech-motor control system under DAF due to time lag in feedback control that results in SLD. This may support our hypothesis of how stuttering-like disfluencies are generated in people who stutter.

In addition, responses to DAF could be interpreted with Levelt's perceptual loop model (1983, 1989). This psycholinguistic model proposed sequential processes for fluent speech production. The first step is conceptualizing what a speaker wants to express. The second step is formulating grammatical and phonological representations (i.e., encoding), and the last step is articulating the representations that the speaker planned. Levelt argued that, during the processes, the speaker monitors his/her speech production using external as well as internal loops. The external loop involves the role of audition. Through auditory feedback, the overt speech is transformed into a phonetic string and is being analyzed as to whether the output was linguistically correct in the speech comprehension system. The result is then forwarded to the initial step for speech production (i.e., conceptualization) for comparisons. If any errors are detected, they are corrected. Thus, the conceptualization process also monitors actual speech output. The internal loop is similar to the external one but it does not include the articulating step for actual speech production or auditory component for monitoring the speech output. The speech plan in the second step (i.e., formulation) is directly delivered to the speech

comprehension system and is examined as to whether it was correct. Delayed auditory feedback might interrupt the external loop for monitoring speech execution. This means that the time gaps between the speech articulatory production and its arrival at the speech comprehension system disturb the external loop, thus the conceptualizer cannot monitor speech production properly. Also, we might suggest that if a speaker was influenced by the external loop more than the internal loop for speech production, s/he might be highly disfluent under DAF, but if a speaker makes more usage of the internal loop for speech monitoring, s/he might be relatively fluent even under DAF.

2. Implications of delay time for auditory-motor integration framework in PWS

For people who stutter, auditory-motor integration under DAF was different depending on the delay time. Due to relatively unstable feedforward control, PWS may be more dependent on feedback control. The positive effects of short delay may reveal that temporal asynchrony allows them to generate more accurate feedforward commands and facilitate speech fluency. A relationship was suggested with higher movement stability of lower lip under DAF. Most PWS showed increased speech-motor stability at 25ms and/or 50ms-amplified DAF condition(s). Importantly, they also read fluently under the shorter delays because few kinematic trials in Study III showed SLD's.

The continuity of responses outlined above suggests a threshold above which persons who stutter lose the fluency inducing effects of DAF. For them, the negative effects of DAF may emerge above certain level of delay. It might make their speech motor system even more unstable than in a natural feedback condition. Indeed, most PWS achieved higher kinematic stability at short delays but produced more SLD under

250ms DAF. The mechanisms involved leading to DAF-induced disfluency in PWS may be similar to the mechanisms inducing high disfluencies in the *High Responders* of Study I.

3. Implications of individual variation in stuttering

PWS also showed individual variation in responses to amplified non-delayed feedback and/or DAF as shown in previous studies. Some showed positive responses (improved speech kinematic stability or diminished stuttering) whereas other showed no significant change or even negative responses (decreased speech kinematic stability or stuttering increment) under these altered feedback conditions. These findings could be related to the nature of stuttering along the line of the dynamic-multifactorial model (Smith & Kelly, 1997) as discussed in Chapter 1, and might support the concept of subtypes of stuttering (Yairi, 2007).

Stuttering, both at onset and later in regards to its maintenance, may be related to multiple factors, such as genetics, brain dysfunction, motor-speech function, language processing, temperament, and/or emotion. Therefore, producing disfluent speech may not be related to problems with a single factor but to the interaction of multiple factors. Regarding the diverse responses to aNAF and DAF, several explanations could be considered based on past work: (1) auditory feedback dependency (Fukawa, Yoshioka, Ozawa, & Yoshida, 1988; Kent, 2000; Max et al., 2004), (2) dissociation between auditory cortical areas and motor areas for speech production (Braun et al., 1997; Fox et al., 1996; Salemlin et al., 1998), and (3) differences in brain morphology (Foundas et al., 2004). As we hypothesized, many PWS may have relatively more unstable/weak

