COMPARISON OF SPEECH AND PRACTICED NONSPEECH INTRAORAL PRESSURE WAVEFORM CHARACTERISTICS

by

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B.A. in Communication Science & Disorders, University of Pittsburgh, 2006

Submitted to the Graduate Faculty of

Communication Science & Disorders in partial fulfillment

of the requirements for the degree of

Master of Science

University of Pittsburgh

2008

UNIVERSITY OF PITTSBURGH

SCHOOL OF HEALTH AND REHABILITATION SCIENCE

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July 22, 2008

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Intraoral pressure waveforms of a learned volitional nonspeech task were compared to that of a parallel speech task in order to drawl inferences regarding a possible shared sensorimotor control mechanism. Similarities between the dependent variables at question (the percents of the increase and decrease interval involved in the total duration and the slopes of the increase and decrease interval) may provide preliminary evidence of a shared generalized motor program. The nonspeech task (which was devised as part of a larger study by Shaiman et al., 2004; 2006) reflected the goal and complexity of speech, by the incorporation of intraoral pressure targets and practiced, co-articulated gestures. Six subjects participated in the study. Subjects practiced the nonspeech task over two sessions, totaling to over 600 repetitions of the task, with KR regarding accuracy of reaching the pressure target provided for 65% of trials. Nonspeech retention data was gathered at the end of both practicing sessions. Parallel speech task data were then taken. The measures of the dependent variables were calculated by the division of the pressure waveform into three distinct intervals: the increase, plateau, and decrease interval. These intervals were automatically detected using a pressure waveform analysis program, which used the first derivative of the pressure signal to mark parts of the waveform. The means for the nonspeech retention data and the speech data were taken for each dependent variable. Univariate analysis revealed no significant difference between the speech and nonspeech condition for any of the four dependent variables ($p<0.05$). The finding of no significant difference for any of the four dependent variables may provide preliminary evidence for a shared generalized motor program for speech and nonspeech gestures. However, future research with data from additional subjects would assess this finding. Also, descriptive observations of waveform shape during the plateau interval indicate the need for further analysis of additional waveform measurements not analyzed in the current study, and also the need to control rate and precision of production in the future.

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PREFACE

I would like to thank my committee, Dr. Mick McNeil and Dr. John Durrant, for their insightful feedback and suggestions. I would also like to thank Mr. Neil Szuminsky for his computer technology expertise and his patience in modifying the kinematic analysis program to suit the needs for this project. Additionally, I would like to acknowledge the valuable statistical consultation of Dr. Elaine Rubenstein. Thank you to Ms. Kimberly Meigh for your contributions to the introduction, and also for your encouragement and helpful advice over the past two years.

Most importantly, I would like to express my endless gratitude to my advisor, Dr. Susan Shaiman, who guided and pushed me through graduate school. You taught me to be confident in my abilities while always driving me to improve. Your dedication and honest enthusiasm as an educator has inspired me and fostered my interest in research. I cannot thank you enough for your guidance over these past years; without your continued encouragement and patience this project would not have been possible.

1.0 INTRODUCTION

The ability to speak is dependent on the successful execution of a series of subtle and carefully coordinated oral gestures, paired with simultaneous coordination of the respiratory and laryngeal structures. Motor control involved in the planning and implementation of speech gestures is a topic of utmost clinical importance, as it guides the treatment of many populations, such as those with dysarthria and apraxia of speech. Clinical observations, such as the disparity between diadokinetic rates and speaking rate in dysarthric speakers, have sparked interest in motor control for speech versus nonspeech movements. Many researchers have examined underlying sensorimotor control systems for speech versus nonspeech tasks, with some contending that speech and nonspeech do not share a common sensorimotor system (i.e. Moore and Ruark, 1996; Weismer and Liss, 1991; Ziegler, 2003), and with others arguing for shared sensorimotor control (i.e. Ballard, Robin and Folkins, 2003; Wang and Robin, 1997). Underlying sensorimotor control mechanisms and neurological organization can be investigated through the comparison of speech and volitional nonspeech oral movements. The present study attempted to draw inferences pertaining to underlying sensorimotor control mechanisms through the examination of intraoral air pressure characteristics of a nonspeech task that was carefully designed to mimic the complexity and goal of a parallel speech task.

Motor control in the present study was examined in terms of Schmidt and Lee's (2005) "generalized motor program." The generalized motor program is defined as "… a motor program for a particular class of actions [that] is stored in memory and that a unique pattern of activity will result whenever the program is executed" (p. 193). The activation of a generalized motor program is not restricted to specific muscles or groups of muscles, but rather is considered to be "…*abstract* with respect to which specific joints and muscles are to be added during the *implementation* of the program" (p. 202). For example, Lashley (1942) noted that an individual's handwriting samples taken with either hand or the teeth all contained letter-formation characteristics particular to that individual, despite being produced by differing groups of muscles. In this way, Schmidt and Lee's model does not confine motor control and organization to specific anatomical structures, but rather views motor control in terms of a psychological model.

As the current study did not attempt to define specific anatomical substrates associated with underlying sensorimotor control, the speech and the parallel nonspeech task in this study were examined in terms of a psychological model. However, past literature directly pertaining to anatomical models of control were also reviewed in order to assess all available evidence pertaining to sensorimotor control of speech versus nonspeech tasks.

A much-debated model of motor control is Zeigler's "task-dependent" model, which segregates motor functioning into vegetative, speech, emotional, and novel volitional motor activities, thus implying separate sensorimotor control for speech and nonspeech tasks (Zeigler, 2003). Included in the evidence to support the task-dependent model is the plethora of literature remarking the dissociation between nonverbal oral apraxia and apraxia of speech (i.e. Bizzozero et al., 2000; Kramer, Delis & Nakada, 1985; LaPointe & Wertz, 1974; Maeshima et al., 1997). This literature indicates that nonverbal oral apraxia and apraxia of speech are independent of each other, supporting task-dependent motor control (Zeigler, 2003). Clinical evidence noting the disparity between diadokinetic rates and speaking rate in dysarthric speakers provides further evidence (Zeigler, 2003).

Additionally, it has been suggested that cortical activation sites differ for nonspeech versus speech movements. Wildgruber et al. (1996) used functional magnetic resonance imaging (fMRI) to compare cortical activation during speaking to the nonspeech task of vertical tongue movements. They found that the speech task resulted in increased activation of the left motor strip, whereas the nonspeech task resulted in bilateral symmetric activation. Riecker, Ackermann, Wildgruber, Dogil, and Grodd (2000) conducted a similar fMRI study in which lateral tongue gestures were associated with bilateral cerebellar activation whereas speaking resulted in unilateral cerebellar activation.

Additional research examining electromyographic (EMG) activity in mandibular muscle tasks pinpoints differing activation patterns for speech versus nonspeech tasks, providing further evidence of task-specificity (Moore, Smith, & Ringel, 1988). Ruark and Moore (1997) used EMG recordings to examine upper and lower lip activity in two-year-old children during the production of speech and nonspeech tasks. The authors found differing coordinative organization of the upper and lower lip for speech versus purposeful nonspeech behaviors, such as lip protrusion and sucking.

Researchers have also interpreted the lack of empirical evidence available to support the transfer of nonspeech oral motor learning to speech production to support the argument for separate motor control systems (e.g., Bunton & Weismer, 1994; Christensen & Hanson, 1981; Davis & Velleman, 2000; Moore, 1993). Schulz, Dingwall, and Ludlow (1999) examined the practice effects on speech tasks and novel oral-movement tasks in subjects with cerebellar cortical atrophy and control subjects. Both groups exhibited practice effects in the speech task but in the nonspeech oral-movement task no change was observed with practice. Differing practice effects between the oral-movement condition and the speech condition are consistent with the view that nonspeech tasks may not share motor control characteristics with speech.

On the other hand, some researchers contend that the task-dependent model falters in the notion that the motor control system is organized around the production of tasks rather than functions (Keele & Ivry, 1987). Ballard, Robins, and Folkins (2003) call for the classification of an "integrative" model in which the "speech motor system is integrated into the functioning of a more general motor system" (p. 38). This model claims that motor control is neither task-dependent nor task-independent, but rather that certain nonspeech oral tasks may share properties with speech and others may not. Ballard and colleagues state, "We hypothesize that, at complex behavioral levels, there must be overlapping functional components and therefore overlapping and integrative neural pathways or networks" (p. 39).

One argument supporting an integrative model is the use of volitional nonspeech tasks in the diagnosis of motor speech disorders. The use of nonspeech tasks in speech assessment is not supported in the task-dependent model, which assumes segregated control of nonspeech and speech movements. Ballard et al. (2003) highlight the clinical utility of nonspeech tasks, such as sustained phonation tasks and diadokinetic rates, in the differential assessment of dysarthria type. An integrative model of motor control accounts for the use of nonspeech tasks in the assessment of speech functioning.

Also supporting integrative motor control is evidence of transfer of motor skills across anatomic structures. A study conducted by Wang and Robin (1997) examined transfer of learning across finger and jaw movements. The authors found that training of either a finger or jaw movement resulted in better initial performance of the movement when executed by the untrained structure than when the movement had not been previously trained. This evidence of transfer does not support discrete motor programming that is organized by task categories, but rather a motor system that overlaps across tasks.

Although extensively studied and debated, current available research that compares speech to nonspeech gestures may be lacking in task design. Nonspeech tasks that involve the isolation of single movement components fail to recognize the complexity of speech (Zeigler, 2003). Zeigler (2003) states "… speaking differs from most nonspeech tasks in that it is generally accompanied by aerodynamic events associated with eggressive airflow, with intraoral pressures, and with supralaryngeal airstream mechanisms" (p. 18). Underlying differences between speech and nonspeech tasks that have been deduced by previous studies may be attributable to a fundamental difference in the complexity of the examined tasks, and therefore may render inferences about separate sensorimotor control systems incorrect (Ballard et al. 2003; Shaiman, McNeil, & Szuminsky, 2004; Shaiman, McNeil, Szuminsky, Meigh, & Kotler, 2006).

In order for learning of one task to transfer to another task, the two tasks must be similar. Hodge & Wellman (1999) state "…muscle fibers are selectively recruited to perform specific tasks, so static non-speech tasks do not account for the precise and coordinated activity needed during speech" (p. 222). Moon, Folkins, Smith, and Luschei (1993) propose that nonspeech comparisons must be made that mimic the complexity of speech and place comparable demands on the motor system. The validity of inferences regarding a shared sensorimotor system for speech and volitional nonspeech movements are dependent on the use of a nonspeech task that reflects the complexity and organization of speech movements.

Shaiman and colleagues attempted to better equate the nonspeech and speech tasks by, among other things, incorporating the goal of intraoral pressure generation into the nonspeech task. The data discussed in this study are a subset of data that have been collected as a part of a larger study conducted by Shaiman and colleagues (2004; 2006).

In order to remedy the dilemma of non-equivalent nonspeech and speech tasks, Shaiman et al. (2004; 2006) suggest using the following three levels to equate speech and nonspeech behaviors. First, the nonspeech task must require the use of a sequence of overlapping gestures. Normal speakers naturally integrate chains of individual oral movements required for sound production into overlapping, coarticulated gestures. Rather than involving segregated and individualized gestures, nonspeech tasks must require the production of movement sequences that demand comparable integration and coarticulation.

Secondly, nonspeech tasks must possess a level of automatic processing and execution. Speech is a highly practiced and learned motor movement that demands minimal attention from the speaker (Schultz et al., 1999). Novel tasks require a greater amount of processing resources in their execution than tasks that have been practiced and learned extensively (Shiffrin & Schneider, 1984). Additionally, novel tasks lack established motor programs that allow for the execution of smooth, coordinated gestures. Gracco (1990) states “Speech motor patterns reflect characteristic ways of manipulating the vocal tract, in the presence of a constant pressure source, to generate recognizable and language-specific acoustic signals” (p. 10). The quick, effortless execution of skilled movements can be explained by the existence of a basic prototypical representation of a movement (Zelanik, Schmidt & Gielen, 1986). These motor programs are established through learning. Hodge and Wellman (1999) state “While motor programs are being learned, coordination increases (i.e. increased movement coordination is a feature of more skilled movements)” (p. 224). In sum, motor programming allows for quick and effortless movement of the articulators. In past studies, nonspeech tasks that were used as speech comparisons were unpracticed and relatively novel movements, thus requiring concentration and effort to execute (see Bunton & Weismer, 1994; Wohlert & Goffman, 1994). The differences in degrees of automatic processing between speech and nonspeech must be comparable before a valid comparison is made.

Finally, Shaiman et al. (2004; 2006) propose that the goal of a nonspeech task should be somewhat analogous to the goal of speech. Speech movements are executed with the ultimate goal of producing an acoustic signal that is recognizable and has meaning for the listener (Folkins, 1985). The achievement of this acoustic signal requires the integration of complex motor activities involving coordination of the velocity and force generated by the articulators as well as the maintenance of multiple control variables, such as intraoral air pressure. Many nonspeech movements do not involve the acoustic-perceptual goal that is fundamental to speech tasks, but rather are executed with the intention of reaching a spatial or sensory reference point (Ziegler, 2003). The goal of a task may influence the motor control system that is responsible for executing the task. Weismer (2006) asserts "… the purpose of a motor behavior has a profound influence on the manner in which the relevant neural topography is marshaled and controlled" (p. 329). Differences between speech and nonspeech tasks may be embedded in differences between the tasks' ultimate goals.

Shaiman et al. (2004; 2006) developed a nonspeech task which attempted to remedy the three afore-mentioned limitations. Subjects were instructed to complete a nonspeech task that involved the sequencing of 15 gestures in conjunction with the generation of specified intraoral air pressure levels. The sequence of nonspeech movements was designed to parallel the speech task of articulating /a pa pa ti tu pa pa/. Subjects were not informed that the task was speech-like; they were intentionally deceived to the purposes of the study and were informed that the study was examining parallel finger and lip movements. This deception was crucial in ensuring that the subjects did not associate the nonspeech gestures with speech. To encourage coarticulation, subjects were instructed to avoid producing separate, isolated gestures but rather to produce overlapping, integrated movements. Instructions were also given to produce the gestures as quickly and as accurately as possible. To achieve a well-learned representation that is comparable to speech, subjects were required to practice the nonspeech gestures over two days.

The specification of the intraoral air pressure levels was included in the Shaiman et al. (2004; 2006) study design in order to better equate the goals of nonspeech and speech through the addition of a control variable. It has been suggested that control variables are regulated during speech to allow the overarching goal of acoustic-perceptual accuracy to be realized (Moon et al., 1993; Müller and Brown, 1980; Warren, Dalston, & Dalston, 1986). Gracco, Gracco, Löfqvist and Marek (1994) examined the effect of a tube bleed on speaker's production of intraoral pressure in voiceless bilabial stops. When pressure was reduced by the tube bleed, speakers used compensatory strategies to maintain the minimal amount of intraoral pressure that is required for speech production, therefore maintaining perceptual accuracy. Maintaining appropriate intraoral pressure allowed speakers to uphold appropriate voicing, fundamental frequency, and sound pressure level (Gracco et al., 1994).

In a similar tube bleed study, Huber, Stathopoulos, and Sussman (2004) suggested that compensatory strategies that are used to maintain pressure are one way that speakers maintained acoustic-perceptual accuracy. Similar to tube bleed studies, studies examining cleft palate speakers provide information regarding the maintenance of aerodynamic stability, despite structural inadequacies that limit the ability to maintain pressure in the oral cavity. Warren

(1986) explained compensatory strategies used by cleft palate speakers, such as the replacement of oral stops with glottal stops, as an attempt to regulate the aerodynamic properties of speech, even if auditory accuracy must be forfeited. Therefore, it can be hypothesized that intraoral air pressure is a speech control variable that is maintained in attempts to preserve perceptual-acoustic accuracy (e.g. Moon et al., 1993; Müller and Brown, 1980; Warren, 1986). As intraoral air pressure maintenance is essential to intelligible speech production, it can be concluded that pressure characteristics are integrally related to acoustic-perceptual properties of speech.

Shaiman et al. (2004; 2006) required subjects to generate intraoral air pressure to levels comparable to that of speech during the nonspeech task. Subjects were shown a graphic display with a horizontal line that represented the amount of intraoral air pressure that should be generated. Intraoral pressure targets were set at 4, 8, and 12 cm H_2O, which are levels representative of intraoral air pressure generated during normal speech. Instructions on the characteristics of intraoral pressure build-up and release were not provided to participants; however subjects did receive feedback on the accuracy of their production relative to the proposed target. After the completion of the nonspeech task, subjects were recorded producing /a pa pa ti tu pa pa/ with the instructions that they were producing speech. This served as a speech comparison to the nonspeech productions.

