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The Effect of Context Diversity in Virtual Reality Environments on Speech Motor Learning in a Person With Aphasia and Apraxia of Speech

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A thesis submitted to the faculty of
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Master of Science

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ABSTRACT

The Effect of Context Diversity in Virtual Reality Environments on Speech Motor Learning in a Person With Aphasia and Apraxia of Speech

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This study explored the effect of contextual diversity on speech motor learning in an individual with apraxia of speech (AOS) using virtual reality (VR). One 62-year-old participant with severe AOS participated in the study where he practiced monosyllabic CVC words in both consistent and diverse VR environments. Kinematic, acoustic, and perceptual data were collected and evaluated for evidence of learning. Kinematic data were collected using electromagnetic articulography where sensors were glued to the participant's upper lip, lower lip, tongue blade, and tongue tip and were tracked with high precision. In addition, acoustic and perceptual data were collected using a microphone and analyzed using Praat software. Results suggest that the diverse condition may have benefitted speech motor learning and retention for the participant as seen by decreased stroke count, reduced duration of speech production, and increased accuracy in the diverse condition. These findings suggest that varied practice in multiple VR contexts might enhance speech motor skill acquisition and retention more effectively than consistent practice. While kinematic metrics show mixed results, overall data align with the hypothesis that diverse learning contexts might facilitate better motor learning outcomes. This research also highlights the potential of VR as a clinical tool for improving speech therapy interventions for individuals with AOS.

Keywords: speech impairments, aphasia, speech improvement, computer simulation, generalization

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DESCRIPTION OF THESIS STRUCTURE AND CONTENT

This thesis, titled *The Impact of Context Diversity in Virtual Reality Environments on Speech Motor Learning in an Individual With Aphasia and Apraxia of Speech*, is written in a hybrid structure that meets university criteria and the standards for publication in communication disorders journals. The initial sections of this thesis follow the university's submission guidelines. Meanwhile, the main body of the thesis aligns with the length and style requirements for submission to communication disorders journals. The literature review is found in Appendix A. Additionally, information regarding Institutional Review Board (IRB) approval and participant consent is in Appendix B. Appendix C contains additional tables.

Introduction

Context-Dependent Memory

The location in which learning takes place has a significant impact on an individual's ability to recall the information learned. This phenomenon is not a new discovery; a significant amount of research has shown that "human memory is inherently context-dependent" (Essoe et al., 2022, p. 1). Learned information becomes automatically connected to the environment in which it was learned. This connection to the environment acts as a contextual cue that can help the learner recall information using their surroundings (Essoe et al., 2022).

Godden and Baddeley (1975) demonstrated this phenomenon of context-dependent memory when they taught participants novel vocabulary on land and underwater. When the participants were tested on the target vocabulary in the same location where they were taught the material, either on land or underwater, their performance on the task was better than those who were taught and tested in different locations. Similarly, Abernethy (1940) evaluated this effect within the classroom setting and found results that supported the same conclusion—when students were tested on course material in the same room where they were taught the material, they earned higher grades.

These results are observed not only in physical locations, but also within virtual environments. Shin et al. (2021) reported context-dependent memory effects within two distinct virtual reality (VR) environments—on Mars and underwater—demonstrating that this phenomenon carries beyond physical locations and into virtual ones. Participants were assigned to one of the two VR learning locations where they were asked to evaluate objects and determine their usefulness. Participants were then randomly assigned to the same or a different context to be evaluated on their recall of the objects encountered during the task. Results from this study are consistent with previous research findings and show that participants perform better when they are tested in the same context in which encoding took place.

Although studies have shown that consistency in learning and testing location can be beneficial to participant performance, there are some potential drawbacks that should be considered. Often, the contextual cues within the encoding environment that aid in remembering can become a “crutch” to learning and retrieval and can result in an inability to recall learned information when removed from the original encoding environment as shown by Essoe et al. (2022). The author compared this idea to a traveler struggling to speak a new language in a foreign country because they only ever practiced speaking in the classroom; it is only when they are removed from their learning environment that this contextual crutch become apparent. One theory suggests that this is because repeatedly learning information within the same context “results in a single memory trace” and removing an individual from the cue to this single memory trace results in forgetting (Smith & Handy, 2014, p. 1583). On the other hand, varying the context in which information is learned may result in multiple memory traces (Smith & Handy, 2014). For example, Rosa et al. (2022) found that children who encounter words in multiple presentation contexts (e.g., books, films, etc.) are more likely to identify the word correctly on a recognition test. The act of varying learning contexts resulted in increased word learning in the participants. In addition, Essoe et al. (2022) found that participants who learned new words in multiple contexts showed less interference and better retention of the material 1 week later than participants who were taught the material within a single context. This is known as the contextual diversity effect. Jones et al. (2017) described contextual diversity as “the number of distinct contexts in which the word occurs” (Jones et al., 2017, p. 242). They further explained that contextual diversity is based on the principle of “likely need,” meaning, if a word has been encountered in numerous distinct contexts during learning, it is more likely that it will be needed in a future context, thus, making it more broadly accessible within the individual's lexicon (Jones et al., 2017, p. 242). The learned information is then less likely to require the crutch of a specific context to be recalled.

It should be noted that context has been interpreted very broadly in the literature. For example, Rosa et al. (2022) defined context as the parts of discourse that surrounded the target word and contributed to its meaning; this could be defined as linguistic context. Apolinário-Souza et al. (2021) interpreted context to be the color and location of the stimuli as they appeared on the computer screen, which could be considered presentation context. On the other hand, Godden and Baddeley (1975) used context to describe the different environments the participants were placed in. This could be defined as environmental context. Additionally, the VR environments used in Shin et al. (2021) could be equated with environmental context. The present study will use environmental contexts to evaluate the effect of contextual diversity on speech motor learning.

Treatment protocols that incorporate diverse and ecologically valid contexts may offer promising ways to optimize speech motor learning in individuals with acquired apraxia of speech. However, little research has been conducted on this topic specifically. Much of the speech motor learning research originates from limb movement literature. Apolinário-Souza et al. (2021) evaluated context variability on limb motor learning in typical adults. They evaluated participants' ability to learn finger typing patterns within two learning conditions—variable and constant. In the variable condition, the participants practiced a key pressing sequence task when presented to them in multiple colors and positions on the computer screen, whereas participants in the constant condition were presented with the stimuli in a consistent color and position on the monitor. Results of this study showed that the variable context facilitated greater generalization of motor learning than the consistent context (Apolinário-Souza et al., 2021).

More research on the effect of context diversity on speech motor learning is needed. For this reason, the present study seeks to analyze the effect of contextual diversity on speech motor learning in an individual with acquired apraxia of speech.

Additionally, logistical limitations such as time, transportation, safety, etc., make it nearly impossible for treatment of these individuals to be contextually diverse using physical environments. Fortunately, technological advancements have created new ways for individuals to experience a new environment without physically leaving their location. VR provides opportunities to be immersed in ecologically valid contexts without losing the feeling of presence that individuals experience in physical environments. VR shows potential to be a useful clinical tool. Previous studies have highlighted the potential benefits of incorporating VR-based contexts in speech therapy interventions by simulating diverse and realistic environments that promote motor learning and generalization of skills (Maas & Mailend, 2012). Research on VR in speech and/or language treatment is limited, but promising. Some uses include a VR application by Halabi et al. (2017) to be used when working with children with autism spectrum disorder. Participants can access a social scenario in VR to practice peer interactions in a low-risk environment. Additionally, Lc and Fukuoka (2020) found VR to be an effective way to help children who stutter to practice public speaking. Overall, VR can serve as a clinical tool with the potential to encourage generalization and capitalize on the effects of contextual diversity. This study seeks to add to the literature about the use of VR as a treatment tool for individuals with apraxia of speech.

As mentioned earlier, certain theories that support the contextual diversity effect propose that its effectiveness is derived from the concept that learning within multiple contexts results in the creation of multiple memory traces, rather than a single trace. Thus, these multiple traces enhance the ease of accessing learned behaviors when adapting to a new environment (Smith & Handy, 2014).

It is hypothesized that increased motor learning will occur when individuals capitalize on the benefits of the contextual diversity effect while following the principles of motor learning including considerations about the role of feedback and practice. When combined, it has the potential to lead to greater skill acquisition, improved retention, and better transfer of learned skills to different situations.

Many studies of location-based learning have measured knowledge acquisition through word or phrase recall. The present study, however, seeks to evaluate environmental impacts on motor learning through measuring speech production at the word level. Thus, the present study addresses not only the accuracy of the recalled stimulus, but the articulatory precision with which it was produced. Principles of motor learning such as practice schedule and feedback were important factors to consider in the development of the treatment phase of this experiment because they have a significant impact on an individual's ability to learn a motor sequence.

Principles of Motor Learning

Principles of motor learning are evidence-based concepts that contribute to the facilitation of motor movements and influence motor learning, including the conditions of practice, feedback, explicit and implicit learning, mental practice, and pre-task performance (Ballard et al., 2015; Whitfield & Holdosh, 2021). By using principles of motor learning to guide treatment, motor sequences can not only be learned, but they can become well-established, automatic movements (Whitfield & Holdosh, 2021).

Practice structure and amount can affect how motor programs are learned and retained. Practice during treatment sessions can be structured in two ways: blocked or random practice. Blocked practice enables the same motor skill to be practiced repeatedly "without intervening trials with other skills," whereas in random practice, target stimuli are arranged in an "unpredictable order so that trials with different skills are interleaved" (Wambaugh, 2021, p. 445). Within limb motor learning research, it has been found that blocked practice results in acquisition of a motor program, and random practice promotes better maintenance and generalization (Ballard et al., 2015). However, since limb motor studies typically use healthy participants, it is not clear how the principles apply to the motor relearning of speech that occurs in individuals with AOS, a motor speech disorder characterized by impairments in planning and programming the sensorimotor commands required for speech (Munasinghe et al., 2023). Wambaugh et al. (2017) found that speech motor learning effect sizes were similar for participants with AOS regardless of whether practice followed a blocked or random structure. Thus, neither blocked nor random practice are considered a preferred format for speech treatment. In addition to practice structure, the amount of speech production practice that occurs influences how well the motor plan will be learned. Whitfield and Holdosh (2021) explained that extended practice leads to well-established behaviors and promotes automaticity of speech production. Greater speech motor automaticity can be shown by decreased interference during attention-demanding tasks.

In addition to practice conditions, feedback plays a significant role in developing motor programs into automatic productions. Two different types of feedback, knowledge of performance and knowledge of results, can be used at different times during the treatment process to facilitate speech motor learning. Knowledge of performance provides the learner with specific instructions about how to correct a motor program. Maas et al. noted that knowledge of performance is beneficial when the learner doesn't have a "reliable internal representation of the movement goal," in other words, when the motor program is still being acquired (2008, p. 288). Providing learners with knowledge of performance feedback can contribute to their development of a strong mental representation of the sequence and their ability to distinguish between correct and incorrect productions.

Once learners have established an initial representation of a motor sequence, knowledge of results feedback should be given. Unlike knowledge of performance, knowledge of results feedback simply informs the learner whether or not their production was correct. Maas et al. highlighted that "knowledge of results feedback may be critical later in therapy and for clients who can better evaluate their own errors" (2008, p. 289). This type of feedback encourages retention of speech motor programs. When determining how frequently feedback should be given, Maas et al. reported that reduced frequency feedback may benefit speech motor learning because it requires individuals to rely on their internal cues and self-evaluation skills to monitor their productions.

Acquired Apraxia of Speech

Acquired apraxia of speech (AOS) manifests as a slow rate of speech, articulatory errors, and abnormalities in prosody, ultimately leading to a diminished quality of life for affected individuals (Munasinghe et al., 2023).

Wambaugh et al. (2006) detailed recommended treatments for AOS, categorizing them into four distinct areas: (a) rhythm and rate, (b) augmentative and alternative communication (AAC), (c) intersystemic facilitation/reorganization, and (d) articulatory kinematic techniques. Of the four categories used in AOS intervention, articulatory kinematic treatment techniques have the strongest evidence base. These treatment techniques aim to improve motor planning in individuals with apraxia through practices such as repetition, reshaping, modeling, and integral stimulation (e.g., watch me, do it with me, now do it). These techniques often incorporate visual and auditory stimuli to prompt individuals with AOS.