feedforward commands than PWNS, thus their dependency on feedback controls for speech production would be higher. Under DAF, PWS may be able to generate accurate feedforward commands. Also, their deficient auditory-to-motor integration results in abnormal error signal detection that may cause stuttering but the dissociation in auditory-to-motor integration has been reduced under AAF (Braun et al., 1997; Fox et al., 1996), allowing more movement sequence stability that yields improved fluency. As the constellation of etiologic factors is theorized to vary, resulting in subtypes of stuttering, it could be expected that some PWS may have normal range of feedforward planning and commands as well as a normal range of motor stability. Under such a scenario, AAF would have little impact on their speech production. One of the etiologic factors may be variability in brain morphology (e.g., Chang, Erickson, Ambrose, Hasegawa-Johnson, & Ludlow, 2008; Foundas, Bollich, Corey, Hurley, & Heilman, 2001; Foundas et al., 2004). Although such brain structural differences may not necessarily be the direct cause of stuttering, they could influence the individual's responses to DAF (Foundas et al., 2004; Yairi, 2007). For example, Foundas et al. (2004) reported the influence of planum temporale (PT) asymmetry on responses to DAF in PWS. PWS who had atypically rightward PT asymmetry showed higher stuttering rate under natural feedback but decreased stuttering under non-delayed condition and 120ms-DAF. In contrast, PWS with typical leftward PT asymmetry showed lower stuttering rate and their responses to the non-delayed feedback and 120ms-DAF was not obvious.

4. Neural correlates of DAF effects in PWS

Recent brain imaging studies that compared functional brain activation between PWS and PWNS may address these findings. These studies reported similar activation patterns for the two groups under DAF compared to non-altered feedback involving increased activation of the superior temporal gyrus (STG). The STG (particularly posterior) is predicted to encompass the brain circuitry that comparing expected auditory feedback with the actual ascending input (Sakai et al., 2009; Watkins et al., 2008). In these studies, the investigators used 200ms delay and reported more disfluent speech compared to non-delayed feedback for both PWS and PWNS. This suggests that disfluency inducing effects of DAF are associated with *increased* activation in the same auditory cortical region for both control and stuttering participants.

CLINICAL IMPLICATIONS

The current study demonstrated ongoing speech production is influenced by changes in auditory feedback whether an individual is a normally fluent speaker or a person who stutters. These changes are especially relevant for developmental stuttering because speech fluency is integrally related to the temporal processing of speech motor commands. Mechanisms underlying disfluency reducing effects of AAF have not been well-explained even though AAF devices have been employed for clinical purposes over a long period. Overall, the information generated by these studies may inform clinical practice in several ways. We found that short delayed feedback (25ms) and noise conditions can stabilize movement sequence patterns in terms of lower STI which is a possible basis for stuttering amelioration. Secondly, a stimulus dependency was

observed because up to 90% of PWS showed higher stability of movement sequence at 25ms-DAF while up to 72% of PWS also showed increased stability at 50ms-DAF during utterance reading. Previous studies support our results that PWS achieve fluency improvement under shorter time delay (e.g., Kalinowski et al., 1993; Kalinowski et al., 1996). Therefore, short delay times may facilitate speech stability and fluency in PWS because of direct effects on speech motor stability.

When feedback is amplified but not delayed, approximately 40% of PWS showed fewer SLD during spontaneous conversation and up to 81% of them achieved higher speech-motor stability during the reading task (many participants overlapped in two experiments). The amplification appears to have similar effects to those of white noise delivered to PWS during speech with its well-known ameliorating effect (Andrews et al., 1982; Cherry et al., 1955; Shane, 1946, 1955; Yairi, 1976), but it is unclear if the same mechanisms are involved. There might be interaction between amplification and the amount of delay. At the longer delays, 250ms-DAF with amplified loudness, PWS showed significantly more speech disruption compared to natural feedback. Previous studies have reported positive effects of longer delays, but it should be noted that the general purpose of longer DAF has been to reduce speech rate (Curlee & Perkins, 1973). If the goal is to achieve fluency without drastically slowing the speaking rate (e.g., 30 words per minute or even up to 120 words per minute) under longer delay, PWS would show higher disfluency rates under DAF than under non-delayed feedback.