The results of the Shaiman et al. (2006) study indicate that subjects learned how to produce the targeted intraoral air pressure values, as demonstrated by a decrease in the absolute error and reduction of the standard deviation over the course of training. At the end of each training session, the subjects’ ability to transfer the behavior was tested through the production of a novel nonspeech task that incorporated varied pressure target values and different sequences of the same nonspeech gestures (e.g. /ti tu pa pa ti tu/) involved in the production of /a pa pa ti tu pa pa/. Decreased absolute error values and reduced standard deviations on the transfer tasks indicated transfer to these unpracticed nonspeech behaviors. Transfer to speech tasks was also examined; after completion of the nonspeech training subjects repeated the task with the knowledge that the movements were speech-like.

Because baseline performance of the speech task could not be obtained prior to completion of the nonspeech training without alerting the participants to the task's similarity to speech, ten separate control subjects were used as speech baseline comparisons. Comparison between the control subjects' productions and the nonspeech subjects' productions following the nonspeech training is consistent with the transfer of the movements to the unpracticed speech behaviors (Shaiman et al., in preparation). These authors intend to compare the kinematic movements of the nonspeech and speech tasks, as well as to explore changes in the kinematic patterns with practice. Ballard et al. (2003) state "If two tasks carried out by the same muscle groups share certain movement characteristics or demands, we hypothesize that the cortical neural tissue involved in executing those tasks will overlap to some degree" (p. 40). Possible similarities between the speech and trained nonspeech kinematics may suggest that the two tasks may be similar, possibly indicating a shared sensorimotor mechanism.

However, differences between the kinematic characteristics of the speech and well-practiced nonspeech behaviors potentially may be a result of the way in which the intraoral pressure was produced by the participants. One potential cause for differences between the nonspeech and speech productions may be related to the way that subjects were instructed to generate the intraoral pressure for the nonspeech task. Shaiman et al. (2004; 2006) attempted to control peak intraoral air pressure levels during the nonspeech task through the use of a target pressure. However, in addition to peak pressure levels, speakers may also control the rate of pressure rise and pressure decay. The Shaiman et al. study did not require subjects to regulate the rise and fall of intraoral air pressure in a manner similar to normal speech production. Thus, it is not known whether the detailed timing characteristics of intraoral pressure build-up and release that is observed in speech would be similar to that of the current nonspeech task.

Examining the temporal structure of the practiced nonspeech versus the speech task may provide support for shared sensorimotor control. Schmidt and Lee (2005) identify relative timing of a gesture as an invariant feature of a generalized motor program. The authors assert that two movements that differ only in movement duration must share the same temporal structure of muscle contractions, and hence share the same generalized motor program. A common way to examine a movement's temporal structure is to examine the ratio of an element of a gesture relative to the gesture's total duration. "If all the ratios are the same in two separate movements, then the temporal structures are the same.… Further, these two movements are assumed to be produced by the same generalized motor program" (Schmidt & Lee, 2005; p. 197). Comparable interval ratios (despite differing total durations) between the practiced nonspeech and speech tasks may indicate a shared generalized motor program.

The examination of the shape and duration of intraoral pressure waveforms provides information regarding characteristics of articulation (Baken & Orlikoff, 2000). Characteristics of pressure waveforms change in accordance with changes of speed, shape, and motion of the articulators (Müller & Brown, 1980). The generation of specific pressure waveform characteristics allows the acoustic-perceptual goal of speech to be achieved. While the Shaiman et al. studies (2004; 2006) required subjects to attempt to reach specific pressure levels during the nonspeech task, the characteristics of the build-up and release of pressure were not controlled. However, the waveform characteristics of the highly-practiced nonspeech pressure signal may resemble those of speech simply as a result of producing the movements for vocal tract closure and opening quickly and efficiently in order to achieve the pressure targets. That is, despite the absence of an acoustic-perceptual goal for the nonspeech task, quick, efficient productions of the nonspeech task may result in similar pressure waveforms to those generated for speech. This finding would contribute to the evidence supporting similarities in the motor programming of speech and nonspeech gestures.

Conversely, if differences are observed between the pressure waveforms for the two tasks, this may reflect the fact that the pressure waveform is shaped in response to specific acoustic-perceptual requirements of speech. That is, for speech production, the pressure waveform is shaped in order to generate an appropriate acoustic-perceptual signal. Alternatively, differences in waveform shapes may reflect a lack of goal constraint for the nonspeech task, with the components of the goal focusing only on the amplitude of the pressure and not including waveform shape. This later possibility suggests that the nonspeech task utilized in the current study may not be adequately similar to speech. Differences in manner of production, such as differences in the clarity, rate, loudness, or effort of the speech production may also result in differing waveforms.

In summary, intraoral pressure characteristics reflect physiological events that occur during speech production. Characteristics of pressure waveforms change in accordance with changes of speed, shape, and motion of the articulators. A variety of studies have concluded that intraoral air pressure is maintained during speech as a control variable to help achieve acoustic-perceptual accuracy (e.g. Moon et al., 1993; Müller and Brown, 1980; Warren, 1986). The incorporation of intraoral air pressure as part of a nonspeech task will allow for a more valid comparison between speech and nonspeech tasks by allowing the two tasks to be comparable in terms of complexity and goal. Once a valid comparison is achieved, inferences may be made regarding possible shared sensorimotor systems for speech and nonspeech tasks. The present study attempted to determine if the pressure signal characteristics of volitional, learned complex nonspeech tasks were similar to those of a speech task in order to provide insight regarding potential sensorimotor control mechanisms.

2.0 METHODS

The data for this study were collected as part of a larger study (Shaiman & McNeil, 2004; Shaiman, McNeil & Szuminsky, 2004). Data collection procedures are described below. Information pertaining to measurement and analysis of intraoral pressure data is new and specific to the current study.

2.1 PARTICIPANTS

Six monolingual native speakers of American English participated in the study. Participants ranged in age from 20 years to 27 years, with a mean age of 23.17 years. Two of the participants were male, and four were female. Participants had no self-reported history of speech, language, hearing or neurological disorders. Participants exhibited normal movement of the lips, tongue, and jaw, as assessed with an oral-motor examination conducted by a certified speech-language pathologist at the start of the experimental session. Participants exhibited normal hearing, based on a screening at 25 dB HL at the following frequencies: 0.5, 1, 2 and 4 KHZ. Participants were paid $8 per hour. Additionally, in order to improve attention and motivation throughout the nonspeech learning protocol, participants were informed that they would receive a bonus of $10 if their intraoral pressure productions were accurate; in fact, all participants received this bonus, regardless of accuracy.

2.2 INTENTIONAL DECEPTION

Participants were intentionally deceived as to the purpose of the study. Awareness that the nonspeech task was speech-like would invalidate the nonspeech data. Participants were told that the purpose of the study was to examine the relationship between finger and lip movements during a motor learning task, and that they had been randomly placed in the “lip movement” group. Upon completion of all nonspeech tasks, participants completed a post-experimental questionnaire which assessed awareness that the nonspeech task was speech-like. Details of the questionnaire are provided in the Procedures section, below.

2.3 INSTRUMENTATION

Intraoral air pressure was measured using a pressure transducer (Glottal Enterprises, PTL) attached to a 5 inch long polyethylene tube (1.67 mm internal diameter) inserted into the oral cavity between the lips at the oral angle. The transducer signal, which has a 0-2 KHz flat bandwidth and sensitivity of 78 mV/cm H_2O, was amplified (Glottal Enterprises, Model MSIF-2) then low pass filtered at 50 Hz (Frequency Devices 900), before digitizing on-line at a sampling rate of 1000 Hz with 14 bit resolution (Dataq). Both a U-tube manometer and the Glottal Enterprises Pneumotach Calibration Unit (Model MCU-4) were used for calibration.

2.4 STIMULI

Participants were trained on a nonspeech task that was comprised of 15 sequential gestures, beginning with the lips at rest. These included: 1) relax; 2) lips apart; 3) lips together; 4) lips apart; 5) lips together; 6) lips apart; 7) tongue up, lips spread; 8) relax; 9) tongue up, lips rounded; 10) relax; 11) lips together; 12) lips apart; 13) lips together; 14) lips apart; 15) relax. Participants were instructed to produce each step of the sequence, and to do so as quickly as possible, in a smooth, overlapping manner, without pausing between each individual gestures. For each of the four "together" gestures, participants were instructed to generate intraoral pressure at either a low target level (4 cm H_2O), a middle target level (8 cm H_2O), or a high target level (12 cm H_2O). Each of the four "together" gestures was to be produced with the same, constant pressure target level (e.g., high-high-high-high, low-low-low-low, etc.). These target levels were chosen as they represent a range of intraoral pressure levels for quiet, conversational and loud speech (Stathopoulos, 1986). Details of the presentation of target levels are described in the Procedures section, below.

The speech task paralleled the nonspeech task, with the exact same gestures as in the nonspeech stimuli produced as speech sounds. The sequence of 15 gestures, beginning with the lips at rest, was: 1) relax; 2) /a/; 3) /p/; 4) /a/; 5) /p/; 6) /a/; 7) /t/; 8) /i/; 9) /t/; 10) /u/; 11) /p/; 12) /a/; 13) /p/; 14) /a/; 15) relax (that is, /a pa pa ti tu pa pa/). Participants were instructed to produce each step of the sequence, and to do so as quickly as possible, in a smooth, overlapping manner, without pausing between each individual gestures. For each of the four "/pa/" gestures, participants were instructed to generate intraoral pressure at either a low target level (4 cm H_2O), a middle target level (8 cm H_2O), or a high target level (12 cm H_2O).

Transfer tasks were incorporated to assess generalization of the learning of target accuracy to novel tasks, including both nonspeech and parallel speech sequences. The transfer tasks varied from the original nonspeech task in either sequence of gestures or order of targeted pressure values. Pressure waveform characteristics of the transfer tasks were not assessed in the current study. Details of the transfer tasks may be found in Shaiman & McNeil (2004) and Shaiman, McNeil & Szuminsky (2004).

2.5 PROCEDURES

Each participant attended two sessions, which took place 24 to 48 hours apart. Throughout both sessions, the deception described above was maintained and reinforced through constant referral to other participants and instrumentation in the “finger movement” group.

Task familiarization procedures took place during the first session. Participants were seated in front of a computer monitor displaying the list of nonspeech movements. Participants were instructed to produce the sequence of gestures as listed, as quickly and as accurately as possible. They were also instructed to produce the gestures as an integrated, overlapping sequence, rather than as isolated gestures. Once participants were successfully able to produce the sequence, the intraoral air pressure tubing was positioned and they were instructed to generate intraoral pressure during each “together” gesture. A graphic display of time on the x-axis and pressure on the y-axis was presented on the monitor beside the written sequence of nonspeech gestures. The graph displayed a green horizontal line at each of the four together gestures, positioned at the middle target level (8 cm H_2O). Participants were instructed to generate intraoral pressure to match the target level for each together gesture. Participants were not able to see their pressure productions in real-time. Rather, upon completion of the sequence of gestures, participants were provided with Knowledge of Results (KR) regarding their pressure productions. KR was in the form of a red diamond indicating the extent of the error and the direction in which it was produced relative to the green target line for each of the four together gestures, in a method similar to that used by Shea and Kohl (1991). Participants were given two trials to produce each of the three pressure targets, with KR provided; this was done in order to provide participants with an indication of the target locations. Figure 1 presents a sample of the graphic display with KR for the middle pressure target.

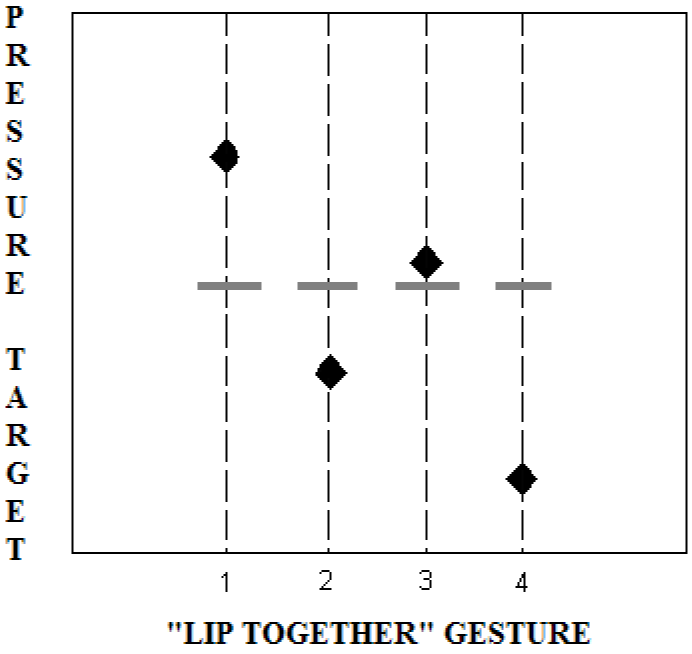

Figure 1. Pressure Target Graph with KR

Targeted intraoral pressure level is represented by horizontal lines. Extent and direction of error are represented by diamonds.

Baseline data were then collected. Participants produced 15 repetitions of the nonspeech task (5 repetitions at each of the 3 target pressure levels, presented in random order), without KR. Participants also produced baseline transfer data for the nonspeech task, which consisted of 15 repetitions of the nonspeech task presented in a different gesture sequence (i.e. pa ti pa tu pa pa) and 10 repetitions of the nonspeech task presented with varied intraoral pressure targets (i.e. 12 cm H_2O; 4 cm H_2O; 12 cm H_2O; 4 cm H_2O). Both nonspeech transfer baseline tasks were presented without KR.

Training on the nonspeech task was then introduced. Six sets of 60 repetitions of the nonspeech task were completed (20 repetitions at each of the 3 target pressure levels, randomly presented). Three to 5 minutes of resting time was taken between each of the six sets. KR was randomly presented after 65% of the individual repetitions, demonstrating how accurate intraoral pressure generation was in relation to the targeted intraoral pressure. KR, as illustrated above, consisted of a red diamond indicating the extent of the error and the direction in which it was produced relative to the green target line for each of the four together gestures. The KR-delay interval, or the "amount of time that KR is delayed after a movement" (Schmidt & Lee, 2005, p. 390), was 3 seconds. KR was displayed for 5 seconds, with a post-KR-delay interval ("the time between the presentation of KR and the production of the next movement") of 7 seconds (Schmidt & Lee, 2005, p. 392). These conditions of practice were selected based on well-established limb research (c.f. Schmidt & Lee, 2005), more recent research specific to speech production (Adams & Page, 2000; Knock, Ballard, Robin, & Schmidt, 2000), and previously-collected data using the described nonspeech task (Shaiman & McNeil, 2004; Shaiman et al., 2004).

It is important to note that participants were trained on their accuracy reaching the targeted intraoral pressure target. They were not, however, trained on specifics of intraoral pressure waveform shape (i.e. how quickly to generate or release pressure or how long to maintain intraoral pressure at the targeted level). Learning that occurred during practice focused on the ability to reach a targeted intraoral pressure level accurately. Changes in the pressure waveform shape that occurred from baseline to the learned nonspeech retention condition occurred either as a result of the increased ability to reach an intraoral pressure target or simply as a result of repeated practice of a gesture (leading to smoother, faster execution).

At the end of the first session, retention of the nonspeech task was assessed. Participants produced 15 repetitions of the nonspeech task (5 repetitions at each of the 3 target pressure levels, presented in random order), without KR.

The second session took place 24 to 48 hours following the first session. Retention was assessed at the beginning of the session with 15 repetitions of the nonspeech task (5 repetitions at each of the 3 target pressure levels, presented in random order), without KR. Participants then continued training, producing three additional sets of the nonspeech task, with KR on 65% of the repetitions, for a total of 180 repetitions. The conditions of practice were the same as described during the first session.

Upon completion of the additional training during the second session, retention was assessed for the nonspeech task. Participants produced 15 repetitions of the nonspeech task (5 repetitions at each of the 3 target pressure levels, presented in random order), without KR. Additionally, performance on the nonspeech transfer tasks was assessed without KR, following the same protocol as the baseline nonspeech transfer assessment as described during the first session.

A post-experimental questionnaire (adapted from Greene, Dusek, Eichenbaum, Levy, & Spellman, 2001 and Thaver & Oakes, 1967) was presented orally upon completion of all nonspeech tasks. Subjects' responses to the questionnaire were tape recorded and later transcribed. The questionnaire contained several items that assessed awareness of the nonspeech task as being speech-like. These target questions were embedded within several foil questions, to ensure that the questionnaire itself did not lead subjects to the awareness of the similarity between speech and nonspeech productions. Pilot data, collected using intentional deception and a post-experimental questionnaire, demonstrated that subjects did not conceive of the nonspeech task as being speech-like (Shaiman & McNeil, 2004; Shaiman et al., 2004). The questionnaire is provided in Appendix A.

Participants were then informed that the true purpose of the study was to determine the similarity between nonspeech and speech movements. On the computer monitor, the list of parallel speech gestures was presented to the participants. Participants were instructed to produce the speech sequence and attempt to generate intraoral pressure to match the target level for each "pa" gesture, in a manner similar to the nonspeech task. Transfer data (without KR) were then collected for 15 repetitions of the speech task, along with speech productions comparable to the nonspeech transfer tasks.