Wambaugh et al. (2006) went on to reveal that the implementation of articulatory kinematic techniques yielded general improvement across participants. Among these techniques, Sound Production Treatment (SPT) emerged as particularly effective as it has a large evidence base and instills the most confidence when employed with individuals dealing with AOS.

Statement of the Purpose

The present study seeks to analyze the effect of contextual diversity, as represented by virtual environmental contexts, on speech motor learning in individuals with acquired apraxia of speech. Additionally, this study intends to validate the use of VR as a treatment tool and contribute to our understanding of effective therapeutic approaches for individuals with AOS.

Research Questions

This study will address the following research questions:

1. Does learning in multiple contexts improve speech motor acquisition in a person with apraxia of speech?
2. What effect does learning in multiple environments have on the retention of speech motor skills in a person with apraxia of speech?

It is predicted that the participant will demonstrate speech motor learning regardless of their learning condition. However, the participant will experience greater learning as demonstrated by increased automaticity and accuracy of speech production in the contextually diverse condition. Additionally, it is predicted that the participant will demonstrate a stronger retention of gains made during the contextually diverse learning phase after a 24-hour period.

Method

The participant, equipment, procedure, stimuli, and analysis are described in the following section. Before participation in the study, the participant was provided with an overview of the study, and he gave his informed consent.

Participant

The study involved one 62-year-old English-speaking participant who had a stroke over 18 years ago. He was recruited by contacting individuals who had consented to be informed of research opportunities at BYU on the BYU Stroke and Brain Injury Registry. He was diagnosed with severe acquired AOS and aphasia, as determined by a motor speech assessment and the Quick Aphasia Battery (QAB) assessment (Wilson et al., 2018). As part of his pretesting, the participant was given a motor speech assessment adapted from the 2013 Duffy Assessment of Motor Speech Programming Capacity to assess the severity of his apraxia of speech (Duffy, 2013). His performance on this assessment revealed difficulties such as slow rate of speech, distorted phoneme production, syllable segregation, relatively inconsistent articulation errors, abnormal prosody, and increased difficulty with more complex words as defined by McNeil et al., (2009) as the necessary characteristics of an AOS diagnosis (Wambaugh et al., 2016). Two researchers agreed that the necessary characteristics of AOS were present in the speech sample.

Additionally, the participant was given the Test of Nonverbal Intelligence (TONI) to evaluate his nonverbal cognitive abilities, specifically within the context of aphasia (Brown et al., 2010). The participant's test scores and characteristics can be found in Table 1 below.

Table 1

Participant Characteristics and Assessment Results

Age	62
Months Post Onset	222
Quick Aphasia Battery (QAB)	Word comprehension: 8.75 Sentence comprehension: 0.83 Word finding: 4.25 Grammatical construction: 3.63 Speech motor programming: 5.00 Repetition: 5.42 Reading: 5.83 QAB overall: 4.55 (Severe)
Test of Nonverbal Intelligence (TONI)	37^{th} Percentile (Average)
Error Awareness Test	Total words with sound errors: 13/25 Total words in error perceived in error: 13/13 Total words produced correctly: 12/25 Total words produced correctly perceived as correct: 9/12
Sleep Diary	Fair (6 hours)

Equipment

During the experiment, simulated environments were displayed to the participant using Meta's Oculus Quest 2 VR headset. This technology enabled the participant to be fully immersed in a 360-degree virtual environment. A picture in picture format was utilized, where a view of the computer desktop was pinned to the center of the 360-degree virtual environment display. The participant could see the PowerPoint presentation with the target words through this view of the desktop. The 360-environments included realistic environments sourced from the VR application, Brink Traveler (Brink XR, 2021). To create the environments on the application (app), developers use volumetric capture of real locations to create immersive and visually appealing virtual environments. A study conducted by Essoe et al. (2022) emphasized the importance of using realistic VR contexts to increase the feeling of presence for the viewers. High-quality VR contexts can make the viewer an active participant in the virtual world, instead of watching the environment passively. Essoe et al. also found that "if an individual does not perceive VR-based contexts as actual environments, then these contexts may have little or no effect on memory outcomes because the 'contexts' themselves would not be subjectively valid" (2022, p. 2). Several times throughout the study, the participant was asked to explore the environment and describe what he was looking at. This engagement with the environment may have helped increase the participant's feeling of presence.

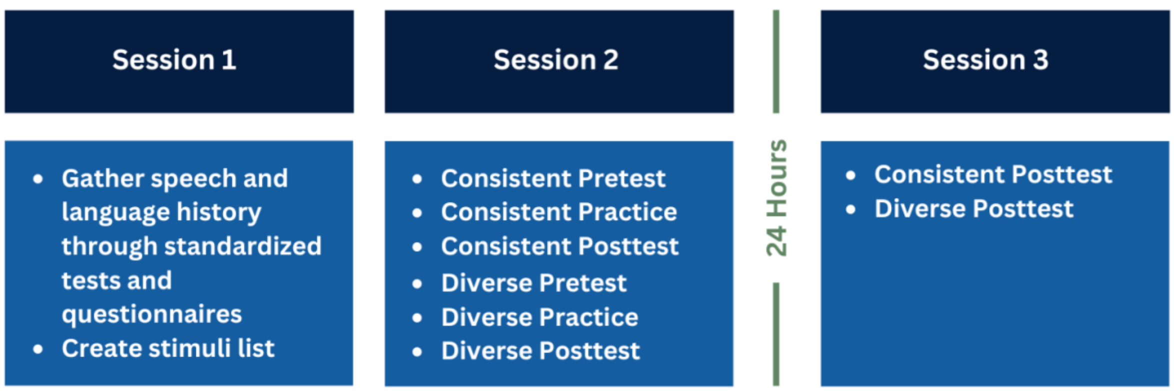
Additionally, kinematic data were collected at 1250 Hz and downsampled to 250 Hz using the Carstens AG501 electromagnetic articulograph (EMA), which measured articulatory movements with high levels of precision. To do this, the EMA has induction coils around the head of the participant that create an electromagnetic field. Small sensor coils were then glued to several of the participant's articulators including his lips, tongue, and teeth. The current produced by the sensors allows the position of the articulators to be determined within the electromagnetic field. The positions of these sensors are then tracked and shown on a computer screen with high precision.

Procedure

The participant completed three sessions—one pretesting session and two experimental sessions. Prior to participating in the sessions, the participant gave his informed consent. The following figure provides an overview of the structure of the data collection sessions.

Figure 1

Data Collection Session Overview



Stimuli

The participant was given an assessment to determine areas of relative difficulty in speech sound production. The participant was asked to repeat words with varying syllable lengths to determine specific phonemes and phonemic contexts in which the participant could just produce the words accurately. Based on these results, two lists of five words were created to be used in the experimental portion of the study. These words were monosyllabic CVC words and can be found in the Table 2.

Table 2

Stimulus Words

Consistent	Diverse
Rain	Witch
Near	Face
Jet	Long
Sad	Nail
Right	Tip

Independent Variables

The participant completed speech motor tasks in both a consistent and a diverse condition. The conditions differed by locations of practice. In the consistent condition, the participant completed the pretest and practice in a single VR environment. In the diverse condition, the pretest and practice took place in multiple environments. The following is a description of the experimental tasks under the consistent condition:

Pretest. In the pretest, the participant was asked to produce the five words from list one, with each word repeated seven times. The order of the words was pseudo-randomized. This pretest took place in a VR environment. Target words were presented in large font on a PowerPoint slide pinned in the virtual environment. Results from this pretest were used as a comparison to the posttest, which was identical except for location.

Practice. The participant then completed eight blocks of practice in the same VR environment as the pretest. Each block consisted of an opportunity to produce each target word. Half of the blocks were presented in a pseudo-randomized order where the participant repeated each target words two times, while the other half were presented in a blocked order with an opportunity to produce each target word five times.

The participant was cued as needed with modelling, integral stimulation, and accuracy feedback. Prompting was provided on an as-needed basis during the pretest and practice phases, but the participant completed the posttests independently.

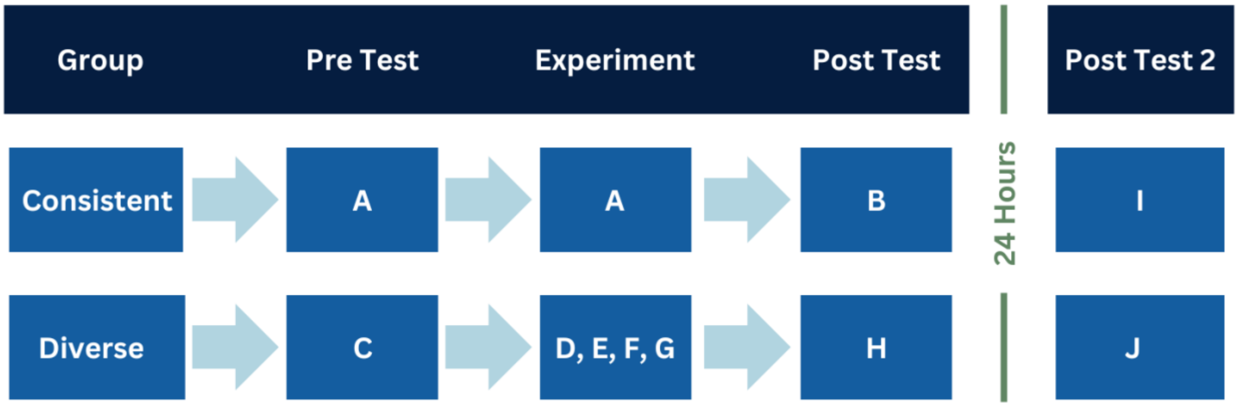
Posttest. Once the practice phase was over, the participant was given a posttest, identical to the pretest, to evaluate his production of the target words from list one, learned during the consistent training phase. This assessment was given in a new VR environment. The participant completed this task independently and was not given any prompting.

In the diverse condition, the practice phase took place across four different virtual environments. The training protocol mirrored the previous condition; however, time allocated to practicing target words was distributed across four VR environments. The participant completed two blocks of practice in each environment. Upon completion of the practice, the participant completed the posttest evaluating their production on list two in a new VR environment.

After 24 hours, the participant returned for a final session. Words from list one that were learned under the consistent condition were evaluated in a new VR environment, while words from list two which were learned under the diverse condition were assessed in another new VR environment. Figure 2 depicts the experimental conditions that were included in this study.

Figure 2

Experimental Conditions



Note. Each letter represents a different virtual environment for testing/practice. For example, environment A represents Pulpit Rock, Norway, while environment B represents Mount Cook, New Zealand, etc.

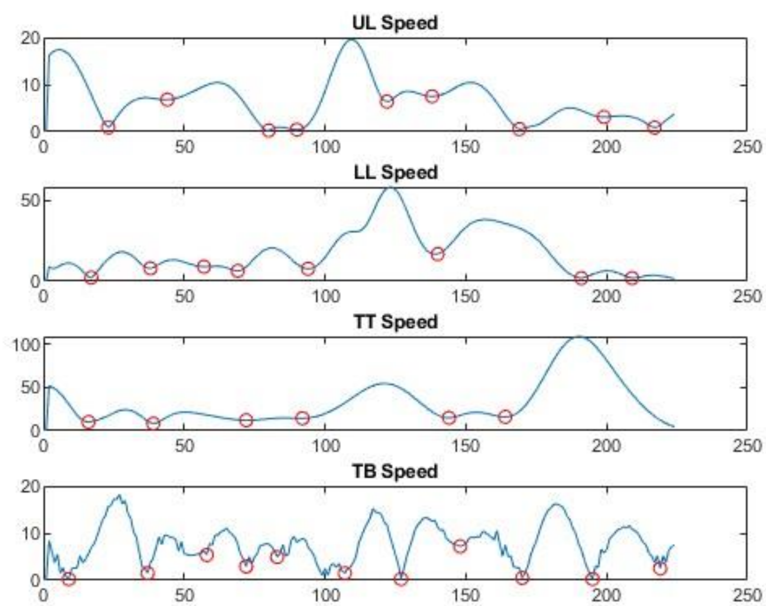
Dependent Variables

Kinematic data were collected via electromagnetic articulography (EMA) during pretest and posttest phases under both conditions. Kinematic measures were analyzed to assess the movement characteristics of the participant's speech production. The kinematic measures consisted of selected stroke metrics, including average stroke count, hull area, onset speed, and peak speed.