SCOPE OF THE STUDIES AND FUTURE DIRECTIONS

As stated above, this dissertation demonstrated individual variability in responses to DAF in normally fluent individuals. According to their responses in terms of changes in stuttering-like disfluencies, speech errors, and articulation rate, it was possible to distinguish between individuals who are minimally affected by DAF (*Low Responders*) and those who are highly susceptible to DAF (*High Responders*). It is important to understand whether or not DAF responsiveness is related to speech motor control. The specific differences in the speech motor control between these two groups, however, were not identified. A different direction of motor stability would be expected: the *Low Responders* might maintain stable speech-motor functions in terms of spatiotemporal index under DAF conditions (i.e., 25ms- and 50ms-DAF) whereas the *High Responders* might show lower speech-motor stability under DAF. Further investigations comparing *Low* and *High Responders* are likely to extend our understanding of the role of auditory-motor integration in speech fluency.

The current studies did not manipulate delay time across a broad temporal interval; only short and long delays were used in different experiments but with different questions. We also did not manipulate amplification levels. Previous studies have found these variables are important for inducing fluency.

The current dissertation project was conducted only with adult speakers. It is known that the magnitude of DAF effects may be greater in children. Among normally fluent individuals, younger children show more susceptibility to DAF than older children and adults, with longer delays being the most disruptive. According to our theoretical framework, speech motor commands of young children are not likely to be as stable as those of older children or adults, thus younger children would be more dependent of

auditory feedback for speech production. Also, the effects of DAF on children who stutter (CWS) have not been adequately investigated. Thus, research comparing DAF effects between CWS and normally fluent age-matched children is desirable because it should provide developmental patterns of auditory-motor integration.

Our central hypothesis was that developmental stuttering is related to a deficiency in auditory-to-motor integration. Several neuroimaging studies have reported that AAF decreases aberrant activity in auditory-sensory and motor-output regions of the brain in PWS (e.g., Fox et al., 1996). The current study investigated DAF because of its unique differential effects on PWS (reducing stuttering) and PWNS (inducing stuttering), but it is unclear whether the effects of other types of AAF for PWS, such as choral speech and frequency altered feedback, are induced by similar auditory-motor integration mechanism. Future research with people who stutter may employ other types of AAF, such as masking noise, choral speech, and frequency altered feedback, and compare changes in speech motor control under the ameliorating conditions to natural feedback condition. Such research would provide a broader map of how AAF influences or promotes auditory-to-motor integration in people who stutter.

Lastly, compensation and adaptation effects under DAF would be expected in people who stutter. Clinical research has reported successful treatment outcomes with AAF devices (e.g., O'Donnell, Armson, & Kiefte, 2008; Stuart, Kalinowski, Saltuklaroglu, & Guntupalli, 2006). It is possible to study whether speech kinematic stability in PWS is improved with long-term exposure to fluency inducing AAF and whether these benefits carry-over to natural feedback condition.

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APPENDIX A. LOUDNESS CATEGORIES FOR STUDIES I, II, AND III

(Cox, R. M., Alexander, G. C., Taylor, I. M., & Gray, G. A. (1997). The contour test of loudness perception. *Ear and Hearing, 18*(5), 388-400.)

1) Very Soft
2) Soft
3) Comfortable, but Slightly Soft
4) Comfortable
5) Comfortable, but Slightly Loud
6) Loud, but O.K.
7) Uncomfortably Loud

APPENDIX B. SCREENING FORM FOR STUDY I

Screening Form

DATE OF VISIT: _____ NAME: _____

DATE OF BIRTH: _____ SEX: MALE / FEMALE

1. Have you ever been diagnosed with hearing loss by a physician or an audiologist? (YES / NO)

2. Have you ever had speech and/or language problems as diagnosed by a physician or speech-language pathologist? (YES / NO)

3. Have you ever had neurological problems, such as a movement disorder, loss of consciousness, head trauma or stroke? (YES / NO)

4. Do you have a history of stuttering in your family or have any knowledge of family memebers who stutter? (YES / NO)

APPENDIX C. EDINBURGH HANDEDNESS INVENTORY FOR STUDIES I, II,

AND III

(Oldfield, R.C. (1971). The assessment and analysis of handedness: The Edinburgh Invertory. *Neuropsychologia, 9(1),* 97-113.)

