2019

An Application of the Two-Stage Model of Motor Learning to Speech Motor Control

Jacob W. Cahn
jwcahn@mix.wvu.edu

An Application of the Two-Stage Model of Motor Learning to Speech Motor Control

Jacob Cahn

Undergraduate Senior Thesis submitted to the College of Education and Human Services at West Virginia University

in partial fulfillment of the requirements for the degree of

Bachelor of Science in Speech-Language Pathology and Audiology

Thesis Advisor: Kimberly Meigh, Ph.D.

Department of Communication Sciences and Disorders

Morgantown, West Virginia 2019

Keywords: Speech motor control, variance, speech pathology, limb motor control

Table of Contents

Introduction

Variance is very difficult to define in motor learning. It is sometimes closely aligned with accuracy of performance, such that movements that have less variance are thought to be more accurate. In speech motor control, increased variance has been associated with negative learning outcomes and less mature speech patterns (Case Julie & Grigos Maria I., 2016). During motor learning, increased variance may mean the movement is more variable, less accurate, slowed, not yet learned (Case Julie & Grigos Maria I., 2016). Specifically, changes in kinematic variables, such as duration, displacement, and velocity of an articulator (or set of speech muscles) is often associated with poor articulatory control or speech that is less mature (Case Julie & Grigos Maria I., 2016). Thus, it is not surprising that variance has been viewed as a component of speech production that should be reduced or eliminated.

However, there is recent research that suggests abnormally *low* variance may also hinder performance (Wu, Truglio, Zatsiorsky, & Latash, 2015). This counterintuitive finding suggests that increased variance may not always result in poor learning outcomes, but may increase overall flexibility and generalization of the movement (Latash,2012). According to Latash (2012), there are two distinct categories of variance which influence learning and performance: *bad variance and good variance.* Bad variance relates to poor accuracy (i.e., error) in the production of a motor movement (Latash, 2012). From a motor learning perspective, bad variance impairs performance and is associated with negative performance factors. One goal of motor learning is to decrease bad variance, such that increased practice will refine the movement resulting in increased accuracy. Consider an example involving the hand where you are walking with a mug of coffee in your hand. To prevent spillage, you must keep the mug vertical at all times. If spillage is error, or bad variance, then minimizing bad variance would mean the mug was kept vertical. However, if you encounter an obstacle in your motor path, such has having to open a closed door with the hand holding the mug, you will need to maintain accuracy (i.e., vertical mug) while meeting the new task demands (i.e., opening the door). Decreasing bad variance cannot assist you in this new motor adaptation, it can only prevent you from spilling your coffee.

Adapting trained movement patterns to new environments or task demands, termed 'generalization,' is the goal of motor learning (Schmidt & Lee, 2005). Good variance may expand the number of degrees of freedom (or independent movements) to allow for adjustments of the movement to meet new task goals or environments (Latash, 2012). Determining how good variance allows for flexibility and adaptability during motor learning is difficult to define. Good variance does not influence accuracy, and may not influence motor learning once accuracy is achieved. However, good variance may also increase the degrees of freedom to increase efficiency or adaptability in achieving new, related tasks (Latash, 2012).

During motor learning, bad and good variance are manipulated independently in a predictable sequence (Latash, 2012). In a two-stage model of learning, training reduces bad variance during the first stage resulting in increased accuracy (Latash, 2012). During this time, good variance is not changed. Once accuracy has reached a ceiling level, bad variance can no longer be decreased any further and the goal of learning changes. This change of goal initiates the second stage of learning where training efforts now influence good variance. Good variance may be modified to allow for increased performance while maintaining high accuracy, such as flexibility and adaptability of the movement or using the movement pattern in a new way.

This two-stage model (Latash, 2012) has currently only been applied to the limb-control literature. However, applying Latash theory (2012) to speech motor control would allow speech theorists to research all types of variance, not just bad variance. Recently, Case and Gringos (2016) challenged the notion that *all* variance is detrimental to speech and is associated with negative learning outcomes. Instead, these authors stated an increase in degrees of freedom or flexibility in the movement may promote generalization. Thus, evaluation of good variance (as well as bad variance) may provide insight into generalization and adaptability of a motor task (Wu et al., 2015). Applying Latash theory (2012) to speech motor control may result in new therapy approaches that don't simply aim to reduce all variability in speech patterns. Instead, therapy may increase adaptability (or good variance) of trained movements, which may lead to more effective therapy techniques in individuals with motor speech deficits.

The primary goal of the current study is to evaluate Latash's theory (2012) of good and bad variance in relation to a speech motor learning task. To do this, stimuli would need to be novel so that features of the stimuli could be learned. Preferably, there would be different speech features learned at different time points throughout the training period to evaluate how each type of variance changes with practice and the complexity of the task. Specifically, less complex (or easier to learn) speech sounds should achieve stage 1 and 2 faster than more complex (or more difficult to learn) speech sounds. There are many features of speech that may exist on a complexity continuum, including manner of articulation (i.e., the pattern of air flow in the vocal tract) (Ogden, 2009)) or the number of syllables in a stimulus. Based on the existing literature in the field, the production of fricative sounds (e.g., /s/) is considered to be a more complex movement than stop sounds (e.g., /t/), which may lead to different learning outcomes

(Meigh, 2017; Sasisekeran et al., 2010). Along with manner of articulation, it is also well-supported that length of stimuli is also associated with complexity; such that the longer words are harder to learn (Jackson et al., 2016; Sasiskeran et al., 2010).

In the current study, we created nonsense speech stimuli (nonwords) to be learned by subjects. Nonwords differed by two main speech characteristics: manner of articulation (/t/ versus /s/) and length of stimuli (4- versus 6-syllable). During training we anticipated that we would observe each stage of Latash's (2012) two stage-model during different time periods based on the complexity of the stimuli. We measured bad variance based on the accuracy of participants' nonword productions with ceiling level accuracy marking the end of stage 1 (Latash, 2012). To evaluate stage 2 of learning (i.e., good variance), we measured duration of participants' nonword productions, which was a variable we anticipated would continue to demonstrate change while accuracy remained at ceiling level. The following predictions were evaluated: First, we predict that subjects will achieve stage 1 (i.e., ceiling level accuracy) earlier during training for simple nonword (i.e., four syllable nonwords; stop productions) than for complex nonwords (i.e., six syllable nonwords; fricative productions). Second, we predict that subjects will show different duration data patterns during stage 2 (i.e., after ceiling level accuracy has been achieved) based on simple nonword productions (i.e., four syllable nonwords; stop productions) and complex nonword productions (i.e., six syllable nonwords; fricative productions).