The average stroke count for each articulator represents the number of articulatory gestures as defined by the movement occurring between two adjacent speed minima (Tasko & Westbury, 2002). Figure 3 shows a speed plot with minima marked that represent strokes. Hull area represents the boundary that encompasses the range of articulator movements across a speech sample as shown in Figure 4. Onset speed refers to the rate at which an articulator begins to move to initiate a speech sound, whereas peak speed refers to the highest speed reached by an articulator.

Figure 3

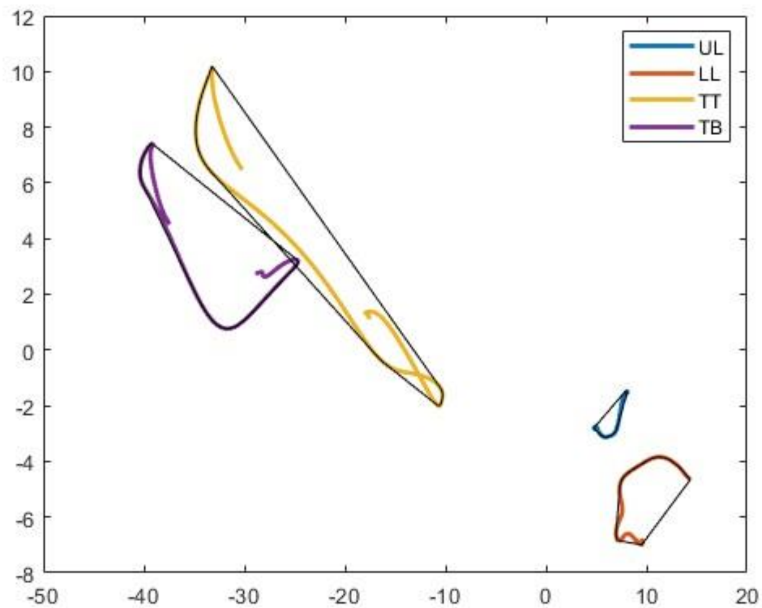
Speed Plot With Minima Marked of Stimulus Word "Face" Under the Diverse Condition



Note. This speed plot was taken from the first production of the word "face" during the Day A posttest under the diverse condition.

Figure 4

Hull Area Plot of Stimulus Word "Right" Under the Consistent Condition



Note. This hull area plot was taken from the fourth production of the word "right" during the Day A posttest under the consistent condition.

The stroke metrics were used to evaluate the participant's movements across the articulatory gestures of the target words. Tasko and Westbury defined movement strokes as "the period between two successive local minima in the speed history of an articulator point" (2002, p. 127). Using stroke metrics as a parsing method is advantageous because it lends itself well to being used with electromagnetic articulography, it provides a logical way for speech units to be defined, and it translates to all types of motor tasks (Tasko & Westbury, 2002). The researchers anticipated that the kinematic data would reveal evidence of learning across both conditions, as shown by increased automaticity and decreased variability of speech production. However, they hypothesized that automaticity and decreased variability would be shown to a greater extent under the contextually diverse condition.

Acoustic data were collected concurrently with a microphone at a sampling rate of 48 kHz, then analyzed using Praat software (Boersma & Weenink, 2024). The average duration of each target word production was found by identifying the start and end of the production and documenting the duration in seconds. This measure provides temporal information that is an important indicator of how quickly speech is produced.

Additionally, perceptual data were collected regarding the perceived accuracy of each production. Each production was scored and given an accuracy rating of 1, 2, or 3 according to the following set of criteria: (1) accurate production, (2) minor distortions, (3) major errors, distortions, or substitutions. The perceived accuracy was averaged across the sessions. A smaller number indicates a more accurate production.

Data Analysis

Kinematic, acoustic, and perceptual measures were analyzed to determine the effect of contextual diversity on changes in speech production both within session (pretest to posttest) and between sessions (Day A to Day B). As this was a case study with a relatively small number of speech samples, inferential statistics were not appropriate for analysis. Analysis is based off descriptive statistics of each type of data.

Results

In this section, the results of the data analyses are provided. Results are organized into three sections, kinematic, acoustic, and perceptual results, for ease and clarity. Throughout the results section, figures will be used to display data so that changes can be represented visually. In addition, the information in the figures can be viewed in table form in Appendix C. Grand averages that include all productions of the stimuli were used for each metric analyzed, unless specifically mentioned. Only changes that represented 20% or greater change from baseline levels (relative change) are reported and discussed.

It should be noted that there were potential problems complicating data interpretation in the data collection process, particularly with the use of the VR headset and EMA. Despite initial testing indicating no interference, further analysis revealed likely interference with articulator tracking caused by the VR headset. The most notable interference was observed with the upper lip sensor, although effects on other articulators cannot be ruled out. Additionally, complications with the tongue blade sensor were observed during the diverse condition posttest on Day A. Findings should be interpreted carefully considering these potential factors.

Kinematic Analyses

Stroke Count

The average number of strokes for the participant's target word productions was calculated for each articulator, including the tongue blade (TB), tongue tip (TT), lower lip (LL), and upper lip (UL). Results from stroke count analysis are shown in Figure 5.

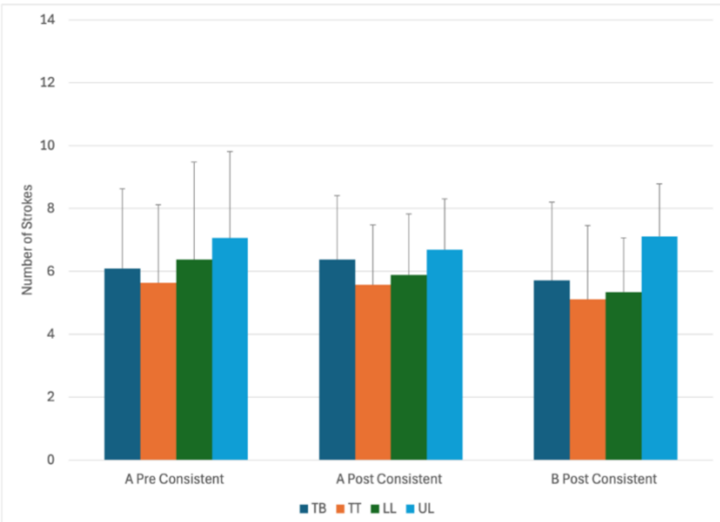
In the consistent condition, TT, LL, and UL stroke count did not experience at least 20% numerical change from baseline within session or at the 24-hour follow-up.

The diverse condition revealed the opposite pattern, with decreased stroke counts for the TT, LL, and UL within session and at the 24-hour follow-up as shown by a greater than 20% numerical change.

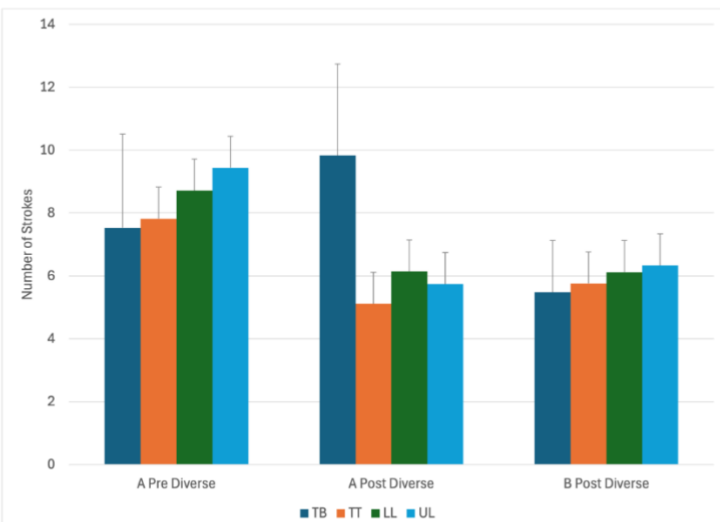
Figure 5

Stroke Count Across Pre, Post, and Follow-Up for Consistent and Diverse Conditions

A



B



Note. The figure represents the average stroke count during the pretest, posttest, and follow-up that occurred 24 hours later for each condition. A represents the first experimental practice session, while B represents the second session. The articulators are represented using the following abbreviations: tongue blade (TB), tongue tip (TT), lower lip (LL), and upper lip (UL).

Hull Area

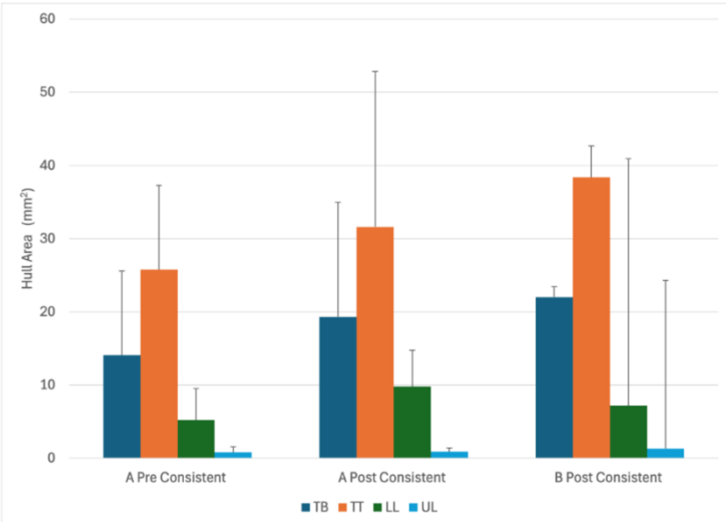
The average hull area for each articulator was determined and is shown in Figure 6. In the consistent condition, all articulators increased in hull area within session on Day A except for the UL. All articulators showed increased hull area on Day B.

The diverse condition revealed mixed changes in average hull area with the UL and LL exhibiting an increase in hull area and the TB showing a decrease. Changes on Day B involved reduced hull area for TB, TT, and LL, and increased hull area for UL.

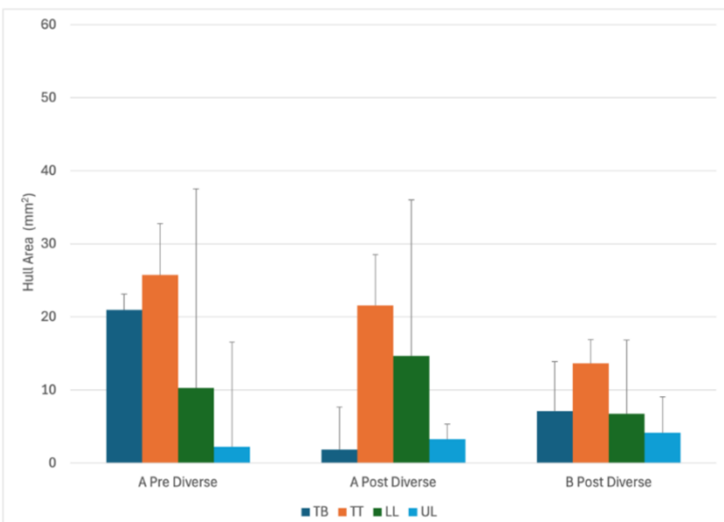
Figure 6

Hull Area Across Pre, Post, and Follow-Up for Consistent and Diverse Conditions

A



B



Note. The figure represents the average hull area during the pretest, posttest, and follow-up that occurred 24 hours later for each condition. A represents the first experimental practice session, while B represents the second session. The articulators are represented using the following abbreviations: tongue blade (TB), tongue tip (TT), lower lip (LL), and upper lip (UL).