Edinburgh Handedness Inventory
(Oldfield, 1971)

DATE OF VISIT: _____ NAME: _____

DATE OF BIRTH: _____ SEX: MALE / FEMALE

Please indicate your preferences in the use of hands in the following activities ***by putting check mark* (√) *in the appropriate column***. Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, put the check mark in "Always Right" or "Always Left" column. If in any case you are really indifferent, put the check mark in "Either One."

Some of the arcivities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets. Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

	Always Right	Sometime Right	Either One	Sometime Left	Always Left
1. Writing					
2. Drawing					
3. Throwing a Ball					
4. Using Scissors					
5. Using a Toothbrush					
6. Using a Knife (without fork)					
7. Using a Spoon					
8. Using a Broom (upper hand)					
9. Striking a Match					
10. Operating a Lid					
TOTAL					

APPENDIX D. READING MATERIALS FOR STUDIES I AND II

(1) Reading materials for aNAF and DAF

(Riley, G. D. (1994). *Stuttering severity instrument for children and adults* (3rd ed.). Austin, TX: PRO-ED.)

<READING 1>

WASHINGTON - Part of the nation's future oil supply may lie within some extraordinary organisms that have been called a "third form of life."

A Colorado State University microbiologist reports obtaining pure hydrocarbon that could be converted to gasoline or lubricating oils from several of the organisms.

The oily substance is "energy-rich, definitely a lubricant, combustible, and isn't soluble in water," says the researcher, Thomas Tornabene. And the oil is free of air-polluting sulfur.

The discovery now is only a laboratory phenomenon; any commercial application is some time away.

"Right now we are concentrating on the organisms' basic mechanisms," Tornabene says. "We have two genetic engineers looking at them to find ways of getting them to grow faster and to pump oil faster."

<READING 2>

The Great Chief in Washington sends word that he wishes to buy our land. How can you buy or sell the sky-the warmth of the land? The idea is strange. We do not own the freshness of the air or the sparkle of the water. How can you buy them from us? We will

decide in our time. Every part of this earth is sacred to my people. Every shining pine needle, every sandy shore, every mist in the dark woods, every clearing, and every humming insect is holy in the memory and experience of my people. For all things share the same breath - the beasts, the trees, the man. All things are connected. Whatever befalls the earth befalls the sons of the earth.

(2) Reading material for nNAF for PWS

(Darley, F. L., Aronson, A. E., & Brown, J. R. (1975). *Motor speech disorders.* Philadelphia, PA: W.B. Saunders.)

You wished to know all about my grandfather. Well, he is nearly ninety-three years old; he dresses himself in an ancient black frock coat, usually minus several buttons; yet he still thinks as swiftly as ever. A long, flowing beard clings to his chin, giving those who observe him a pronounced feeling of the utmost respect. When he speaks, his voice is just a bit cracked and quivers a trifle. Twice each day he plays skillfully and with zest upon our small organ. Except in the winter when the ooze or snow or ice prevents, he slowly takes a short walk in the open air each day. We have often urged him to walk more and smoke less, but he always answers,

"Banana oil!"

Grandfather likes to be modern in his language.

APPENDIX E. HEARING SCREENING FORM FOR STUDIES I, II, AND III

Hearing Screening Form

NAME: _____ AGE: _____ CASE No.: _____

EXAMINER: _____ DATE: _____

Check (√) frequencies passed:

Frequencies / Ear	250	500	1000	2000	4000	8000
Right						
Left						

Tone presented by: A/C at _____ dB
re: _____ ISO _____ ASA _____ ANSI

Testing Conditions:
Response Required:
Comments regarding ease of conditioning, false positives and other behaviors:

APPENDIX F. CLASSIFICATION LIST BASED ON THE PAM ANALYSIS IN SPONTANEOUS SPEECH (STUDY I)