2.6 INTRAORAL PRESSURE WAVEFORM ANALYSIS

Identification, measurement and analysis of the intraoral pressure waveforms are new and specific to the current study.

All measurements of the pressure waveform were made on the second of the four intraoral pressure peaks contained in nonspeech and speech tasks. This specific pressure peak was selected for analysis as the lip closing-opening gestures are in the same surrounding gesture context for all experimental conditions examined in the Shaiman et al. (2004; 2006) larger study. Pressure waveform measurements were made for the following conditions from the first data collection session: 1) nonspeech baseline, 2) nonspeech learning (with the provision of KR), and 3) nonspeech retention (production of the nonspeech task subsequent to all practice trials during the first session). From the second data collection session, the following conditions were measured: 1) nonspeech retention (retention of the gestures practiced during the first session, prior to session two learning trials), 2) nonspeech learning (with the provision of KR), 3) nonspeech retention at the end of the session, subsequent to all learning trials, and 4) speech (i.e., the same task as the nonspeech task produced as speech).

Pressure waveform analysis was performed using custom pressure analysis software written in Delphi (CodeGear), using DSP subroutines (Dew Research). Pressure signals were digitally filtered bidirectionally, to eliminate phase shift from affecting timings. Filter settings were selected to minimize signal distortion. Based on a preliminary review of the pressure signals, a third order low-pass elliptic filter setting at a frequency of .03 Hz was utilized. Ripple was set at .01 dB, with attenuation at 90 dB.

The characterization and measurement of intraoral air pressure may provide information regarding the articulatory movements that occur during speech productions. As stated by Subtelney, Worth, and Sakuda (1966), "… the duration, onset, and decay characteristics of a turbulent sound and associated features of pressure and flow, are influenced by the speed of movement of articulators and the time they remain in a position appropriate for an effective noise generation" (p. 499). For the purposes of this study, measurements of both the nonspeech and speech intraoral pressure waveforms focused on characteristics specific to voiceless bilabial stop productions. Characterization of the waveform profile was based on three articulatory points of the voiceless bilabial stop, which are reflected in the characteristics on intraoral pressure rise and fall. The intraoral air pressure waveform can be divided into three phases of production: the pressure increase interval, the plateau interval, and the pressure decrease interval (see Figure 2 for an example of a typical production of a voiceless bilabial stop consonant).

Each of these three phases of bilabial stop production (pressure increase, plateau, and decrease) will be described in detail below, accompanied by descriptions of how other researchers have identified the onsets and offsets of each interval. This will be followed by a description of the identification of the onsets and offsets of each of the three phases for the purposes of the current study. Subsequently, the specific measurements of this study will be described.

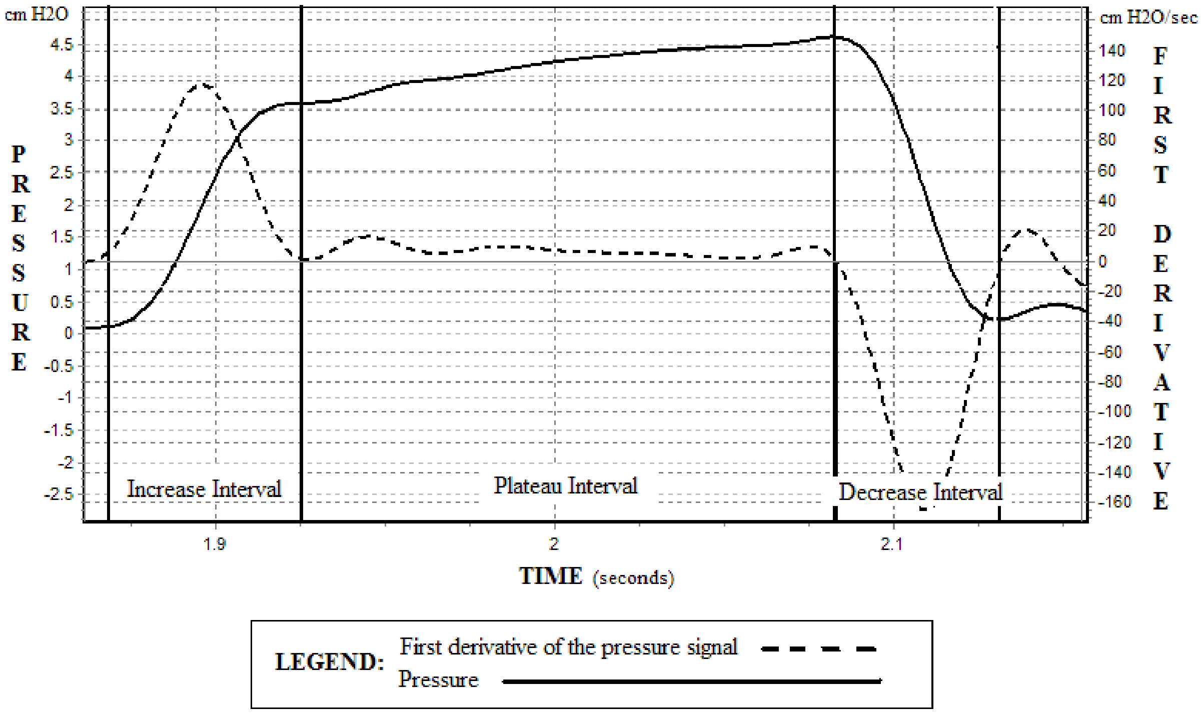

Figure 2. Typical Voiceless Bilabial Stop Consonant

During the production of a voiceless bilabial stop, the lips begin to move toward each other and the velopharyngeal port begins to close. As a result of the initiation of constriction at the point of articulation, air pressure within the oral cavity begins to rise (Müller & Brown, 1980). Research suggests that intraoral air pressure begins to rise as much as 10ms before complete closure of the lips is achieved (Müller & Brown, 1980). Löfqvist and Gracco (1997) reported that the lips are already moving toward each other at the time when the intraoral air pressure first begins to rise from baseline, with the lower lip moving at close to its peak velocity at this point in time. Pressure continues to rise as complete constriction of the lips is achieved. Müller and Brown (1980) argue that the actual time between the rise of pressure and achievement of complete closure depends on the velocity of the articulators. Kent and Moll (1969, 1972) and Perkell (1969) provide evidence that closure of the articulators takes between

10 and 20 msec. Subtelney et al. (1966) report that pressure rise for /p/ in a VCV context takes about 47 msec.

The pressure increase interval of a voiceless bilabial stop corresponds to the period of the voiceless bilabial stop production in which the vocal tract is closing. Kinematically, it may be considered the “closing” phase. In general terms, pressure increase is characterized by the lips and the velopharyngeal port moving toward closure, which permits pressure within the oral cavity to rise. Once complete constriction of the vocal tract is achieved, the plateau interval begins. Complete constriction allows for further build-up of intraoral air pressure, resulting in the acoustic/perceptual characteristic of the stop gap. The release of the articulatory constriction at the lips marks the beginning of the pressure decrease interval, in which turbulent air quickly escapes the oral cavity, resulting in a rapid decrease in intraoral pressure and the acoustic/perceptual characteristics of the burst release.

The beginning of the pressure increase interval is often measured as the time of the initiation of intraoral pressure rise from baseline level (i.e. Löfqvist & Gracco, 1997; Müller & Brown, 1980; Subtelney et al., 1966). Lucero and Koenig (2006) used 10% of the peak pressure relative to baseline for the identification of the onset of the rising portion of the pressure peak. The current study defined the onset of the pressure increase interval as the initiation of the pressure rise from baseline level. The first derivative of the pressure signal was used to automatically identify all relevant points in the waveform. The customized pressure analysis software automatically identified and marked the greatest positive and negative peaks in the first derivative of the pressure signal. Using these peaks, the software then identified the moments before and after the peak when the first derivative signal crossed zero cm H_2O/sec. For matter of simplicity, these points were referred to as the “zero crossings.” The zero crossing preceding the preceding the positive peak of the first derivative signal was used to mark the onset of the pressure increase interval (see Figure 3).

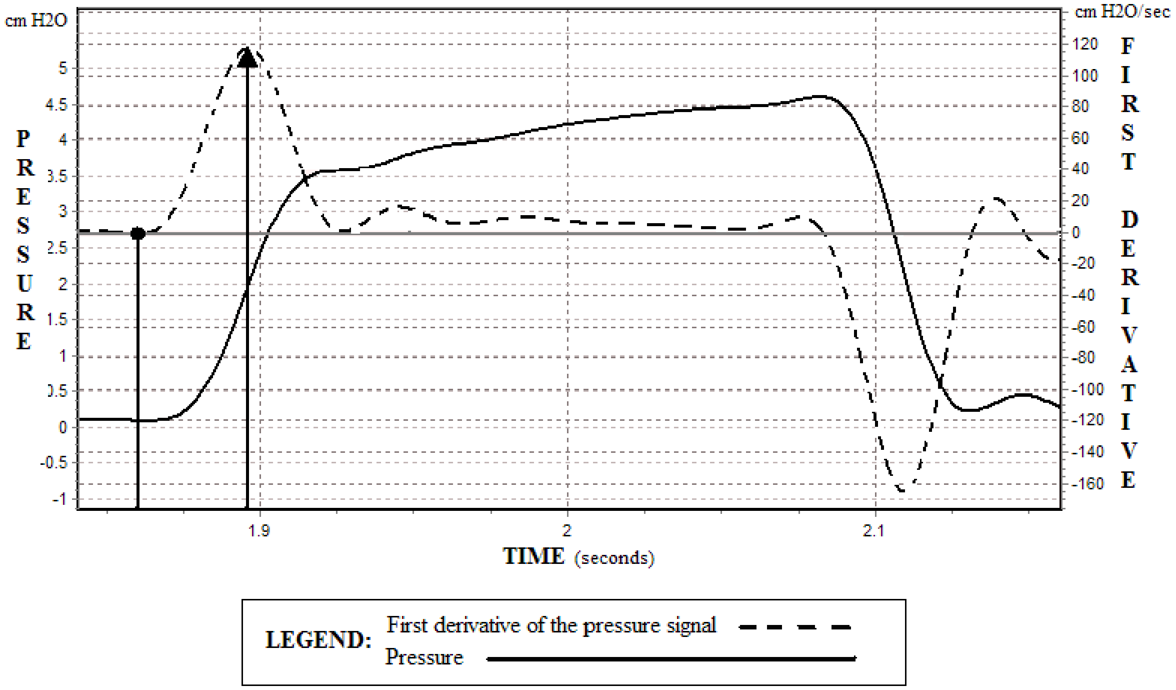

Figure 3. Identification of the Onset of the Increase Interval

The highest positive peak of the first derivative of the pressure signal is marked by a vertical line topped with a triangle; the preceding crossing of the first derivative of the pressure signal at zero cm H_2O/ sec (which marks the onset of the increase interval) is marked with a vertical line topped with a circle.

The offset of the increase phase is also the onset of the plateau phase. The pressure plateau interval corresponds to the period of the voiceless bilabial stop when the vocal tract is occluded. That is, once the lips come together and the velopharyngeal port closes, the vocal tract is then completely obstructed. After the lips close, intraoral pressure may continue to increase slightly, until the point of release (Gracco et al., 1994; Müller & Brown, 1980). Although complete constriction of the lips has already been achieved, Löfqvist and Gracco (1997) suggest that the lower lip may continue to move upwards approximately 3-6 mm before reaching its peak position. This compression of the lip tissues may serve to ensure an airtight seal (Löfqvist & Gracco, 1997). A typical speaker will generate intraoral pressure levels within an average range of 3 and 6 cm H_2O during the production of oral consonants (Arkebauer, Hixon, & Hardy, 1967; Brown & McGlone, 1974). Acoustically, the plateau phase (referred to acoustically as the stop gap) is an interval of minimal energy, due to the compete obstruction of the vocal tract (Kent & Read, 2002).

The offset of the increase interval (and onset of the plateau interval) has been identified in a variety of ways by different researchers. These various methods include points of identification not only on the intraoral air pressure signal, but also on the airflow and kinematic signals. Löfqvist and Gracco (1997) identified the offset of the increase interval as the point of "peak force of labial contact" (p. 881), where the lower lip reached its highest vertical position and the derived lip aperture signal was at its minimum value. While the pressure characteristics at this point in time were not described, figures provided by the authors suggest that intraoral air pressure continued to increase slightly beyond this point.

Subtelney and colleagues (1966) described the end of the increase interval (which they refer to as the end of the "rise time") as "the earliest point at which a relatively stable elevated oral pressure was attained" or, in other words, "the termination of rapid rise" (p. 504). Müller and Brown (1980) marked the termination of the increase interval and the onset of occlusion as the initial zero point in the volume velocity (airflow) signal, which indicates the point at which the articulators are completely closed. This instant of complete closure generally coincides with the region of break in the pressure waveform (Müller & Brown, 1980). Müller and Brown found that approximately 70% of waveforms of voiceless bilabial stops contained a noticeable breaking point. Their data indicate that intraoral air pressure continues to increase after this point. Lucero and Koenig (2006) used 90% of the peak pressure relative to baseline as the end of the rising portion of the pressure pulse.

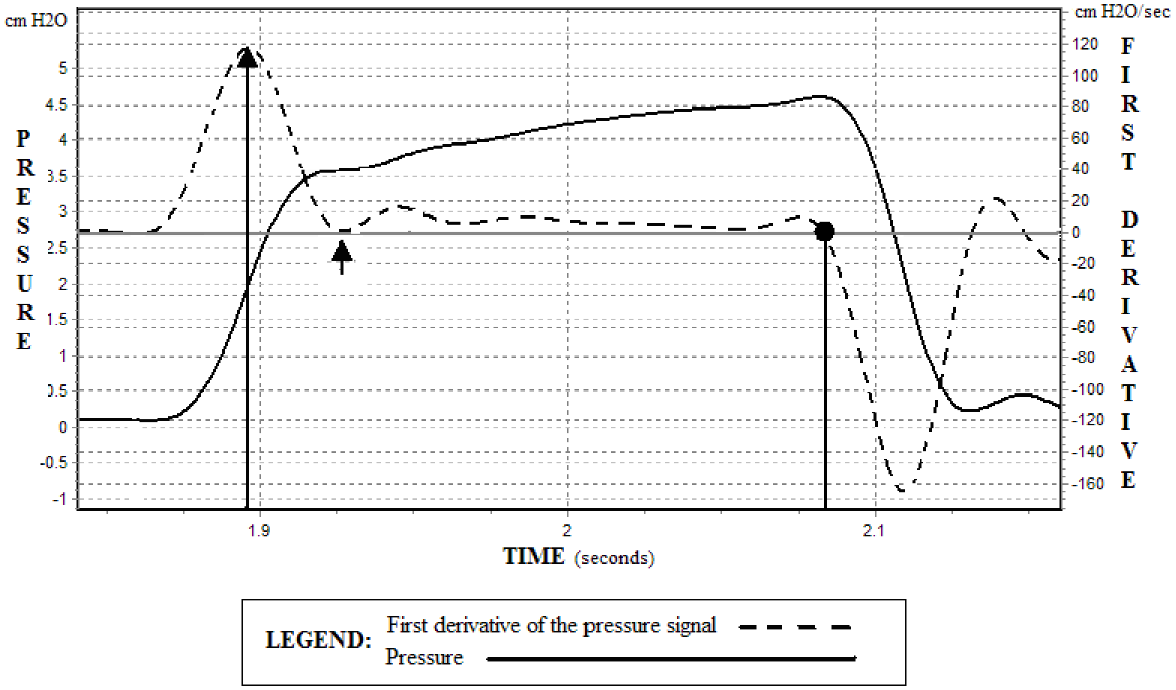

Figure 4. Identification of the Offset of the Pressure Increase Interval.

The positive peak of the first derivative is marked by a vertical line topped with a triangle. The offset of the increase interval is marked with an arrow, which indicates the point at which the first derivative reaches 10% of the positive peak value. Note that the first derivative signal does not actually cross zero cmH_2O/sec until much later in the pressure signal. In order to illustrate the signal's asymptotic-like behavior, the earliest zero crossing following the positive peak of the first derivative is marked with a vertical line topped with a circle.

In identification of the offset of the increase interval for the current study, preliminary examination of a random sample of the data showed that the first derivative signal often exhibited asymptotic-like behavior, in which the first derivative "hovered" over zero cm H_2O/sec without actually crossing zero. Using the zero crossing when such asymptotic behavior occurred would incorrectly identify the end of the increase interval (and the beginning of the plateau interval) at the point of the release of the intraoral pressure buildup (see Figure 4, for example).

Rather than using the zero crossing, the present study identified the offset interval (and onset of the plateau interval) using 10% of the highest peak of the first derivative. This was accomplished by first identifying the value of the highest positive peak of the first derivative of the pressure signal. Then, the earliest point following this positive peak at which the signal first reached 10% of the peak value was identified (see Figure 4 for an example). This 10% point was used to mark the offset of the increase interval (and the beginning of the plateau interval).