Speed

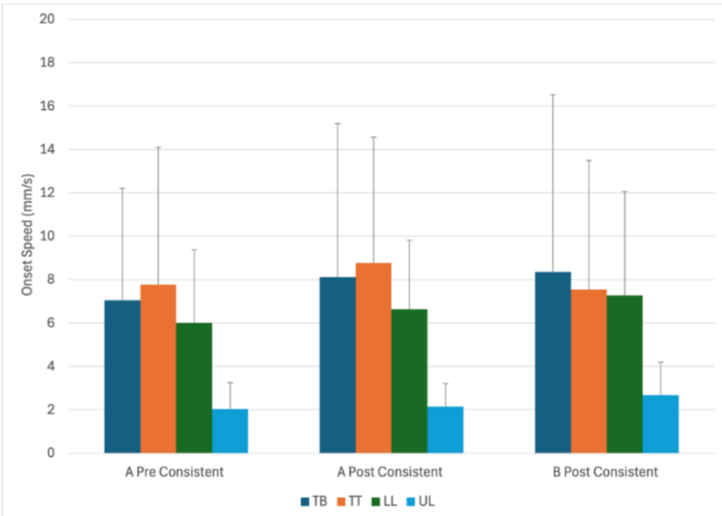
The onset speeds were found for each articulator and are outlined in Figure 7. The consistent condition changes did not reach 20% from baseline for the within session posttest for all articulators. On Day B, the UL and LL showed an increase in onset speed.

Under the diverse condition, the TT, LL, and UL showed a general numeric increase in onset speed within session, while the TB showed a decrease on Day A. Changes on Day B showed that the onset speed increased for the UL and decreased for the TT and LL.

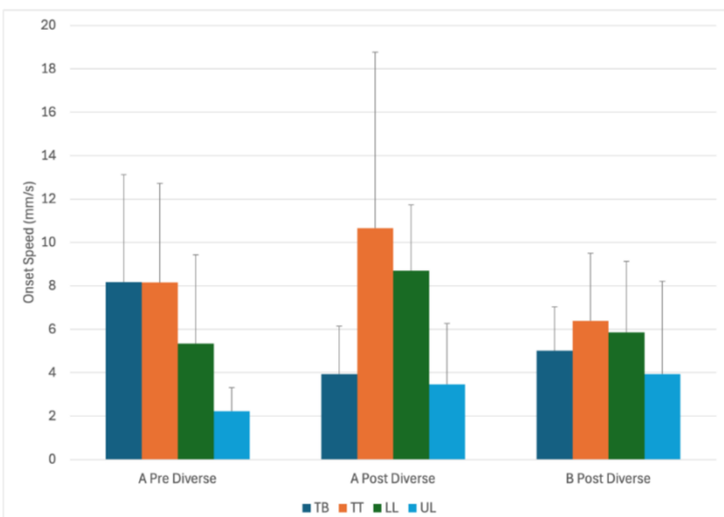
Figure 7

Onset Speed Across Pre, Post, and Follow-Up for Consistent and Diverse Conditions

A



B



Note. The figure represents the average onset speed during the pretest, posttest, and follow-up that occurred 24 hours later for each condition. A represents the first experimental practice session, while B represents the second session. The articulators are represented using the following abbreviations: tongue blade (TB), tongue tip (TT), lower lip (LL), and upper lip (UL).

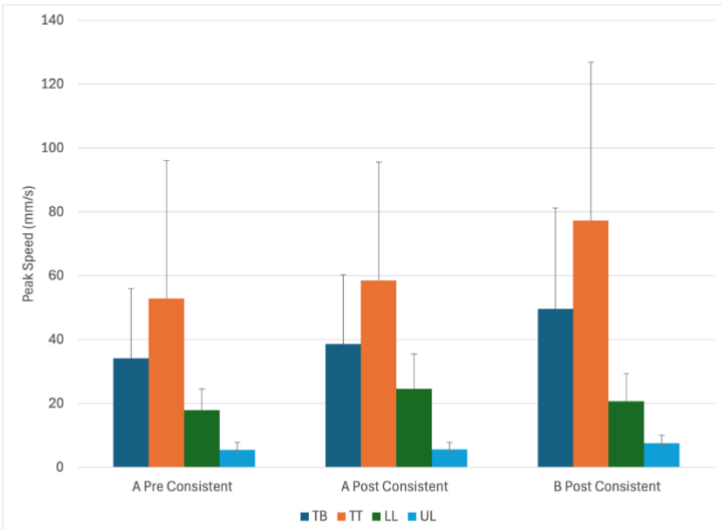
In addition, the peak speed was determined for each articulator as shown in Figure 8. In the consistent condition, the LL showed an increase in peak speed within the session on Day A. The peak speed increased for the TB, TT and UL on Day B.

Under the diverse condition, peak speed increased for the TT, LL, and UL within session. The TB decreased within session. During the 24-hour follow up on Day B, the UL showed an increase in peak speed.

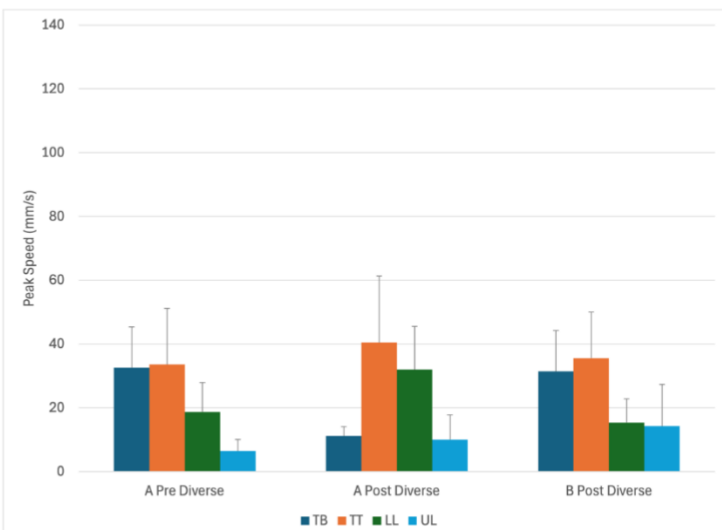
Figure 8

Peak Speed Across Pre, Post, and Follow-Up for Consistent and Diverse Conditions

A



B



Note. The figure represents the average peak speed during the pretest, posttest, and follow-up that occurred 24 hours later for each condition. A represents the first experimental practice session, while B represents the second session. The articulators are represented using the following abbreviations: tongue blade (TB), tongue tip (TT), lower lip (LL), and upper lip (UL).

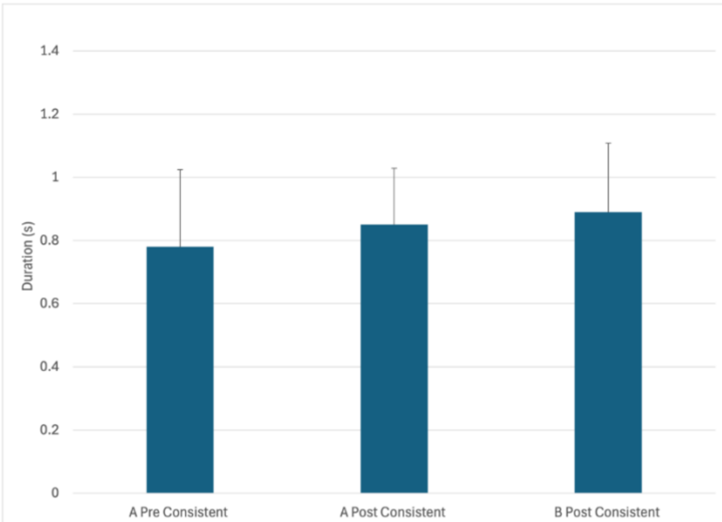
Acoustic Analysis: Duration

The average duration for each target word production was measured. The results of the duration analysis are shown in Figure 9. Under the consistent condition, average duration did not show a change greater than 20% within session on Day A or between Day A and Day B. In the diverse condition, average duration decreased within session and between Day A and Day B.

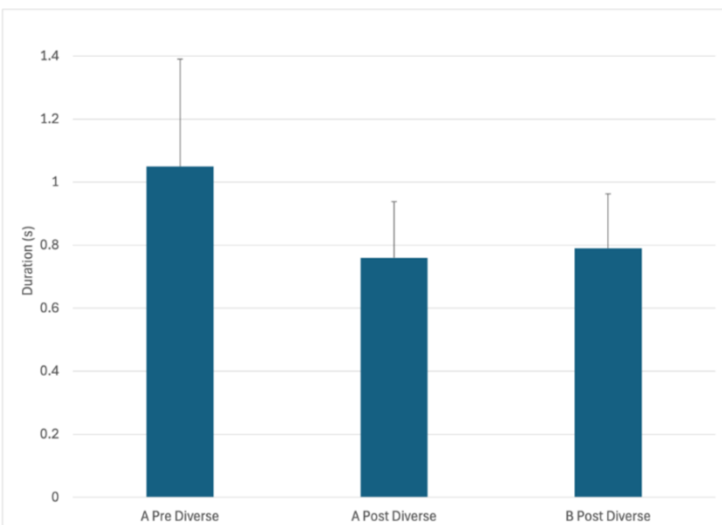
Figure 9

Duration Across Pre, Post, and Follow-Up for Consistent and Diverse Conditions

A



B



Note. The figure represents the average duration during the pretest, posttest, and follow-up that occurred 24 hours later for each condition. A represents the first experimental practice session, while B represents the second session.

Perceptual Analysis: Accuracy

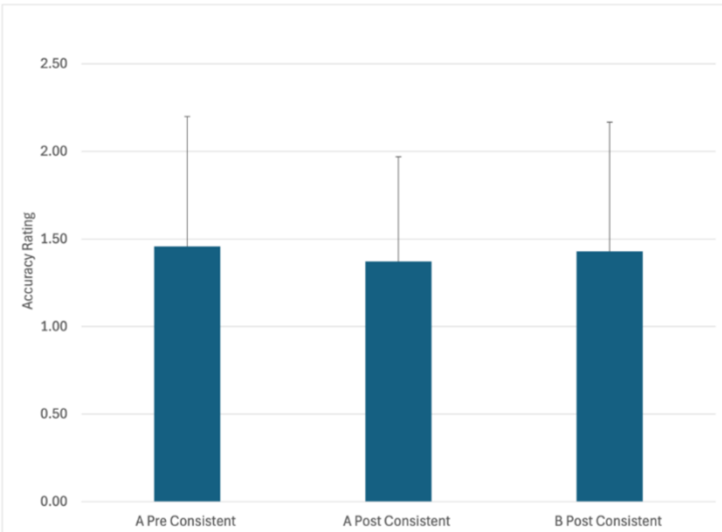
Finally, the data was subject to perceptual analysis specifically regarding the perceived accuracy of each production. Results to this perceptual analysis can be found in Figure 10.

In the consistent condition, the participant demonstrated below 20% numerical changes within session on Day A and between sessions at the 24-hour follow up. Under the diverse condition, the participant exhibited increased accuracy (as shown by a smaller number on the accuracy rating scale) within the session on Day A. Similarly, the participant showed increased accuracy as demonstrated during the 24-hour follow up on Day B.

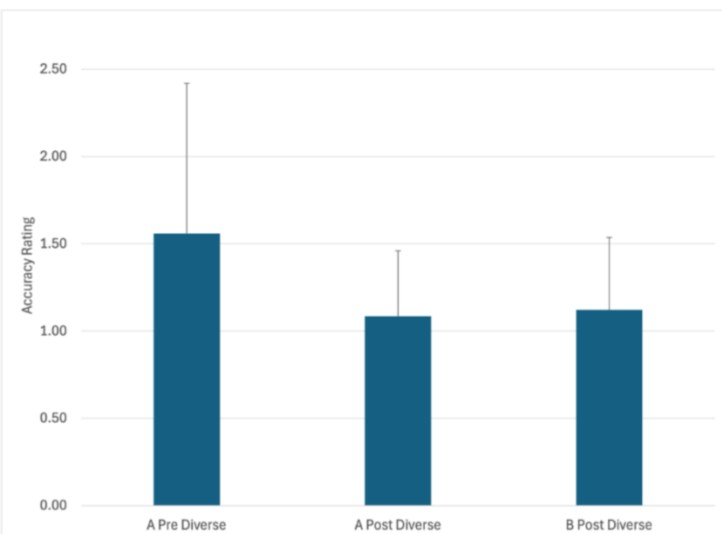
Figure 10

Accuracy Across Pre, Post, and Follow-Up for Consistent and Diverse Conditions

A



B



Note. The figure represents the average accuracy during the pretest, posttest, and follow-up that occurred 24 hours later for each condition. A represents the first experimental practice session, while B represents the second session. Accuracy was determined based on the following criteria: (1) accurate production, (2) minor distortions, (3) major errors, distortions, or substitutions. Thus, lower scores indicate more accurate productions.