Low Responders (N = 18)	*Middle Responders (N = 32)*	*High Responders (N = 12)*
DAF006Ju	DAF012Ga	DAF002Ky
DAF013Li	DAF014Da	DAF017Ca
DAF028Je	DAF021Mi	DAF020Vi
DAF032Ho	DAF030Je	DAF025Mi
DAF033Sa	DAF035Me	DAF041Ju
DAF038Ni	DAF036Ka	DAF044Ja
DAF043Je	DAF037Ka	DAF048Ma
DAF045Ca	DAF039Du	DAF063An
DAF047Er	DAF050Co	DAF091Dr
DAF072Br	DAF051Ma	DAF095Ji
DAF073Ma	DAF052Ka	DAF099Ka
DAF082Ch	DAF053Jo	DAF119Da
DAF089Da	DAF054Co	
DAF102Jo	DAF066Ja	
DAF112Lo	DAF067Ab	
DAF115Ab	DAF068Mi	
DAF117Ma	DAF075Ja	
DAF123Am	DAF079Ry	
	DAF080Li	
	DAF081Ki	
	DAF083Ja	
	DAF084Br	
	DAF090Mi	
	DAF098Er	
	DAF104Mi	
	DAF105Cl	
	DAF107Mc	
	DAF113Bi	
	DAF120Ch	
	DAF125Co	
	DAF129Da	
	DAF131Ni	

APPENDIX G. CLASSIFICATION LIST BASED ON THE PAM ANALYSIS IN READING (STUDY I)

Low Responders (N = 18)	*Middle Responders (N = 24)*	*High Responders (N = 20)*
DAF006Ju	DAF014Da	DAF002Ky
DAF012Ga	DAF020Vi	DAF017Ca
DAF013Li	DAF030Je	DAF021Mi
DAF025Mi	DAF032Ho	DAF041Ju
DAF028Je	DAF035Me	DAF044Ja
DAF033Sa	DAF036Ka	DAF048Ma
DAF038Ni	DAF037Ka	DAF052Ka
DAF053Jo	DAF039Du	DAF063An
DAF054Co	DAF043Je	DAF067Ab
DAF066Ja	DAF045Ca	DAF081Ki
DAF068Mi	DAF047Er	DAF083Ja
DAF079Ry	DAF050Co	DAF084Br
DAF090Mi	DAF051Ma	DAF091Dr
DAF102Jo	DAF072Br	DAF095Ji
DAF112Lo	DAF073Ma	DAF098Er
DAF115Ab	DAF075Ja	DAF099Ka
DAF123Am	DAF080Li	DAF104Mi
DAF129Da	DAF082Ch	DAF105Cl
	DAF089Da	DAF119Da
	DAF107Mc	DAF125Co
	DAF113Bi	
	DAF117Ma	
	DAF120Ch	
	DAF131Ni	

APPENDIX H. INSTITUTIONAL REVIEW BOARD (IRB) APPROVAL AND CONSENT FORMS FOR STUDIES I, II, AND III

UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN

Office of the Vice Chancellor for Research
Institutional Review Board
528 East Green Street
Suite 203
Champaign, IL 61820

September 23, 2009

Torrey Loucks
Speech & Hearing Science
228 SHS Bldg
M/C 482

RE: *The Effects of Delayed Auditory Feedback on Speech Fluency in Adults*
IRB Protocol Number: 08090

Dear Torrey:

Your response to stipulations for the continuing project entitled *The Effects of Delayed Auditory Feedback on Speech Fluency in Adults* has satisfactorily addressed the concerns of the University of Illinois at Urbana-Champaign Institutional Review Board (IRB) and you are now free to proceed with the human subjects protocol. The IRB approved the protocol as described in your IRB-1 application, by expedited continuing review. The expiration date for this protocol, UIUC number 08090, is 09/17/2010. The risk designation applied to your project is *no more than minimal risk*. Certification of approval is available upon request.

Copies of the enclosed date-stamped consent forms must be used in obtaining informed consent. If there is a need to revise or alter the consent forms, please submit the revised forms for IRB review, approval, and date-stamping prior to use.

Under applicable regulations, no changes to procedures involving human subjects may be made without prior IRB review and approval. The regulations also require that you promptly notify the IRB of any problems involving human subjects, including unanticipated side effects, adverse reactions, and any injuries or complications that arise during the project.

If you have any questions about the IRB process, or if you need assistance at any time, please feel free to contact me or the IRB Office, or visit our Web site at http://www.irb.illinois.edu.