Acoustically, the pressure plateau interval is the period of minimal energy in the vocal tract. The plateau interval corresponds to the spectrographic depiction of the stop gap. Past analyses of voiceless bilabial stops have noted the presence of a "break" in the pressure waveform profile marking the commencement of the plateau interval. This visual break in the waveform may parallel articulatory gestures, such as the achievement of complete closure of the lips and velopharyngeal port, which results in the end of rapid pressure increase (Kent & Read, 2002).

Typically, intraoral air pressure continues to rise slowly during the plateau interval. In the past, researchers have described this period of occlusion as a "plateau" in the pressure waveform as it occurs directly after a period of quick pressure increase. However, the term "plateau" is be misleading as pressure generally continues to rise slightly during this interval. In concurrence with the current literature, the present study will refer to this period of occlusion as the "plateau" interval for lack of a better term.

In some instances, a definitive break in the pressure waveform is visually identifiable, as can be seen in Figure 4. In other waveforms, a definitive break in the pressure waveform is not visually identifiable. These instances reflect closing of the vocal tract that is immediately followed by opening of the vocal tract, without any time spent in vocal tract occlusion (see

Figure 5). The absence of a visible break indicates pressure increase that is directly followed by pressure release, preventing a true pressure plateau interval from occurring.

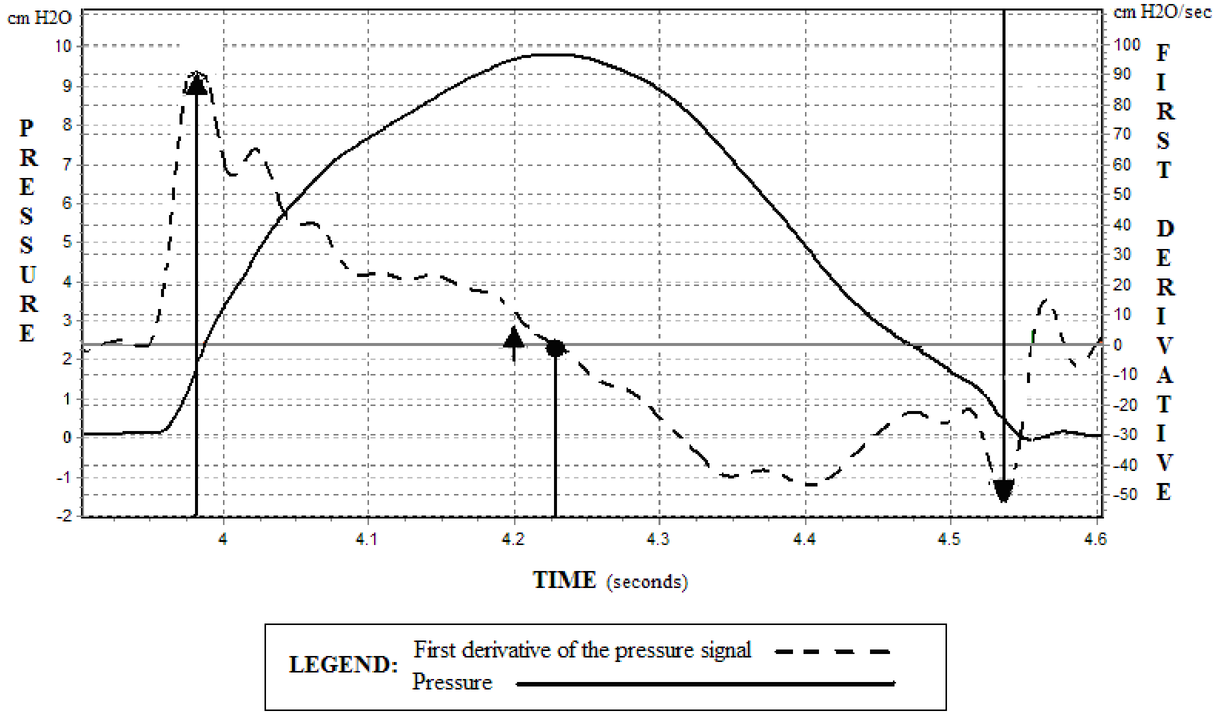

Figure 5. Waveform that Lacks a Clearly Defined Plateau Interval

The offset of the increase interval (and onset of the plateau interval) is marked by a short arrow pointing to the time of the first derivative signal where the profile reaches 10% of the highest positive peak. The onset of the decrease interval is marked by a vertical line topped with a circle, which marks the zero crossing immediately preceding the lowest negative peak (marked by the vertical line with a down-ward facing arrow).

In order to maintain consistency within the data set, the pressure plateau interval was identified in all waveform profiles regardless of the absence of an extended plateau interval or the absence of a visually identifiable break. The number of trials in which the above-described 10% point (that marks the beginning of the plateau interval) did not coincide with a visually-determined break was counted, and the frequency of this occurrence is described.

The end of the plateau interval (and beginning of the pressure decrease interval) was identified as the zero crossing in the first derivative signal preceding the negative peak in the first derivative signal.

A small number of researchers have explored and quantified the shape of the intraoral pressure waveform during the plateau interval, suggesting that this may provide information regarding physiologic events that occur during production. Müller and Brown (1980) classified waveforms according to the shape of the pressure curve; they labeled waveforms as “convex,” “concave,” “bimodal,” “linear” or “delayed”. Convex waveforms were more typical of voiceless stops, while other waveform shapes were more typical of voiced stops (Müller & Brown, 1980). Dart (1987) states that a convex but unrounded curve results from a rapid increase in respiratory muscle force during the first 150 milliseconds of a stop production. Lucero and Koenig (2006) presented preliminary data demonstrating limitations of the Müller and Brown measurement technique; their current research is exploring new methods for quantifying and describing the intraoral pressure pulse shape. The current study did address waveform shape during the plateau interval, leaving this for future research.

The offset of the plateau interval is also the onset of the pressure decrease interval. After pressure has risen to appropriate levels, the articulatory constriction is released and impounded intraoral air pressure is released from the oral cavity. Acoustically, this results in the release burst, which is one of the shortest acoustic events in the production of speech, typically no more than 30 msec in duration (Kent & Read, 2002). In general, a slowed opening of the lips will result in a longer opening phase. Subtelney et al. (1966) indicate that the average time of decay (or fall of pressure) is 52 msec for a voiceless bilabial stop.

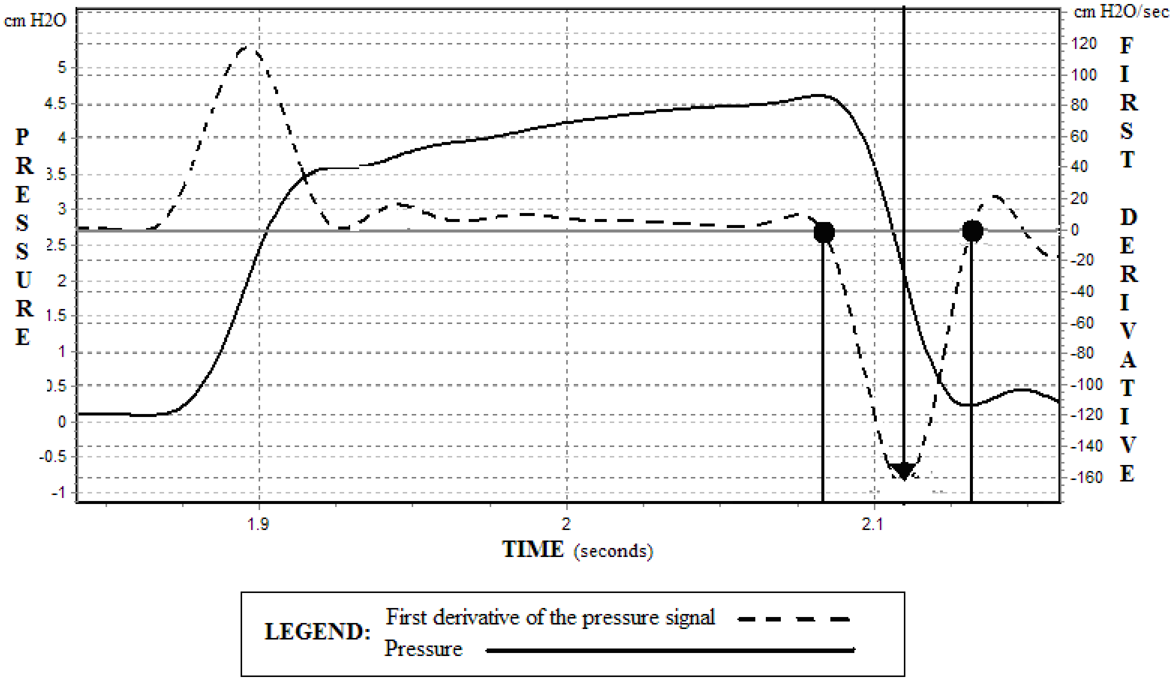

Figure 6. Identification of Onset and Offset of the Pressure Decrease Phase

The greatest negative peak of the first derivative signal is indicated by a horizontal line with a triangle. The zero crossing immediately preceding the peak, marking the onset of the decrease phase, is marked by a vertical line topped with a circle. The zero crossing directly following the negative peak marks the offset of the decrease phase.

In the pressure waveform, the beginning of the pressure decrease phase has generally been defined as the point at which stable elevated intraoral pressure begins to fall (Löfqvist & Gracco, 1997; Müller & Brown, 1980; Subtelney et al., 1966). Acoustically, the onset of the decrease interval has been defined as “the presence of an apparent release burst in the acoustic signal” (Löfqvist & Gracco, 1997, p. 881). Müller and Brown (1980) define the onset of the decrease interval as the point at which there is an onset of airflow. In the current study, the onset of the decrease interval was identified as the zero crossing in the first derivative signal preceding the negative peak in the first derivative signal (see Figure 6 for an example).

After the lips open, pressure within the oral cavity falls rapidly as air escapes from between the lips. Subtelney et al. (1996) defined the offset of the opening phase as the “earliest point at which the oral pressure returned to baseline" (p. 504). The present study defined the offset of the pressure decrease phase as the return to baseline, which was identified as the zero crossing in the first derivative signal following the greatest negative peak in the first derivative signal (see Figure 6).

2.7 MEASUREMENTS

Once the three phases of the intraoral pressure signal were identified and marked, amplitude and durational measures of the waveform were computed, as described below. These values were then used to derive the dependent variables which were used to characterize the intraoral pressure waveform.

Measurements of the amplitude of the pressure waveform were made. The amplitude of the pressure signal during the increase interval (in cm H_2O) was calculated by subtracting the amplitude of the pressure signal at the offset of the increase interval from the amplitude at the onset of the increase interval. The amplitude of pressure signal during the decrease interval (in cm H_2O) was calculated in the same fashion; the amplitude of the pressure signal at the offset of the decrease interval was subtracted from the amplitude at the onset of the decrease interval. Although pressure may continue to rise slightly during the plateau interval, changes that occurred during the plateau interval were not analyzed in the current study.

Several durational measures were calculated. The total duration of the pressure signal (in seconds) was calculated by subtracting the time at the onset of the increase interval from the time of the offset of the decrease interval. The duration of the increase decrease interval (in seconds) was calculated by subtracting the time of offset of the interval from the time of onset of the interval. When present, the duration of the plateau interval, from onset to offset, also was measured.

The above measures were used to derive the four dependent variables analyzed in the current study: the percent of the increase interval involved in the total duration of the waveform, the percent of the decrease interval involved in the total duration, the slope of the increase interval, and the slope of the decrease interval.

The first two dependent variables (the percent of the increase interval involved in the total duration and the percent of the decrease interval involved in the total duration) were chosen for statistical analysis because similar measures of relative timing for nonspeech and speech productions may indicate a common generalized motor program. As previously discussed, two movements that differ only in total duration but share the same relative temporal structure are assumed to share a common generalize motor program (Schmidt & Lee, 2005). Comparisons of the relative timing of the pressure increase and decrease intervals of the pressure waveform may provide information regarding shared sensorimotor control. These normalization measurements represent the relative temporal structure of the articulatory movements reflected in the pressure waveform, regardless of whether the trial was produced early in learning when movements were slow and uncoordinated, or later in learning when movements were produced more quickly and efficiently.

The percents of the increase and decrease intervals were measured by dividing the duration of the interval by the total duration of the pressure signal. The proportion of the increase and decrease interval is presented as a decimal figure. This decimal represents a percentage of the total duration. For example, if the proportion of the increase interval was equal to 0.43, this signifies that the proportion of the interval was equal to 43% of the entire duration of the waveform.

The third and fourth dependent variables (the slope of the increase interval and the slope of the decrease interval) were chosen as they reveal characteristics of the pressure slope which reflect the kinematic movement of the articulators. The slope of the pressure signal represents the amount of pressure change per second. A larger (or steeper) slope, for example, signifies fast closing of the lips and velopharyngeal port which resulted in a quick increase of pressure. See Figure 7 for illustration of a steep slope.

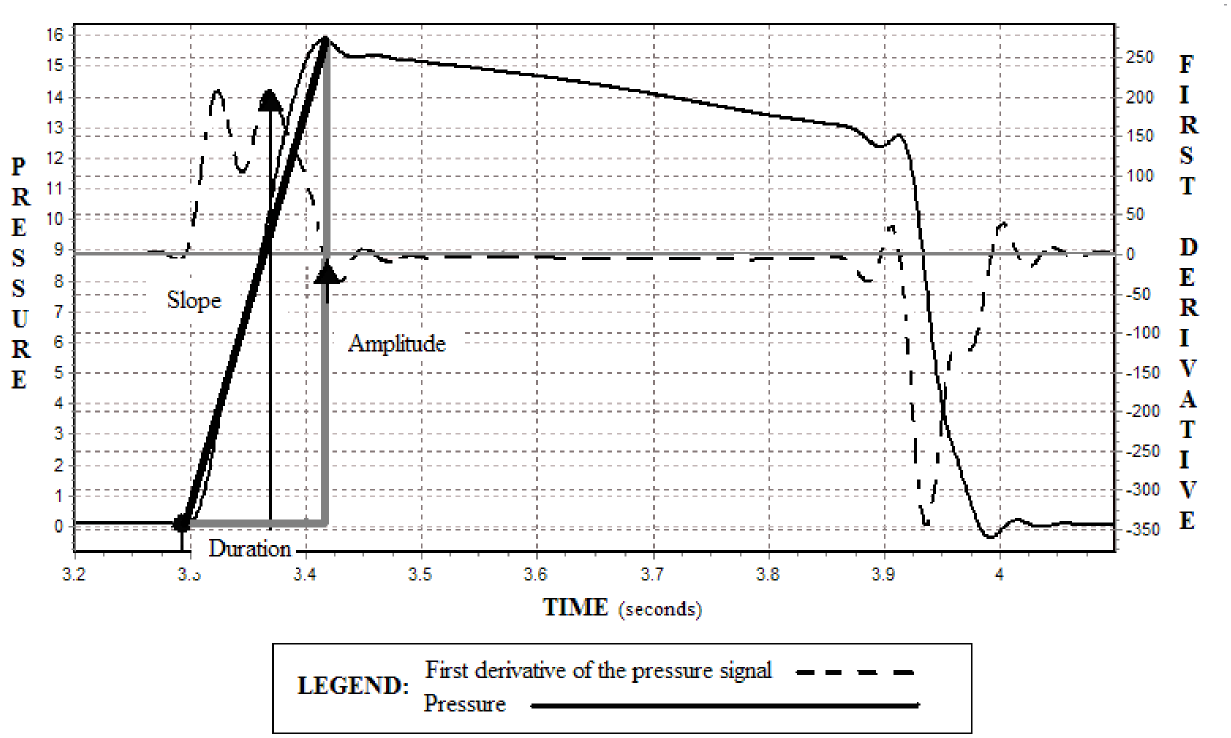

Figure 7. Steep Increase Interval Slope

Example of a steep increase interval slope. The onset of the increase interval is marked with a vertical line topped with a circle. The offset of the increase interval, which occurs at 10% of the peak of the first derivative signal, is marked with a short arrow. These points are used to determine the duration of the interval (the bottom of the triangle) and the amplitude of the interval (the right side of the triangle).

A shallow slope, on the other hand, reflects a slow pressure change that was spread over a longer period of time. Kinematically, a shallow slope may indicate a lack of coordination and precision in executing the task's gestures, resulting in slow, unsynchronized closing of the lips and velopharyngeal port. See figure 8 for an illustration of a shallow increase interval slope.