Methods

Participants

The participants of the study were 12 young adults (13 females, 5 males) between the ages of 18-35 years (M = 20.6, SD = 1.76). English was the native language for all participants, and all participants reported no history of speech or hearing disorders. Participants' hearing was screened using pure tone thresholds at 35 dB HL at 500, 1000, 2000, and 4000 Hz in at least one ear. All participants correctly identified at least 98% of all words using the Northwestern University Auditory Test No.6 word list (Tillman & Carhart, 1966). Conversational speech of all participants was evaluated for fluency and articulation errors by a certified and licensed speech language pathologist. In order to screen out individuals with speech disorders, an oral motor exam and the Test of Minimal Articulation sentence and reading screening subtests (Secord, 1981) were also conducted. Participants' working memory ability was evaluated using the Digit Span and Nonword Repetition Subtests from the Comprehensive Test of Phonological Processing, Second Edition (CTOPP-2; Wagner, Torgesen, Rashotte, & Pearson, 2013). Minimum raw scores on the Digit Span subtest (score = 17) and the Nonword Repetition subtest (score = 18) were required for all participants to ensure errors made during the experimental task were not due to limited working memory capacity. All participants signed informed consent documents approved by West Virginia University's Institutional Review Board and were compensated for their participation in this study.

Stimuli

Four types of nonwords were created to examine the effects of manner of articulation (stops vs. fricatives) and length of nonword (four vs. six syllables; Table 1). Voiceless sounds /t/

and /s/ were used to control for voicing as a potential contributor of complexity. The consonants were chosen based on placement of articulation so that maximal displacement of the tongue was possible, making kinematic differences between the two manners of articulation more apparent. All nonwords consisted of the same vowel sequence, and all syllables were produced with equal stress emphasis. All stimuli were within one standard deviation of the average biphone probability and positional probability present in the Irvine Phonotactic Online Dictionary (Vaden et al., 2009).

Table 1: Experimental stimuli

	4-syllable	6-syllable
Stop	/ta|to|te|tut/	/ta|to|te|tu|tɔ|tit/
Fricative	/sa|so|se|sus/	/sa|so|se|su|sɔ|sis/

Data Acquisition and Processing

Speech movement data was collected using the WAVE Speech Research System (NDI, Waterloos, Ontario, Canada). Participants were seated in a chair with their head next to the WAVE while movements were captured at a sampling rate of 100 Hz. A 6 degrees of freedom (DOF) reference sensor was attached to a headband to collect head movement data. Tongue, lip, and jaw movements were obtained using 5 DOF sensors, with respect to head movements. Two sensors were placed on the mid-sagittal plane of the tongue at the tip and blade. Jaw movements were obtained by attaching two 5 DOF sensors to the mandible gumline between the canine and incisor teeth on the right and left side. Lip sensors were attached to the upper and lower vermillion border between the philtrum ridges. Kinematic data was low pass filtered at 15 Hz and parsed based on acoustic waveforms of the nonword. All kinematic data was evaluated for error using a Matlab-based software, Speech Movement Analysis for Speech and Hearing research (SMASH; Green, Wang, & Wilson, 2013)

Procedures

This experiment consisted of single session with three tasks: acclimation, practice, and the experimental task. Participants were acclimated to the sensors by saying alternating and sequential diadochokinetic rates and repeating sentences with the targeted phonemes. Following this, the experimental task was reviewed with participants during a practice task. Eprime (Schneider, Eschman, & Zuccolotto, 2002) played an alert signal through a speaker followed by a nonword. The participant then repeated the nonword into the lapel microphone. This process repeated for a total of eight trials, where each nonword was presented twice with immediate feedback provided by the examiner on production accuracy. Following practice, participants repeated the nonword stimuli for twelve blocks with three repetitions of each nonword per block. No visual or auditory feedback to the participant was provided during the nonword repetition task, but participants were encouraged to take breaks between each block.

Visual Analysis

Data from twelve participants were analyzed. Subject attrition was due to failing the screening procedures (N=3), equipment failure (N=3). Prior to statistical analysis, a visual analysis of raw data was conducted. Using Microsoft Excel, accuracy (percent of accurate nonword production) and duration data were graphed across the twelve training blocks (time). Duration data was normalized in order to accurately compare temporal changes in fricative and stop production. This was done by averaging the durations of stop and fricative productions of the same syllable length within a given block, and then subtracting the average duration from each stimulus' duration in the block (e.g., 4-syllable stop and fricatives nonwords from block 1 were averaged and then this number was subtracted from each stimulus). Missing duration data was considered "0" by excel and graphed accordingly; however, this data was not considered for the visual analysis.

It was anticipated that accuracy would increase and duration would decrease over time with practice (Stage 1; Latash, 2012). This visual inspection was conducted to informally evaluate if Stage 1 was achieved at different times for the independent variables. This analysis was also used to investigate whether a second stage of learning (Stage 2; Latash, 2012) was evident. This second stage was hypothesized to be a change in duration while accuracy remained at ceiling level. During this stage, Latash (2012) predicts changes in variance only pertain to good variance. All visual comparisons were across manner of articulation (i.e., stops versus fricatives) but within the same syllable length (e.g., all four-syllable nonwords).

The first step in the visual comparison was to determine which subjects had achieved Stage 1 learning (i.e., ceiling level accuracy). In this experiment, ceiling level accuracy is defined as an accuracy of 90% or higher for at least three consecutive training blocks, where the second consecutive training block was the point of measurement for reaching and maintaining the ceiling effect. This second consecutive training block was also considered the point in learning where Stage 1 of learning was complete and Stage 2 was initiated. The average training block number and range for reaching ceiling effect was calculated for each subject.

Not all participants completed Stage 1 learning of the stimuli. Due to equipment malfunction and human error, there were some instances of missing data in the experiment. Participants who had three or more training blocks with missing data were not included in the visual analysis.

For the subjects who successfully completed Stage 1, three main categories of learning emerge from the data. The first category exemplifies the typical predicted sequence of motor learning. Subjects in this category (e.g., Subject 13), began training with lower accuracy. As training progresses, they eventually reach ceiling level accuracy (i.e., completed Stage 1). After they reached ceiling level accuracy, their accuracy remains at ceiling level for the remainder of training.

Subjects in category 2 produced ceiling level accuracy from the initial training block during training. The accuracy of production for these subjects were at or above 90% from the start of training to the end of training (i.e., training block 1 through 12). This category of learning is exemplified by Subject 16's performance.

Subjects in category 3 either began training at ceiling level accuracy, similar to category 2, or reached ceiling level accuracy at some point in training after training block 1, similar to category 1. However, after achieving three consecutive training blocks at or above 90% accuracy (i.e., reaching ceiling level accuracy), subjects in category 3 did not remain at ceiling level accuracy for the remainder of training. At some point during ceiling performance, subjects in category 3 had decreased accuracy below 90% accuracy (i.e., below ceiling level accuracy). This category of learning will be shown visually by Subject 10. Each category of learning will be described below in reference to the independent variables.

4-Syllable Nonword Accuracy

Stop Accuracy (ST4):

Out of the twelve recorded subjects, there were four subjects discarded due to missing data. Out of the eight remaining subjects, all eight subjects successfully reached ceiling level accuracy during training. Of the subjects who achieved ceiling level accuracy, the mean training where they achieved ceiling level accuracy was training block 2.25, and the range was 2 training blocks.

