The Effect of Event Boundaries on Repetition Reduction Among Individuals with Previous Experience of mTBI

by

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Abstract

Previous research has shown that event boundaries have a ‘reset’ effect on repetition reduction within conversational speech. Other studies have shown that the ‘Location Updating Effect’ impacts memory, even within a virtual environment. However, these two ideas have only been examined separately, within a typical population of participants. The present study examined the effect of event boundaries on repetition reduction among individuals who have a history of mTBI, within a virtual environment. It was hypothesized that the effect of event boundaries would be less extensive among the concussion group, due to potential mild deficits in motor speech and memory. Ten individuals participated in the study (5 with previous experience of mTBI, 5 typical, without history of mTBI). Participants produced 8 stories (4 all within a single room, and 4 with a change in rooms in the middle) that included 10 target phrases. Each target phrase was measured for duration, pitch range, and AAVS to determine any changes following room change. Data revealed no significant group differences between the concussion group and the typical group following a room change. When all participants were analyzed together, however, there was evidence of repetition reduction within a single room, but decreased reduction immediately following a room change. This supports the hypothesis that speech can be affected by event boundaries through perceptual engagement in a virtual environment alone.

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List of Abbreviations

AAVS	Articulatory-Acoustic Vowel Space
AMR	Alternating Motion Rate
CEB	Concussion Event Boundary
L/R	Left/Right
LOC	Loss of Consciousness
M/F	Male/Female
MoCA	Montreal Cognitive Assessment
mTBI	Mild TBI
nH/L	non-Hispanic/Latino
s	seconds
SMR	Sequential Motion Rate
t/c	typical/concussion
Tx	Treatment
y/mo	years/months

Introduction

Repetition Reduction

Repetition reduction is a type of phonetic reduction affecting previously uttered content words in a speaker's conversation (Fowler, 1988). This means that after a word has been spoken once in a conversation, the speaker will likely reduce the duration, or produce the word more quickly as it is mentioned repetitively in future utterances. It is one way in which the speaker differentiates old words to the listener, as opposed to their newly spoken words of longer duration (Fowler & Housum, 1987). Phonetic reduction may also occur through other acoustic phenomena, such as a lowered pitch (Chafe, 1974) or the more recently studied vowel centralization (e.g., /ʌl/ for /ɔɪl/) (Eijk et al., 2020). These have been noted to occur despite an otherwise steady rate of speech (Fowler, 1988). Although this durational shortening has been shown to negatively impact the intelligibility of words (Fowler, 1988; Fowler & Housum, 1987), listeners are typically still able to identify the repeated utterances due to the increased context when compared to that of the first production. Therefore, the predictability of the repeated word in its context increases (Fowler, 1988).

There are many reasons that repetition reduction might occur. These reasons are based on the assumption that attenuations are made actively and purposefully based on the talker's own systematic assessment of redundancy (Fowler, 1988). Other than for the purpose of discriminating old words from new, talkers may exhibit repetition reduction for their own convenience – a sort of 'Least Effort Principle' as proposed by Fowler's study of differential shortening of repeated content words (Fowler, 1988). Essentially, speakers will provide the least amount of communicative information required by the listener (Fowler & Housum, 1987). This also follows Lindblom's theory of hyper and hypo-articulation, stating that speakers will hyperarticulate when the listener requires more acoustic information (Lindblom, 1990). Therefore, if the word is easily predicted from its context, the speaker will likely provide a less informative production of the word, acoustically speaking, than if it were to be a new word or a word with low probability in its context (Fowler & Housum, 1987; Lindblom, 1990).

These predictable contextual situations in which less intelligible words are able to be identified by the listener often occur in more casual speech between well-acquainted conversants. This is due to the fact that those who are familiar with each other often share considerable knowledge, leading to less careful articulatory productions in speech (Fowler, 1988). This 'Least Effort Principle' may be misleading, however, due to the fact that it implies that the shortening is carried out for the speaker's benefit. Many other theories propose that it is done for the listener's sake (Fowler, 1988). Reductions could additionally be made based on the speaker's assessment of where the listener's attention is focused. If the talker assumes that the listener's attention is focused on the "given", or more commonplace information in the discourse, they might subsequently emphasize "new" or unexpected words that have less support in the context in order to draw the listener's attention and highlight these more informative words, while attenuating the more redundant words (Bard et al., 2000; Chafe, 1974; Fowler & Housum, 1987; Lieberman, 1963). Accentuating "new" words also allows the listener to understand that the non-emphasized, reduced words refer back to the previously given information in the conversation (Fowler & Housum, 1987). Another reason for phonetic reduction could be attributed to the fact that speakers simply put forth less articulatory effort as repetitions increase, or they form a routine of specific word productions that become facilitated through repetition (Fowler & Housum, 1987).

It is important to note the finding that in order for repetition reduction to occur, the words must be produced in a communicative context with the presence of a listener (Fowler, 1988). When tested, more reduction was seen in meaningful prose than when reading prose into a microphone (Fowler, 1988; Van Son & Pols, n.d.). This was recognized as being due to the speaker's assumption that the listener has contextual or background information that will help them more easily distinguish the less carefully articulated words. One should consider, however, that spontaneous speech typically occurs at a slower rate than that of read speech (Fowler, 1988).

Repetition reduction is a topic that has been researched for half a century, and continues to be a topic of interest today. As previously mentioned, there is some variation in research findings as to exactly how this repetition reduction has been measured. According to Chafe, talkers lower their voice pitch and reduce the stress of words conveying given information (Chafe, 1974). According to Bolinger, however, talkers tend to create a durational lengthening of lower-probability words (Bolinger, 1963). They may also produce more centralized, less intelligible vowels (Eijk et al., 2020). In connected speech, phonetic reduction by duration and centralized vowels is most likely to occur when the word has many phonological neighbors (many words that are phonologically similar) (Gahl et al., 2012). Although there are different ways that talkers may implement phonetic reduction, it is evident that it is carried out in a systematic way.

Changes in repeated speech have been researched in many ways, and among many populations. In a review of repetition reduction literature, it was found that most studies were carried out within a population that spoke a variety of English, however there were several exceptions in which there were speakers of other languages, and even multiple languages (Kaland & Himmelmann, 2020; Lam & Marian, 2015). Among these language variations, duration proved to be the most common and consistent acoustic measure of reduction. Even further, Lam and Marian found that mere concept-level repetition had the potential to result in reduction, meaning that repetitions of words that are merely semantically-related to the original word can result in reduction, particularly among balanced bilinguals (those who have a similar level of word activation for all concepts across both languages) (Lam & Marian, 2015). The current pilot study, however, will focus on word-level repetition among speakers of American English.

Understanding the ‘why’ behind repetition reduction is important because it helps us better understand certain patterns of communication. Understanding how these patterns typically show up allows us to then look at what happens to the patterns when communication breaks down, or is altered in some way. The act of reducing repeated words can facilitate communication on both the speaker’s part, as previously discussed, as well as the listener’s part. If the speaker’s reduction allows the listener to identify old words from new, this may facilitate their retrieval of old information and integrating it with what is currently being spoken in the discourse (Fowler & Housum, 1987). According to a study carried out by Jacobs et al. (2015), repetition reduction is likely to use auditory working memory. This allows the speaker to remember whether or not a word was recently produced, and if the listener has recently heard the word (Jacobs et al., 2015). In other words, the authors believe that “having an auditory memory of a phonological sequence drives repetition reduction”(Jacobs et al., 2015, p. 45). Therefore, if someone were to have deficits in their working memory, it is reasonable to believe that they might show differences in their repetition reduction as well. Perhaps their reduction would be produced to a lesser extent. These ideas will be explored later on.

Event Boundaries

There are many ways to describe how the brain makes sense of our daily occurrences and interactions. One informative theory has been that of event cognition, which refers to "how people perceive, conceive, talk about, and remember events" (Radvansky & Zacks, 2017, p. 133). People do this through the use of different event models. Event models allow our cognitive systems to form and update representations of different events (Radvansky & Zacks, 2017). Put more simply, event cognition and event models work together in the brain to categorize the different events that one experiences. The Event Horizon Model, proposed by Radvansky and Zacks (2017), provides us with "a framework for how such representations of events are created, structured, and remembered" (Radvansky & Zacks, 2017, p. 133). One of the principles that makes up the Event Horizon Model is the idea that people tend to mentally segment ongoing activity into sequences of event models. Of these sequences, only the current event model is held in working memory, making it more available when probed. When key features of the event change (location, characters, objects, etc.), this is experienced as an event boundary, resulting in an update of the current event model. Features that are present across multiple events are typically recalled with greater ease. However, if there is overlapping of multiple event models due to shared features, there will be interference when attempting to retrieve only one of the event models. Lastly, event models are organized in long term memory through their cause-and-effect relationships. Events that are causally related are processed quicker and remembered with greater ease (Radvansky & Zacks, 2017).

A couple of other components that make up the Event Horizon Model include the Location Updating Effect and the Event Segmentation Theory (Radvansky & Zacks, 2017). The Location Updating Effect proposes the idea that when there is a shift in location, the new and updated event structure will impede on one's memory. This means that as the brain obtains new information and updates its event model, the accessibility of old event information becomes diminished. As this occurs when people walk through doorways, or even imagine walking through doorways (Lawrence & Peterson, 2014), it can be said that memory is better in the absence of a location shift (Radvansky & Zacks, 2017).