Sincerely,

Sue Keehn, Director, Institutional Review Board

Enclosures

c: Hee-Cheong Chon
Shelly-Jo Steger

telephone (217) 333-2670 • *fax* (217) 333-0405 • *email* IRB@illinois.edu

University of Illinois at Urbana-Champaign
Department of Speech and Hearing Science
901 South Sixth Street, Champaign, IL 61820
Telephone: (217) 333-2230

ADULT CONSENT FOR PARTICIPATION IN RESEARCH
Delayed Auditory Feedback Study
Visit 1

Investigators directing DAF research: Hee-Cheong Chon, M.S., Shelly Jo Steger, M.A., CCC-SLP, David Gooler, Ph.D., CCC-A, Torrey Loucks, Ph.D., Nicoline G. Ambrose, Ph.D., CCC-SLP. Each individual is either a full-time student or full-time employee of the University of Illinois at Urbana-Champaign.

Title of the Study: The Effects of Delayed Auditory Feedback on Speech Fluency in Adults

Principal Investigators: Torrey Loucks, Ph.D., Nicoline G. Ambrose, Ph.D., CCC-SLP, University of Illinois at Urbana-Champaign. Contact information is listed on page 2.

Department: Speech and Hearing Science, University of Illinois at Urbana-Champaign

Purpose of Research Project:
We are studying how people respond to changes in how they hear their voice while they are speaking. The changes in how you hear your voice are produced by using a computer to delay what you hear. We call this "delayed auditory feedback (DAF)."

Description of Procedure:
You will be given a series of short speech and language tests by a research investigator. Your speech will be recorded using this delayed auditory feedback and then without any delays. You will listen to your own speech through headphones. You will be asked to:

1) Complete a hearing screening.
2) Complete a handedness inventory.
3) Speak freely with an investigator with headphones on.
4) Read passages with headphones on.
5) Listen to, and re-tell a story with headphones on.
6) Read passages while performing a quiet task with headphones on: monitor for the speech sound /s/ on the reading passages and press a button when producing the /s/ sound.

We will record your speech and videotape you while you do these tasks. Testing and recording will be conducted at the University of Illinois at Urbana-Champaign in the Stuttering Research Laboratory of the Speech and Hearing Science Building.

Time Required and Potential Risks:
This study will take about 50 minutes to complete. Your participation in these tasks does not have any risks that are higher than experienced during any average day.

Benefits:
There are no direct benefits, but you will help scientists learn more about normal speech and hearing function and in the disorder of stuttering.

Remuneration:
If you are a student in SHS 170 or SHS 199G, you will be given class credit for your participation. Individuals who are interested in participating in the study but are not in SHS 170 or SHS 199G will not be compensated for the first visit.
Any individual who returns for the second visit will be compensated regardless of whether s/he is registered in one of the classes. Visit 2 is a separate experiment, so participation in visit 1 does not obligate you in any way to return for visit 2. The remuneration that will be provided if you participate in Visit 2 is $10 per hour.

Confidentiality:
All of the information we gather will remain confidential. The results from this study may be published in scientific journals and/or used for academic lecture; no identifying information will be used, published, or identified in any document or presentation. You may check a consent box at the end of this form if you would permit the use of your audio and/or videotapes to be used for educational and scientific presentations.

Voluntary Participation and Withdrawal:
You may stop participating at any time without penalty or prejudice against you. This project is completely voluntary. The decision to participate, decline or withdraw from participation will have no effect on the subject's grades at, status at, or future relations with the University of Illinois. Please feel free to ask questions at any time.

Contact Information:
You will be given a copy of this consent form. If you have any questions about this particular study you may call Professor Torrey Loucks at 217-244-6576 or email to tloucks@uiuc.edu. You may also call Professor Nicoline G. Ambrose at (217) 244-2559 or email to nambrose@uiuc.edu. If you have questions or concerns regarding your rights as a participant in the study, please contact the University of Illinois Institutional Review Board office at (217) 333-2670 or irb@uiuc.edu.

I, _____, am over the age of 18 and agree to be a participant in the project described above conducted in the Speech and Hearing Science Building at the University of Illinois at Urbana-Champaign.

Signature of Participant: _____ Date: _____

I do _____ do not _____ give permission to use audio and video tapes for instructional purposes, without personal identification (i.e., your name will not be used).