Category 1: There was one subject who was a category 1 learner (Figure 1).

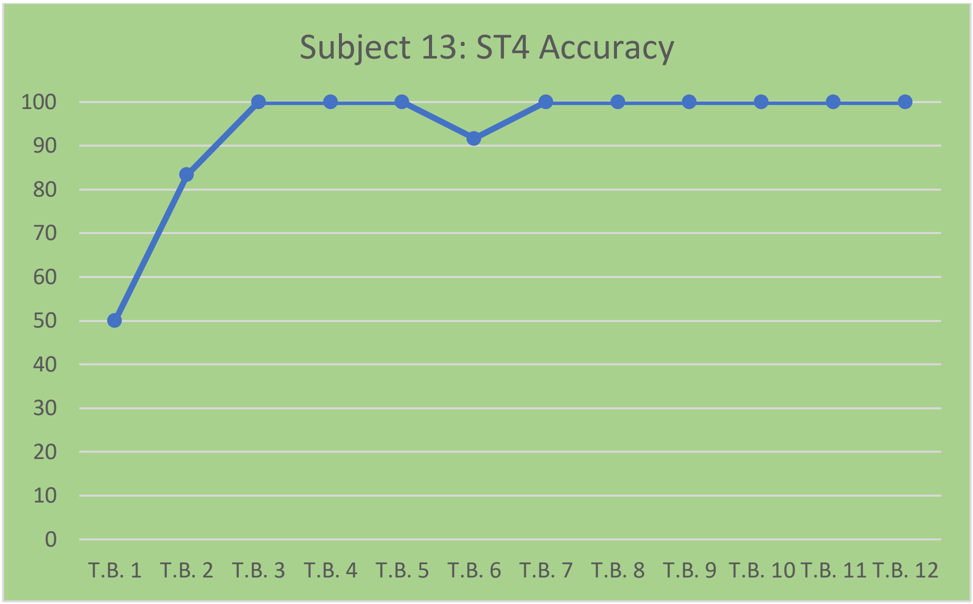

Figure 1: Subject 13 exemplifies category 1 learners for ST4 productions.

Category 2: There were five subjects who were category 2 learners (Figure 2).

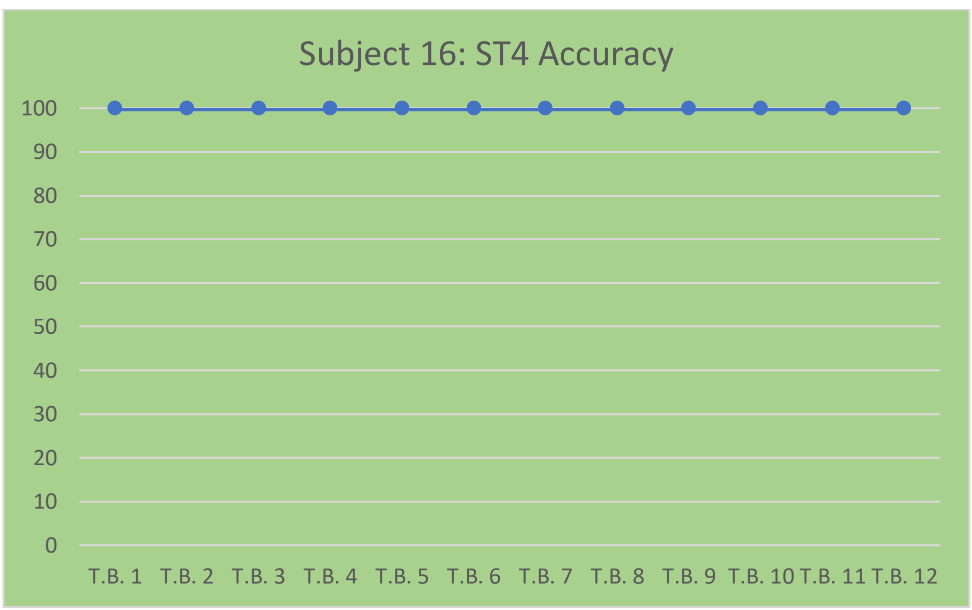

Figure 2: Subject 16 exemplifies category 2 learners for ST4 productions.

Category 3: There were two subjects who were category 3 learners (Figure 3).

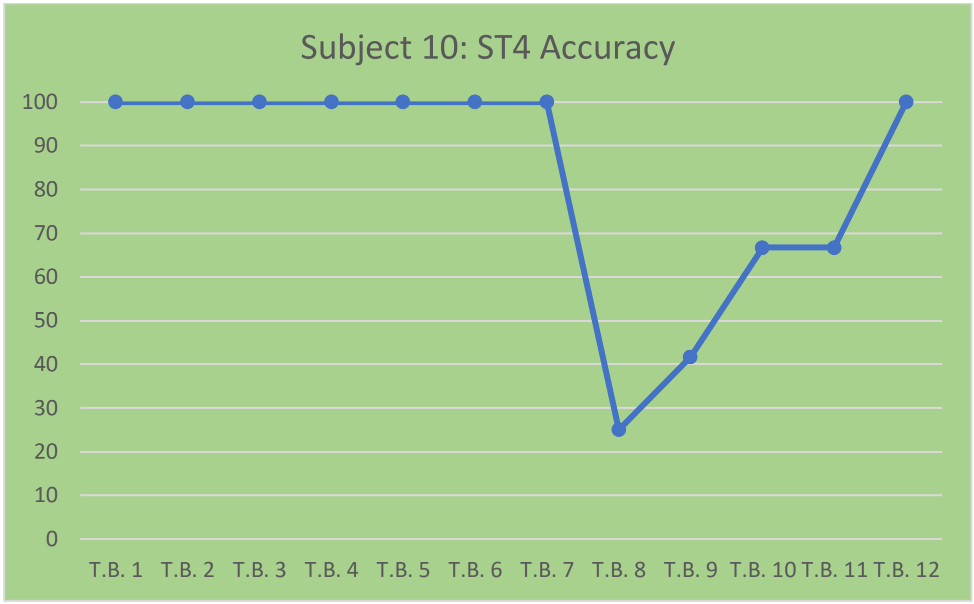

Figure 3: Subject 10 exemplifies category 3 learners for ST4 productions.

Fricative Accuracy (FR4):

Out of the twelve recorded subjects, there were three subjects discarded due to missing data. Out of the remaining nine subjects, all nine subjects successfully reached ceiling level accuracy during training. Of the subjects who achieved ceiling level accuracy, the mean training where they achieved ceiling level accuracy was training block 2.56, and the range was 3 training blocks.

Category 1: There was one subject who was a category 1 learner (Figure 4).