The Event Segmentation Theory proposes the idea that people are able to use current event models to make predictions about upcoming events (Radvansky & Zacks, 2017). However, when significant features of the current event model are changed, such as location, characters, or objects, the brain categorizes it as a new event, therefore updating the event model. This causes an increase in prediction error, and is realized as an event boundary (Radvansky & Zacks, 2017). These event boundaries are said to occur "when perceivers shift participation in one event to another" (Meagher & Fowler, 2014, p. 562). Because of this shift, information from the previous event is pushed into the background as the information from the current event is foregrounded. The brain is usually signaled to create new events as a result of physical structures in the environment (often doorframes). To explore these ideas further, Radvansky and a number of other researchers completed a series of experiments. In relation to event boundaries, they explored situation models and experienced space, environmental integration, degree of immersion, and active and passive interaction, among other aspects of event cognition. One of their conclusions that will be important for the current study is their finding that the 'doorway' event boundary influences both recognition and recall, consistent with the Event Horizon Model (Pettijohn & Radvansky, 2018; Radvansky et al., 2011). Similarly, Meagher and Fowler found that event boundaries typically result in a reduced performance on tests that require retrieval of information from previous events, due to the decreased accessibility of that information

(Meagher & Fowler, 2014). This reflects the ideas proposed in the Event Horizon Model when it suggests that information from prior event models is less available than that of the current event model, which is highly available (Radvansky & Zacks, 2017). It is important to understand the basics of event cognition, event models, and event boundaries for a variety of reasons. As mentioned in Radvansky and Zacks' text, events are at the center of human experience (Radvansky & Zacks, 2017). Event boundaries affect how much people remember and are able to recall about the different activities and experiences that they encounter on a day-to-day basis. Deficits in this understanding could adversely affect people's ability to generalize what they are learning in therapy sessions, and therefore prevent or limit them from carrying over their skills and progress to their natural environment.

A study that will be influential for our purposes is that carried out by Meagher and Fowler in 2014, "Embedded Articulation: Shifts in Location Influence Speech Production". The purpose of their study was to assess whether or not physical changes in setting would impact the repetition reduction effect, measured as word duration. This was measured through a map task in which participants (Guides) were instructed to verbally describe the given map using 10 key words, in order to have the other individual (Follower) recreate the map with as much accuracy as possible. After 2 trials, conditions were manipulated and participants changed rooms, changed partners, both, or neither. Their findings showed that changing rooms resulted in an immediate increase in the duration of their words. On the other hand, there was a negative linear pattern of word duration when participants did not shift locations. Changing partners showed no effect on speech duration. This study shows the effect and significance that event boundaries have on conversational speech (Meagher & Fowler, 2014).

There is some research that supports the idea that event boundaries may have a different effect among those who have experienced lesions to the frontal lobe; namely, they may have greater difficulty identifying transitons between events (Zalla et al., 2003). Specifically, it could lead to “severe impairments in executing complex and demanding tasks” (Zalla et al., 2003, p. 1626). There is potential that this could affect the quality of life and daily experiences of those who have experienced a mild traumatic brain injury (mTBI) differently than it would a healthy, typically developing person, since the memory and cognition of a mTBI population might already be imparied. This brings up part of the concentration of our present study. We are interested in understanding how event boundaries affect the memory of those who have experienced mTBI, and if the injury results in event boundaries having a greater, lesser, or equal influence on them when compared to a healthy population. With regards to our previously discussed topic of repetition reduction, we are also interested in exploring how event boundaries affect a speaker’s repetition reduction after sustaining a mild traumatic brain injury (mild TBI/mTBI/concussion).

Mild TBI

Motor Speech Deficits in mTBI

It is not common to see motor speech disorders that result from sport injuries unless the injury is severe. It typically requires repeated concussions, intracranial bleeding, brain stem damage, and peripheral nerve damage to cause a motor speech disorder to develop (Cannito, 2014; Duffy, 2020). The 10 most common irregularities of speech resulting from mild to severe TBI are as follows (in order of most to least frequent): hypernasality, reduced rate, imprecise consonants, reduced pitch variation, decreased breath support, abnormal stress patterns, reduced phrase length, impaired overall intelligibility, prolonged intervals, reduced loudness variation (Cannito, 2014).

Motor speech disorders include apraxia of speech or dysarthria of speech. As previously mentioned, it is very uncommon to see apraxia of speech resulting from a closed-head injury such as mTBI. This is mostly seen with open-head injury or stroke, and often co-occurs with nonfluent aphasia (Cannito, 2014; Duffy, 2020). According to Mayo Clinic data from 1999 to 2008, incidence of apraxia of speech after head trauma was associated with brain tumor resection and was about 4% of cases (Duffy, 2020).

Although mTBI is not likely to result in outright dysarthria, there could potentially be subclinical motor speech changes, which we are interested in studying. Dysarthrias, or slurred speech, are "generalized motor disturbances that affect the musculature of speech" that result from diverse damage to the motor system (Cannito, 2014, p. 222). These motor disturbances can affect any or all aspects of speech, including articulation, resonation, phonation, and/or respiration. The specific manifestations of motor disturbances will depend on which neuromotor structures and pathways are damaged (Cannito, 2014; Duffy, 2020). In a review of surveys looking at the occurrence of dysarthria after TBI, it was estimated that dysarthria incidence ranges from 23% in outpatient clinics to 65% in acute care (Cannito, 2014). In a study of speech and motor performance in student athletes, performed by Salvatore et al. (2019), diadochokinetic (DDK) and finger repetition tasks were executed to measure motor repetition rates among both a healthy population and those with current diagnoses of Sports-Related Concussions (SRCs). Time post-onset ranged from 1-33 days. Results showed that the SRC group produced a smaller mean repetition rate across all DDK tasks, as well as a statistically significant difference in finger repetition tasks (Salvatore et al., 2019). Therefore, although lasting clinical motor speech deficits are not common after closed-head injury, there is evidence for short-term deficits within at least the acute phase, but little research into subclinical deficits in the chronic stage.

Cognitive Deficits in mTBI

An mTBI, as defined by the Mild TBI Committee of the American Congress of Rehabilitative Medicine is a diagnosis given to individuals with mTBI present with a Glasgow Coma Scale score between 13 and 15 at 30 minutes post-injury, and one or more of the following symptoms: <30 min loss of consciousness; <24 hours post-traumatic amnesia (PTA); impaired mental state at time of accident (confusion, disorientation, etc.); and/or transient neurological deficit (Lefevre-Dognin et al., 2021). Although for many, there are few residual deficits attributable to mTBI after 90 days, there has not been a common agreement with regard to executive functioning deficits after mTBI (Bazarian et al., 1999; Cassidy et al., 2014; Davis et al., 2017; Hanten et al., 2013; Hiploylee et al., 2017; Oldenburg et al., 2016; Schretlen & Shapiro, 2003; Silverberg et al., 2020). According to Hanten et al. (2013), most children recover from mTBI after no longer than 3 months, with TBI severity as a defining factor. Children typically have a longer recovery period than that of adults, with adolescents often exhibiting more symptoms and greater severity of concussion than that do younger children (Davis et al., 2017). According to Silverberg et al. (2020), 1 in 5 people with mTBI will display cognitive symptoms continuing longer than 1 month. Perhaps it can be assumed that those who have experienced mTBI will recover in a time frame sometime between 1 and 3 months. This is similar to the findings of Schretlen and Shapiro's meta-analysis in 2003, in which it was concluded that cognitive functioning typically returns to baseline within 1-3 months of mild head injury (Schretlen & Shapiro, 2003). It is important to note that the definition and characteristics of mTBI now are nearly identical to that of how it was defined in the early 2000s (Lefevre-

Dognin et al., 2021). Despite the typical quick recovery, it is also said that of those who experience mTBI, around 15% (Bazarian et al., 1999) to 23% (Cassidy et al., 2014) will have post-concussion symptoms (PCS) that persist longer than a year. In a study of 110 participants with sport-related concussion, no one who had PCS lasting 3 years or longer was able to make a full recovery (Hiploylee et al., 2017). Quantity of initial symptoms and pre-existing health conditions may prolong recovery (Silverberg et al., 2020), and it is important to consider sex as women are more likely to develop post-concussion symptoms after mTBI than men (Oldenburg et al., 2016). Women may also be more vulnerable to concussion, specifically within sports settings, than men; however, this research is underdeveloped within non-sport populations (Merritt et al., 2019).

One mental skill that falls under the set of executive functions is memory. It is shown that memory is most affected by frontal lobe lesions, which are also marginally associated with poorer performance on memory tasks (Hanten et al., 2013). In a study carried out by Oldenburg et al. (2016), researchers found that individuals with mTBI demonstrated poorer performance on an assessment of memory in the areas of encoding and long-term retrieval, showing that deficits arise from the early stages of encoding and executive memory (specifically working memory and organization). Age of injury also plays a role in the potential for recovery. Gorman et al. (2012) found evidence for certain more severe working memory deficits to be associated with a younger age of injury, suggesting that ongoing pediatric cerebral development makes them more vulnerable to damage than adults who have already developed their cognitive skills. This also brings up the concept of cognitive reserve. Scarmeas & Stern (2003) tell us that “the concept of cognitive reserve (CR) suggests that innate intelligence or aspects of life experience like educational or occupational attainments may supply reserve, in the form of a set of skills or repertoires," providing some individuals with better compensation after a brain injury (Scarmeas & Stern, 2003, p. 625). Based on Weschler Adult Intelligence Scale, individuals with lower cognitive reserve proved to be over 4 times more likely to present post-concussion symptoms (PCS) lasting longer than 3 months (Oldenburg et al., 2016). In this study, there was a positive correlation between level of education and recovery, as well as skill level and recovery. Thus, we see again that lower cognitive reserve seems to be associated with a greater risk for PCS after mTBI (Oldenburg et al., 2016).

We are interested in creating a pilot study to examine how mTBI affects an individual's perception of event boundaries. According to a study by Zalla et al. (2003), damage to the prefrontal cortex is shown to result in deficits in distinguishing large event boundaries from small ones, or the hierarchical representation of complex events. This was determined based on a population of individuals with lesions to the frontal lobe, signaling at least a moderate TBI. They found that when distinguishing small event boundaries, there was no significant difference in the parsing of events between individuals with frontal lobe damage and normal controls, meaning that their ability to perceive small event boundaries was spared. This suggests that the prefrontal cortex plays a role in the analysis of action sequences, or 'goal-oriented chunking' (Zalla et al., 2003). For the purposes of our study, large action sequences can be represented by the doorways that mark event boundaries, typically signaling the creation of a new event model within the minds of healthy individuals. TBI patients in Zalla's study also exhibited difficulty in discriminating isolated actions from ongoing sequences of higher-order events. This will likely manifest functionally as deficits in the performance of complex tasks (Zalla et al., 2003). With regards to repetition reduction, we are also interested in investigating how it is affected by deficits in working memory after mTBI.