Discussion

The purpose of this study was to evaluate the effect of contextual diversity on speech motor learning in a person with AOS. Learning contexts were presented as VR environments where the participant was able to complete experimental tasks while being immersed in realistic VR environments. Kinematic, acoustic, and perceptual data were collected using electromagnetic articulography (EMA) and analyzed using Matlab (The MathWorks Inc., 2023) and Praat software. This study used stroke metrics to examine stroke count, hull area, onset speed, and peak speed. Additionally, the acoustic measure of duration and perceptual measure of accuracy were also used to evaluate the changes made in the participant's performance. In this section, the results will be explained and implications for the results will be discussed.

Discussion of Kinematic, Acoustic, and Perceptual Results

Kinematic, acoustic, and perceptual metrics including stroke count, hull area, onset speed, peak speed, duration, and accuracy were used to analyze the effect of contextual diversity on speech motor learning.

First, evaluation of the data revealed that average stroke count decreased under the diverse condition, whereas the consistent condition did not show any meaningful changes in stroke count. This decrease in stroke count may represent an improvement in motor learning as shown by more smooth, free-flowing speech. Adams et al. (1993) reported that slow speaking rate resulted in an increased number of velocity peaks compared to fast speech. Velocity peaks are related to stroke count in that an increase in velocity peaks would also likely indicate an increase in stroke count. Decreased stroke count and decreased velocity peak count are both likely associated with faster flowing speech. Although measures of velocity and speed are similar, the inherent differences between them (i.e. velocity includes direction whereas speed does not) prevent these measures from being identical.

Additionally, duration decreased in a more meaningful way under the diverse practice condition than the consistent condition. This reduction in duration likely correlates with the decreased stroke count, reflecting less hesitation and potentially more free-flowing speech under the diverse condition. Perceived accuracy was also determined, and the results suggested that practice in the diverse condition may have been more supportive of learning, as anticipated. Perceptual accuracy rating was based on the following criteria: (1) accurate production, (2) minor distortions, (3) major errors, distortions, or substitutions. Under the consistent condition there were no meaningful changes observed in accuracy levels; accuracy levels remained near pretest levels, signifying little or no improvement in accuracy under this condition. Conversely, the diverse condition showed meaningful improvement within the session and increased retention after a 24-hour period, reflecting improved accuracy.

The congruence of the acoustic, perceptual, and some of the kinematic data points in the direction of the hypothesis suggests a possible advantage for the diverse learning condition as shown by decreased stroke count, shorter durations, and improved accuracy. These results would align with previous research by Smith and Handy (2014), Essoe et al. (2022), and Apolinário-Souza et al. (2021) which explain that practice within a variable environment can be more beneficial to learning and retention than practice in a consistent environment. One theory notes this is because learned material becomes contextualized to the environment in which it was practiced, and removing the learner from the environment can result in forgetting (Smith & Handy, 2014). In contrast, when learning is varied across multiple environments, the learned material is not automatically connected to environmental cues, resulting in a greater ability to remember learned skills in new environments. This contrast between consistent and diverse learning conditions is similar to the blocked versus random principle of motor learning, where random ordered practice has shown to be especially helpful with retention and generalization of motor skills, particularly for participants with chronic AOS and aphasia (Ballard et al., 2015). In this context, the diverse condition resembles random practice and may result in better generalization of skills as compared to consistent practice.

Importantly, this study extends the possible advantages of contextual diversity in learning to include a disordered speaking population. Previous research has mainly focused on typical speakers as seen in Smith and Handy (2014), Essoe et al. (2022) and Apolinário-Souza et al. (2021). In contrast, this study contributes to the literature by examining the effects of contextual diversity on learning in an individual with AOS. Although this is a case study, and its results cannot be generally applied to the wider population of all people with AOS, it provides valuable insight into the feasibility of capitalizing on the contextual diversity effect to increase learning for individuals with AOS.

It is important to note that the participant received limited sleep in the intervening 24 hours between data collection sessions. He reported having slept for 6 hours as opposed to 7 to 8 hours as recommended by the National Sleep Foundation (Hirshkowitz et al., 2015). Since evidence shows that sleep influences consolidation of speech motor learning (van Zelst Anne & Sayako, 2024), it is reasonable that poor sleep quality and inadequate time resting may have reduced the potential effects of practice on the second day, as the patient rated his sleep quality as fair and quantity as only 6 hours.

The findings regarding hull area, onset speed and peak speed were variable for the diverse condition, and as a result are less conclusive. While the acoustic and perceptual metrics supported the idea of speech production improvements for the diverse condition, the kinematic data, except for stroke count, did not clearly align. This discrepancy could be explained by the specific kinematic metrics utilized. Hull area, onset speed, and peak speed each examine different aspects of speech movements, none of which directly relate to production accuracy. Consequently, the perceptual and acoustic data assessed speech differently compared to these kinematic metrics. For instance, stroke metric data on speed "is not influenced by the reference axes that are chosen to frame the data" (Tasko & Westbury, 2002, p. 128). In other words, the collected speed data focused solely on velocity without considering the articulator's location relative to the target region for accurate production. Therefore, this metric does not relate to accuracy. When comparing the kinematic data to perceptual and acoustic data, it is essential to recognize that different aspects of speech are being evaluated. Tasko and Westbury stated, "It is unlikely that movement strokes, as we've described them, map directly onto abstract speech production 'units' or 'targets,' however they might be defined" (2002, p. 140). Therefore, comparing these different metrics can be challenging because they do not perfectly align with how speech is perceived. Only a few kinematic factors were considered in this study, and additional metrics, such as coordination and consistency metrics, could provide further insights into the articulatory changes that occurred. Note that while not all the kinematic data clearly supported the hypothesis, there was also no clear evidence to suggest that these kinematic data contradicted the hypothesis.

Limitations

This study had several limitations that affect its ability to be conclusive. First, it was limited by its narrow focus on a single participant. While case studies offer valuable insights, caution must be exercised in extrapolating their results to the wider population of all people with AOS.

Next, the potential electromagnetic interference in the kinematic data collection process, particularly with the use of the VR headset and EMA, poses a significant limitation. As a result of this interference, it is difficult to confidently draw conclusions based on the kinematic data, particularly for the UL sensor.

Another limitation that should be noted relates to the stimuli used in the experiment. It is difficult to fully compare across conditions because the stimuli used were not the same, and so there may have been interactions between the stimuli and the practice condition. Comparison of the stroke counts and duration measures between the lists at pretesting suggests differences between the word lists prior to practice. These inherent differences in the stimuli may have led to increased opportunity for change for one set of stimuli compared to the other. This may explain why hull area tended to increase with practice in the consistent condition, but changes were mixed with practice in the diverse condition. Although the word lists have similar word complexity measures as defined by Stoel-Gammon in 2010, differences in the stroke metrics between the word lists during the pretest condition suggest that the phonetic differences between the lists influenced the stroke metrics. This suggests that the use of stroke metrics as a global measure of motor control (Dromey & Black, 2017; Nissen et al., 2007) may be less appropriate on the single word scale. Previous studies that employ stroke metrics have used sentence or paragraph length stimuli as compared to single words. For example, Dromey and Black (2017) used sentence length stimuli including the sentences, “It’s time to shop for two new suits” and, “A good AC should keep your car cool.” Additionally, Nissen et al. (2007) used paragraph length stimuli including a magazine passage, a 1-minute monologue, and a 30-second picture description. These stimuli are considerably longer than the single word stimuli used in the current study and may be better suited for stroke metric analysis.

Lastly, due to study design and time restrictions, the participant was given relatively little time to practice during the learning portion of the experiment. Studies have shown that intense practice leads to "robust improvements in speech production" (Whitfield & Holdosh, 2021, p. 1905). In their synthesis article, Wambaugh et al. (2006) evaluated 59 publications regarding treatment of individuals with AOS. The results revealed that the studies provided an average of 33.5 sessions throughout the treatment with an average of 2.7 sessions per week. In contrast to the treatment studies included in this review, the practice intensity was very limited in the current study as it only consisted of a brief instance of treatment. Therefore, the results are only a glimpse into motor learning possible under contextually diverse practice conditions. If the participant had been allotted more intense practice, it is possible that greater changes would have been observed in the stroke data, providing more concrete evidence of changes in stroke metrics during speech motor learning.

Implications for Future Research

Despite these limitations, the study still offers valuable insights, particularly regarding the use of VR as a clinical tool. Halabi et al. (2017) demonstrated the effectiveness of VR as a resource for working with autistic children. Similarly, Lc and Fukuoka (2020) showed that VR can benefit children who stutter. However, there has been more limited research on the use of VR with adults. One notable VR program for adults with aphasia is EVA Park which was "developed and implemented to encourage social interaction and provide teletherapy for people with acquired and lifelong communication disability" (Bryant et al., 2020, p. 368; Marshall et al., 2016). EVA Park offers a space for people with aphasia to interact with peers and therapists in an interactive, virtual world . However, the present study differs in its focus. While EVA Park emphasizes utilizing VR to facilitate social interactions in PWA, the present study emphasizes using VR as a tool for intentionally introducing variability and contextual diversity into therapy in people with aphasia and apraxia of speech. It allows for the opportunity to practice speech production skills in multiple controlled contexts beyond the traditional therapy room, without the need to physically leave the room. Although more research is needed to understand how to effectively integrate VR into therapy, this study marks progress in this area and emphasizes the potential of VR as a valuable tool in speech therapy with adults with apraxia of speech.

This pilot study aimed to explore the feasibility of VR use in treatment, and the findings suggest that it could serve as a feasible clinical tool. The participant in the current study interacted well with the VR headset during the session. Although the use of VR had its limitations in this study, no major issues were observed that would obviously preclude it from being used in treatment with people with aphasia and AOS. Namely, utilizing VR to change environments during sessions could enhance client learning by leveraging the contextual diversity effect.

Future research with larger groups and improved data collection methods will help confirm and build upon these findings. Expanding the study to include more participants would enhance its generalizability to a broader population of people with AOS. Additionally, addressing the interference caused by the VR headset during data collection is crucial for future kinematic work in the area. Implementing measures to mitigate this interference, such as refining the setup, gathering baseline data without the headset, or utilizing alternative technologies, would improve the reliability of the data. Moreover, the use of more carefully controlled stimuli across conditions would enable cross-condition comparisons to be made more easily. Incorporating these adjustments would strengthen the validity of the data and provide a more comprehensive understanding of the relationship between contextual diversity and speech motor learning in individuals with AOS.

Conclusion

Findings of this study revealed that, for this participant with aphasia and AOS, diverse practice may have been more beneficial for motor learning and retention than consistent practice as demonstrated by improvements in acoustic and perceptual metrics and at least one kinematic metric. Moreover, this study contributes to the literature on the use of VR in speech pathology as a potential clinical tool. Moving forward, future studies should further investigate these principles with improved methods in order to advance our understanding of how contextual diversity and VR can impact interventions for individuals with AOS.

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APPENDIX A

Annotated Bibliography

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Objective: Previous investigations have shown that an experience can be most readily recalled in an environment that has the most strong and direct connections to the memory being recalled. This truth has been observed in both humans and animals. Previous studies have also observed that the extent to which changes are made to the environment have proven to affect the degree to which recall is affected. Most of these studies that have proven this have been investigated within a laboratory setting. The present study sought to evaluate the effects of environmental contexts within the school setting since that is an environment in which this finding would have particular relevance. The researchers were interested in discovering whether or not the findings from a school-based study would agree with previous laboratory-based studies.