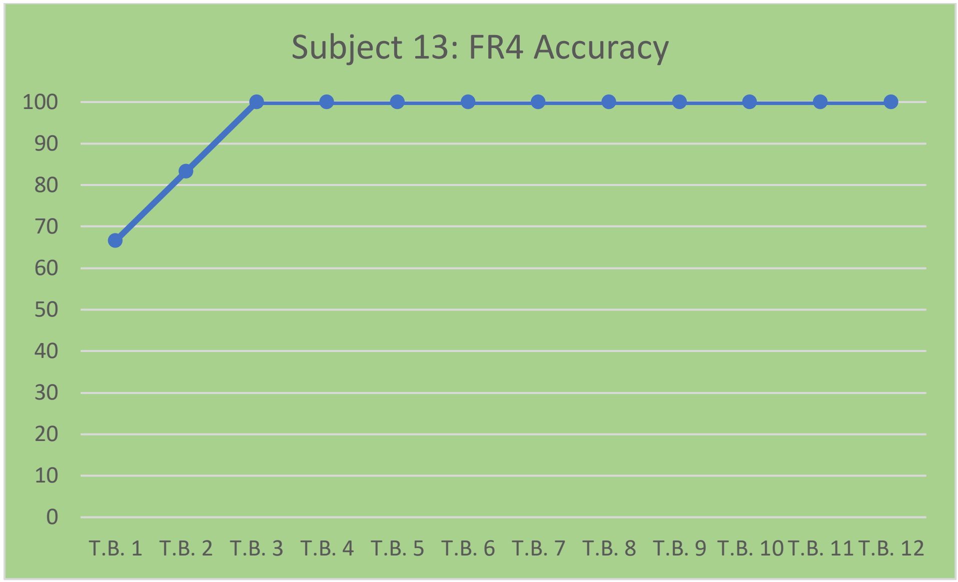

Figure 4: Subject 13 exemplifies category 1 learners for FR4 productions.

Category 2: There were six subjects who were category 2 learners (Figure 5).

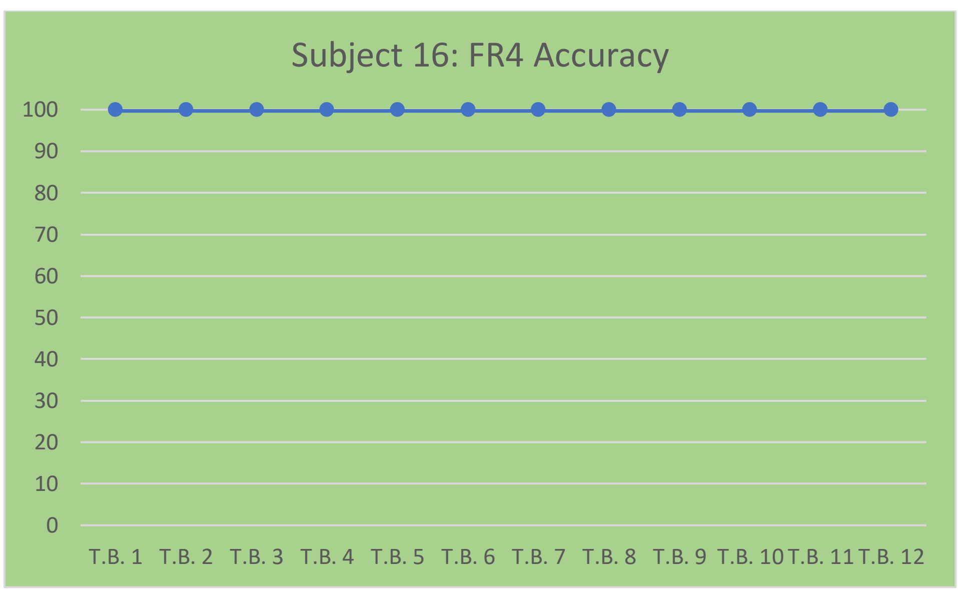

Figure 5: Subject 16 exemplifies category 2 learners for FR4 productions.

Category 3: There were two subjects who fell under category 3 based on their stage sequencing (Figure 6).

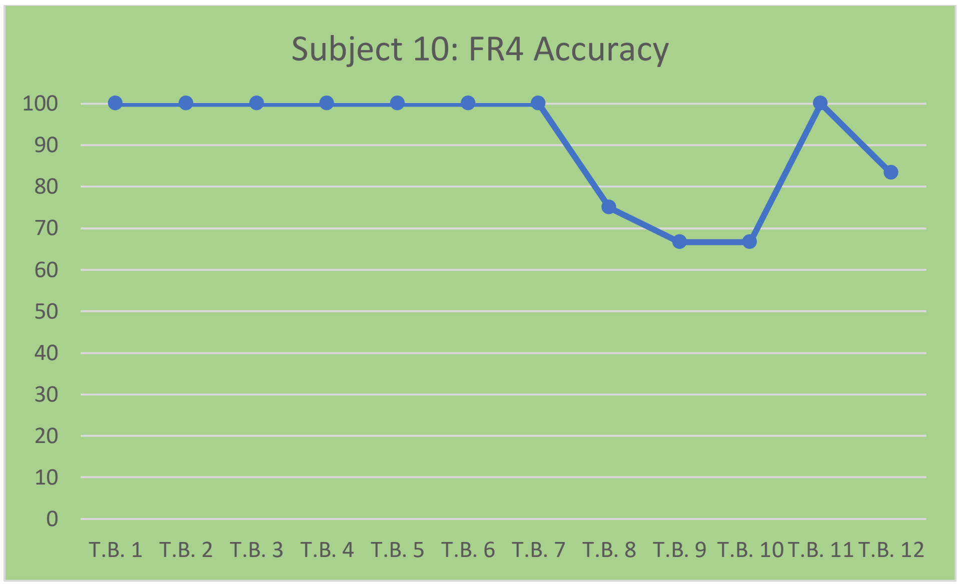

Figure 6: Subject 10 exemplifies category3 learners for FR4 productions.

6-Syllable Nonword Accuracy

Stop Accuracy (ST6):

Out of the twelve recorded subjects, there were three subjects discarded due to missing data. Out of the remaining nine subjects, eight subjects successfully reached ceiling level accuracy during training, and one subject failed to reach ceiling level accuracy during training. Of the subjects who achieved ceiling level accuracy, the mean training where they achieved ceiling level accuracy was training block 3.5, and the range was 4 training blocks.

Category 1: There were three subjects who were category 1 learners (Figure 7).