Purpose

The purpose of this pilot study is to examine the effects that changing event boundaries has on repetition reduction in persons with a history of mTBI. Specific aims of the current pilot study are as follows:

Specific Aim 1: The first aim is to run a pilot study to confirm Meagher and Fowler's findings of event boundary effects on repetition reduction within a virtual environment, with key changes in the task and mode..

Specific Aim 2: The second aim is to compare repetition reduction in persons with a history of mTBI with healthy control participants.

Specific Aim 3: The third aim is to compare the role that event boundaries play in running speech in persons with mTBI with healthy control participants.

We hypothesize that if memory deficits are present among the mTBI sample, they will demonstrate reduced repetition reduction, as well as reduced 'reset' when event boundaries are changed, owing to possible mild motor speech and memory difficulties. This is because, in order for repetition reduction to occur within a single event model, the individual must subconsciously hold previously spoken words in their auditory working memory. Therefore, if memory deficits are present, they may not remember which words have been spoken, and therefore will reduce the duration of their utterances to a lesser extent. Our prediction that less 'reset' will be present is based on the Zalla et al. (2003) idea that those with frontal lobe damage exhibit difficulty in discriminating large event boundaries. This means that their minds will not recognize the boundaries that typically signal new event models, and subsequently will neglect to reset the previous reductions, if any, in the durations of their utterances.

Methods

Participants

In order to recruit participants for the study, digital and paper flyers were posted in community and campus locations. Flyers were also shared with professionals who had potential mTBI clients on their caseload (e.g., professors of kinesiology). Personal Health Information (PHI) was not requested from health care providers. Instead, it was requested that flyers be shared with potential participants, and the individuals or their families contact the researchers at their own will. Participants were not included if they met the following requirements: acute head injury (less than one week post-onset), any neurological diseases or history of TBI with a greater than mild severity, developmental motor or cognitive deficits, or a failed vision or hearing screening.

The study included two experimental groups, with a total of ten participants. Prior to their scheduled participation in the experiment, each individual completed a general health questionnaire in order to gain information about demographics, lifestyle, and medical conditions or comorbidities that might affect brain function or speech. The general health questionnaire also inquired about neurological diseases to eliminate any sources (aside from concussion) of potentially impaired brain function and/or speech. All participants were monolingual, native speakers of American English. There was no reported concern regarding speech/language and no previous history of speech/language treatment among any of the participants. See Table 1 for complete demographic information.

The control group consisted of 5 participants (1 male and 4 female) between the ages of 19 and 55, with a mean age of 33.4 and a mean level of education of 16 years. There was no reported history of TBI, stroke, or neurological damage.

In addition to the general health questionnaire, participants with a history of concussion were given a semi-structured concussion history questionnaire in order to obtain information about their injuries (e.g., time elapsed since the concussion(s), severity, symptoms, and treatment). This group consisted of 5 participants (3 male and 2 female) between the ages of 21 and 52, with a mean age of 28.8 and a mean level of education of 17.2 years. Time elapsed since their most recent concussion ranged from 6 to 12 years. Participants of the concussion group were not controlled for amount of time post-concussion, as they were admitted into the study as a convenience sample. See Table 2 for complete concussion history information.

Table 1. Demographic Information

Part. ID	Sex	Age	Years education	Handedness	Race/ethnicity	High School Language?	Hx TBI/Stroke/Neuro damage?
CEB-t-1	M	55	Bachelor	R (L toothbrush)	White-nH/L	Spanish, 4y	No
CEB-t-2	F	50	Bachelor	R	White-nH/L	Spanish, 4y	No
CEB-t-3	F	19	Some college, student	R	White-nH/L	Spanish, 1y	No
CEB-t-4	F	23	Bachelor, student	L, R (throwing/cutting), either (toothbrush)	African American	Spanish, 7y	No

CEB-t-5	F	20	Some college, student	R	White-nH/L	French, 2y	No
CEB-c-1	M	52	Graduate	L	White-nH/L	Spanish, 3-4y	Yes
CEB-c-2	F	23	Bachelor, student	R	White-nH/L	N/A	Yes
CEB-c-3	F	21	Some college, student	R	White-nH/L	Spanish, 2y	Yes
CEB-c-4	F	24	Bachelor, student	R (L match)	Other-H/L	Spanish, 2y	Yes
CEB-c-6	M	24	Bachelor	R	White-nH/L	Spanish, 2y	Yes

Table 2. Concussion History

Data	Participant				
	CEB-c-1	CEB-c-2	CEB-c-3	CEB-c-4	CEB-c-6
Sex	M	F	F	F	M
Age	52	23	21	24	24
Time since concussion	7y, 5mo	9y, 8mo	12y	7y, 5mo	6y, 2mo
Return to Activities	within month	within week	within week	within week	within month
Symptom Duration	4-6 days	4-6 days	1-3 days	1 week - 3 months	1-3 days
Symptoms	"Didn't feel right", difficulty remembering, LOC	headache, "didn't feel right", drowsiness, difficulty concentrating, neck pain, fatigue/low energy, dizziness, "pressure in head", trouble sleeping, sensitivity to light, irritable, feeling slowed down, sadness, feeling "in a fog"	"Didn't feel right", fatigue/low energy, confusion	Headache, "didn't feel right", difficulty concentrating, nausea/vomiting, fatigue/low energy, dizziness, "pressure in head", trouble sleeping, sensitivity to light, more emotional, irritable	Headache, drowsiness, balance problems
Do symptoms return?	No	No	No	Yes, during academic tasks, when exposed to a lot of stimuli for extended period of time (e.g., bright lights), more irritable	No
LOC	0-30 min	N/A	>30 min and <24 hours	0-30 min	0-30 min

Data	Participant				
Treatment	Anti-nausea medicine, avoiding physical exertion	Ibuprofen, brain rest, shortened/modified school/work day, avoiding physical exertion	Acetaminophen, brain rest, RTL program, avoiding physical exertion	Acetaminophen, Ibuprofen, brain rest, avoiding physical exertion, no longer plays soccer	Acetaminophen, Ibuprofen

Procedure

Questionnaires and Screenings

Participants volunteered to take part in this study. The project was approved by the Auburn University Institutional Review Board. Prior to the start of the experiment, all participants completed a vision screening through the ZEISS Online Vision Screening.[1] ZEISS is a technology enterprise that operates internationally in optics and optoelectronics. The screening consisted of a visual acuity check, contrast vision check, and color vision check. Participants were instructed to email screenshots of their results upon completion of the screening. Vision screenings were completed in order to ensure that participant performance was not impacted by vision loss.

Participants also completed an online hearing screening provided by MDHearingaid, a midwestern hearing aid company.[2] The screening consisted of participants identifying the lowest threshold of auditory detection for a variety of frequency tones presented in each ear (250, 500, 1000, 2000, 4000, and 8000 Hertz). The test was calibrated to the maximum volume setting on the user's device. Results revealed hearing by severity, as well as an audiogram of the participant's reported thresholds. Participants were again instructed to share their results with the researchers following completion of the screening. Hearing screenings were completed in order to ensure that participant performance was not impacted by hearing loss. See Table 3 and 4 for a summary of results from vision and hearing screenings, respectively.

[1] https://www.zeiss.com/vision-care/us/better-vision/vision-screening.html#:~:text=Use%20the%20online%20ZEISS%20Online%20Vision%20Screening%20Check%2C,professional%20for%20expert%20advice%20Check%20your%20vision%20online

[2] https://www.mdhearingaid.com/hearing-test?ref=innerbody&campaign_phone=18003156284

Table 3. Vision Screening Results

Participant	Glasses/ Contacts prescribed?	Glasses/ Contacts worn?	Participa nt Concern?	Zeiss Visual Acuity	Zeiss Contrast Vision	Zeiss Color Vision
CEB-t-1	Yes	No	No	Optimal	Optimal	Optimal
CEB-t-2	Yes	Yes	No	Optimal	Optimal	**< Optimal**
CEB-t-3	Yes	Yes	No	Optimal	Optimal	Optimal
CEB-t-4	Yes	Yes	No	Optimal	**< Optimal**	Optimal
CEB-t-5	No	No	No	Optimal	Optimal	Optimal
CEB-c-1	Yes	Yes	No	Optimal	Optimal	Optimal
CEB-c-2	No	No	No	Optimal	Optimal	Optimal
CEB-c-3	No	No	No	Optimal	Optimal	Optimal
CEB-c-4	No	No	No	Optimal	Optimal	Optimal
CEB-c-6	No	No	No	Optimal	Optimal	Optimal

Table 4. Hearing Screening Results

Participant	Hearing Aids/Concern?	Hearing Screen Results (L)	Hearing Screen Results (R)
CEB-t-1	No	**Mild**	**Mild**
CEB-t-2	No	Healthy	Healthy
CEB-t-3	No	Healthy	Healthy
CEB-t-4	No	**Moderate**	Healthy
CEB-t-5	No	Healthy	Healthy
CEB-c-1	No	Healthy	Healthy
CEB-c-2	No	Healthy	Healthy
CEB-c-3	No	Healthy	Healthy
CEB-c-4	No	**Mild**	**Mild**
CEB-c-6	No	Healthy	Healthy

During the scheduled experimental sessions, all participants were administered the Montreal Cognitive Assessment (MoCA) Version 8.1[3] (Nasreddine et al., 2005) as a cognitive screening tool. The MoCA was selected due to the extensive amount of normative data obtained

[3] https://www.mocatest.org/

through its use (Rossetti et al., 2011), as well as research supporting its use to acutely screen global cognition following mTBI in adult populations (Bruijnen et al., 2020; Frenette et al., 2019). For the visuoconstructional skills portion, participants were instructed to draw the items on their own paper, and subsequently hold the drawing up to the camera. Screenshots of their completed drawings were later scored with the rest of the assessment. Upon completion, participants were given scores of up to 30 points. The mean scores for the typical group and the concussion group were grossly equal, with the concussion group (mean of 26.6) being slightly lower than the typical group (mean of 26.8). See Table 5 for a summary of MoCA results.