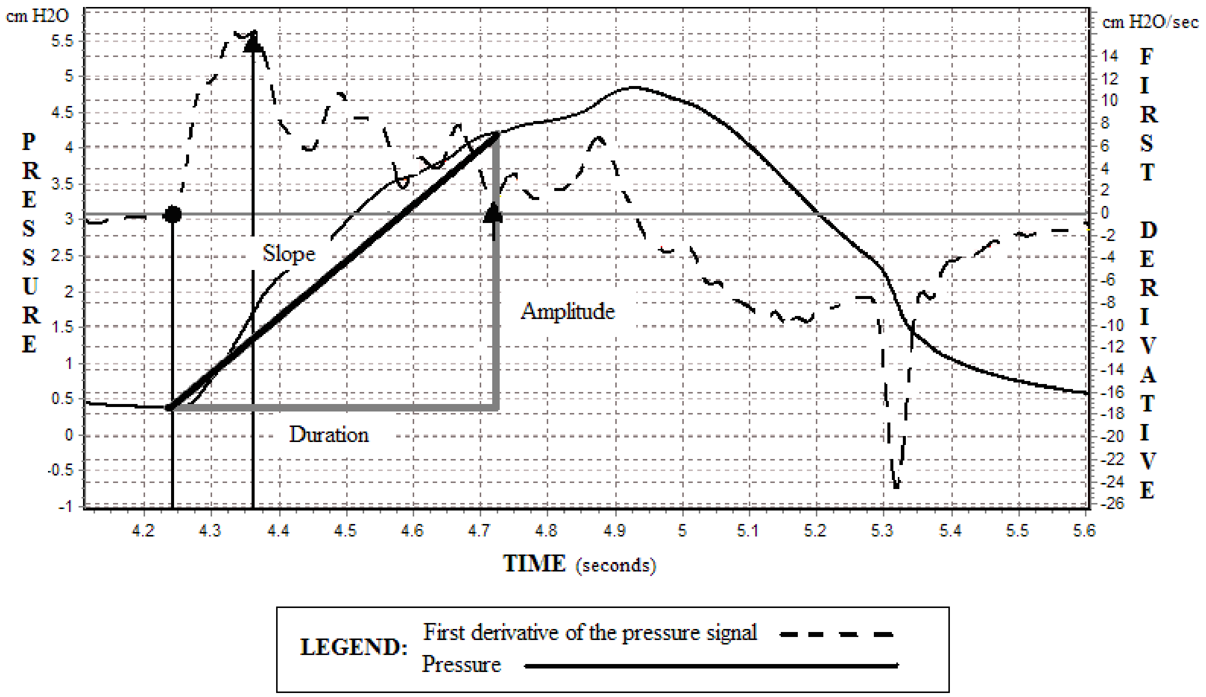

Figure 8. Shallow Increase Interval Slope

The onset of the increase interval is marked with a vertical line topped with a circle. The offset of the increase interval, which occurs at 10% of the peak of the first derivative signal, is marked with a short arrow. These points are used to determine the duration (the bottom of the triangle) and the amplitude (the right side of the triangle).

Slope measurements were calculated by dividing the amplitude of the pressure signal from the onset to offset of the interval (in cm H_2O) by the duration of the interval (in seconds).

In order to develop a general description of the waveform characteristics of the data set, a count was taken of the number of trials that consisted of three clearly identified intervals (as described above) versus the number of trials consisted of only two identified intervals (increase and decrease, without a sustained plateau phase), as not all trials included a clearly defined plateau interval.

2.8 STATISTICAL ANALYSIS

Statistical analyses were conducted to determine if there were significant differences in the dependent variables between the learned nonspeech retention condition (which occurred at the end of the second day of training, upon the completion of all training trials) and the speech condition. The dependent variables for this study were: (1) proportion of the total duration involved in the increase interval, (2) proportion of the total duration involved in the decrease interval, (3) slope of pressure increase for the increase interval, and (4) slope of pressure decrease for the decrease interval. With an *n* of 6 subjects, there were too few subjects for a multivariate analysis. Therefore, a separate univariate analysis (two-tailed paired samples t-test) was conducted for each dependent variable. Determination of the alpha level for each univariate analysis took into consideration the fact that we have a small *n* and that these are preliminary data. Setting the alpha level at .01 would decrease the probability of a Type I error (finding significance just due to chance); however, it would also decrease power (Cohen, 1988). Therefore, it was determined to use an alpha level of $p < .05$ for each univariate analysis.

Descriptive analyses (means and standard deviations) also are provided from baseline and training phases of data collection. These data are presented in order to describe any observable trends. These data, however, were not subjected to statistical analyses.

2.9 HYPOTHESES

The present study predicts that there are no significant differences between the speech and practiced nonspeech condition for any of the four dependent variables. The nonspeech task was designed to reflect the fundamental properties of speech. By encouraging the rapid, coordinated, overlapping gestures of intraoral pressure production, it is expected that the practiced nonspeech task will reflect the speed and coordination of the speech task. Following practice, some level of automaticity is expected in the nonspeech task, making it comparable to speech. It is predicted that practice will allow the nonspeech movement to be executed quickly and efficiently, resulting in relative duration and slope measures that are comparable during both conditions.

It is predicted that following practice the characteristics of the waveform profiles for both the nonspeech task and the speech task will be similar. This will result in a comparable number of trials that contain all three phases of the voiceless bilabial stop production (increase, plateau, and decrease interval) for both experimental conditions.

3.0 RESULTS

The present study attempted to determine if the pressure signal characteristics of volitional, practiced complex nonspeech tasks were similar to those of a parallel speech task in order to draw inferences about a possible shared sensorimotor control mechanism. It was predicted that no significant differences would be found between the practiced nonspeech condition and the speech condition in any of the four dependent variables (i.e. the proportion of the increase interval to the total duration, the proportion of the decrease interval, the slope of the increase interval, and the slope of the decrease interval). It was hypothesized that practice of the nonspeech task would allow the gestures to be executed in a quick, efficient manner that would reflect the temporal characteristics of the speech task.

Data for each dependent variable are presented separately, below. Descriptive data (means and standard deviations) are presented graphically from baseline and learning trials, as well as the practiced nonspeech data and the data from the parallel speech task. General trends in these group data are presented, in order to document changes in the dependent variable across the entire study.

Results of the statistical analysis are presented in tables, and include comparisons of the two experimental conditions in question: the practiced nonspeech and speech conditions. Univariate analysis was used to determine if there was a significant difference between the nonspeech and speech means. Individual subject data are presented in order to determine if individual subjects followed the group trends. Individual data is presented descriptively, with effect sizes to be completed in future studies involving this data.

3.1 DEPENDENT VARIABLE #1: INCREASE INTERVAL'S PERCENT OF THE TOTAL DURATION

The first dependent variable was the increase interval's percent of the total duration. This was calculated by dividing the duration of the increase interval by the total duration of the waveform profile. The proportion of the increase interval is presented as a decimal figure which represents the percentage of the total duration that the increase interval occupied. As previously discussed, this normalization measurement was selected to facilitate comparison between the speech and practiced nonspeech condition through representation of the relative temporal structure of the pressure waveform.

3.1.1 DV #1: Descriptive Analysis

Descriptively, the increase interval's percent of the total duration increased slightly from the nonspeech baseline condition to the practiced nonspeech retention condition. Across practice trials the increase interval began to take on a slightly larger proportion of the entire duration than during baseline. By the end of all practice trials (retention at the end of session 2), the nonspeech condition tended to have a slightly larger percent of the total duration than the speech condition. See Figure 9 for a graphical depiction of the means and standard deviations for the first dependent variable.

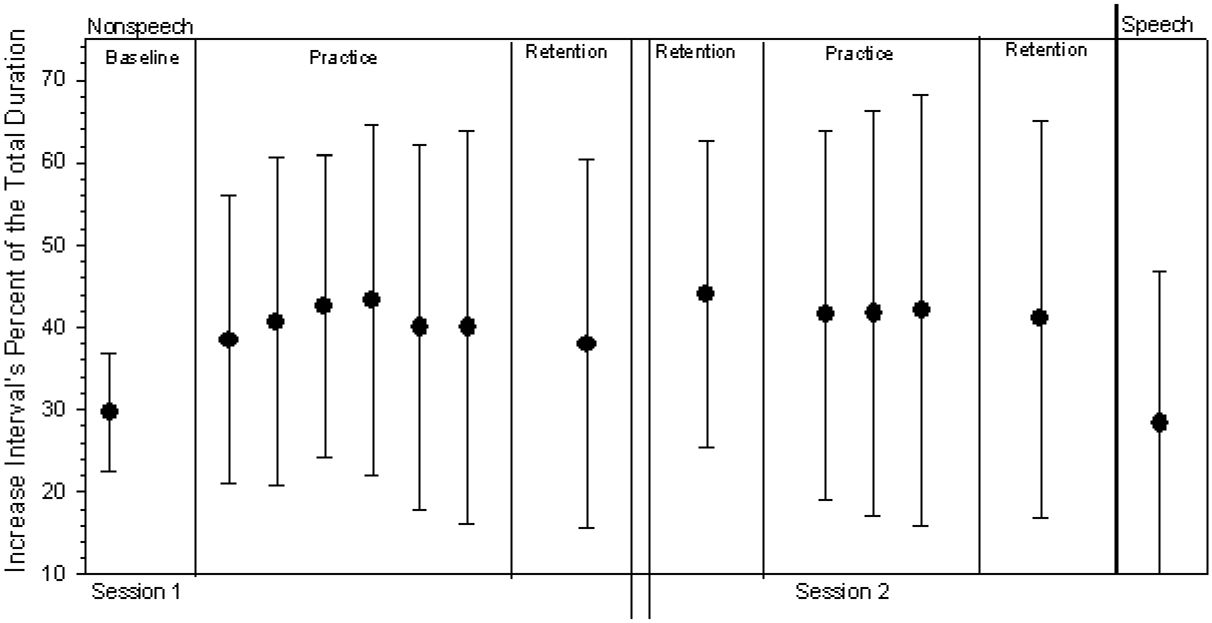

Figure 9. Group Means and Standard Deviations of the Percent of the Increase Interval

3.1.2 DV#1: Statistical Analysis

The mean percent of the increase interval for the nonspeech condition was 0.43. The speech condition mean was 0.31. Univariate analysis revealed no significant difference between the nonspeech and speech conditions (p= 0.284), following the author's hypothesis. As can be seen from the 95% confidence interval, there is a 95% probability that the true difference between the speech and nonspeech means falls within the interval of -0.138 and 0.379. Thus, the *possibility* exists that, in fact, there maybe no difference between these two conditions. However, a more precise estimate of the true difference could be made with a larger number of subjects.

Table 1. Statistical Results of the Increase Interval's Percent of the Total Duration

		Paired Samples Statistics			Paired Samples Correlations		Paired Samples Test		
		Mean	*N*	*Standard Deviation*	*Correlation*	*Significance*	*Degrees Freedom*	*t*	*Significance (2-tailed)*
Mean	Nonspeech	0.43	6	0.261	0.438	0.385	5	1.198	0.284
	Speech	0.31	6	0.015					

	Paired Differences				
	Mean	*Standard Deviation*	*Standard Error Mean*	*95% Confidence Interval of the Difference*	
				Lower	Upper
Mean	0.12	0.246	0.100	-0.138	0.379

The results of the univariate analysis for the increase interval's proportion of the total duration followed the prediction that no significant differences would be found between the practiced nonspeech and speech conditions.

3.1.3 DV #1: Individual Subject Results

When examining individual subjects, all of the subjects exhibited a change from baseline to the learned nonspeech condition. As subjects became more accurate at reaching a targeted intraoral pressure value (and executed the gesture more smoothly) the percent of the increase interval changed. Three of the six subjects showed a clear learning pattern from baseline to learned nonspeech retention, with subject #2's percent of the increase phase occupying gradually more of the total duration over practice, and subjects #3 and #5 occupying proportionally less of the total duration throughout practice. The remaining three subjects showed differences from baseline to practiced nonspeech, but with fairly flat performance throughout practice trials. Subjects #1 and #4 exhibited baseline values occupying a markedly lower percentage of the total duration than during the learned nonspeech. Subject #6 also exhibited this pattern, but with baseline being only slightly lower than the practiced nonspeech condition.

When comparing the baseline condition to speech, three of the six subjects showed baseline values that were approximately equal to the speech values (S1, S2, and S4). Three of the subjects had baseline values that were different from the speech values (with S5 and S3's baseline values being higher and S6's being lower).

Three of the six subjects' practiced nonspeech increase intervals were relatively longer than their speech intervals (S1, S2, and S4). Subjects #5 and #3 had increase interval proportions that were approximately equal. Subject #6's increase interval percentage was higher for speech than practiced nonspeech.

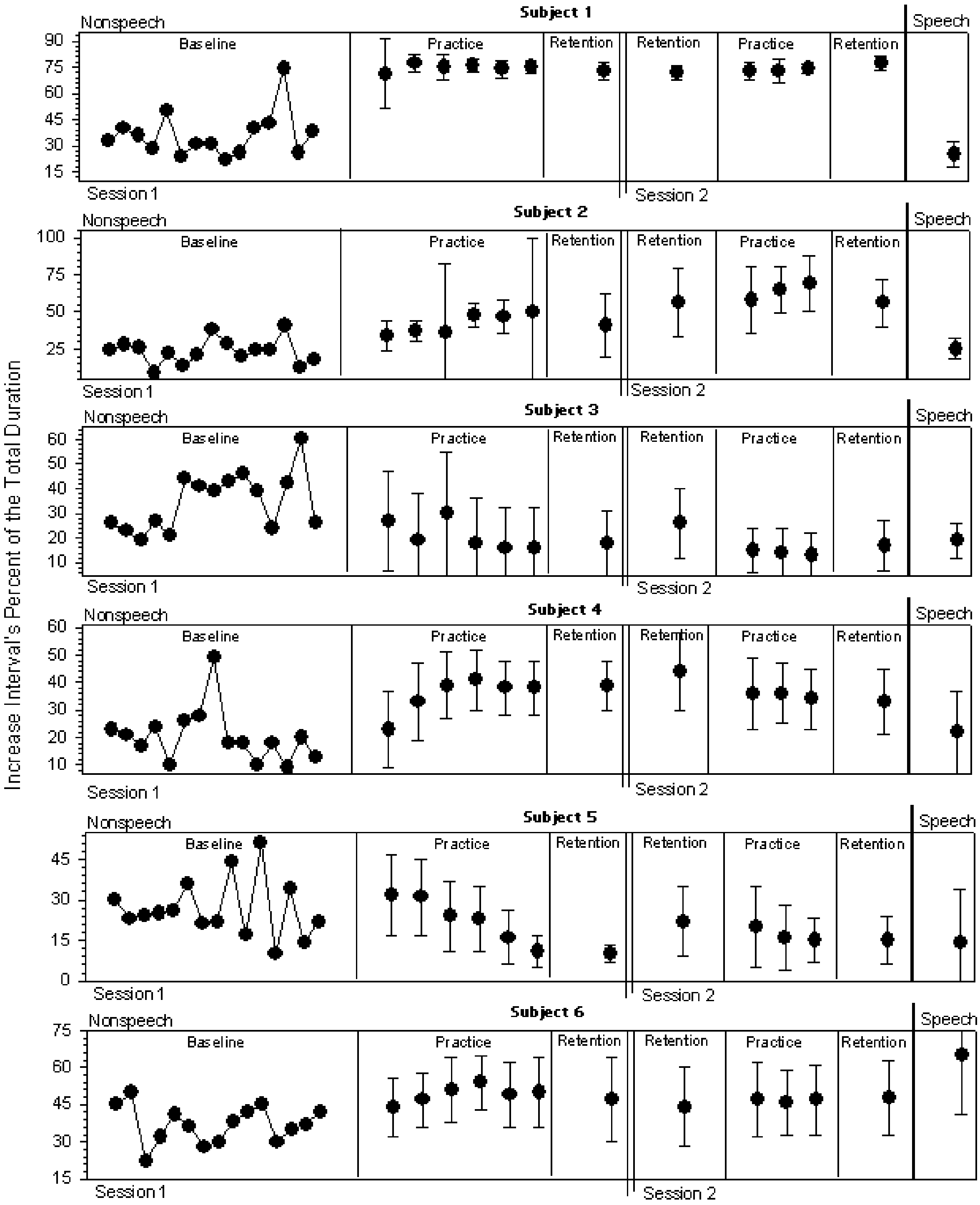

Figure 10. Individual Subject Means and Standard Deviations of the Percent of the Increase Interval

Graphical depiction of the means and standard deviations of the increase interval's percent of the total duration across all trials presented for each individual subject.

3.2 DEPENDENT VARIABLE #2: DECREASE INTERVAL'S PERCENT OF THE TOTAL DURATION

The second dependent variable was the decrease interval's percent of the total duration. This was calculated by dividing the duration of the decrease interval by the total duration of the waveform profile. The proportion of the decrease interval is presented as a decimal figure which represents the percentage of the total duration that the increase interval occupied. As previously discussed, this normalization measurement was selected to facilitate comparison between the speech and practiced nonspeech condition through representation of the relative temporal structure of the pressure waveform.