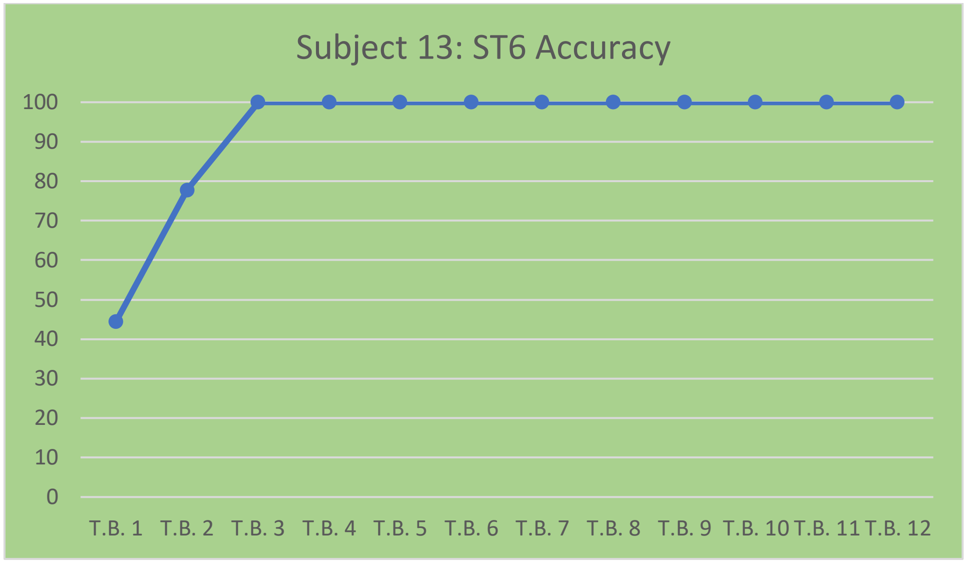

Figure 7: Subject 13 exemplifies category 1 learners for ST6 productions.

Category 2: There was one subject who was a category 2 learner (Figure 8).

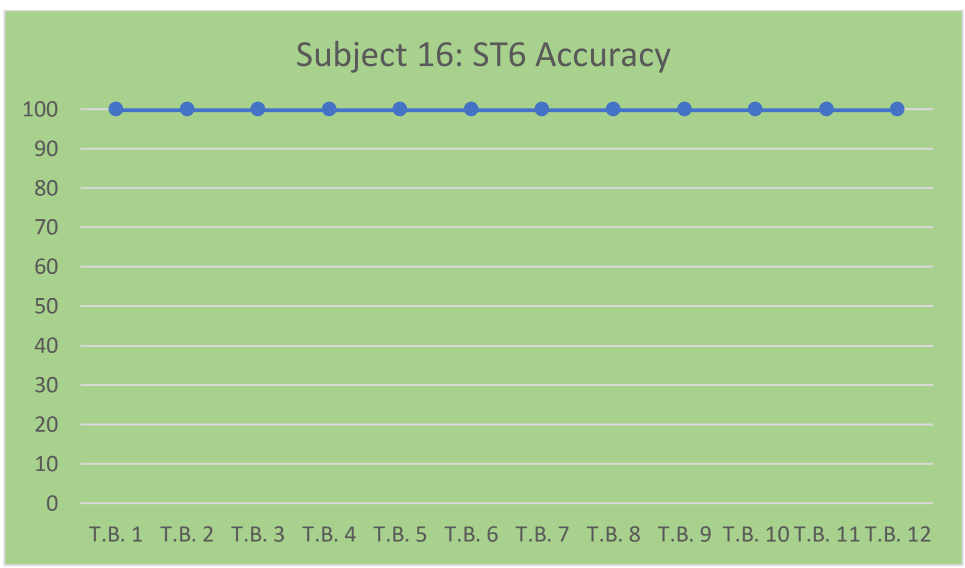

Figure 8: Subject 16 exemplifies category 2 learners for ST6 productions.

Category 3: There were four subjects who were category 3 learners (Figure 9).

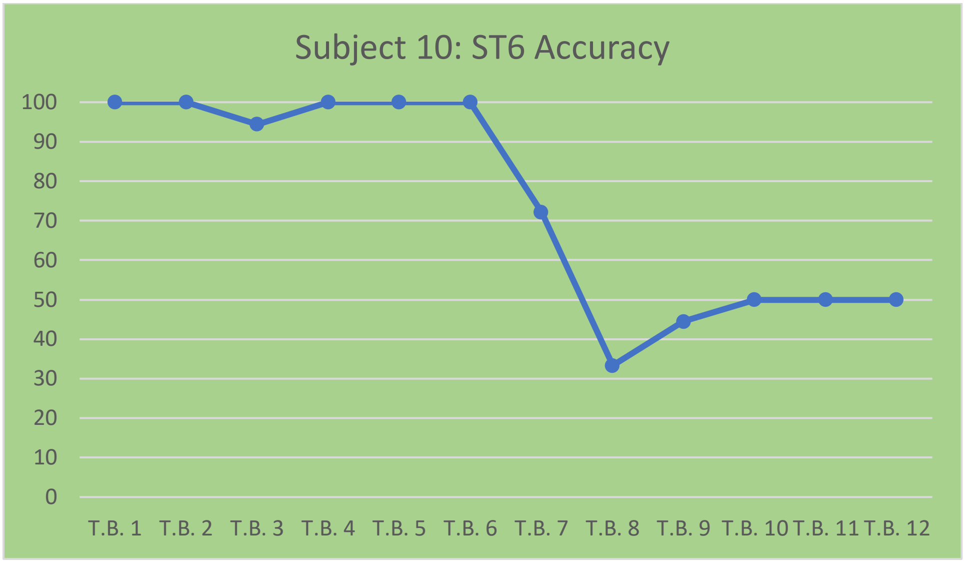

Figure 9: Subject 10 exemplifies category 3 learners for ST6 productions.

Fricative Accuracy (FR6):

Out of the twelve recorded subjects, there were two subjects discarded due to missing data. Out of the remaining ten subjects, eight subjects successfully reached ceiling level accuracy during training, and one subject failed to reach ceiling level accuracy during training. Of the subjects who achieved ceiling level accuracy, the mean training where they achieved ceiling level accuracy was training block 3.75, and the range was 7 training blocks.

Category 1: There were two subjects who were category 1 learners (Figure 10).

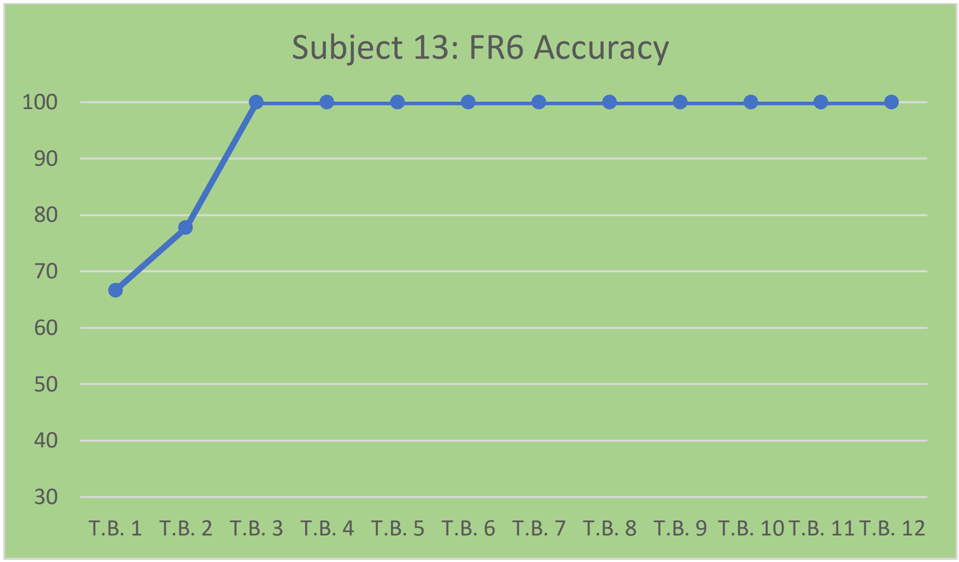

Figure 10: Subject 13 exemplifies category 1 learners for FR6 productions.