Additionally, participants completed both forward and reverse digit spans ranging from 3 to 7 digits. Digits were presented both auditorily and visually. Auditory presentation consisted of pre-recorded single-digits to control for the natural human tendency to chunk numbers during auditory presentation (Raiford et al., 2010). Scores were determined as percentages of trials completed correctly. For forward digit span, the typical group completed 82.6% of the trials correctly, while the concussion group performed with 73.4% accuracy. For reverse digit span, the typical group performed at 69.2%, while the concussion group successfully completed 58.6% of trials. Therefore, the typical group performed 12.53% higher than did the concussion group for forward digits, and 18.09% higher for reverse digits. This suggests that the concussion group may have mild deficits in both immediate recall and working memory. As expected, both groups scored higher on forward digit span than reverse digit span, suggesting that immediate recall is stronger than working memory among all participants.

Table 5. MoCA Results

Participant	CEB-t-1	CEB-t-2	CEB-t-3	CEB-t-4	CEB-t-5
MoCA Score	29	27	25	30	23

Participant	CEB-c-1	CEB-c-2	CEB-c-3	CEB-c-4	CEB-c-6
MoCA Score	27	28	21	27	30

As part of the Duffy structure and function examination (Duffy, 2020), participants were required to produce sequential motion rates (SMRs) and alternating motion rates (AMRs). These are two traditional diadochokinetic assessments of motor speech production with typical SMR norms for adults of 6-7 repetitions per second for /pʌ/ and /tʌ/ syllables, and 5.5-6.5 repetitions for the /kʌ/ syllable (Kent et al., 2015). AMR norms are 2.5 repetitions per second for adults.

DDK rates were calculated with a common denominator of 2 seconds to allow for adequate comparison of data. The typical group produced a mean SMR of 12.7 in 2 seconds, and a mean AMR of 4.3 in 2 seconds. The concussion group produced a mean SMR of 12.13 in 2 seconds, and a mean AMR of 4.6 in 2 seconds. Therefore, the concussion group produced SMRs at a slightly slower rate, and AMRs at a slightly higher rate than that of the typical group. These differences were deemed negligible.

Upon completion of these prerequisite questionnaires and screenings, each individual was able to schedule their participation in the experiment. Audio recordings were retrospectively analyzed for the presence of deviant speech characteristics, using the Duffy form for perceptual rating of motor speech disorders. Eight of the ten participants exhibited at least mildly deviant speech characteristics throughout the session. Notably, the distribution of these participants was equal among the two experimental groups (4 in the typical group, 4 in the concussion group).

Most of these deviations only ranged from mild to moderate when judged on frequency of occurrence, with the exception of one participant displaying marked hypernasality, and another that presented with a markedly monopitch voice. See table 6 for complete information regarding deviant speech characteristics.

Table 6. Deviant Speech Characteristics

Participant	Deviant Speech Characteristics
CEB-t-1	N/A
CEB-t-2	mildly imprecise consonants (/k/ AMR); poorly sequenced SMR (mild)
CEB-t-3	marked monopitch, mildly harsh voice, mildly distorted vowels, poorly sequenced SMRs (moderate)
CEB-t-4	marked hypernasality, moderate harshness (fry)
CEB-t-5	poorly sequenced SMRs (mild)
CEB-c-1	moderate variable rate, mild repeated phonemes
CEB-c-2	mild low pitch
CEB-c-3	mild monopitch
CEB-c-4	moderate hypernasality, moderately low pitch
CEB-c-6	N/A

Materials and Design

Materials. Materials for the experiment included 2 lists (list A and list B, found in Appendix A) of 10 novel word combinations beginning with stops and ending with fricatives (e.g., peering goats). This allows for clear boundaries when measuring word duration for data analysis. The novel combinations contained a variety of vowels and diphthongs for contrast. Each participant was provided with a list of these word combinations and was told to use them to create stories. They were told not to change the words, but to pronounce them exactly as written. For example, if the word is *stops*, they must not say *stop, stop sign*, or *bus stop*. Dummy words (e.g., purple beans, burning trash) were incorporated to facilitate participant creation of new stories, however these words were not included in data analysis.

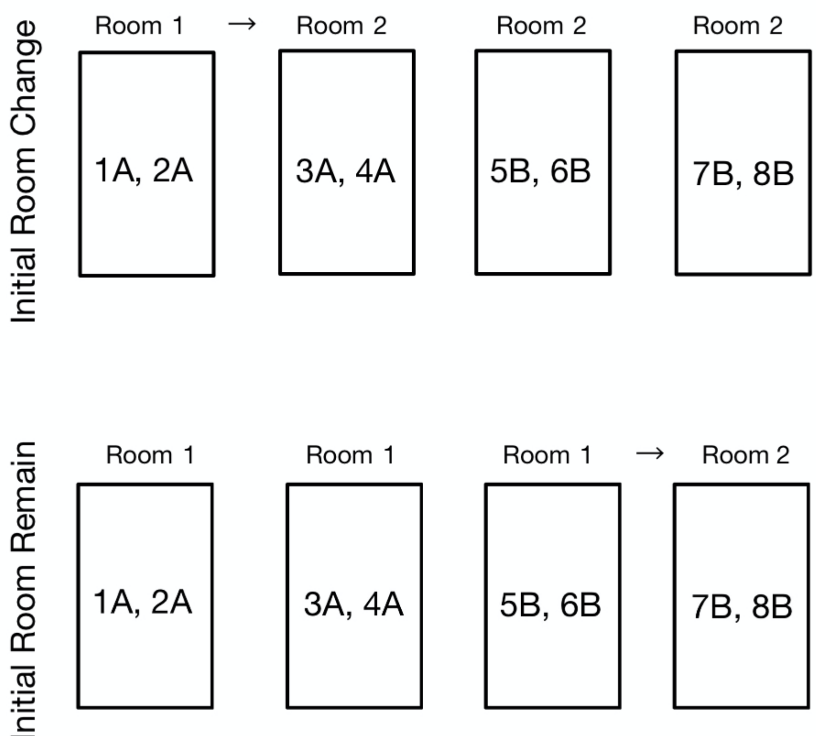
Design. The experiment took place in an online walkthrough of a virtual apartment - Riverbend Residence - one of Shapespark's virtual designs.[4] The participant was told to open the free online voice recorder, Resonate Recordings[5], which reports a target bit rate of 768 kbps and a sampling rate of 44.1 kHz. Participants were asked to open the voice recorder in a Chrome web browser, if possible, as recommended by the Resonate Recordings team. The researcher then shared their screen of the virtual apartment via Zoom, a video conferencing software. Participants were instructed to ensure that they were in a quiet room with no distractions, using headphones with a connected microphone. The participants pinned the researcher's video box in the corner of their screen to simulate the researcher's presence within the apartment. The presence of the researcher is important due to Fowler's claim that a listener must be present, making the prose more conversational and meaningful, in order for repetition reduction to occur (Fowler, 1988). After participants were told to press the record button on the Resonate Recordings website, the researcher announced the participant by study ID. Both conditions (Initial Room Change and Initial Room Remain) were subsequently carried out.

Participants were grouped into 2 conditions. In order to create a within-subject design, all participants experienced both conditions, however the order in which they experienced the conditions differed (see Figure 1 for visual layout). Condition 1 was labeled 'Initial Room Change' and condition 2 was labeled 'Initial Room Remain'. The procedure for the Initial Room Change condition is as follows: Participants were given list A and were told to create a story. Then, a dummy word was added to the list as they were told to create a second story using list A,

[4] https://www.shapespark.com
[5] https://resonaterecordings.com/voice-recorder/

along with incorporation of the dummy word. After the first 2 stories, participants were taken on a 1-minute virtual apartment tour, ultimately ending up in another room (hence the name ‘Room Change’). Once in room 2, participants were given another dummy word and were told to create a third story using word list A, and after that another dummy word to create a fourth story using word list A. After story 4, the condition changed. This is when participants were given word list B to continue creating stories. Remaining in room 2, they created story 5, and then story 6 with a dummy word. After the first 2 stories using word list B, participants remained in room 2 for the final 2 stories (7 and 8), using 2 new dummy words. The following figure depicts a visual layout of the two conditions.

Figure 1. Design Layout



Condition 2, 'Initial Room Remain,' did the exact opposite of Condition 1. They were given list A and told to create a story. Then, a dummy word was added in and they were told to create a second story with list A plus the dummy word. After the first 2 stories, participants remained in room 1 instead of initially changing to room 2. Still in room 1 (Initial Room Remain), participants were given another dummy word and were told to create a third story using word list A, and after that another dummy word to create a fourth story using word list A. After story 4, participants were given word list B to continue creating stories. Remaining in room 1, they created story 5, and then story 6 with a dummy word. After the first 2 stories using word list B, participants were given a 1-minute virtual apartment tour and ended up in room 2 for the final 2 stories (7 and 8), using 2 new dummy words. All participants in both conditions were given breaks of approximately 1 minute between each story.

After the experiment, waveform audio (WAV) files were downloaded from the Resonate Recordings website to the participant's computer while still logged on to the Zoom session. Resonate Recordings does not store any recordings on their website, as files are downloaded directly from the participant's web browser to their personal computer. From there, participants uploaded the files to a Box link (a link to a cloud storage company) sent by the researcher, where they could then be downloaded for analysis.

Data Analysis

The verbal story productions were recorded as WAV files on Resonate Recordings and saved to the participants' personal computers. Each participant uploaded their WAV file to a Drop Box, from which they were directly uploaded to a Box folder. Files were retrieved individually in Praat, a speech analysis software (Boersma & Weenink, 2021). In order to understand patterns of repetition reduction, the acoustic measurements of 10 repeated novel word combinations were examined using various custom scripts in MATLAB Statistics (The Mathworks, 2022), a programming language and numeric computing environment. The dependent variables included duration, vowel centralization and vowel space, as well as pitch. First, durations of the voiced segments of target word productions within each story were measured through a custom MATLAB script using landmark detection to measure the amount of time between voice onset and offset (Boyce et al., n.d.). The concept of articulatory-acoustic vowel space (AAVS) was used to measure vowel centralization. This was completed through a custom MATLAB script measuring F1-F2 variance within each targeted utterance that represents a global articulatory-acoustic range of motion (Whitfield & Goberman, 2014). This is the articulatory space that we are looking for. Lastly, maximum and minimum frequency measurements were taken for the voiced segments of the first mentions of each target word in order to find the ranges of pitch.