3.2.1 DV #2: Descriptive Analysis

Descriptively, the group data for the percent of the decrease interval followed the same pattern as the percent of the increase interval. The decrease interval's percent of the total duration increased slightly from the nonspeech baseline condition to the practiced nonspeech retention condition, taking on a larger proportion of the entire duration from baseline through learning conditions. The learned nonspeech condition took on a larger total percent of the decrease interval in the practiced nonspeech condition that the speech condition. The speech condition had a lower percent of the decrease interval than during baseline. See Figure 11 for a graphical depiction of the group means and standard deviations for the second dependent variable.

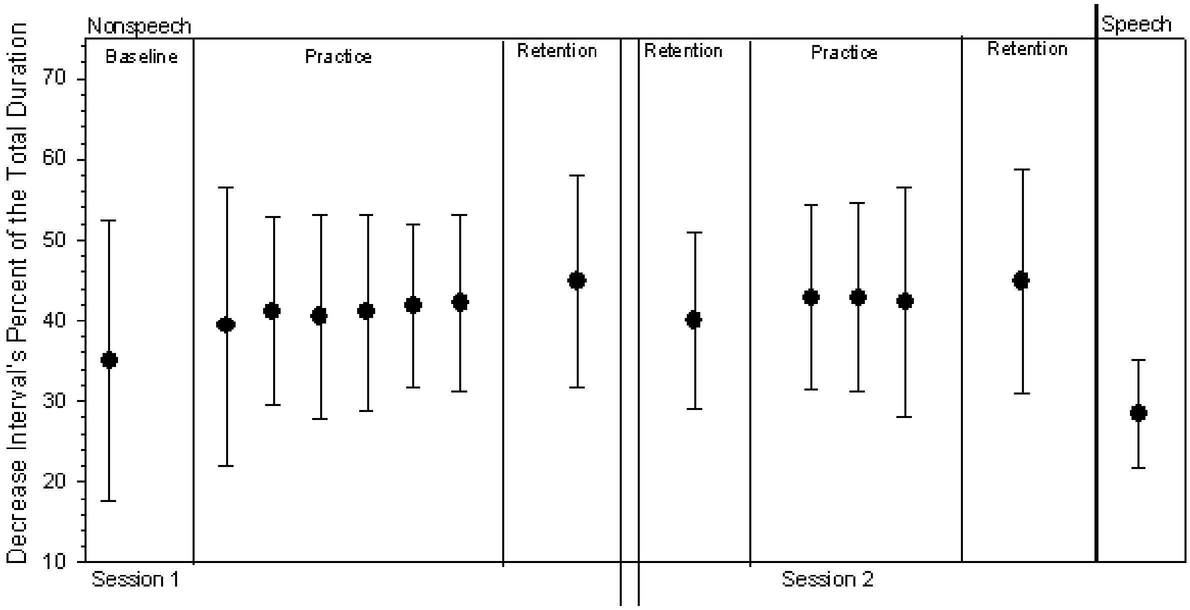

Figure 11. Group Means and Standard Deviations of the Percent of the Decrease Interval

3.2.2 DV #2: Statistical Analysis

The mean proportion of the decrease interval for the nonspeech condition was 0.42. The speech condition mean was 0.29. Univariate analysis revealed no significant difference between the means of the nonspeech and speech conditions for the second dependent variable (p=0.188).

The results of the univariate analysis for the decrease interval’s percentage of the total duration followed the prediction that no significant difference would be found between the practiced nonspeech and speech conditions. As can be seen from the 95% confidence interval, there is a 95% probability that the true difference between the speech and nonspeech means falls within the interval of -0.089 and 0.350. Thus, the *possibility* exists that, in fact, there maybe no difference between these two conditions. However, a more precise estimate of the true difference could be made with a larger number of subjects.

Table 2. Statistical Results of the Decrease Interval's Percent of the Total Duration

		Paired Samples Statistics			Paired Samples Correlations		Paired Samples Test		
		Mean	*N*	*Standard Deviation*	*Correlation*	*Significance*	*Degrees Freedom*	*t*	*Significance (2-tailed)*
Mean	Nonspeech	0.42	6	0.161	-0.627	0.183	5	1.526	0.188
	Speech	0.29	6	0.067					

	Paired Differences				
	Mean	*Standard Deviation*	*Standard Error Mean*	*95% Confidence Interval of the Difference*	
				Lower	Upper
Mean	0.13	0.209	0.086	-0.089	0.350

3.2.3 DV #2: Individual Subject Results

Four of the six subjects showed a change in performance with practice. Baseline data for the majority of the subjects (S3, S4 and S6) began with a generally lower proportion, and gradually increased across the practice trials. Subject #2's decrease interval proportion decreased throughout practice trials. Subject #5's practiced nonspeech data revealed the decrease interval maintaining approximately the same percentage of the total duration throughout all nonspeech trials, from baseline and throughout learning to nonspeech learned retention trials. Subject #1 showed no change from baseline to practiced nonspeech, with relatively flat performance throughout all trials.

Four of the six subjects exhibited a faster relative decrease interval in the speech condition that in the nonspeech condition. The remaining two subjects, subjects #1 and #2 showed approximately equal practiced nonspeech and speech values.

Interestingly, baseline values for four of the six subjects were approximately equal to the speech values for the percent of the decrease interval (S1, S2, S4, and S6). Subjects #3 and #5 showed baseline values that were slightly higher than the speech values.

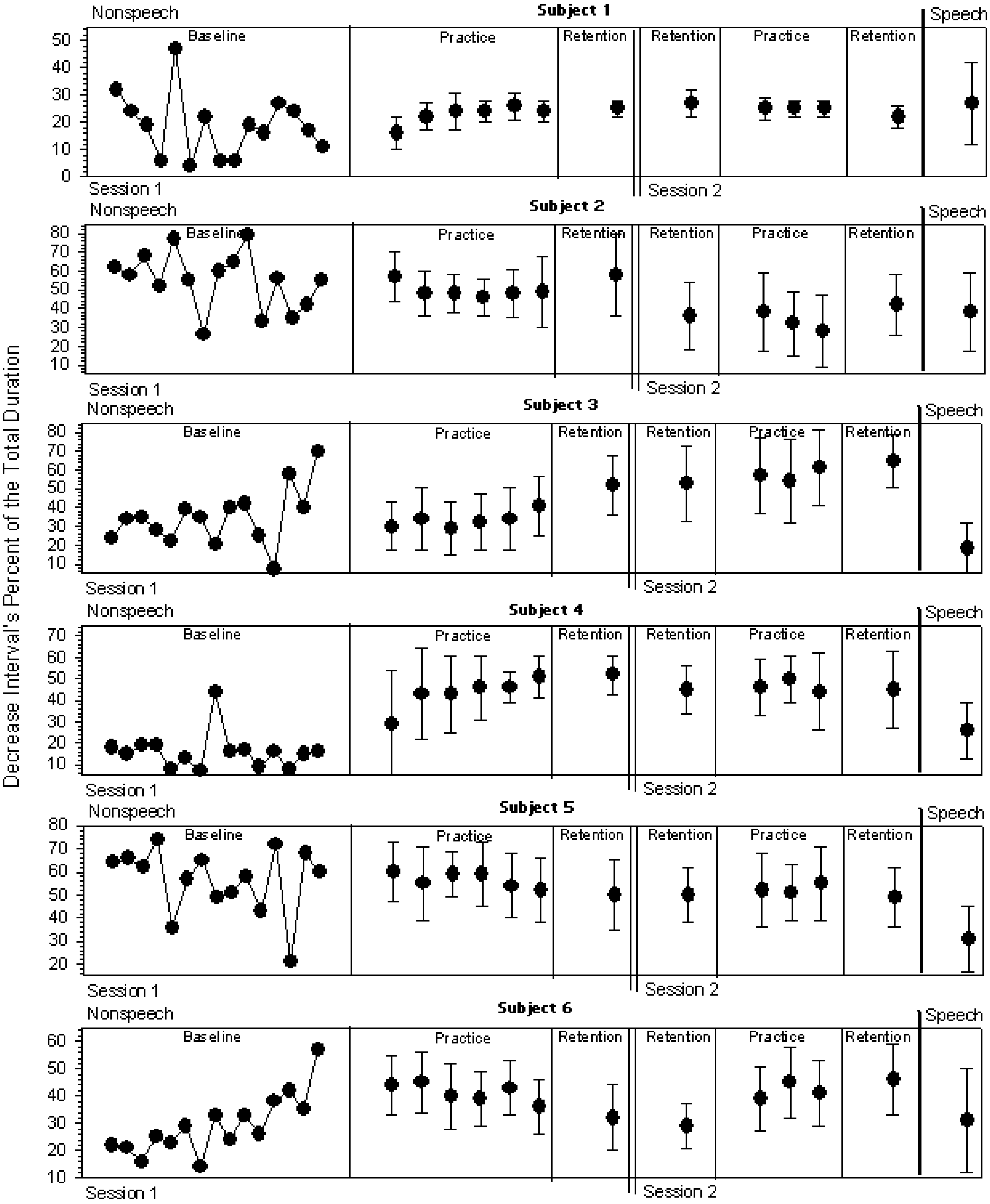

Figure 12. Individual Subject Means and Standard Deviations of the Percent of the Decrease Interval

Graphical depiction of the means and standard deviations of the decrease interval's percent of the total duration across all trials, presented for each individual subject.

3.3 DEPENDENT VARIABLE #3: SLOPE OF THE INCREASE INTERVAL

The third dependent variable was the slope of the increase interval. This measurement was calculated by dividing that amplitude of the pressure signal from the onset to offset of the increase interval (in cm H_2O) by the duration of the increase interval (in seconds). This dependent variable was chosen as it may be related to characteristics of the pressure slope which reflect the kinematic movement of the articulators. For example, a steep increase interval slope, which indicates a quick pressure increase, is reflective of fast, coordinated closure of the lips and velopharyngeal port. A shallow increase interval, on the other hand, reflects slow pressure increase that is spread over a longer period of time. Kinematically, a shallow increase interval slope may indicate a lack of coordination and precision in executing the task's gestures, resulting in slow, unsynchronized closing of the lips and velopharyngeal port. A shallow slope is represented by a lower number than a steeper slope. For example, a slope of 500 cm H_2O/sec will be steeper than a slope of 100 cm H_2O/sec.

3.3.1 DV#3: Descriptive Analysis

Descriptively, the group analysis of the slope of the increase interval showed an increasing slope from baseline to learned nonspeech. That is, as subjects practiced the gestures and were provided feedback on intraoral pressure target accuracy, they began to produce a steeper increase interval slope. Overall, a sharper slope for the speech condition than the practiced nonspeech condition was found. See Figure 13 for a graphical depiction.

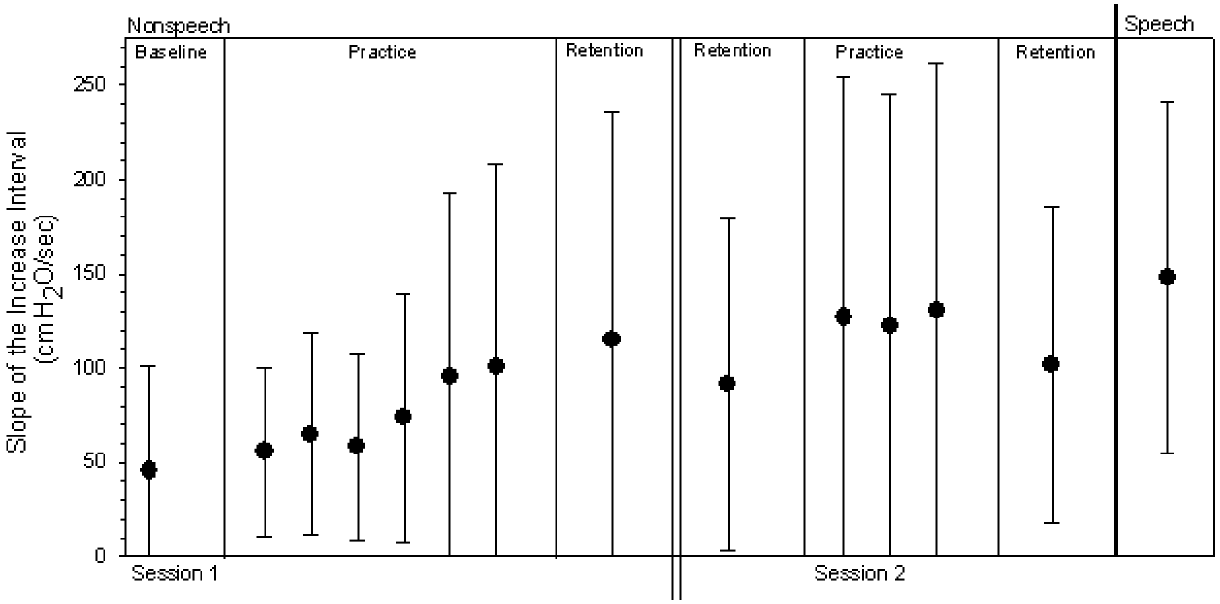

Figure 13. Group Means and Standard Deviations of the Slope of the Increase Interval

3.3.2 DV#3: Statistical Analysis

The mean slope of the increase interval was 104.220 for the nonspeech condition and 147.811 for the speech condition. Univariate analysis revealed no significant difference between the means of the nonspeech and speech conditions for slope of the increase interval (p=0.135).

The results of the univariate analysis for the slope of the increase interval followed the prediction that no significant difference would be found between the practiced nonspeech and speech conditions. As can be seen from the 95% confidence interval, there is a 95% probability that the true difference between the speech and nonspeech means falls within the interval of -106.429 and 19.247. Thus, the *possibility* exists that that there may, in fact, be no difference between these two conditions. However, a more precise estimate of the true difference could be made with a larger number of subjects.

Table 3. Statistical Results for the Slope of the Increase Interval

		Paired Samples Statistics			Paired Samples Correlations		Paired Samples Test		
		Mean	*N*	*Standard Deviation*	*Correlation*	*Significance*	*Degrees Freedom*	*t*	*Significance (2-tailed)*
Mean	Nonspeech	104.220	6	85.481	0.779	0.068	5	-1.783	0.135
	Speech	147.811	6	93.316					

	Paired Differences				
	Mean	*Standard Deviation*	*Standard Error Mean*	*95% Confidence Interval of the Difference*	
				Lower	Upper
Mean	-43.59	59.878	24.445	-106.429	19.247

3.3.3 DV#3: Individual Subject Results

Four of the six subjects showed an increase in the slope of the increase interval from baseline to practiced nonspeech retention. The remaining two subjects (S4 and S6) had baseline values that were approximately equally to those of the practiced nonspeech condition. Interestingly, four of the six subjects (S2, S3, S4 and S6) showed relatively flat learning throughout practice trials, with subject #2 and #3's practiced nonspeech retention data remarkably higher than during practice trials (and the practiced nonspeech data for S6 and S4 maintaining the flat learning curve).

In comparison of practiced nonspeech to speech, five of the subjects exhibited steeper slopes for the speech condition. The remaining subject, S5, showed values for nonspeech and speech that were approximately equal.

Four of the subjects exhibited baseline values that had lower increase interval slopes than the speech condition. The remaining two subjects, S4 and S6, showed baseline and speech values that were approximately equal.