Category 2: There were three subjects who were category 2 learners (Figure 11).

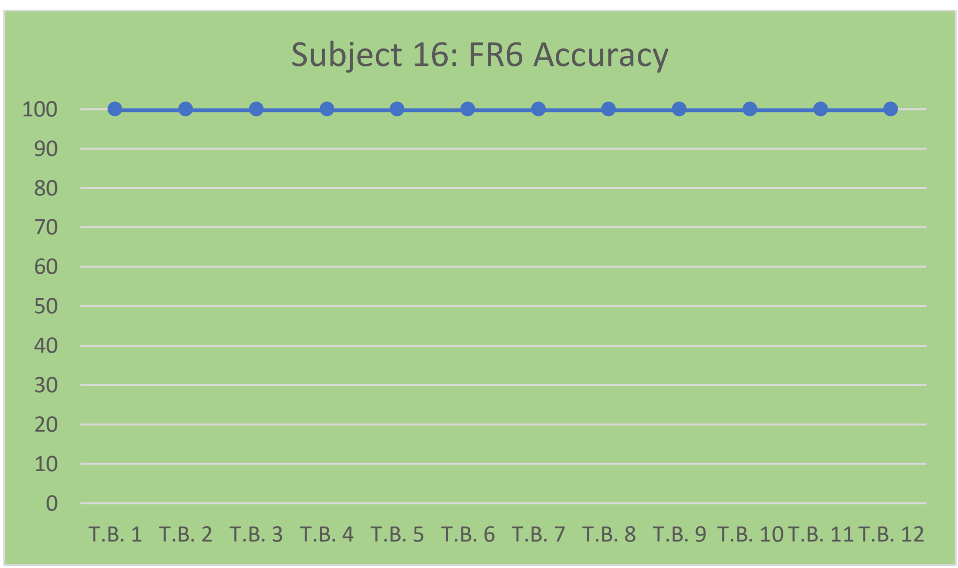

Figure 11: Subject 16 exemplifies category 2 learners for FR6 productions.

Category 3: There were three subjects who were category 3 learners (Figure 12).

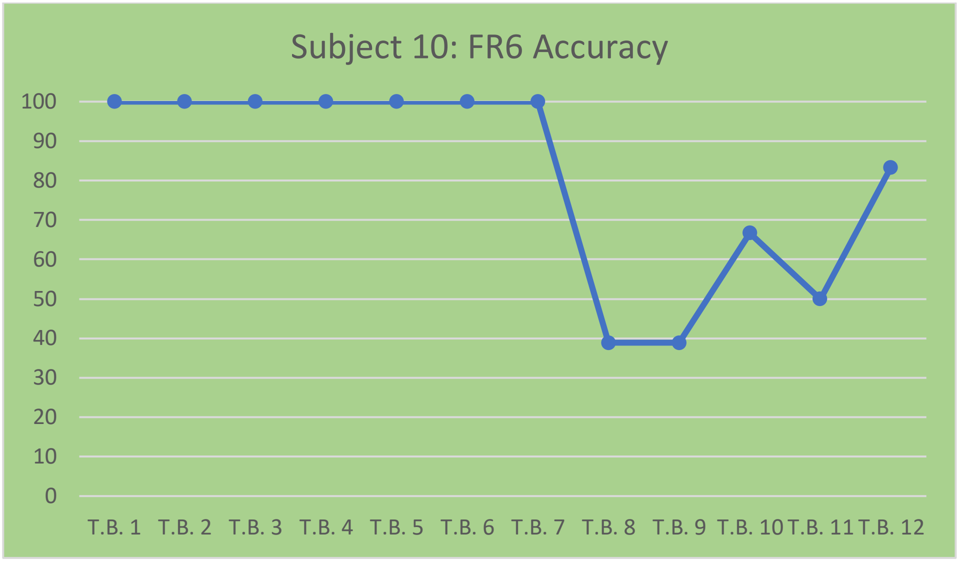

Figure 12: Subject 10 exemplifies category 3 learners for FR6 productions.

In summary, most participants were able to meet Stage 1 of learning (i.e., consistent accuracy at 90% or better). The longer the nonword (regardless of manner of articulation), the longer it took to achieve ceiling performance (Table 2). Shorter nonwords had similar ceiling acquisition rates regardless of manner of articulation, but differences in ceiling acquisition rates were observed between manner of articulation in six-syllable nonwords (range of 7 blocks). There were also twice as many category 3 learners when six-syllable nonwords were being produced compared to four-syllable nonwords.

	Mean	Range
ST4	2.25	2
FR4	2.56	3
ST6	3.5	4
FR6	3.75	7

Table 2: Mean and range number of blocks required to achieve Stage 1 criteria

The next research question in this study aimed to detect differences in duration of nonword production after ceiling level accuracy had been achieved (Latash; Stage 2). At this level of analysis, we compared differences in nonword duration among subjects who had successfully achieved ceiling level accuracy.

As defined by Latash (2012), Stage 2 cannot initiate until Stage 1 is completed (i.e., ceiling level accuracy is achieved). During this level of analysis, subjects who failed to achieve ceiling level accuracy were disregarded. Additionally, only six syllable nonwords were visually inspected, as four syllable nonwords were relatively indiscernible in their visual patterns between stop and fricative productions.

At the current stage of visual analysis, it proved more difficult to detect and describe differences in nonword duration data patterns compared to nonword accuracy data patterns. Based on the three categories of learning described previously, duration data was graphed by subject for both six syllable nonword types (i.e., ST6, FR6). To maintain consistency with stage 1 analysis, the same exemplary subjects will be used to describe the data (category 1 = subject 13, category 2 = subject 16, and category 3 = subject 10).

Duration Visual Analysis

Category 1: On average, fricative nonword productions were slower and had more variability in duration compared to stop nonword productions (Figure 13).