Reliability

In order to test for reliability, a second researcher re-analyzed 20% of the tokens. An intra-class correlation coefficient (ICC) test was run for each dependent variable for the 20% that both researchers analyzed, to calculate inter-rater reliability. ICC for duration was 0.965 with a 95% confidence interval between 0.952 and 0.974 (F [159]= 55.448, $p < 0.001$). The qualitative interpretation of these results for duration is that they are of excellent clinical significance. ICC for pitch measurements was 0.697 with a 95% confidence interval between 0.608 and 0.769 (F [159]= 5.611, $p < 0.001$). The reliability coefficient for pitch is of good clinical significance. Qualitative interpretations of the ICCs come from Cicchetti (Cicchetti, 1994).

Results

Duration

Fixed effect estimates for the mixed linear model for duration, summarized in Table 7.1, revealed no significant group differences between the concussion group and the typical group. However, there was an effect of story number. With story 1 set as the baseline, story 2 was estimated at 79ms shorter; $p = .015$. Figure 2 shows linear trends for the duration measures, separated by group (set A and B), across stories.

Table 7.1.

Fixed effects:						
Parameter	Estimate	*SE*	*df*	*t-value*	*p-value*	
(Intercept)	1.21892	0.04103	7.51977	29.711	4.52E-09	***
Group	-0.08277	0.08204	7.5147	-1.009	0.344415	
Story 2	-0.07944	0.03267	606.2438	-2.432	0.015308	*
Story 3	-0.08122	0.03482	215.612	-2.333	0.02058	*
Story 4	-0.15385	0.03813	77.49877	-4.035	0.000127	***
Set B	-0.0859	0.03951	14.37904	-2.174	0.046839	*
Group: Story 2	-0.07261	0.06532	606.1223	-1.112	0.266777	
Group: Story 3	-0.01444	0.06963	215.4263	-0.207	0.835929	
Group: Story 4	-0.05598	0.07626	77.47468	-0.734	0.465102	
Group: Set B	-0.06599	0.07902	14.40065	-0.835	0.417298	
Story 2: Set B	0.05083	0.04552	534.6013	1.117	0.264644	
Story 3: Set B	-0.05515	0.0463	117.9127	-1.191	0.235972	
Story 4: Set B	0.03445	0.0476	29.74658	0.724	0.474821	
Group: Story 2: Set B	0.17137	0.09106	534.6335	1.882	0.060378	.
Group: Story 3: Set B	0.08469	0.09261	117.9428	0.914	0.362327	
Group: Story 4: Set B	0.13024	0.09521	29.76816	1.368	0.18157	

Notes: '***' p <.001 '*' 0.05 '.' 0.1. *SE*: Standard Error. *df*: degrees of freedom

When story number was treated as an integer in a second model, the relationship between story number and duration had a negative slope (-.046ms; p = .0003). Another pair of mixed effects linear models was performed with story 2 as the baseline for each condition, to compare durations for story 2 and story 3. For set A (room change condition), summarized in Table 7.2, story 3 was not significantly different in duration than story 2; p = 0.957. For set B (room remain condition), summarized in Table 7.3, story 3 was significantly shorter in duration than that of story 2 (average of about 108ms shorter); p = .0009.

Table 7.2.

Releveled (intercept = Story2; control Group; Set A

Fixed effects:						
Parameter	Estimate	*SE*	*df*	*t-value*	*p-value*	
(Intercept)	1.13948	0.03666	6.53139	31.084	2.41E-08	***
Group	-0.15538	0.0733	6.5274	-2.12	0.0746	.
Story 1	0.07944	0.03267	606.1646	2.432	0.0153	*
Story 3	-0.00178	0.03267	606.1645	-0.054	0.9566	
Story 4	-0.07441	0.03484	219.7387	-2.136	0.0338	*
Set B	-0.03507	0.04092	10.61805	-0.857	0.4103	
Group: Story 1	0.07261	0.06532	606.0433	1.112	0.2668	
Group: Story 3	0.05817	0.06532	606.0433	0.891	0.3735	
Group: Story 4	0.01663	0.06968	219.6949	0.239	0.8116	
Group: Set B	0.10539	0.08184	10.63007	1.288	0.2251	
Story 1: Set B	-0.05083	0.04552	534.1453	-1.117	0.2647	
Story 3: Set B	-0.10598	0.04552	534.1453	-2.328	0.0203	*
Story 4: Set B	-0.01638	0.04634	119.0906	-0.354	0.7243	
Group: Story 1: Set B	-0.17137	0.09106	534.178	-1.882	0.0604	.
Group: Story 3: Set B	-0.08668	0.09106	534.1781	-0.952	0.3416	
Group: Story 4: Set B	-0.04113	0.0927	119.1739	-0.444	0.6581	

Notes: '***' p <.001 '*' 0.05 '.' 0.1. *SE*: Standard Error. *df*: degrees of freedom

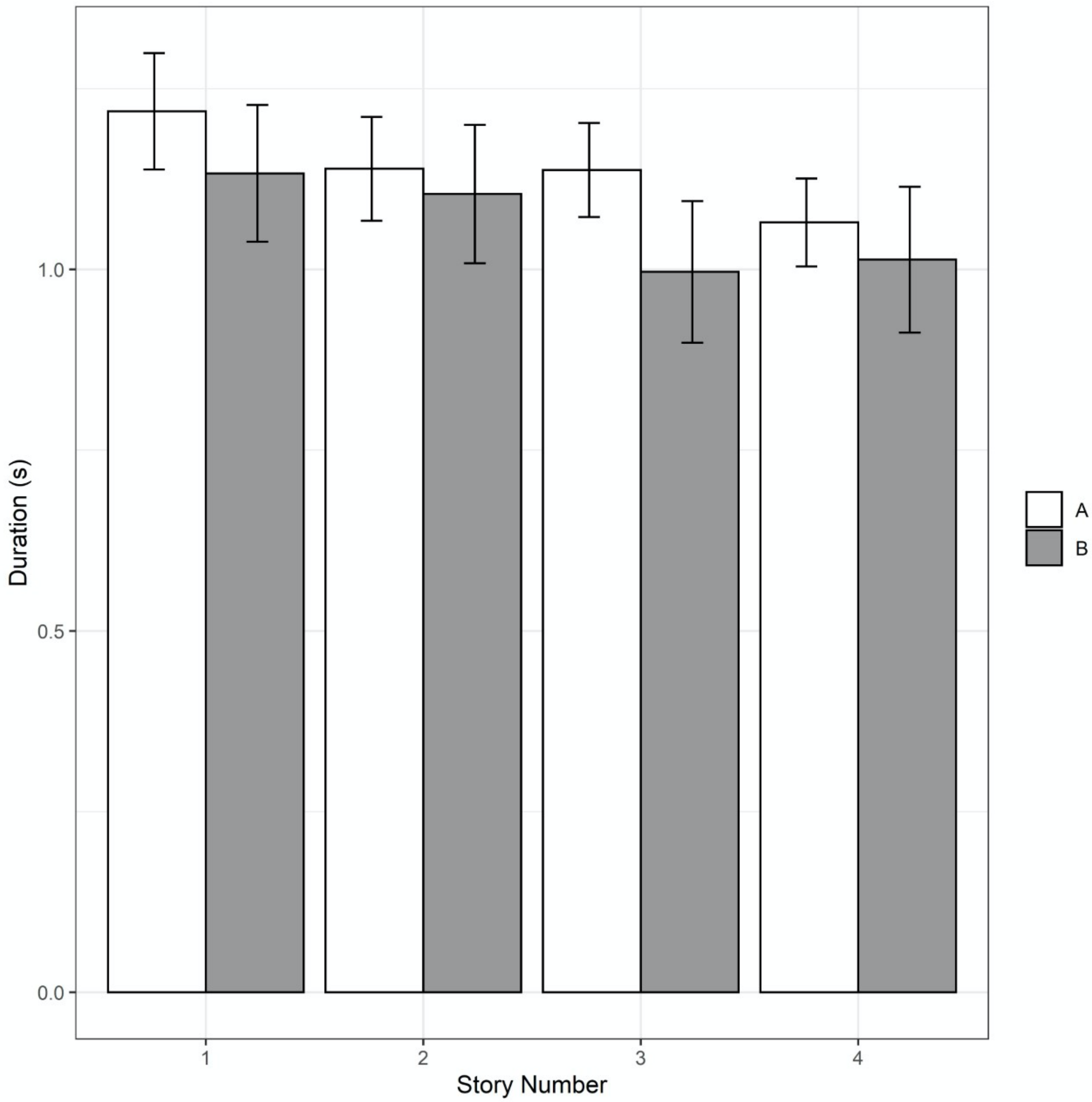
Table 7.3.

Releveled (intercept = Story2; control Group; Set B

Fixed effects:						
Parameter	Estimate	*SE*	*df*	*t-value*	*p-value*	
(Intercept)	1.10441	0.04884	10.07342	22.611	5.76E-10	***
Group	-0.05	0.09769	10.07837	-0.512	0.619812	
Story 1	0.02861	0.03249	588.2934	0.88	0.378989	
Story 3	-0.10776	0.03249	588.2934	-3.317	0.000968	***
Story 4	-0.09079	0.03367	170.5024	-2.697	0.007702	**
Set A	0.03507	0.04092	10.76103	0.857	0.410112	
Group: Story 1	-0.09876	0.06501	588.5677	-1.519	0.129262	
Group: Story 3	-0.02851	0.06501	588.5677	-0.439	0.661166	
Group: Story 4	-0.0245	0.06735	170.8298	-0.364	0.716519	
Group: Set A	-0.10538	0.08184	10.77323	-1.288	0.224827	
Story 1: Set A	0.05083	0.04552	534.7228	1.117	0.26464	
Story 3: SetA	0.10598	0.04552	534.7228	2.328	0.020278	*
Story 4: Set A	0.01638	0.04634	119.5563	0.353	0.724369	
Group: Story 1: Set A	0.17137	0.09106	534.7547	1.882	0.060378	.
Group: Story 3: Set A	0.08668	0.09106	534.7547	0.952	0.341557	
Group: Story 4: Set A	0.04113	0.0927	119.6395	0.444	0.658093	

Notes: '***' p <.001 '*' 0.05 '.' 0.1. *SE*: Standard Error. *df*: degrees of freedom

Figure 2. Linear Trends for Duration



Pitch

Fixed effect estimates for the mixed linear model for pitch, summarized in Table 8.1, revealed no significant main effects on pitch measurements; p = 7.73E-04. When story number was treated as an integer in a second model, the relationship between story number and pitch was not significant; $p = .239$. Another pair of mixed effects linear models was performed that set story 2 as the baseline for each condition, to compare pitch for story 2 and story 3. For both set A (room change condition) and set B (room remain condition), summarized in Table 8.2 and 8.3, respectively, story 3 was not significantly different in duration than story 2 ($p = .327$, $p = .359$, respectively).