Signature of Investigator: _____ Date: _____

UNIVERSITY OF ILLINOIS
APPROVED CONSENT
VALID UNTIL
SEP 17 2010

University of Illinois at Urbana-Champaign
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ADULT CONSENT FOR PARTICIPATION IN RESEARCH
Delayed Auditory Feedback Study

Investigators directing DAF research: Hee-Cheong Chon, M.S., Shelly Jo Steger, M.A., CCC-SLP, David Gooler, Ph.D., CCC-A, Torrey Loucks, Ph.D., Nicoline G. Ambrose, Ph.D., CCC-SLP. Each individual is either a full-time student or full-time employee of the University of Illinois at Urbana-Champaign.

Title of the Study: The Effects of Delayed Auditory Feedback on Speech Fluency in Adults

Principal Investigators: Torrey Loucks, Ph.D., Nicoline G. Ambrose, Ph.D., CCC-SLP, University of Illinois at Urbana-Champaign. Contact information is listed on page 2.

Department: Speech and Hearing Science, University of Illinois at Urbana-Champaign

Purpose of Research Project:
We are studying how normally fluent speakers and people who stutter respond to changes in how they hear their voice while they are speaking. The changes in how you hear your voice are produced by using a computer to delay what you hear. We call this "delayed auditory feedback (DAF)."

Description of Procedure:
You will be given a series of short speech and language evaluations by a research investigator. Your speech will be recorded with and without altered auditory feedback, which will be presented to you through headphones. You will also listen to your normal voice without wearing headphones. You will be asked to:

1) Complete a hearing screening.
2) Complete a handedness inventory.
3) Speak freely with an investigator with and without headphones on.
4) Read passages with and without headphones on.
5) Listen to, and re-tell a story with and without headphones on.
6) Read passages while performing a quiet task with headphones on: monitor for the speech sound /s/ on the reading passages and press a button when producing the /s/ sound.

We will record your speech and videotape you while you do these tasks. Testing and recording will be conducted at the University of Illinois at Urbana-Champaign in the Stuttering Research Laboratory of the Speech and Hearing Science Building.

Time Required and Potential Risks:
This study will take about 1 hour to complete. Your participation in these tasks does not involve any risks that are higher than experienced during an average day.

Benefits:
There are no direct benefits, but you will help scientists learn more about normal speech and hearing function and in the disorder of stuttering.

Remuneration:
You will be paid $10 through the Illinois Stuttering Research Program for your participation.

Confidentiality:
All of the information we gather will remain confidential. The results from this study may be published in scientific journals and/or used for academic lecture; no identifying information will be used, published, or identified in any document or presentation. You may check a consent box at the end of this form if you would permit the use of your audio and/or videotapes to be used for educational and scientific presentations.

Voluntary Participation and Withdrawal:
You may stop participating at any time without penalty or prejudice against you. This project is completely voluntary. The decision to participate, decline or withdraw from participation will have no effect on future relations with the University of Illinois. Please feel free to ask questions at any time.

Contact Information:
You will be given a copy of this consent form. If you have any questions about this particular study you may call Professor Torrey Loucks at 217-244-6576 or email to tloucks@uiuc.edu. You may also call Professor Nicoline G. Ambrose at (217) 244-2559 or email to nambrose@uiuc.edu. If you have questions or concerns regarding your rights as a participant in the study, please contact the University of Illinois Institutional Review Board office at (217) 333-2670 or irb@uiuc.edu.

I, _____, am over the age of 18 and agree to be a participant in the project described above conducted in the Speech and Hearing Science Building at the University of Illinois at Urbana-Champaign.

Signature of Participant: _____ Date: _____

I do _____ do not _____ give permission to use audio and video tapes for instructional purposes, without personal identification (i.e., your name will not be used).