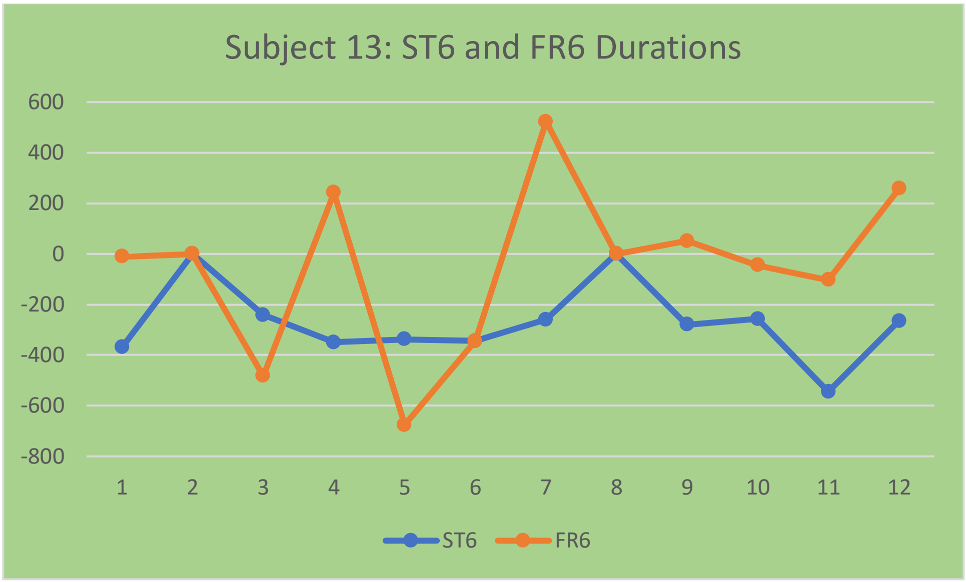

Figure 13: Duration of ST6 and FR6 productions for Subject 13

Category 2: On average, fricative nonword productions were slower and had more variability in duration compared to stop nonword productions (Figure 14).

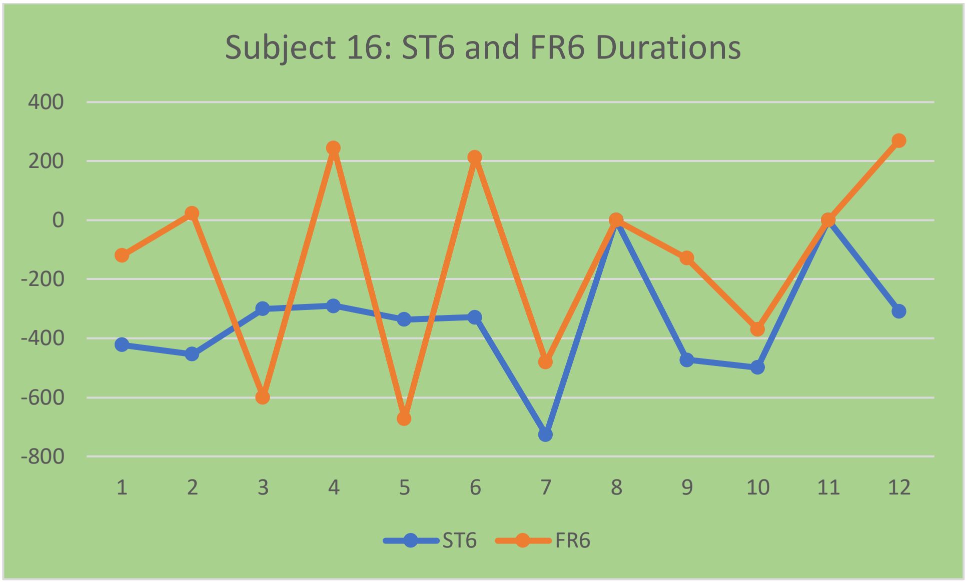

Figure 14: Duration of ST6 and FR6 productions for Subject 16

Category 3: On average, fricative nonword productions were slower than stop nonword productions. Fricative nonword productions and stop nonword productions had a similar level of consistency for category 3 learners (Figure 15).

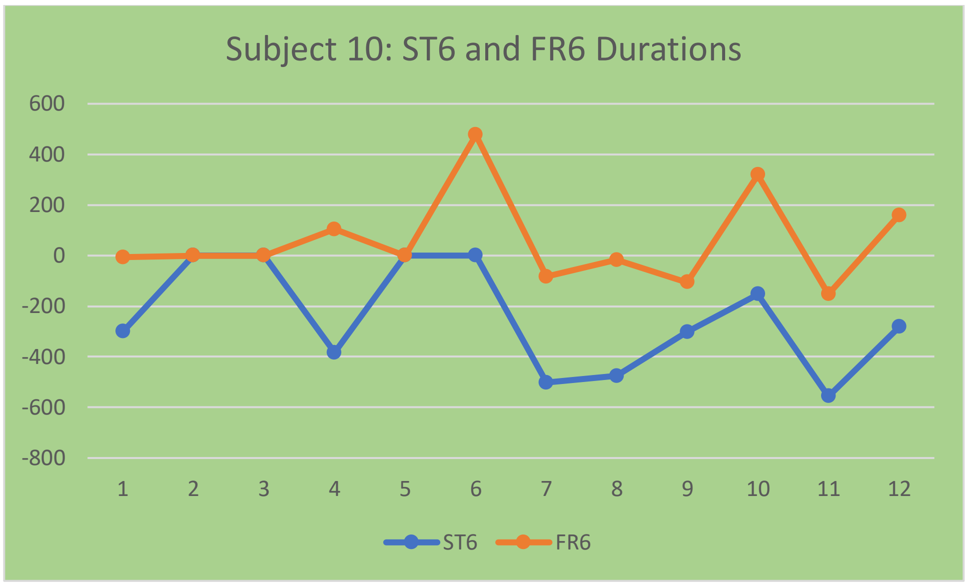

Figure 15: Duration of ST6 and FR6 productions for Subject 10

Discussion

In this study, complexity was defined by two measurable nonword characteristics; length (i.e., four syllables, six syllables) and manner of articulation (i.e., stops, fricatives). By these parameters, the order of complexity for the four nonwords used from least complex to most complex was ST4, FR4, ST6, and FR6. The first hypothesis of this experiment was that subjects would achieve stage 1 (i.e., achieve ceiling level accuracy) earlier during training for simple nonwords (e.g., ST4) than for complex nonwords (e.g., FR6). Participants in this study completed stage 1 of learning earlier for simple nonwords than for complex nonwords based on both types of complexity (length and manner of articulation). The average number of blocks required to achieve stage 1, as well as the variability in achieving this stage (as noted with range) were markedly different between each type of stimuli. Thus, stage 1 learning was evident for the nonword learning task, and stimuli with low levels of complexity (e.g., ST4) achieved stage 1 learning sooner than more complex stimuli (e.g., FR6) as predicted. Interestingly, the number of category 3 learners, i.e., the learners who achieved stage 1 early in learning but were unable to maintain accuracy, increased for more complex stimuli (e.g., FR6).

The second hypothesis of this experiment was that subjects would demonstrate different duration patterns during stage 2 (i.e., after ceiling level accuracy has been achieved) based on simple nonword productions (e.g., ST4) and complex nonword productions (e.g., FR6). Based on our initial visual analysis, there were observable differences in duration data patterns based on nonword manner of articulation. In stage 2, for category 1 and category 2 learners, the duration of fricative nonword productions were more variable than the duration of stop nonword productions. Moreover, the duration for stop nonword production was faster than for fricative nonword production across all categories of learners. However, evaluation of category 2 learners' stage 2 performance provided additional insight into speech motor learning.