Methods: The entire study took place over 5 years, however there were only 4 weeks of actual experimentation. Each week, the participants had a lecture on a specific topic (one per week), participated in an interactive activity as a class, and took a test. There were 181 participants who were assigned to four conditions: Regular instructor, regular classroom (1), regular instructor, classroom B (2), instructor B, regular classroom (3), instructor C, classroom C (4).

Findings: The researchers concluded that environmental context changes do cause efficiency of recall to decline which agrees with laboratory studies done previously. A

new finding that this study highlighted was that there are individual differences in whether or not individuals are affected by the changes in environment. High achieving students appeared to be less affected than poorer performing students.

Relevance to study: This study adds to the research of context-dependent memory, which is one of the main purposes of the present study.

Benoit, M., Guerchouche, R., Petit, P., Chapoulie, E., Manera, V., Chaurasia, G., Drettakis, G., & Robert, P. (2015). Is it possible to use highly realistic virtual reality in the elderly? A feasibility study with image-based rendering. *Neuropsychiatric Disease and Treatment, 11,* 557–563. https://doi.org/10.2147/NDT.S73179

Objective: This article sought to validate the use of Virtual Reality with the elderly population. One of the biggest arguments to using VR with this population is the "cyber sickness" effect that often accompanies VR use.

Methods: Participants completed a memory task within the VR environment and then were asked to report on certain aspects of their experience. Participants filled out a cybersickness questionnaire after completing the VR experience.

Findings: Results from the questionnaire showed that the amount of cybersickness that people experienced was not significant enough for it to be a problem. The lack of cybersickness may have been due to the participants sitting while wearing the VR headset.

Relevance to study: The present study is utilizing VR with the elderly population. This article provides a good framework for strategies to avoid cybersickness and proposes a cybersickness questionnaire that can be filled out by the participants.

Bislick, L. P., Weir, P. C., & Spencer, K. A. (2012). Investigation of feedback schedules on speech motor learning in individuals with apraxia of speech. *Journal of Medical Speech - Language Pathology*, *20*(4), 18+. https://link-gale-com.byu.idm.oclc.org/apps/doc/A328852875/AONE?u=byuprovo&sid=bookmark-AONE&xid=f6ff4008

Objective: This study investigated the effect of feedback frequency on acquisition and retention of learned speech motor movements

Methods: There were ten participants with mild to moderate aphasia and AOS who participated in this study. They were asked to repeat two phrases 2x and 3x as slow as their typical speech. Half of the participants were given feedback every trial while the other half were given feedback every fifth trial.

Findings: The researchers found that participants in the high frequency feedback did better on the 2x as slow condition. Whereas participants in the low frequency feedback condition did better on the 3x as slow condition. This was contrary to their hypothesis.

Relevance to study: Aphasia+apraxia results in interesting dynamics in SML that I should be aware of while planning my study. Also, the importance of feedback in general in learning motor programs.

Christopher, D., & Emily, B. (2005). Speech interactions with linguistic, cognitive, and visuomotor tasks. *Journal of Speech, Language, and Hearing Research*, *48*(2), 295–305. https://doi.org/10.1044/1092-4388(2005/020)

Objective: This article explored the relationship between linguistic, cognitive and visuomotor tasks, specifically the effect they can have on speech. Previous research has shown that increased cognitive load has a negative effect on speech accuracy, but this article’s intent was to focus more specifically on the changes in articulatory displacement and velocity and how that impacted speech as a whole.

Methods: Twenty healthy young adults participated in the study. They all completed seven tasks which focused on speech, linguistic, cognitive and visuomotor skills. Each participant was tested on these subjects in isolation and simultaneously with a speech task.

Findings: After analysis of the collected data, the authors found that normally speaking adults (unimpaired) change their performance when participating in multiple cognitively demanding activities. Adults who struggle from a language disorder must struggle at least as much, or more, when asked to divide their attention. The most intriguing results I found were related to the combined visuomotor condition. The researchers discovered that there was a significant decrease in utterance duration on the combined speech and visuomotor task. The researchers speculate that this was due to the speech task becoming "automatic" and requiring less cognitive demand to complete the task. Next, the researchers found that although lip-jaw displacement decreased in the speech-visuomotor combined condition, the SPL increased under the same conditions. The researchers were unsure of this reasoning and highlighted the need for more research in this area. Additionally, the researchers noted that the visuomotor task may have been too simple for the participants. A harder visuomotor task possibly would have resulted in differing effects on speech. Overall, there is a need for more research on this specific topic.

Relevance to study: This article analyzed lip-jaw displacement when evaluating the speech of the participants. This would be an interesting metric to analyze in my current study and may provide insight into how my methods can be adapted to look at this articulator movement.

Godden, D. R., & Baddeley, A. D. (1975). Context-dependent memory in two natural environments: On land and underwater. *British Journal of Psychology,* http://eric.ed.gov/ERICWebPortal/detail?accno=EJ127053

Objective: The philosopher John Locke once recalled the story of a young man who learned to dance in a room that housed an old trunk. Although he learned to dance very well within the room with the trunk, he was unable to perform his dance correctly in any other room in the house. His ability to perform was so intertwined with the presence of the old trunk that he was unable to complete the steps without it. The researchers in this article set out to examine the validity of this story. They evaluated whether or not memory and learning are context-dependent. Previous studies have proved similar ideas, however they were in the context of highly artificial environments within the laboratory, whereas the current study sought to observe this phenomenon within a naturalistic setting- underwater and on dry land. The researchers expected recall performance to be significantly higher when learning and recalling took place in the same condition (i.e. both underwater or both on land) than when learning and recalling took place in different conditions (i.e. learning underwater and recalling on land or learning on land and recalling underwater).

Methods: The participants consisted of eighteen (13 male and five female) experienced scuba divers. Each participant completed a word learning and recalling task where they had to write down the learned vocab in either same or different contexts. Each participant completed the task in all four conditions on land and/or underwater (WW, DD, DW, WD).

Findings: The results of the study clearly aligned with the researchers' initial hypothesis. They found that success in word recall performance was dependent on the environment in which the words were learned. The results were so significant that one can be very confident that this is truly a context-dependent phenomenon.

Relevance to current study: This study provides preliminary data for the current study because it supports the idea of context-dependent memory. The present study is seeking to build on the idea of context-dependent memory by looking at the effect of virtual environments on memory. Instead of recalling the learned words, the present study will evaluate learning through word production.

Halabi, O., Abou El-Seoud, S., Alja'am, J., Alpona, H., Al-Hemadi, M., & Al-Hassan, D. (2017). Design of immersive virtual reality system to improve communication skills in individuals with autism. *International Journal of Emerging Technologies in Learning, 12*(5), 50. https://doi.org/10.3991/ijet.v12i05.6766

Objective: This article tested the validity of a VR therapy environment for children with ASD.

Methods: The system they used set up a scenario for participants to learn to introduce themselves, something that children with ASD often have difficulty with.

Findings: They found that VR shows potential for helping ASD children to improve their communication abilities. They suggest that more research should be done in this area because their sample size was small.

Relevance to current study: This study validated the use of virtual reality during speech and language therapy with a specific population. The present study seeks to do the same thing, validate the use of VR therapy with a population of people with Aphasia.

Johnson, R. K., Lott, A., & Prebor, J. (2018). A comparison of outcome measures for speech motor learning in acquired apraxia of speech using motor learning guided treatment. *Clinical Archives of Communication Disorders*, 3(1), 1–13. https://doi.org/10.21849/cacd.2018.00304

Objective: The purpose of this study was to evaluate the impact of motor learning guided treatment on articulation accuracy and suprasegmental characteristics of speech motor learning in people with AOS and Aphasia.

Methods: Two participants with moderate to severe AOS and aphasia participated in the study. Participants were given motor learning guided treatment 2 days a week for 18 sessions.

Findings: This study found that a qualitative and quantitative outcome measure in treatment for people with AOS can lead to significant speech motor improvement.

Relevance to current study: This study is relevant to the present study because it was with people with AOS. The methods of this study can serve as a guideline for the present study when making decisions about the number of participants and introductory assessments to give.

Lc, R., & Fukuoka, Y. (2020). Machine learning and therapeutic strategies in VR. In Paper presented at the ARTECH '19 Proceedings of the 9th International Conference on Digital and Interactive Arts, 1–6. https://doi.org/10.1145/3359852.3359908

Objective: This article looked at the effect that treatment within a virtual reality environment can have on people who stutter.

Methods: They used a virtual environment for people who stutter to practice speaking in social situations. The virtual environments simulated public speaking scenarios. During treatment, they used techniques used by psychologists to help patients with PTSD become desensitized to their trigger environments in order to desensitize the participants to stressful environments that trigger stuttering episodes.

Findings: Virtual reality showed potential for desensitizing people who stutter to triggering situations through exposure therapy.

Relevance to current study: This study validated the use of virtual reality during speech and language therapy with a specific population. Similarly, the present study seeks to validate the use of VR therapy with a population of people with aphasia.

Maas, E., Robin, D. A., Austermann Hula, S. N., Freedman, S. E., Wulf, G., Ballard, K. J., & Schmidt, R. A. (2008). Principles of motor learning in treatment of motor speech disorders. *American Journal of Speech-Language Pathology*, 17(3), 277–298. https://doi.org/10.1044/1058-0360(2008/025)

Objective: The purpose of this review/tutorial article was to evaluate the principles of motor learning (non speech) and how they can be applied to speech motor learning. The researchers sought to evaluate how well motor learning principles can be applied to treatment of motor speech disorders.

Methods: This article critically reviewed and compiled research from prominent journals about motor learning. The authors paid particular attention to include articles about how motor learning can apply to speech motor learning and treatment.

Findings: This article found that certain aspects of motor learning can be applied to treatment of motor speech disorders, however few studies have directly researched this. More research needs to be done in order to fully answer this question.

Relevance to current study: This article provides relevant details about the core

principles of motor learning. It will provide a framework that can be used in the present study to develop a treatment plan using motor learning principles that will help improve speech motor production in participants with AOS.

Nissen, S. L., Dromey, C., & Wheeler, C. (2007). First and second language tongue movements in Spanish and Korean bilingual speakers. *Phonetica,* 64(4), 201–216. https://doi.org/10.1159/000121373

Objective: This study used stroke metrics to evaluate how kinematics affects perceived fluency in native and learned languages. The researchers measured the speed, duration, and distance of tongue movements during speech. They defined stroke as 'the period between two successive local minima in the speed history of an articulator point.' Each stroke corresponds to the movement of the tongue from one articulatory position to another.

Methods: Participants consisted of 10 native Spanish speakers and 10 English speakers who were proficient in Korean. The participants completed multiple speaking tasks in both language. The following metrics were analyzed for each stroke: (a) peak stroke speed (maximum speed in millimeters per second generated within a stroke), (b) average stroke speed (mean speed during an entire stroke in millimeters per second), (c) stroke distance (distance in millimeters from one speed minimum to the next, measured point by point in x-y space along the movement path, which could be either curved or straight), and (d) duration (duration between successive speed minima).

Findings: They found that speakers of L2 showed slower stroke peak speeds and were perceived as "less fluent" (thicker accent).

Relevance to current study: This study used stroke metrics in order to evaluate the quality of speech production. The present study aims to evaluate speech production, as opposed to a recall memory task, so this study provides insight into the methods that can be used when evaluating speech production. Strokes appear to be a good metric to use in this process in the present study. This study provides a good introduction to and explanation for strokes and how they are used in collecting data.

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. https://doi.org/10.1111/j.1467-7687.2009.00911.x

Objective: The purpose of this study was to add to the literature on changes in speech movement coordination with nonword repetition in both the developing motor systems in 9- to 10-year-olds. The researchers hypothesized that (a) child will make more errors, (b) adults will show changes in coordination within a session, (c) short term changes in accuracy will persist overnight, (d) both children and adults will be able to be more accurate in their nonword production.

Methods: This study included 19 children 9–10 years old and 19 adults 18–25 years old. Four nonwords and one control word were the stimuli for the study. Two to four nonwords were adopted from Walsh et al. (2006). Each nonword began with the same syllable and ended with the same phoneme in order to make it easier to identify clear boundaries between non words. Participants were hooked up to the Optotrak with IREDs attached to the upper lip, lower lip and jaw. Teach phase on Day 1 where experimenters helped until they got two correct productions. Then tested within a carrier phrase, "say ___ again." Day 2 was not given practice. Day 1 lasted 60 minutes and Day 2 lasted 30.