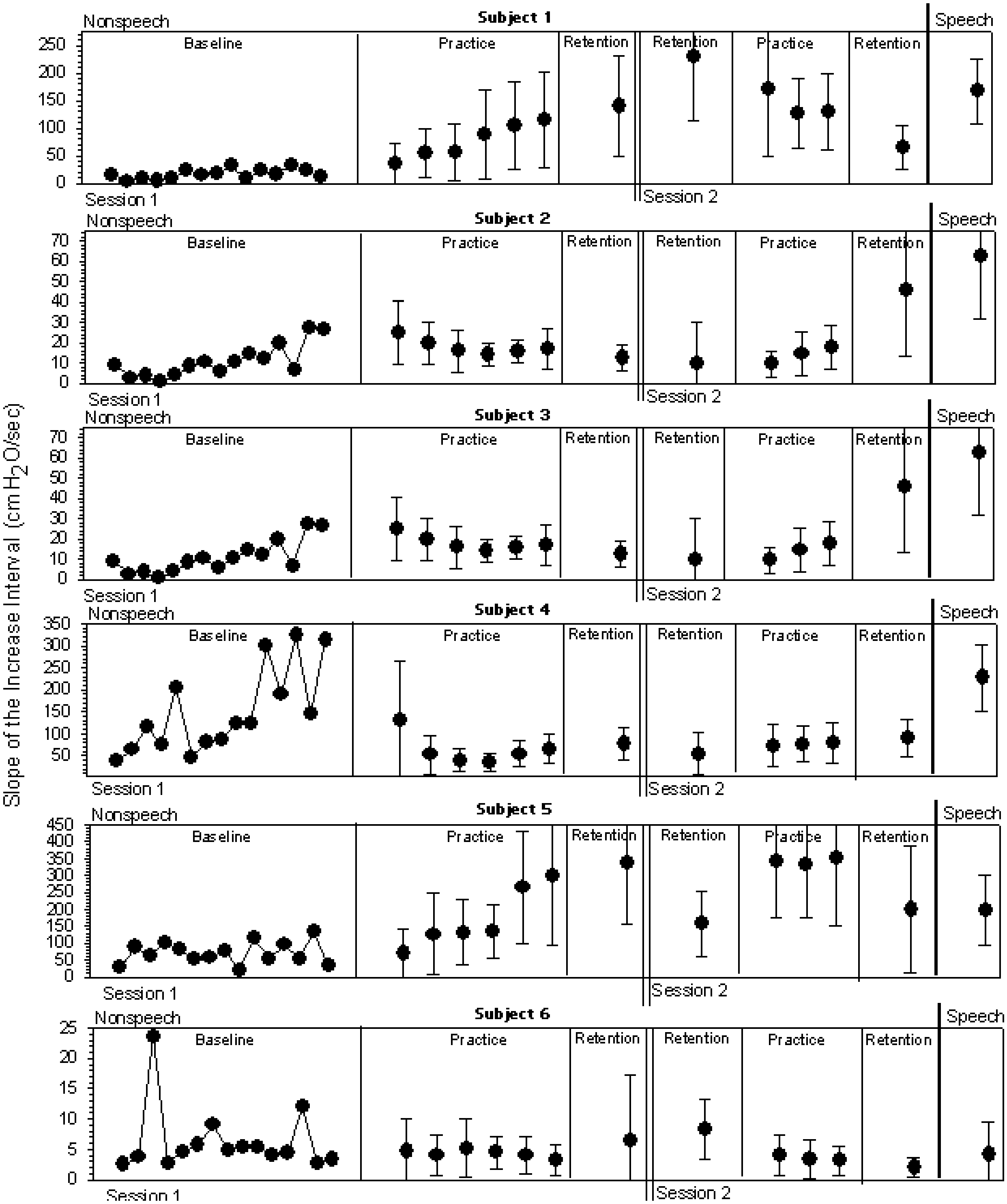

Figure 14. Individual Subject Means and Standard Deviations of the Slope of the Increase Interval

Graphical depiction of the means and standard deviations of the slope of the increase interval across all trials, presented for each individual subject.

3.4 DEPENDENT VARIABLE #4: SLOPE OF THE DECREASE INTERVAL

The fourth dependent variable was the slope of the decrease interval. This measurement was calculated by dividing that amplitude of the pressure signal from the onset to offset of the decrease interval (in cm H_2O) by the duration of the decrease interval (in seconds). This dependent variable was chosen as it reveals characteristics of the pressure slope which reflect the acoustic-perceptual properties of the voiceless bilabial stop. The decrease interval corresponds to the time of the release burst during the production of a voiceless bilabial stop. The release burst is marked by a quick release of intraoral pressure, creating the acoustic energy that perceptually distinguishes the phoneme /p/. Differences in the slope of the decrease interval may indicate differences in the goals of the nonspeech and speech task.

3.4.1 DV#4: Descriptive Analysis

Group analysis of the data for the slope of the decrease interval showed means that were slightly higher for the speech condition than the nonspeech condition. Performance on the nonspeech task from baseline and throughout practice trials remained relatively flat, with little change in slope with practice and feedback on achievement of the intraoral pressure target.

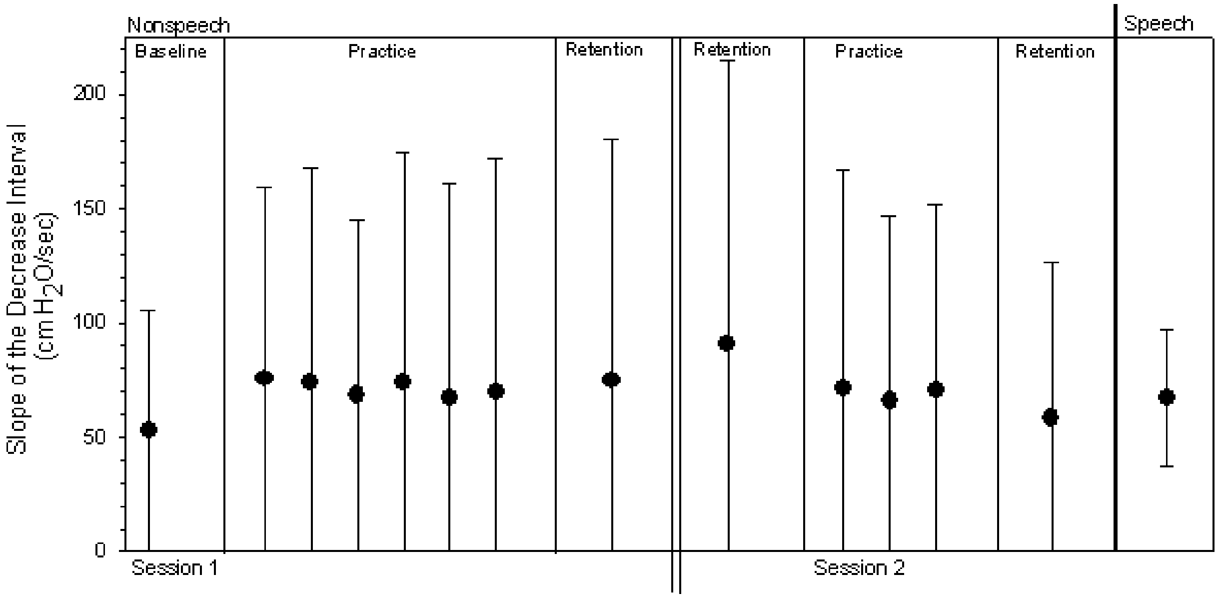

Figure 15. Group Means and Standard Deviations of the Slope of the Decrease Interval

3.4.2 DV#4: Statistical Analysis

The mean slope of the decrease interval for the nonspeech condition was 58.476 and 67.319 for the speech condition. Univariate analysis revealed no significant difference between the decrease interval slopes for the nonspeech and speech conditions (p=0.762).

The results of the univariate analysis for the slope of the increase interval followed the prediction that no significant difference would be found between the practiced nonspeech and speech conditions. As can be seen from the 95% confidence interval, there is a 95% probability that the true difference between the speech and nonspeech means falls within the interval of -80.043 and 62.358. Thus, the *possibility* exists that that there may, in fact, be no difference between these two conditions. However, a more precise estimate of the true difference could be made with a larger number of subjects.

Table 4. Statistical Results for the Slope of the Decrease Interval

		Paired Samples Statistics			Paired Samples Correlations		Paired Samples Test		
		Mean	*N*	*Standard Deviation*	*Correlation*	*Significance*	*Degrees Freedom*	*t*	*Significance (2-tailed)*
Mean	Nonspeech	58.476	6	67.805	0.220	0.675	5	-0.319	0.762
	Speech	67.319	6	30.012					

	Paired Differences				
	Mean	*Standard Deviation*	*Standard Error Mean*	*95% Confidence Interval of the Difference*	
				Lower	Upper
Mean	-8.84	67.846	27.698	-80.043	62.358

3.4.3 DV#4: Individual Subject Results

Three of the six subjects showed no change in the slope of the decrease interval with practice (S3, S5, and S6). Subjects #1 and #2 showed an increase in the decrease interval slope following practice, while subject #4 showed decreased slopes from baseline to practiced nonspeech.

Subjects #2, #3 and #6 exhibited speech means that were higher than the nonspeech means (or in other words, steeper decrease intervals for speech than the practiced nonspeech condition). Subjects #4 and #5 showed speech and practiced nonspeech means that were approximately equal. Subject #1's slope of the decrease interval was shallower for speech than nonspeech.

Interesting, baseline data for the slope of the decrease interval was approximately equal to speech data for three of the six subjects. Subjects #2 and #3 exhibited speech values with a sharper slope for speech than baseline. Subject #4's speech data was slightly lower than baseline.

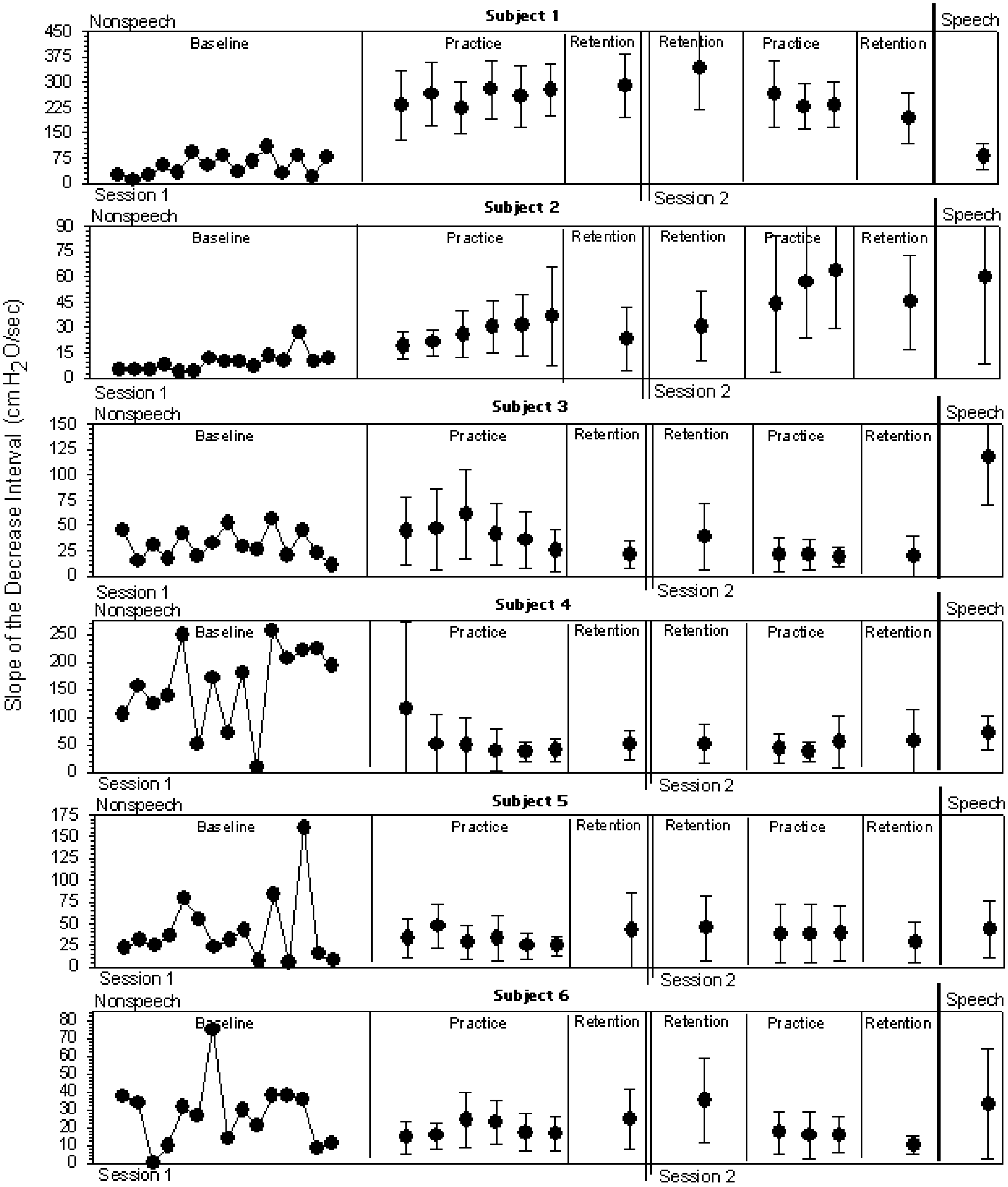

Figure 16. Individual Subject Means and Standard Deviations of the Slope of the Decrease Interval

Graphical depiction of the means and standard deviations of the slope of the decrease interval across all trials, presented for each individual subject.

3.5 PLATEAU INTERVAL DESCRIPTION

Although the present study did not address waveform shape during the plateau interval, basic measurements of the plateau interval were taken in order to account for gross differences in the pressure waveform profile between the two conditions. Past analyses of voiceless bilabial stops have noted the presence of a “break” in the pressure waveform profile marking the commencement of the plateau interval. This visual break in the waveform may parallel articulatory gestures, such as the achievement of complete closure of the lips and velopharyngeal port, which results in the end of rapid pressure increase (Kent & Read, 2002). The absence of a visible break indicates pressure increase that is directly followed by pressure release, preventing a true pressure plateau interval from occurring. See Figures 17 & 18 for illustration.

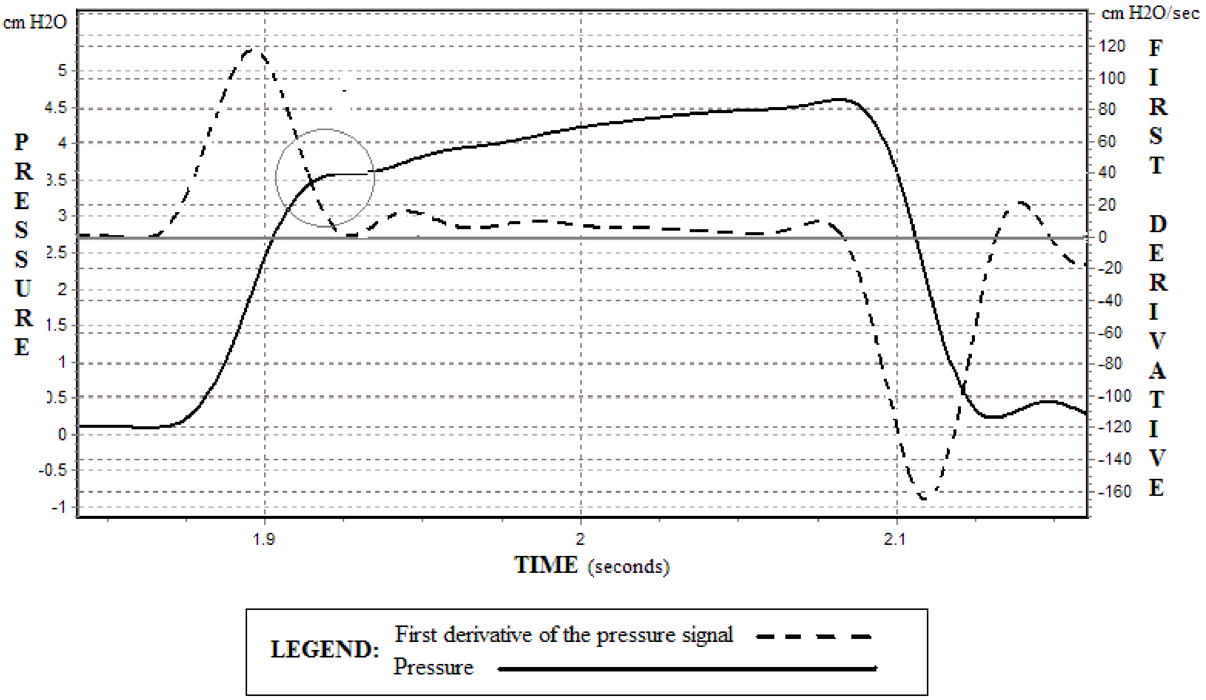

Figure 17. Waveform with Visually-Identifiable “Break”

Example of a speech production containing a visually-identifiable break. The area of the break is circled.

The frequency of a visually identifiable break in the pressure waveform was counted across all subjects for the baseline condition, the practiced nonspeech condition, and the speech condition. In the baseline condition, a visually identifiable break occurred in 62 of 90 trials, or in 69% of baseline trials. Thirty-three percent of the practiced nonspeech trials (30/90) contained a visually identifiable break. Of the speech condition, 81% (73/90) of the pooled trials contained a visually-identifiable break. It was predicted that following practice the characteristics of the waveform profiles for both the nonspeech task and the speech task would be similar, resulting in a comparable number of trials that contained all three intervals of the voiceless bilabial stop (increase, plateau, and decrease). However, the number of trials containing a break, (which visually marks the beginning of the plateau interval) was notably different for the speech and practiced nonspeech conditions.