Table 8.1

Fixed effects:

Parameter	Estimate	*SE*	*df*	*t-value*	*p-value*	
(Intercept)	89.121	12.103	4.927	7.363	7.73E-04	***
Group	-18.162	24.204	4.928	-0.75	0.48728	
Story 2	-11.157	7.257	370.582	-1.537	0.125043	
Story 3	-4.032	8.274	62.737	-0.487	0.627749	
Story 4	-6.702	9.744	24.505	-0.688	0.498037	
Set B	2.957	11.49	14.444	0.257	0.80056	
Group: Story 2	-1.117	14.512	370.593	-0.077	0.938702	
Group: Story 3	-8.672	16.546	62.739	-0.524	0.602041	
Group: Story 4	-28.042	19.486	24.51	-1.439	0.162778	
Group: Set B	-1.585	22.979	14.451	-0.069	0.94595	
Story 2: Set B	10.561	10.707	135.566	0.986	0.325715	
Story 3: Set B	-3.243	13.139	21.507	-0.247	0.807411	
Story 4: Set B	-4.061	16.414	10.373	-0.247	0.809416	
Group: Story 2: Set B	4.999	21.417	135.701	0.233	0.815796	
Group: Story 3:Set B	10.619	26.277	21.524	0.404	0.690103	
Group: Story 4: Set B	29.904	32.827	10.378	0.911	0.382994	

Notes: ‘***’ p <.001 ‘*’ 0.05 ‘.’ 0.1. *SE*: Standard Error. *df*: degrees of freedom

Table 8.2

Releveled (intercept = Story2; control Group; Set A

Fixed effects:						
Parameter	Estimate	*SE*	*df*	*t-value*	*p-value*	
(Intercept)	77.965	11.421	5.599	6.827	0.000649	***
Group	-19.28	22.84	5.602	-0.844	0.433139	
Story 1	11.158	7.257	370.569	1.537	0.125037	
Story 3	7.125	7.257	370.569	0.982	0.326832	
Story 4	4.455	8.286	63.18	0.538	0.592709	
Set B	13.517	8.532	40.621	1.584	0.120872	
Group: Story 1	1.117	14.512	370.579	0.077	0.938682	
Group: Story 3	-7.556	14.512	370.579	-0.521	0.602931	
Group: Story 4	-26.926	16.57	63.197	-1.625	0.109155	
Group: Set B	3.412	17.065	40.65	0.2	0.842517	
Story 1: Set B	-10.562	10.708	135.562	-0.986	0.325694	
Story 3: Set B	-13.803	10.708	135.562	-1.289	0.199548	
Story 4:Set B	-14.622	13.147	21.518	-1.112	0.278334	
Group: Story 1: Set B	-4.999	21.417	135.696	-0.233	0.815778	
Group: Story 3:Set B	5.621	21.417	135.696	0.262	0.79336	
Group: Story 4: Set B	24.906	26.294	21.535	0.947	0.354041	

Notes: '***' p <.001 '*' 0.05 '.' 0.1. *SE*: Standard Error. *df*: degrees of freedom

Table 8.3

Releveled (intercept = Story2; control Group; Set B

Fixed effects:						
Parameter	Estimate	*SE*	*df*	*t-value*	*p-value*	
(Intercept)	91.4821	12.251	7.4802	7.467	0.000101	***
Group	-15.8655	24.5039	7.4864	-0.647	0.536671	
Story 1	0.5959	7.2724	241.3517	0.082	0.934759	
Story 3	-6.6785	7.2724	241.3517	-0.918	0.359361	
Story 4	-10.1672	8.2331	32.8732	-1.235	0.225611	
Set A	-13.518	8.5317	40.6235	-1.584	0.120849	
Group: Story 1	-3.8819	14.5499	241.7123	-0.267	0.789849	
Group: Story 3	-1.9348	14.5499	241.7123	-0.133	0.894324	
Group: Story 4	-2.0206	16.4699	32.9265	-0.123	0.903103	
Group: Set A	-3.4138	17.0645	40.6524	-0.2	0.842436	
Story 1: Set A	10.5614	10.7074	135.5574	0.986	0.325716	
Story 3: Set A	13.8039	10.7074	135.5574	1.289	0.199528	
Story 4: Set A	14.6226	13.1465	21.5158	1.112	0.278291	
Group: Story 1: Set A	4.9986	21.4167	135.6917	0.233	0.815804	
Group: Story 3: Set A	-5.6205	21.4167	135.6917	-0.262	0.793385	
Group: Story 4: Set A	-24.9043	26.2934	21.5332	-0.947	0.354062	

Notes: '***' p <.001 '*' 0.05 '.' 0.1. *SE*: Standard Error. *df*: degrees of freedom

Articulatory-Acoustic Vowel Space (AAVS)

Just as for pitch, fixed effect estimates for the mixed linear model for AAVS, summarized in Table 9.1, revealed no significant differences in group, story, or set; *p* = 1.51E-05. Data analysis revealed a slight possibility of a group difference (concussion vs typical); however, the difference was not deemed significant; p = .0911.

When story number was treated as an integer in a second model, the relationship between story number and AAVS was likewise not significant; *p* = .917. Another pair of mixed effects linear models was performed that set story 2 as the baseline for each condition, to compare AAVS for story 2 and story 3. For both set A (room change condition) and set B (room remain condition), summarized in Table 9.2 and Table 9.3, respectively, story 3 was not significantly different in AAVS than story 2 (*p* =.428, *p* = .886, respectively).

Table 9.1

Fixed effects:

Parameter	Estimate	*SE*	*df*	*t-value*	*p-value*	
(Intercept)	64641.96	6087.604	6.949	10.619	1.51E-05	***
Group	-23859.1	12173.57	6.949	-1.96	0.0911	.
Story 2	-5701.89	3629.436	45.382	-1.571	0.1231	
Story 3	-2799.6	3686.08	47.109	-0.76	0.4513	
Story 4	-1082.56	3778.599	40.551	-0.286	0.776	
Set B	-2182.42	4214.417	18.456	-0.518	0.6107	
Group: Story 2	3013.985	7257.897	45.382	0.415	0.6799	
Group: Story 3	4963.767	7371.169	47.109	0.673	0.504	
Group: Story 4	-2302.2	7556.182	40.551	-0.305	0.7622	
Group: Set B	22040.77	8427.703	18.456	2.615	0.0173	*
Story 2: Set B	12718.53	5106.564	43.887	2.491	0.0166	*
Story 3: Set B	10342.31	5108.803	44.246	2.024	0.049	*
Story 4: Set B	3478.231	5112.533	44.269	0.68	0.4998	
Group: Story 2: Set B	-14069.3	10211.76	43.887	-1.378	0.1753	
Group: Story 3: Set B	-21187.1	10216.23	44.246	-2.074	0.0439	*
Group: Story 4: Set B	-2438.76	10223.69	44.269	-0.239	0.8126	

Notes: ‘***’ p <.001 ‘*’ 0.05 ‘.’ 0.1. *SE*: Standard Error. *df*: degrees of freedom

Table 9.2

Releveled (intercept = Story2; Set A

Fixed effects:						
Parameter	Estimate	*SE*	*df*	*t-value*	*p-value*	
(Intercept)	58940.09	6004.548	8.617	9.816	5.74E-06	***
Group	-20845.1	12007.48	8.617	-1.736	0.1181	
Story 1	5701.888	3629.428	45.382	1.571	0.1231	
Story 3	2902.298	3629.428	45.382	0.8	0.4281	
Story 4	4619.338	3686.068	47.109	1.253	0.2163	
Set B	10536.22	4248.901	22.561	2.48	0.0211	*
Group: Story 1	-3013.99	7257.881	45.382	-0.415	0.6799	
Group: Story 3	1949.782	7257.881	45.382	0.269	0.7894	
Group: Story 4	-5316.19	7371.145	47.109	-0.721	0.4743	
Group: Set B	7971.415	8496.661	22.561	0.938	0.3581	
Story 1: Set B	-12718.6	5106.554	43.887	-2.491	0.0166	*
Story 3: Set B	-2376.16	5106.554	43.887	-0.465	0.644	
Story 4: Set B	-9240.17	5108.796	44.246	-1.809	0.0773	.
Group: Story 1: Set B	14069.3	10211.74	43.887	1.378	0.1753	
Group: Story 3: Set B	-7117.78	10211.74	43.887	-0.697	0.4895	
Group: Story 4: Set B	11630.61	10216.22	44.246	1.138	0.2611	

Notes: '***' p <.001 '*' 0.05 '.' 0.1. *SE*: Standard Error. *df*: degrees of freedom

Table 9.3
Releveled (intercept = Story2; Set B

Fixed effects:						
Parameter	Estimate	*SE*	*df*	*t-value*	*p-value*	
(Intercept)	69477.53	6749.066	9.556	10.294	1.75E-06	***
Group	-12873.2	13496.32	9.556	-0.954	0.3637	
Story 1	-7016.68	3635.532	45.165	-1.93	0.0599	.
Story 3	526.113	3635.532	45.165	0.145	0.8856	
Story 4	-4620.88	3709.993	44.723	-1.246	0.2194	
Set A	-10536.4	4248.939	22.562	-2.48	0.0211	*
Group: Story 1	11055.34	7270.087	45.165	1.521	0.1353	
Group: Story 3	-5168.02	7270.087	45.165	-0.711	0.4808	
Group: Story 4	6314.374	7418.989	44.723	0.851	0.3992	
Group: Set A	-7971.69	8496.737	22.562	-0.938	0.3581	
Story 1: Set A	12718.6	5106.582	43.887	2.491	0.0166	*
Story 3: Set A	2376.153	5106.582	43.887	0.465	0.644	
Story 4: Set A	9240.159	5108.822	44.245	1.809	0.0773	.
Group: Story 1: Set A	-14069.3	10211.79	43.887	-1.378	0.1753	
Group: Story 3: Set A	7117.778	10211.79	43.887	0.697	0.4895	
Group: Story 4: Set A	-11630.6	10216.27	44.245	-1.138	0.2611	