Category 2 learners achieved stage 1 learning very early (within the first block of training) and maintained ceiling levels of accuracy throughout all of their training blocks. For many category 2 learners, there were no differences in performance based on manner of articulation or length of the nonwords during stage 1. According to traditional models of motor learning, this would indicate that learning had concluded (e.g., Schmidt & Lee, 2005). However, analysis of stage 2 learning using a more continuous variables, such as duration, provided insight into the different learning patterns between different levels of complexity in speech production. Shorter nonwords (regardless of manner of articulation), as well as stops (regardless of length), were faster and more consistent in duration compared to longer nonwords or nonwords with fricatives. This observation supports the notion that when evaluating learning and performance that ceiling level accuracy does not necessarily indicate the task has been completely learned.

Other surprising findings involved category three learners, where ceiling level effects were not maintained during stage two learning. This phenomenon requires investigation, and it may provide further insight into generalization deficits for speech motor tasks. In the two-stage model described by Latash (2012), Stage 2 of training is when the learner controls good variance in order to become more flexible and generalize the motor skill to similar tasks. During this second stage of learning, ceiling level accuracy achieved during Stage 1 of learning is maintained throughout Stage 2. In this study, both category 1 and category 2 learners met this description, but category 3 learners did not. Factors that may have contributed to the regression in accuracy for category 3 learners may be fatigue and boredom during the lengthy training session. Neither boredom nor fatigue were measured or accounted for in the design of this experiment. Other factors may relate to the programming mechanism used in speech motor control. Individuals with apraxia of speech (AOS) are able to reach ceiling level accuracy during therapy but their inability to generalize learned speech motor skills in the real world is diminished (Case Julie & Grigos Maria I., 2016). Future studies should investigate if speech programming includes generalization abilities, which would increase our understanding of clients with AOS.

In summary, this study provides evidence for the two-stage model of motor learning (Latash, 2012) in speech motor learning. It highlights two suspected variables of complexity, length and manner of articulation, as well as providing evidence that motor learning may still be occurring despite ceiling level accuracy effects. Additionally, this study provides evidence for evaluation of variables that may influence good variance, as well as decrease bad variance, to support overall motor learning. However, this study did have limitations that must be considered.

This study took place only over one single session for each subject. This limited our ability to measure long-term learning of nonwords, including retention and transfer effects to novel nonwords. Each training block included identical nonword productions with only the nonword sequence changing between training blocks, and as result, the learner was never required to generalize learned motor movements. Thus, it is unclear whether the proposed learning effects visually observed would have generalized to new stimuli.

Additionally, the length of the experimental session was over an hour. This may have caused fatigue and/or boredom for subjects which may have influenced their performance. The length of the experimental session may have negatively affected some subjects' ability to maintain ceiling level accuracy during Stage 2 of learning (i.e., category 3 learners). The length component of stimuli complexity may be the primary cause of error in stage sequencing as there were more category 3 learners for the 6-syllable nonwords than the 4-syllable nonwords, regardless of manner of articulation. This supports the notion that fatigue and/or boredom may have affected performance. Neither fatigue nor boredom were accounted for in the design of this experiment.

Finally, a main limitation of the current status of the results from this study is that a more thorough statistical analysis has not yet been conducted. The visual analysis did allow for detection of general patterns throughout the learning process, but for a more accurate analysis of distinct data patterns based on levels of complexity, especially for stage 2 (i.e., duration), a statistical analysis is necessary. This would allow for evaluation of statistical significance, and specific identification of interactions between the independent variables (length and manner of complexity) and learning (block).

The results from this study establish a foundation for future research regarding variance in speech motor learning. With the existing data from the current study, a statistical analysis will allow for a better understanding of more precise learning patterns for stage 1 and 2 learning. An immediate future goal is to create a study that can measure a subject's ability to generalize learned speech motor skills. This future study will be similar to the current study, but rather than using training blocks consisting of identical nonword repetitions throughout training, training blocks consisting of similar nonwords will occur later in training, requiring subjects to generalize learned speech motor skills to similar tasks. The long-term goal of applying the two-stage model of motor learning (Latash, 2012) to a speech motor learning is to apply the findings to individuals with motor speech disorders, such as AOS. The main objective of this line of research is to improve the clinical approaches for individuals with motor speech disorders through a deeper and more accurate understanding of the relationship between variance, generalization, and complexity in speech motor learning and performance.

References

Case Julie, & Grigos Maria I. (2016). Articulatory Control in Childhood Apraxia of Speech in a Novel Word–Learning Task. *Journal of Speech, Language, and Hearing Research*, *59*(6), 1253–1268. https://doi.org/10.1044/2016_JSLHR-S-14-0261

Jackson, E. S., Tiede, M., Riley, M. A., & Whalen, D. H. (2016). Recurrence quantification analysis of sentence-level speech kinematics. Journal of Speech, Language, and Hearing Research, 59(6), 1315–1326.

Latash, M. L. (2012). *Fundamentals of Motor Control*. Retrieved from http://ebookcentral.proquest.com/lib/wvu/detail.action?docID=945450 Ogden, R. (2009). *An Introduction to English Phonetics*. Retrieved from http://ebookcentral.proquest.com/lib/wvu/detail.action?docID=537027

Meigh, K. M. (2017). A Novel Investigation of GMP Theory: Syllable Stress as a Motor Class Variable. Journal of Speech & Hearing Research, 60(6S), 1685–1694.

Sasisekaran, J., Smith, A., Sadagopan, N., & Weber-Fox, C. (2010). Nonword repetition in children and adults: effects on movement coordination. Developmental Science, 13(3), 521–532.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). E-Prime user's guide (Version 2.0). Pittsburgh, PA: Psychology Software Tools.

Secord, W. (1981). Test of minimal articulation competence. *San Antonio, TX: Psychological Corporation*.

Tillman, T. W., & Carhart, R. (1966). *An expanded test for speech discrimination utilizing CNC monosyllabic words: Northwestern University Auditory Test No. 6*. Retrieved from DTIC

Document website:
http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=AD063963
8

Vaden, K.I., Halpin, H.R., Hickok, G.S. (2009). Irvine Phonotactic Online Dictionary, Version 2.0. [Data file]. Available from http://www.iphod.com.] Wagner, R. K., Torgesen, J. K., Rashotte, C. A., & Pearson, N. A. (2013). *CTOPP-2: Comprehensive Test of Phonological Processing*. Austin, TX: Pro-Ed.

Wu, Y.-H., Truglio, T. S., Zatsiorsky, V. M., & Latash, M. L. (2015). Learning to combine high variability with high precision: lack of transfer to a different task. *Journal of Motor Behavior*, *47*(2), 153–165. https://doi.org/10.1080/00222895.2014.961892