Signature of Investigator: _____ Date: _____

UNIVERSITY OF ILLINOIS
APPROVED CONSENT
VALID UNTIL

2 SEP 17 2010

UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN

Office of the Vice Chancellor for Research
Institutional Review Board
528 East Green Street
Suite 203
Champaign, IL 61820

July 2, 2009

Nicoline Ambrose
Speech & Hearing Science
226 SHS Bldg
M/C 482

RE: *Subtypes and Associated Risk Factors in Stuttering*
IRB Protocol Number: 02011

Dear Nicoline:

This letter authorizes the use of human subjects in your continuing project entitled *Subtypes and Associated Risk Factors in Stuttering*. The University of Illinois at Urbana-Champaign Institutional Review Board (IRB) approved the protocol as described in your IRB-1 application, by expedited continuing review. The expiration date for this protocol, UIUC number 02011, is 06/28/2010. The risk designation applied to your project is *no more than minimal risk*. Certification of approval is available upon request.

Note: Please forward a copy of the Eastern Illinois University approval letter when it is received.

Copies of the enclosed date-stamped consent forms must be used in obtaining informed consent. If there is a need to revise or alter the consent forms, please submit the revised forms for IRB review, approval, and date-stamping prior to use.

Under applicable regulations, no changes to procedures involving human subjects may be made without prior IRB review and approval. The regulations also require that you promptly notify the IRB of any problems involving human subjects, including unanticipated side effects, adverse reactions, and any injuries or complications that arise during the project.

If you have any questions about the IRB process, or if you need assistance at any time, please feel free to contact me or the IRB Office, or visit our Web site at http://www.irb.illinois.edu.

Sincerely,

Sue Keehn, Director, Institutional Review Board

Enclosures

c: Ehud Yairi
Torrey Loucks

telephone (217) 333-2670 • *fax* (217) 333-0405 • *email* IRB@illinois.edu

University of Illinois at Urbana-Champaign
Department of Speech and Hearing Science
901 South Sixth Street
Champaign, IL 61820
Telephone: (217) 333-2230

ADULT CONSENT FOR PARTICIPATION IN RESEARCH

I, _____ , am 18 years of age or older and voluntarily agree to my participation in a program of research being conducted by Professors Nicoline Ambrose, Torrey Loucks, and their staff. The purpose of the research is to investigate the development of stuttering in children and to identify possible subtypes. I voluntarily agree to undergo standard speech, language, hearing, psycho-social, and motor speech testing, and to provide background information concerning familial history of stuttering and other possibly related disorders. I also agree to respond to various questionnaires about myself and my family. These will include questions about personality, family environment, and behavior.

The project involves a series of speech, language, motor, hearing, and psycho-social tests that will be administered by project staff in two to three sessions over a period of one month. The combined sessions will take approximately two hours. The project will also involve audio and video tape recording of my speech. Testing will be conducted at the University of Illinois at Urbana-Champaign. Data analyses will also be conducted at the University of Wisconsin-Milwaukee, Eastern Illinois University and the University of Iowa. Tapes and data will be stored in securely locked cabinets with limited access by only project staff and will be kept indefinitely.

The risks anticipated in the proposed research are not greater than those ordinarily encountered in daily life. However, I understand that test results and personal information will be collected during the study. Confidentiality will be maintained. No personal identification will be used in published scientific reports.

I understand that I will be consulted by the project staff about my speech and the speech of family members. However, I acknowledge that I have been informed that participation in this research does not involve any therapy program. I further acknowledge that I have been informed that participation in the research may not necessarily benefit me personally other than the knowledge that participation may contribute to future treatment of people who stutter.

I have been informed of the need for the research, the benefits to be derived from it, and the risks involved. I have also been informed that the research can best be conducted with a subject population including adults and minors because of the nature of the research.

Each individual who participates will be paid $40 - $60 (for the two to three sessions) for participation in this project, depending upon distance/travel time.

I acknowledge that _____(research staff member) has fully informed me that I may withdraw from participation at any time without prejudice against me; has offered to answer any inquiries which I may make concerning the procedures to be followed; and has informed me that I will

receive a copy of this consent form. I freely and voluntarily consent to my participation in this research project.

If there are any questions about this project you may call Professors Nicoline Ambrose or Torrey Loucks collect at the number listed above. Questions about research subject rights should be directed to the Institutional Review Board at (217) 333-2670 or at irb@uiuc.edu.

I ____do ____do not give permission to use audio and video tapes for instructional purposes, without personal identification.

Signature of Staff Member	Date	Signature of Participant	Date

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APPROVED CONSENT
VALID UNTIL

JUN 2 8 2010