Notes: ‘***’ p <.001 ‘*’ 0.05 ‘.’ 0.1. *SE*: Standard Error. *df*: degrees of freedom

Discussion

In this experiment, 10 individuals produced 8 stories within a virtual environment. Ten target phrases were analyzed for significant changes in pitch, duration, and AAVS across the 10 stories. Specifically, these variables were analyzed between story 2 and story 3 of each condition (room change and room remain) to determine whether or not event boundaries affect speech differently for individuals who have experienced mTBI than they do for typical individuals, without a history of brain injury. All aims for the study were successfully accomplished. The first aim was to run a pilot study to confirm Meagher and Fowler's findings, with key changes in task and mode, within a virtual environment. We hypothesized that we would be able to accomplish this aim through a partial replication of their study. Our study supports this hypothesis as it is the first partial replication of the effects of event boundaries found within their experiment. Meagher and Fowler recommended that future studies investigate the degree to which spontaneous speech is affected by active, physical and perceptual engagement (Meagher & Fowler, 2014). Our study confirmed that there is an event boundary-based phonetic reduction effect, even within a virtual environment. According to Radvansky et al. (2011), virtual environments produce deficits in cognition (i.e., less accurate performance secondary to a lesser amount of spatial cues) that do not occur within real environments. Although the effects of repetition reduction may be reduced within this virtual environment, they are still present. This suggests that physical engagement is not required for this effect to be seen, but that perceptual engagement is the more essential factor.

Our second aim was to compare repetition reduction in persons with a history of mTBI with healthy control participants. We hypothesized that the mTBI sample would demonstrate reduced repetition reduction secondary to deficits in auditory working memory. There was not evidence to support this hypothesis, as there was not a significant difference seen between the two experimental groups (concussion and typical) for duration.

The third aim was to compare the role that event boundaries play in running speech in persons with mTBI with healthy control participants. We hypothesized that the mTBI group would demonstrate reduced 'reset' when event boundaries were changed, secondary to potential deficits in discriminating large event boundaries (Zalla et al., 2003). Again, there was no evidence to support this hypothesis as no significant difference was seen between the two groups following a room change. In fact, no significant effect was found between groups for duration, pitch, or AAVS. This supports Cannito's findings that it is not common to see notable deficits or disorders that result from sport injuries unless the injury is severe (Cannito, 2014). It may be that these participants' injuries did not significantly affect cognition or memory due to their mild severity, and that more severe damage and frontal lobe involvement may be necessary to have a negative effect on these higher order skills (Zalla et al., 2003). Another explanation for the lack of differences seen between groups could be the amount of time that each participant had been post head injury (6-12 years). Per Schretlen and Shapiro's findings, cognitive functioning typically returns to baseline within 1-3 months of mild head injury (Schretlen & Shapiro, 2003). Therefore, the concussion participants may have reached their baseline cognitive skills long before their participation in this experiment. Lastly, due to the limited number of participants, this study may have lacked the statistical power necessary for the effect between groups to be seen. Perhaps between-group differences would be evident within a larger sample size.

Limitations

There are a few limitations to the present study that merit discussion. There was a limited number of participants (n=10). This may have provided insufficient power for the effect size, and may be a reason that no significant difference was seen in duration, pitch, or AAVS between the two groups (concussion and typical). Also, it is possible that the variation in sex and age between groups may have obscured changes in pitch. The typical group contained a greater number of females and a slightly higher mean age than that of the concussion group. Future research should normalize for speakers' baseline fundamental frequencies. Similarly, the non-significant differences seen within AAVS may be attributed to lack of normalizing AAVS by each individual's baseline measure. Future research should examine these variables within a larger, more controlled population, and with normalized values for pitch and AAVS. Additionally, participants within the concussion group were not controlled for amount of time post-concussion. This sample was obtained by convenience due to a number of factors, including number of available participants, time constraint, and the limiting effects of the Coronavirus pandemic. If future studies target a population that is closer to time of injury, perhaps between-group differences will be more evident.

Lastly, there were a number of uncontrolled variables due to the nature of the virtual environment. Each participant completed the study on their own computer, within a variety of settings. Although it was recommended that they complete the study away from noise and other distractions, some participants chose to participate in public settings (e.g., a library). Surrounding activity may have taken away from their immersion within the virtual environment. Other participants experienced internet malfunctions, such as disconnections from Zoom or from the Shapespark website hosting the virtual environment. It is recommended that future studies be conducted within a controlled environment (e.g., a lab), and that all participants complete the experiment on a common computer to control for these differences.

Conclusion

Despite the limitations, the present research provides intriguing results that will be useful for future research and clinical application. The data show that phonetic reduction does occur within a single virtual room, and that walking through virtual doorways does result in a lesser reduction in duration. Specifically, Meagher and Fowler's basic finding were successfully confirmed within a virtual environment. Thus, the present study supports and expands on Meagher and Fowler's basic finding that event boundaries, specifically doorways, do prompt 'resets' of phonetic reduction within running speech (2014). This provides an idea of how speech can be affected by perceptual engagement alone. These results should be kept in mind when treating patients within multiple different settings. Carryover of learned skills may be affected by event boundaries when treating any patient, especially those with more severe brain injuries. The results may be explained by the Event Horizon model (Radvansky & Zacks, 2017), which suggests that walking through doorways prompts the brain to create a new event model. Once that new event model is created, information from the previous event model is less accessible. Therefore, patients with severe brain injuries may require greater repetition, or learning within a variety of settings in order to demonstrate successful recall and carryover of new information.

Although no significant effects were seen within acoustic speech characteristics between the two groups, there was a difference seen within digit span results. The typical group scored higher on both forward and reverse digits; however, MoCA scores were nearly identical between the two groups. This suggests that perhaps cognitive functioning is not greatly affected by concussion, but that working memory is the more affected function. Although the MoCA does address reverse digit span, it only contains 1 trial of a 3-digit reversal. Therefore, the digit span reversal within the digit span assessment itself far more extensive than that within the MoCA.

Overall, there is evidence for underlying subclinical differences in working memory between the two groups, even within a limited sample size.

Due to the recent increase in use of teletherapy secondary to the effects of the Coronavirus, it should be kept in mind that the effects of event boundaries are evident within a virtual environment as well. Therefore, therapists should be aware of potential event boundaries within their therapy sessions, whether it be on the patient's end (patient walking through a doorway), or on the therapist's end (therapist walking through a doorway), triggering a new event model within the patient's brain. This may be a barrier to the patient's generalization of skills or information learned within their therapy session. However, therapists may also use this to their advantage by allowing the patient to practice their skills within a variety of different rooms and environments to make novel information more accessible.

References

Bard, E. G., Anderson, A. H., Sotillo, C., Aylett, M., Doherty-Sneddon, G., & Newlands, A. (2000). Controlling the Intelligibility of Referring Expressions in Dialogue. *Journal of Memory and Language*, *42*(1), 1–22. https://doi.org/10.1006/jmla.1999.2667

Bazarian, J. J., Wong, T., Harris, M., Leahey, N., & Dombovy, S. M. & M. (1999). Epidemiology and predictors of post-concussive syndrome after minor head injury in an emergency population. *Brain Injury*, *13*(3), 173–189. https://doi.org/10.1080/026990599121692

Boersma, P., & Weenink, D. (2021). *Praat: Doing Phonetics by Computer* (6.1.16). http://www.praat.org/

Boyce, S., Fell, H., & Macauslan, J. (n.d.). *SpeechMark: Landmark Detection Tool for Speech Analysis*.

Bruijnen, C. J. W. H., Dijkstra, B. A. G., Walvoort, S. J. W., Budy, M. J. J., Beurmanjer, H., De Jong, C. A. J., & Kessels, R. P. C. (2020). Psychometric properties of the Montreal Cognitive Assessment (MoCA) in healthy participants aged 18–70. *International Journal of Psychiatry in Clinical Practice*, *24*(3), 293–300. https://doi.org/10.1080/13651501.2020.1746348

Cannito, M. P. (2014). Clinical assessment of motor speech disorders in adults with concussion. *Seminars in Speech and Language*, *35*(3), 221–233. https://doi.org/10.1055/s-0034-1384684

Cassidy, J. D., Boyle, E., & Carroll, L. J. (2014). Population-based, inception cohort study of the incidence, course, and prognosis of mild traumatic brain injury after motor vehicle collisions. *Archives of Physical Medicine and Rehabilitation*, *95*(3 SUPPL), S278–S285.

https://doi.org/10.1016/j.apmr.2013.08.295

Chafe, W. L. (1974). *LANGUAGE AND CONSCIOUSNESS*. https://about.jstor.org/terms

Cicchetti, D. V. (1994). Guidelines, Criteria, and Rules of Thumb for Evaluating Normed and Standardized Assessment Instruments in Psychology. *Psychological Assessment*, *6*(4), 284–290. https://doi.org/10.1037/1040-3590.6.4.284

Davis, G. A., Anderson, V., Babl, F. E., Gioia, G. A., Giza, C. C., Meehan, W., Moser, R. S., Purcell, L., Schatz, P., Schneider, K. J., Takagi, M., Yeates, K. O., & Zemek, R. (2017). What is the difference in concussion management in children as compared with adults? A systematic review. In *British Journal of Sports Medicine* (Vol. 51, Issue 12, pp. 949–957). BMJ Publishing Group. https://doi.org/10.1136/bjsports-2016-097415

Eijk, L., Fletcher, A., McAuliffe, M., & Janse, E. (2020). The effects of word frequency and word probability on speech rhythm in Dysarthria. *Journal of Speech, Language, and Hearing Research*, *63*(9), 2833–2845. https://doi.org/10.1044/2020_JSLHR-19-00389

Fowler. (1988). DIFFERENTIAL SHORTENING OF REPEATED CONTENT WORDS PRODUCED IN VARIOUS COMMUNICATIVE CONTEXTS". In *LANGUAGE AND SPEECH* (Vol. 3).