Findings: Kinematic data revealed the following results: a) adults showed shorter durations when producing nonwords and b) adults showed more control and less variability than children did. Additionally, LA VAR reduction was seen between Days 1 and 2 in both groups as nonword complexity increased

Relevance to study: This study explains how nonwords were selected for task stimuli. It provides a good framework for considerations that should be made when selecting target words. Additionally, it uses kinematic measures such as lip aperture variability (LA VAR) and duration to analyze the effects. These may be useful kinematic measures to look at in the present study.

Schmidt, M., Frings, C., & Tempel, T. (2021). Context-dependent memory of motor sequences. *Journal of Cognition*, 4(1), 15. https://doi.org/10.5334/joc.152

Objective: This article also evaluated the effect that environmental context has on memory. Researchers investigated the role of intentional and incidental context features on perceived environmental changes.

Methods: Participants learned finger pattern movements by pressing certain keys in a particular order. Unlike previous studies, the learned stimuli were not words or phrases, but motor movements.

Findings: Like previous studies, these researchers found that learning and being tested in different environments had a negative effect on the participant's ability to recall learned stimuli. The results suggested that more research should be conducted to clarify the actual role they play in affecting environmental context perception and memory.

Relevance to current study: This study sought to evaluate the role the environment plays in the memory of motor movements. Similarly, the present study seeks to evaluate the role context diversity/environmental changes play on motor learning in speech. Although this study doesn't look at speech motor learning, it is still applicable because it deals with motor learning. Additionally, it supports the research that the environment affects memory and learning, which is the basis for the present study.

Schor, A., Aichert, I., & Ziegler, W. (2012). A motor learning perspective on phonetic syllable kinships: How training effects transfer from learned to new syllables in severe apraxia of speech. *Aphasiology,* 26(7), 880–894. https://doi.org/10.1080/02687038.2012.660458

Objective: Previous research by the authors has suggested that syllabic motor plans are not holistic phonetic entities, instead they are internal structuring of speech motor programs. This study sought to explore the relationship between syllables exercised in a learning trial and how those exercises can benefit new syllables.

Methods: The researchers recruited 11 participants but ended up with only three eligible participants. Each was diagnosed with severe AOS. Two participants had global aphasia and the other had a diagnosis of Broca's aphasia. Participants practice four different syllables with a high number of repetitions. The target syllables were systematically related to untrained syllables. Participants were assessed for accuracy of syllable production before and after practicing.

Findings: Two participants showed significant learning effects after the training segment. The results from this study show that the training syllables were learned as syllable components rather than segments. They concluded that since the participant pool was so small, more research must be done in order to strengthen this finding.

Relevance to current study: This study provides a good framework to follow when determining the methods for the current study. This study supports the decision to use a relatively small sample size because the participants all have AOS.

Shin, Y. S., Masís-Obando, R., Keshavarzian, N., Dáve, R., & Norman, K. A. (2021). Context-dependent memory effects in two immersive virtual reality environments: On mars and underwater. *Psychonomic Bulletin & Review*, 28(2), 574–582. https://doi.org/10.3758/s13423-020-01835-3

Objective: Past research has shown that there are important elemental factors in context-dependent memory. This study aimed to explore what these elements were and how they may be manipulated.

Methods: Through using virtual reality, participants were dropped into an underwater or Mars environment. Participants were selected to be tested in either the same or different environment they learned the information. The participants' tests consisted of three tasks: (a) a foraging task, (b) the context-specific initiation sequence, and (c) item-finding actions. Each of these tasks were learned motor tasks. They then participated in an immediate and/or delayed word recall task in the environments.

Findings: This study found that there is better recall for items retrieved in the same context as the study context. However, these effects were only obtained for items that were judged to be useful survival in the encoding environment. The results also revealed that delayed memory recall (one day) showed greater context-dependent differences than immediate recall. It is important to note that participants in this study were not informed that a memory test would follow the virtual reality activities, eliminating the chances of the participants to create mnemonic devices to remember the content being learned.

Relevance to current study: This study provides valuable insights into the potential uses of VR in research, as well as some of its limitations. It also provides a good example framework of how virtual reality location can be used to study its effect on learning. Additionally, the premise of this study is similar to the current study in that context-dependent memory is being analyzed within VR environments. This study can help determine the current study's methods such as participant number, and virtual reality environments.

Stolfa, J., Stolfa, S., O'Connor, R. V., & Messnarz, R. (2017). Overcoming public speaking anxiety of software engineers using virtual reality exposure therapy. In J. Stolfa, S. Stolfa, R. V. O'Connor, & R. Messnarz (Eds.), *Systems, Software and Services Process Improvement: Vol. 748. Communications in Computer and Information Science (p. 191–202).* Springer. https://doi.org/10.1007/978-3-319-64218-5_15

Objective: It has been observed that software engineers often lack the social skills required to thrive in an environment that requires public speaking and presentations. The purpose of this study was to verify the use of virtual reality with this population of people to help them overcome the fear and anxiety surrounding public speaking.

Methods: Six novice software engineers (majority female) were recruited for this study. They underwent a form of exposure therapy where they were given 30–45 minutes to practice public speaking within a realistic auditorium virtual reality environment. Participants spoke on one of three controversial topics to a crowd of virtual people. Researchers measured the participant's anxiety levels before, during, and after the public speaking simulation.

Findings: The researchers found that the participants experienced high levels of anxiety during the virtual presentation, similar to those levels during a typical in person presentation. They concluded that virtual reality appears to be an effective way to simulate and practice for these anxiety inducing experiences.

Relevance to current study: The current study seeks to validate the use of virtual reality in treatment for people with aphasia. This study provides a good basis for virtual reality use in therapy.

Tasko, S. M., & Westbury, J. R. (2002). Defining and measuring speech movement events. *Journal of Speech, Language, and Hearing Research*, 45(1), 127–142. https://doi.org/10.1044/1092-4388(2002/010)

Objective: It has been believed that speech is created by simply stringing together a series of discrete units or sounds. However, this view of speech is inconsistent with our perception of speech that sounds smooth and continuous. The purpose of this study was to define speech movement events in a different way.

Methods: Eighteen participants completed an oral reading task. Utterances were broken up into “strokes” and analyzed based on stroke distance, peak stroke speed, stroke duration, and boundary speed.

Findings: A stroke can be defined as the period between two local minima in the speed history of a speech sample. Using strokes as a way to segment a speech sample is helpful when collecting kinematic data from the tongue blade, dorsum, lower lip and jaw, etc.

Relevance to current study: They found that this type of parsing method is useful for use with data collected by point tracking techniques (electromagnetic articulography.) Strokes are a valuable form of measurement to be used since the present study is collecting kinematic measures data using an articulograph. This article also provides clear

definitions of what stroke metrics are that can be used in my introduction and methods.

Wambaugh, J. L. (2021). An expanding apraxia of speech (AOS) treatment evidence base: An update of recent developments. *Aphasiology*, 35(4), 442–461 https://doi.org/10.1080/02687038.2020.1732289

Objective: Many new forms of treatment for people with AOS have emerged but have not been included in a summary article. This study sought to create an updated summary of the current AOS treatments since 2012. This paper's purpose is to highlight the advances that have strengthened and expanded the AOS treatment evidence base.

Methods: Fifty-nine treatment studies were examined and categorized depending in the type of AOS treatment approach used. The articles were categorized based on the following guidelines: (a) articulatory-kinematic treatments, (b) rate/rhythm control treatments, (c) intersystemic facilitation/reorganization treatments, and (d) alternative augmentative communication (AAC) training. The paper's purpose was to summarize the types of AOS treatment, not to be a systematic review.

Findings: This paper shows that AOS treatment approaches mainly focus on articulatory-kinematic approaches. Additionally, musical/rhythmic approaches have been popularized due to their positive effects on speech production in recent years.

Relevance to current study: The preset study seeks to evaluate the effects of treatment within virtual reality on speech motor learning in people with AOS. This article may help inform the specifics decisions for how treatment will be administered during the study.

Wambaugh, J., Nessler, C., Wright, S., Mauszycki, S., & DeLong, C. (2016). Sound production treatment for acquired apraxia of speech: Effects of blocked and random practice on

multisyllabic word production. *International Journal of Speech Language Pathology*, 18(5), 450–464. https://doi.org/10.3109/17549507.2015.1101161

Objective: SPT employs commonly used AOS therapy techniques such as modeling/repetition, integral stimulation, articulatory cueing and repeated practice in a response-contingent hierarchy. The purpose of the study was to evaluate the effects of practice schedules on multiple targets within multisyllabic words for people with AOS using SPT.

Methods: Participants included four people with Broca's aphasia + apraxia. Participants received one type of treatment and then two weeks later another treatment type was used. Pre and post testing was collected. Stimuli for each participant differed and each word included phonemes/clusters that each participant had difficulty producing. Participants had 20-40 treatment sessions. SPT was used during treatment and included the following: modeling/repetition, orthographic cueing, integral stimulation ("watch me, listen to me, say it with me"). Participants had either blocked or random practice applied during treatment.

Findings: Both practice schedules led to improvement in articulation accuracy of trained words. It appeared that some response and stimuli generalization occurred. Participants tended to enjoy random practice more than blocked, despite similar improvement being made in both types of practice.

Relevance to the study: I am planning on using target stimuli that are fitted to each participant based on their abilities. This is a good article to reference when trying to figure out a way to evaluate their abilities in my own study.

Whitfield, J. A., & Holdosh, S. R. (2021). Practice mediates bidirectional dual-task interference

when performing a novel sequential nonword repetition task. *Journal of Speech, Language, and Hearing Research*, 64(6), 1904–1917. https://doi.org/10.1044/2021_JSLHR-20-00605

Objective: This study’s purpose is to investigate the extent to which practice influences the degree of interference during a dual task activity of a novel nonword sequence activity and an action demanding visuomotor pursuit task. This study was heavily influenced and in response to Whitfield and Goberman (2017a, 2017b).

Methods: Twenty-five young adult students split into two groups. One of the groups had a long time to practice the non word task (EPG) while the LPG group had limited time to practice. Fifteen students in the EPG completed the tasks over 2 days. On the first day, they learned/practiced the NWR task. Then on the next day, they were given a couple practice trials and then tested under the dual task (DT) procedures. Overall, the EPG had 15 blocks of practice. The LPG was composed of 10 participants who followed the same Day 2 protocol as the EPG and were only given a few trials to practice the activity. This group was only given three blocks of practice. The nonwords in the nonword task were “toop gite bap pawp koys deek” and selected based on the following: (a) the nonwords were orthographically legal in English, (b) the nonwords were of the CVC form, (c) the initial consonants of all nonwords were stop consonants, (d) the nonword sequence included the four corner vowels and two diphthongs. Researchers analyzed participants’ performance on the non-word repetition and visuomotor task. They analyzed the number of correct versus incorrect syllables.

Findings: The researchers found that participants in the LPG who were afforded a limited number of practice blocks exhibited significantly poorer task performance during the concurrent task than the participants in the EPG who were given more time to practice. Clearly, practice heavily influences the degree of interference during dual task activities.

Relevance to current study: The present study is using a non-word repetition task, similar to the one described in this study. The researchers' guidelines they followed when creating the nonwords provide a good framework to be followed in the present study.

APPENDIX B

Institutional Review Board Approval and Consent Form

Memorandum

To: Dallin Bailey
Department: BYU - EDUC - Communications Disorders
From: Sandee Aina, MPA, HRPP Associate Director
Wayne Larsen, MAcc, IRB Administrator
Bob Ridge, Ph.D., IRB Chair
Date: January 12, 2024
IRB#: IRB2023-415
Title: Using Virtual Reality to Examine Effects of Contextual Diversity on Speech and Language Learning in People with Aphasia

Brigham Young University's IRB has approved the research study referenced in the subject heading as expedited level, categories 4, 6, and 7. This study does not require an annual continuing review. Each year, near the anniversary of the approval date, you will receive an email reminding you of your obligations as a researcher. The email will also request the status of the study. You will receive this email each year until you close the study.