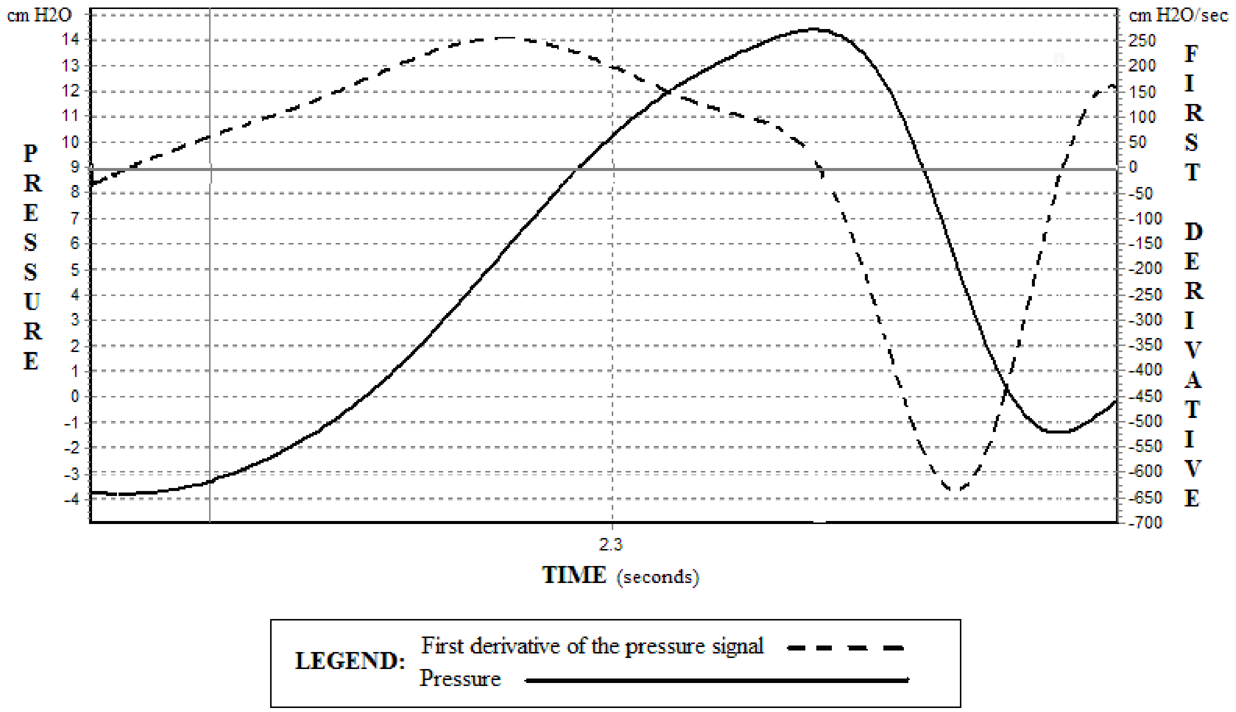

Figure 18. Waveform Lacking a Visually-Identifiable "Break"

The validity of the 10% marker for the plateau interval onset was determined by counting the frequency of trials in which the 10% marker did not coincide with the visually-identified break. This frequency of occurrence was counted for the baseline, practiced nonspeech retention, and speech conditions. Of the trials that contained a visually identifiable break, the 10% point coincided with the breaking point of the waveform in 86% (142/165) of trials.

In order to provide further description of the characteristics of the plateau interval throughout learning, the plateau interval's percent of the total duration was calculated for the baseline, practiced nonspeech, and speech conditions. In the baseline condition, the average percentage of the total duration of the plateau interval was 37%. On average, the plateau interval occupied 14% of the total duration of the waveform for the practiced nonspeech condition, and 40% for the speech condition. This suggests that during the practiced nonspeech condition subjects opened and closed the articulators quickly with little time spent in occlusion, which resulted in waveform profiles that had short plateau intervals; in the speech condition subjects appeared to hold the articulators closed for a longer period of time before releasing them, resulting in a longer plateau interval. See Figure 17 for an example of a nonspeech trial with a short plateau interval.

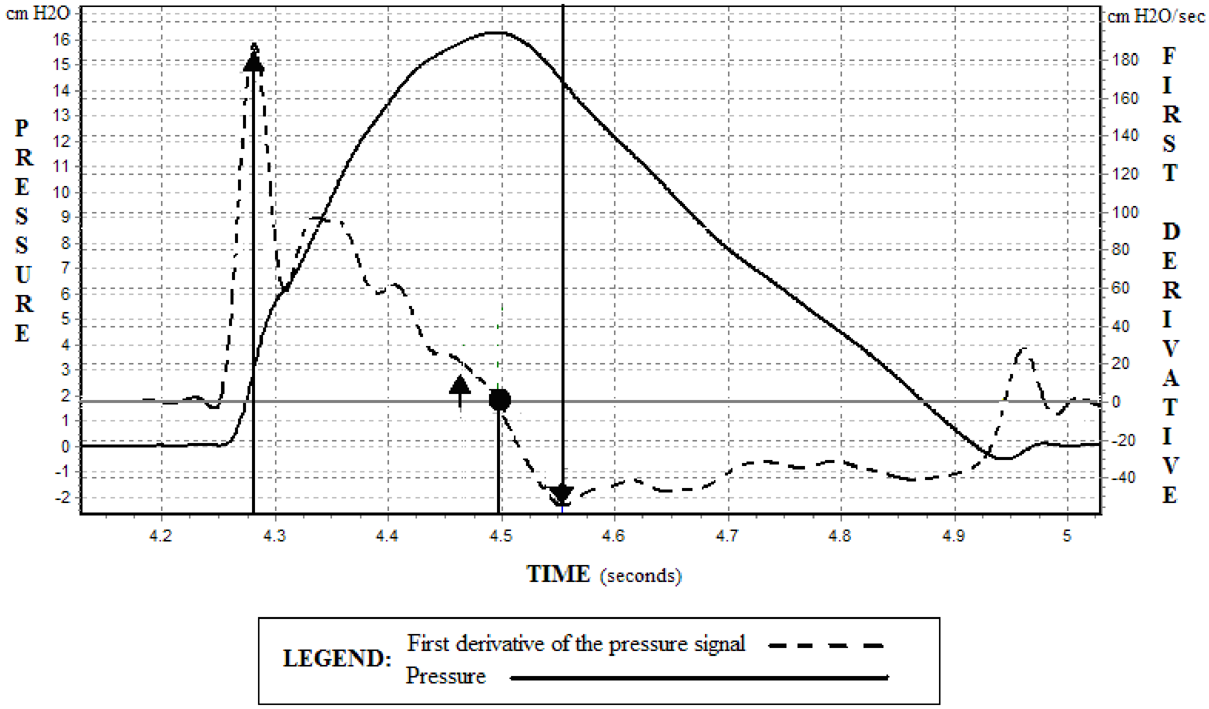

Figure 19. Nonspeech Trial with a Short Plateau Interval

The positive peak of the first derivative is marked by the long upwards-pointing arrow. The short upwards-pointing arrow indicates the point where the first derivative reaches 10% of the highest positive peak, which is used to mark the onset of the plateau interval. The offset of the plateau interval if marked with a vertical line tipped with a circle (which is identified as the zero-crossing immediately preceding the lowest peak of the first derivative, marked by a downwards-pointing arrow.) Note that this plateau interval is less than .05 seconds in duration.

4.0 DISCUSSION

The present study attempted to determine if the intraoral pressure waveform characteristics of a volitional, learned complex nonspeech task were similar to those of a speech task, in order to provide insight regarding a possible common sensorimotor mechanism. It was hypothesized that there would be no significant difference between the practiced nonspeech and speech task on any of the four statistically-analyzed dependent variables (the percent of the duration of the increase and decrease intervals, and the slope of the increase and decrease intervals). It was also predicted that the two conditions would be similar in overall waveform shape, as measured by the percent of trials that contained a visually-marked "break" in the two conditions. Similarities between the practiced nonspeech and speech conditions provided evidence in support of a possible shared generalized motor program for the two tasks.

Statistical analysis revealed no significant differences between the practiced nonspeech and speech for any of the four dependent variables, supporting the said hypothesis. However, large differences were observed between the two conditions for the frequency of a visually-identified break and also for the plateau interval's percent of the total duration, with the nonspeech condition having a visually-identifiable break less frequently than the speech, and the plateau interval occupying a lower proportion of the total duration in the nonspeech condition.

The first two dependent variables, which measured the percent of both the increase and decrease intervals involved in the total pressure waveform duration, were included as measures of relative timing. Movements that differ only in total duration but share the same relative temporal structure are assumed to share a common generalized motor program (Schmidt & Lee, 2005). Statistical analysis revealed that the practiced nonspeech task and the speech task showed no significant differences in the relative timing of the increase and decrease intervals of the pressure waveform. This finding may provide at least preliminary support for a common generalized motor program for the articulatory movements that produced the pressure waveform profile. However, it must be noted that the finding of no significant differences does not indicate that the practiced nonspeech and the speech condition were the same, but rather indicates that a difference between the two conditions failed to be detected.

As predicted, no significant differences were found between the two conditions for the slopes of the increase and decrease intervals. This indicates that subjects were producing the onset and offsets of the pressure waveforms utilizing a similar rate of change for both speech and nonspeech tasks. As above, these findings for the third and forth dependent variables lend support to the idea of a common generalized motor program for speech and nonspeech behaviors, although more data from additional subjects is needed to confirm this finding.

Of particular interest is the decrease interval slope. As previously discussed, the decrease interval involves release of the impounded intraoral pressure in the oral cavity. During the production of a voiceless bilabial stop, this release corresponds to the acoustic cue of the release burst, which is essential for the perception of a stop consonant. Statistical analysis indicated no significant difference between speech and practiced nonspeech productions on this measure. These data suggest that the release of intraoral pressure, whether generated for production of a voiceless stop or generated merely for the release of air impounded when attempting to hit a nonspeech target, is a result of a rapid release of the constriction of the oral cavity. That is, no significant difference between the nonspeech and speech tasks in the slope of the pressure decrease interval suggests that voiceless bilabial stops may be marked by particular pressure waveform characteristics simply because of articulatory movements that are quick and efficient. For a speech task, these quick and efficient movements result in the acoustic-perceptual goal of the burst release. Future studies may consider the acoustic characteristics that result from this release, in order to determine if comparable acoustic characteristics occur for the nonspeech task, despite the absence of an acoustic-perceptual goal.

Conversely, if there were a difference between decrease interval slopes for speech and practiced nonspeech, one might expect the speech productions to have steeper slopes. This would suggest that a rapid declination in the pressure waveform is necessary to accomplish the acoustic-perceptual goal of speech; rapid pressure decline would not be necessary for nonspeech as the nonspeech task does not include an acoustic-perceptual goal. Related to this is the fact that the statistical testing for all dependent variables was done using two-tailed t-tests. That is, no specific direction of difference was hypothesized for any of the dependent variables. However, for the decrease interval slope, one might hypothesize that, if a difference was detected, a steeper slope would be predicted for speech productions, as there is a critical rate of change that would be necessary to generate the appropriate acoustic-perceptual goal. Thus future research should consider a one-tailed t-test for the decrease interval slope, with predictions for a steeper slope for speech than nonspeech.

Unlike the statistical data involving the four dependent variables, descriptive data concerning the plateau interval seems to indicate large subjectively-defined differences for the relative timing of the plateau interval between the two conditions. Data for the plateau intervals were based upon visual inspection only, with no statistical comparisons having been performed to verify descriptive differences in the data set. However, descriptive differences in the plateau interval duration suggest that perhaps the practiced nonspeech task and the speech tasks are, in fact, different. Perhaps the dependent variables selected for this study may have failed to provide a complete picture of the waveform shape.

On average, the percentage of the plateau interval for the practiced nonspeech condition was 14%, as compared to 40% for the speech condition. If the plateau interval is assumed to be a period of complete oral constriction, during which intraoral pressure may increase slightly, many speech productions appear to include this interval, while most nonspeech productions do not. Contrary to the evidence provided by the relative timing measures of the percent of the increase and decrease intervals, a difference in the plateau interval's percent of the total duration would provide evidence to support a separate generalized motor program for speech and nonspeech tasks. However, characteristics of the plateau interval were not addressed in detail in the current study.

Future research should incorporate additional information into statistical testing, including measures such as the duration of the plateau interval and the presence or absence of a break (and detail on how to objectively identify the break). For example, past researchers studying pressure waveform profiles have relied heavily on accompanying airflow measures to aid in the demarcation of the various voiceless bilabial stop intervals. Müller and Brown (1980) marked the onset of the plateau interval as the initial zero point in the airflow signal, which indicates the point at which the articulators are completely closed. The current study used 10% of the peak of the first derivative of the pressure signal to mark this point. Airflow measures would provide additional information concerning the production of the voiceless bilabial stop and would provide concurrent validity to the measurements chosen in the present study. Future research involving both pressure and airflow analysis would provide valuable information concerning the production of intraoral air pressure for both tasks.

Interestingly, the literature examining waveform shape indicates that breaks occur with some frequency during speech production, but there is no discussion in this literature concerning the reason breaks occur (or do not occur) during speech. Additionally, literature fails to discuss the variability of waveform shapes within an individual's speech productions. The plateau interval should be a portion of particular interest in future studies.

There is literature that indicates that kinematic characteristics differ as speech is manipulated across variables such as speaking rate, loudness, clarity (clear speech versus causal speech), etc. However, the effect of such manipulations on the shape of the pressure waveform is unknown. Manipulations of quality of production (such as rate and clarity) were not controlled in the present study. It is likely that after subjects had produced the nonspeech task repetitively over two days of practice (more than 700 repetitions in total), subjects were tired and bored of the task. This may have resulted in nonspeech productions that were produced very rapidly and casually. It is possible that subjects may not have even completely occluded the oral cavity during productions, possibly resulting in little or no plateau interval in the practiced nonspeech task. When subjects were then instructed to produce speech, at the very end of data collection, maybe they produced speech with more care and precision than we would have expected, because they were contrasting the speech task with the previous nonspeech task (despite instructions to produce the speech task the same way that they produced nonspeech). Thus, future studies would need to consider how to control or systematically manipulate factors such as rate and precision for both speech and nonspeech task, in order to determine their role in pressure waveform shape.

Pressure waveform shapes are created by the kinematic movements of the articulators, and thus characteristics of waveform profiles must reflect articulatory gestures to some extent. However, the link between kinematic movements and pressure waveform shapes has not been studied sufficiently to create a direct link between the changes in waveform shape as a result of specific articulatory gestures. Kinematic data that parallels the pressure profiles that were analyzed in the current study have been collected by Shaiman and colleagues. Pending analysis of these data, greater confidence could be placed in the conclusions drawn in the present study regarding kinematic movements through the analysis of parallel pressure profiles.

Statistical analysis of all four dependent variables analyzed in the current study revealed no significant differences between the practiced nonspeech and speech conditions. Although inspection of the 95% confidence interval for all four of the dependent variables indicates that a *possibility* exists that there may be no difference between these two conditions, the finding of no significant difference does not indicate that the two conditions are the same. The current study contained only six subjects; future research involving larger subject numbers would help narrow the 95% confidence interval and aid in the identification of group trends. Additional data collection by Shaiman and colleagues is in progress.

The addition of a third condition in the statistical analysis, in which we would expect there to be a significant difference, would be useful. Concerning the current study, the addition of the nonspeech baseline condition would create three levels of the independent variable that could be statistically analyzed using repeated measures ANOVA. In this case it would be expected that baseline nonspeech condition would be significantly different from the practiced nonspeech and speech conditions, with no significant difference between practiced nonspeech and speech.

Statistical analysis of the single subject data should be completed in future studies. Analysis of the data as a group, as completed in the present study, fails to reflect trends exhibited by individual subjects. Descriptive review of individual subject data showed that some subjects showed changes in the dependent variables from baseline to practiced nonspeech, while other subjects did not. Future studies should include computation of effect sizes for individual subject performance to better quantify changes that occurred in the dependent variables.

In conclusion, no significant differences were found between the practiced nonspeech and speech conditions for the four dependent variables statistically analyzed in the current study (the percents of the increase and decrease interval involved in the total duration and the slopes of the increase and decrease interval). However, the finding of no significant differences between the two conditions does not indicate that the speech and practiced nonspeech are the same, but rather indicates that no difference could be detected in the present study. Data from additional subjects is necessary to confirm this finding. However, the observation of visually-identified differences in waveform shape (particularly in the shape and duration of the plateau interval) revealed a portion of the waveform that may be of particular interest in future studies, as descriptive data revealed notable differences between the plateau intervals of the speech and practiced nonspeech condition. Future research should include additional measures of the plateau interval, along with measurement of how this portion of the waveform changes with systematic manipulations of rate and precision.

APPENDIX

POST EXPERIMENTAL QUESTIONNAIRE

1. During the experiment, did you think there was any particular pattern to when you were given feedback for the movements? If so, what was the pattern?

2. During the experiment, what did you think was the point of the trials where you were not given feedback on your performance?

3. While you were performing the finger or lip movements, did you think there was anything special about these movements? If so, what did you think was special?

4. During the experiment, did you do anything differently on the trials immediately following feedback? If so, what did you do differently?

5. During the experiment, did you think you were supposed to make the finger or lip movements in any particular way or did you change the way in which you made the movements? If so, how?

6. How accurate do you think you were on getting close to the green target line on the lip task? On the finger task?

7. Do you think that practicing the lip task helped you improve on the finger task?

8. Were you familiar with the sequence of the finger or lip movements before the experimental session? If so, how?

9. Would instructions to develop a rhythm to the movements have made a difference in your performance? If so, how?

10. Do you think that the lips movements were at all speech-like?

11. While you were doing the experiment, before I asked you if the lip movements were like speech, did you at all think of the lip movements as being speech-like?

12. When you were doing the lip movements, were you thinking of them as speech movements? Or did you merely recognize that they were like speech?

13. Were you thinking of any specific speech sounds while you were producing the movements? If so, what sounds were you thinking of?

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