The IRB may re-evaluate its continuing review decision for this decision depending on the type of change(s) proposed in an amendment (e.g., protocol change that increases subject risk) or as an outcome of the IRB's review of adverse events or problems.

The study is approved as of 01/12/2024. Please reference your assigned IRB identification number in any correspondence with the IRB.

Continued approval is conditional upon your compliance with the following requirements:

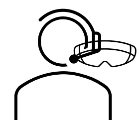
1. A copy of the approved informed consent statement and associated recruiting documents (if applicable) can be accessed in iRIS. No other consent statement should be used. Each research subject must be provided with a copy or a way to access the consent statement.
2. Any modifications to the approved protocol must be submitted, reviewed, and approved by the IRB before modifications are incorporated into the study.
3. All recruiting tools must be submitted and approved by the IRB before use.
4. All data and the investigator's copies of the signed consent forms must be retained for at least three years following the termination of the study.
5. In addition, serious adverse events must be reported to the IRB immediately, with a written report by the PI within 24 hours of the PI's becoming aware of the event. Serious adverse events are (1) the death of a research participant or (2) serious injury to a research participant.
6. All other non-serious unanticipated problems should be reported to the IRB within two weeks of the PI's first awareness of the problem. Prompt reporting is important, as unanticipated problems often require some modification of study procedures, protocols, and/or informed consent processes. Such modifications require the review and approval of the IRB.

Consent to be a Research Subject

Title of the Research Study: Using Virtual Reality to Examine Effects of Contextual Diversity on Speech and Language Learning in People with Aphasia
Principal Investigator: Dr. Dallin J. Bailey, PHD CCC-SLP

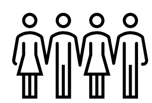
Introduction

This research study is being supervised by Dr. Dallin J. Bailey, associate professor in the Communication Disorders Department at Brigham Young University.



It is being conducted to measure the effects of practice in virtual reality environments on speech motor learning in people with apraxia of speech.
This study will involve some speech and language testing, wearing a VR headset, and repeating words with small sensors temporarily attached to your tongue, teeth, and lips.
You are invited to participate in this study if:

- You are 18 years old or older
- You have apraxia of speech
- You also are at least 6 months post stroke and/or injury
- You have no history of other neurological conditions/diseases
- You have no current dysphagia symptoms
- English is your primary language
- You are available for in-person interview at our lab in Provo, UT.
- 3 other participants with apraxia of speech are also being recruited for this study.

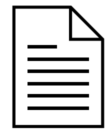


IRB NUMBER: IRB2023-415
IRB APPROVAL DATE: 01/12/2024

Procedures

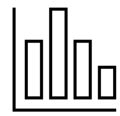
If you agree to participate in this research study, the following will occur:

1. You will first complete a demographic questionnaire. This will last about 5 minutes.



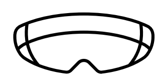
2. You will then complete hearing and vision screenings; these will last about 2-4 minutes.

3. You will complete a collection of cognitive, speech, and language testing. This will include tests of your nonverbal cognitive skills, your motor speech abilities, and your language abilities. This will take between 40 and 80 minutes.

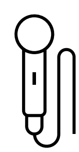


4. While you are wearing a virtual reality (VR) headset, your speech kinematics will be measured in two sessions using an articulograph. There will be a 24-hour period between sessions.

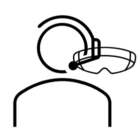
   a. Small sensors will be attached to your tongue, jaws, and lips.
   b. You will wear a VR headset, with additional sensors attached to it to correct for head movements during recording, or sensors may be placed behind your ears.



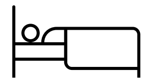
   c. You will briefly wear a mouthpiece.
   d. You will be audio recorded during study procedures.

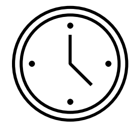


   e. You will be assigned to practice pronouncing words in different virtual environments.
   f. This will require between 45 minutes and 1.5 hours total for both sessions.

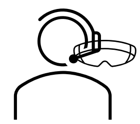


5. After the initial assessment phase of the study, you will return home and continue your typical routine. As you go about your routine you also be asked to complete a brief sleep diary to report on your sleep hours and quality. This will take approximately 2-5 minutes.





6. Twenty-four hours later you will return to the lab to complete the second and final speech assessment. Please bring your sleep diary.



7. Your total time commitment will be between 1.5-3 hours, spread over multiple days.

8. This study will take place at Brigham Young University in room 106 of the Taylor Building.

Risks/Discomforts

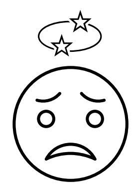
There are minimal risks associated with participation in this study.

- There is a potential risk for infection as the sensors used will be used on multiple participants. However, between each participant, all equipment will undergo a sterilization process to avoid this risk.

- It is possible that you may feel slight discomfort due to the small sensors which attach to strategic locations on the tongue (tongue tip and tongue blade), jaws, and lips (upper and lower). Additional sensors are located on transparent goggles to correct for head movements during recording and on a briefly worn mouthpiece to calibrate the articulograph to the occlusal plane of each individual participant. If at any time, you feel uncomfortable, you may choose to excuse yourself from the study. All equipment used in this study has been used in previous research studies with no adverse effects. If you are concerned about this, you may choose not to participate in this study.

- There is a small risk of breach of confidentiality. However, we will store your data in data storage locations accessible only by approved research staff who have been given passwords, keys, digital access, and/or combinations. Also, we will not label your data with any personal identifying information.

- You may feel frustrated or discouraged when being asked to speak and repeat words. However, the frustration is unlikely to be different from what you may experience outside of this study.
- You may feel some dizziness, nausea, or headache, associated with using the VR headset. We have chosen virtual environments that have low potential to elicit these unpleasant feelings. In the event that you do experience them, they are likely to subside within minutes or hours after completing the study. However, you are free to abandon the study at any time. We will monitor you for how you are feeling throughout the study, especially while you are wearing the headset.

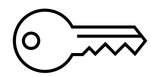


Benefits

There will be no direct benefits to you. It is hoped, however, that through your participation, researchers may gain insight into how practicing in VR environments can improve speech articulation skills in people with apraxia of speech compared to traditional environments of practice. The findings may provide insight into how to better help people with apraxia of speech to speak more clearly.

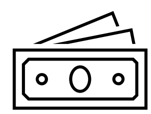
Confidentiality

There will be no reference to your identification in paper or electronic records (audio and kinematic) at any point during the research. Non-identifying information, such as age, sex, and race, may be associated with your data. An identification number will be used to organize the data we collect. The research data will be kept on a password-protected computer that is only accessible to the researcher and assistants. Your electronic data (audio and kinematic) will be retained indefinitely by the principal investigators, although the link to the data will be deleted in December 2026.



Compensation

Upon completion of your data collection session, you will receive $40 cash for your participation. Compensation will not be prorated.

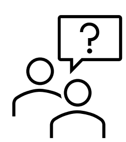


Participation

Participation in this research study is voluntary. You have the right to withdraw at any time or refuse to participate entirely without jeopardy to your class status, grade, or standing with the university.

Questions about the Research

If you have questions, concerns or complaints regarding this study, you may contact the Principal Investigator, Dr. Dallin J. Bailey at 801-400-4286, dallinbailey@byu.edu for further information.



Questions about Your Rights as Research Participants

If you have questions regarding your rights as a research participant contact Human Research Protections Program by phone at (801) 422-1461; or by email: BYU.HRPP@byu.edu.

Statement of Consent

I have read, understood, and received a copy of the above consent and desire of my own free will to participate in this study. I give my consent for my audio recordings and kinematic movement data recordings to be used in this study.

Name (Printed): ________________________

Signature: __________________________ Date: _____________

APPENDIX C

Supplemental Tables

Table 3

Average Stroke Count Results for the Four Sensors, Across Condition and Timepoint

Condition	TB	TT	LL	UL
A Pre Consistent	6.1	5.6	6.4	7.1
Standard Deviation	2.5	2.5	3.1	2.8
A Post Consistent	6.4	5.6	5.9	6.7
Standard Deviation	2.0	1.9	1.9	1.6
B Post Consistent	5.7	5.1	5.3	7.1
Standard Deviation	2.5	2.3	1.7	1.7
A Pre Diverse	7.5	7.8	8.7	9.4
Standard Deviation	3.0	2.9	3.1	4.0
A Post Diverse	9.8	5.1	6.1	5.7
Standard Deviation	2.9	1.9	1.5	1.9
B Post Diverse	5.5	5.8	6.1	6.3
Standard Deviation	1.6	2.1	1.7	2.2

Table 4

Average Hull Area Results for the Four Sensors, Across Condition and Timepoint

Condition	TB	TT	LL	UL
A Pre Consistent	14.1	25.8	5.2	0.8
Standard Deviation	11.5	21.3	4.3	0.8
A Post Consistent	19.3	31.6	9.8	0.9
Standard Deviation	15.7	25.9	5.0	0.6
B Post Consistent	22.0	38.4	7.2	1.3
Standard Deviation	1.4	4.8	33.7	23.0
A Pre Diverse	21.0	25.7	10.3	2.2
Standard Deviation	2.1	7.1	27.3	14.4
A Post Diverse	1.8	21.6	14.7	3.3
Standard Deviation	5.8	7.0	21.3	2.1
B Post Diverse	7.1	13.6	6.7	4.1
Standard Deviation	6.8	3.3	10.1	4.9

Table 5

Average Onset Speed Results for the Four Sensors, Across Condition and Timepoint

Condition	TB	TT	LL	UL
A Pre Consistent	7.1	7.8	6.0	2.0
Standard Deviation	5.2	6.3	3.4	1.2
A Post Consistent	8.1	8.8	6.6	2.2
Standard Deviation	7.1	5.8	3.2	1.1
B Post Consistent	8.4	7.5	7.3	2.7
Standard Deviation	8.2	5.9	4.8	1.5
A Pre Diverse	8.2	8.2	5.3	2.2
Standard Deviation	5.0	4.6	4.1	1.1
A Post Diverse	3.9	10.7	8.7	3.5
Standard Deviation	2.2	8.1	3.0	2.8
B Post Diverse	5.0	6.4	5.9	3.9
Standard Deviation	2.0	3.1	3.3	4.3

Table 6

Average Peak Speed Results for the Four Sensors, Across Condition and Timepoint

Condition	TB	TT	LL	UL
A Pre Consistent	34.1	52.9	17.9	5.4
Standard Deviation	21.9	43.3	6.6	2.4
A Post Consistent	38.6	58.5	24.6	5.7
Standard Deviation	21.7	37.1	10.8	2.2
B Post Consistent	49.7	77.3	20.7	7.5
Standard Deviation	31.5	49.7	8.7	2.6
A Pre Diverse	32.5	33.6	18.7	6.5
Standard Deviation	12.9	17.6	9.2	3.6
A Post Diverse	11.1	40.4	31.9	10.1
Standard Deviation	2.9	20.9	13.6	7.7
B Post Diverse	31.4	35.5	15.3	14.2
Standard Deviation	12.8	14.5	7.5	13.1

Table 7

Average Duration Across Condition and Timepoint

Condition	Duration (s)
A Pre Consistent	0.8
Standard Deviation	0.2
A Post Consistent	0.9
Standard Deviation	0.2
B Post Consistent	0.9
Standard Deviation	0.2
A Pre Diverse	1.1
Standard Deviation	0.3
A Post Diverse	0.8
Standard Deviation	0.2
B Post Diverse	0.8
Standard Deviation	0.2

Table 8

Average Duration Across Condition and Timepoint

Condition	Accuracy
A Pre Consistent	1.5
Standard Deviation	0.7
A Post Consistent	1.4
Standard Deviation	0.6
B Post Consistent	1.4
Standard Deviation	0.7
A Pre Diverse	1.6
Standard Deviation	0.9
A Post Diverse	1.1
Standard Deviation	0.4
B Post Diverse	1.1
Standard Deviation	0.4

Note. Accuracy was determined based on the following criteria: (1) accurate production, (2) minor distortions, (3) major errors, distortions, or substitutions. Thus, lower scores indicate more accurate productions.