Fowler, & Housum. (1987). Talkers' signaling of "new" and "old" words in speech and listeners' perception and use of the distinction. *Journal of Memory and Language*, *26*(5), 489–504. https://doi.org/10.1016/0749-596X(87)90136-7

Frenette, L. C., Tinawi, S., Correa, J. A., Alturki, A. Y., LeBlanc, J., Feyz, M., & de Guise, E. (2019). Early detection of cognitive impairments with the Montreal Cognitive Assessment in patients with uncomplicated and complicated mild traumatic brain injury. *Brain Injury*, *33*(2), 189–197. https://doi.org/10.1080/02699052.2018.1542506

Gahl, S., Yao, Y., & Johnson, K. (2012). Why reduce? Phonological neighborhood density and phonetic reduction in spontaneous speech. *Journal of Memory and Language*, *66*(4), 789–806. https://doi.org/10.1016/j.jml.2011.11.006

Hanten, G., Li, X., Ibarra, A., Wilde, E. A., Barnes, A., McCauley, S. R., McCarthy, J., Hoxhaj, S., Mendez, D., Hunter, J. V., Levin, H. S., & Smith, D. H. (2013). Updating memory after mild traumatic brain injury and orthopedic injuries. *Journal of Neurotrauma*, *30*(8), 618–624. https://doi.org/10.1089/neu.2012.2392

Hiploylee, C., Dufort, P. A., Davis, H. S., Wennberg, R. A., Tartaglia, M. C., Mikulis, D., Hazrati, L. N., & Tator, C. H. (2017). Longitudinal study of postconcussion syndrome: Not everyone recovers. *Journal of Neurotrauma*, *34*(8), 1511–1523. https://doi.org/10.1089/neu.2016.4677

Jacobs, C. L., Yiu, L. K., Watson, D. G., & Dell, G. S. (2015). Why are repeated words produced with reduced durations? Evidence from inner speech and homophone production. *Journal of Memory and Language*, *84*, 37–48. https://doi.org/10.1016/j.jml.2015.05.004

Kaland, C., & Himmelmann, N. P. (2020). Repetition Reduction Revisited: The Prosody of Repeated Words in Papuan Malay. *Language and Speech*, *63*(1), 31–55. https://doi.org/10.1177/0023830918820044

Kent, R. A. Y. D., Kent, J. F., & Rosenbek, J. C. (2015). *MAXIMUM PERFORMANCE TESTS OF SPEECH PRODUCTION Phonation Volume*. *52*(November 1987), 367–387.

Lam, T. Q., & Marian, V. (2015). Repetition reduction during word and concept overlap in bilinguals q. *Journal of Memory and Language*, *84*, 88–107.

https://doi.org/10.1016/j.jml.2015.05.005

Lawrence, Z., & Peterson, D. (2014). *Mentally walking through doorways causes forgetting: The location updating effect and imagination*. https://doi.org/10.1080/09658211.2014.980429

Lefevre-Dognin, C., Cogné, M., Perdrieau, V., Granger, A., Heslot, C., & Azouvi, P. (2021). Definition and epidemiology of mild traumatic brain injury. *Neurochirurgie*, *67*(3), 218–221. https://doi.org/10.1016/j.neuchi.2020.02.002

Lieberman, P. (1963). Some Effects of Semantic and Grammatical Context on the Production and Perception of Speech. *Language and Speech*, *6*(3), 172–187. https://doi.org/10.1177/002383096300600306

Lindblom, B. (1990). *Explaining Phonetic Variation - A Sketch of the H&H Theory*. 2015.

Meagher, & Fowler. (2014). Embedded articulation: Shifts in location influence speech production. *Language, Cognition and Neuroscience*, *29*(5), 561–567. https://doi.org/10.1080/01690965.2013.791704

Merritt, V. C., Padgett, C. R., & Jak, A. J. (2019). *The Clinical Neuropsychologist A systematic review of sex differences in concussion outcome: What do we know?* https://doi.org/10.1080/13854046.2018.1508616

Nasreddine, Z. S., Phillips, N. A., Bedirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J. L., & Chertkow, H. (2005). The Montreal Cognitive Assessment, MOCA: A brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society*, *53*(4), 695–699.

Oldenburg, C., Lundin, A., Edman, G., Nygren-de Boussard, C., & Bartfai, A. (2016). Cognitive reserve and persistent post-concussion symptoms—A prospective mild traumatic brain injury (mTBI) cohort study. *Brain Injury*, *30*(2), 146–155. https://doi.org/10.3109/02699052.2015.1089598

Pettijohn, K. A., & Radvansky, G. A. (2018). *Walking through doorways causes forgetting: recall*. https://doi.org/10.1080/09658211.2018.1489555

Radvansky, G. A., Krawietz, S. A., & Tamplin, A. K. (2011). Walking through doorways causes forgetting: Further explorations. *The Quarterly Journal of Experimental Psychology*, *64*(8), 1632–1645. https://doi.org/10.1080/17470218.2011.571267

Radvansky, G. A., & Zacks, J. M. (2017). Event boundaries in memory and cognition. In *Current Opinion in Behavioral Sciences* (Vol. 17, pp. 133–140). Elsevier Ltd. https://doi.org/10.1016/j.cobeha.2017.08.006

Raiford, S. E., Coalson, D. L., Saklofske, D. H., & Weiss, L. G. (2010). CHAPTER 2 - Practical Issues in WAIS-IV Administration and Scoring. In *WAIS-IV Clinical Use and Interpretation* (pp. 25–59).

Rossetti, H. C., Lacritz, L. H., Cullum, C. M., & Weiner, M. F. (2011). Normative data for the montreal cognitive assessment (MOCA) in a population-based sample. *Neurology*, *78*(10), 765–766. https://doi.org/10.1212/01.wnl.0000413072.54070.a3

Salvatore, A. P., Cannito, M. P., Hewitt, J., Dolan, L. D., King, G., & Brassil, H. E. (2019). Motor speech and motor limb status in athletes following a concussion. *Clinical Archives of Communication Disorders*, *4*(3), 214–222. https://doi.org/10.21849/cacd.2019.00150

Scarmeas, N., & Stern, Y. (2003). Cognitive reserve and lifestyle. In *Journal of Clinical and Experimental Neuropsychology* (Vol. 25, Issue 5, pp. 625–633). Taylor & Francis Group .

https://doi.org/10.1076/jcen.25.5.625.14576

Schretlen, D. J., & Shapiro, A. M. (2003). International Review of Psychiatry A quantitative review of the effects of traumatic brain injury on cognitive functioning A quantitative review of the effects of traumatic brain injury on cognitive functioning. *International Review of Psychiatry*, *15*, 341–349. https://doi.org/10.1080/09540260310001606728

Silverberg, N. D., Iaccarino, M. A., Panenka, W. J., Iverson, G. L., McCulloch, K. L., Dams-O'Connor, K., Reed, N., McCrea, M., Cogan, A. M., Park Graf, M. J., Kajankova, M., McKinney, G., & Weyer Jamora, C. (2020). Management of Concussion and Mild Traumatic Brain Injury: A Synthesis of Practice Guidelines. *Archives of Physical Medicine and Rehabilitation*, *101*(2), 382–393. https://doi.org/10.1016/j.apmr.2019.10.179

The Mathworks. (2022). *MATLAB Statistics*. The Mathworks, Inc. https://www.mathworks.com/products/matlab.html

Van Son, R. J. J. H., & Pols, L. C. W. (n.d.). *An acoustic description of consonant reduction*. Retrieved March 20, 2022, from www.elsevier.nl/locate/specom

Whitfield, J. A., & Goberman, A. M. (2014). Articulatory-acoustic vowel space: Application to clear speech in individuals with Parkinson's disease. *Journal of Communication Disorders*, *51*, 19–28. https://doi.org/10.1016/j.jcomdis.2014.06.005

Zalla, T., Pradat-Diehl, P., & Sirigu, A. (2003). Perception of action boundaries in patients with frontal lobe damage. *Neuropsychologia*, *41*(12), 1619–1627. https://doi.org/10.1016/S0028-3932(03)00098-8

Appendix A. Word Lists

Novel Word Combinations, List A:

1. Peering goats
2. Poor bees
3. Prying hawks
4. Tearing pages
5. Popping noise
6. Black juice
7. Twister clouds
8. Boastful donkeys
9. Proper gifts
10. Bare books

Novel Word Combinations, List B:

1. Boring fears
2. Barking oysters
3. Powerful claws
4. Ghostly plains
5. Backup authors
6. Tiny blueberries
7. Popular clowns
8. Bending roads
9. Pirate hooks
10. Babbling rabbits

Dummy Words:

1. Burning Trash
2. Glistening Flowers
3. Grumpy Cats
4. Purple Beans
5. Captivating Wish
6. Pink Sauce

Appendix B. Adult Research Participant History Form

Adult Research Participant History Form

Participant code:____

Age: __________

Sex: ☐ *Male* ☐ *Female*

Highest Education Level: ☐ *Incomplete HS* ☐ *Some college* ☐ *Bachelor's degree* ☐ *Graduate studies*

Current Occupation:____________________________________

Native language English: ☐ *yes* ☐ *no*
 If no, has English been spoken since childhood? ☐ *yes* ☐ *no*

Monolingual: ☐ *yes* ☐ *no*
 If no, what other languages are spoken and how often?

Any languages studied in school? Which? How long?

History of TBI, stroke, or neurological disease? ☐ *yes* ☐ *no*

Any speech/language complaint/concern?

Any speech/language treatment history? *(type of treatment and approximate dates)*

Hearing:

Aid(s): YES NO (*unilateral: R L or bilaterally fitted)*

Participant concern: YES NO

MDHearingAid Online Hearing Test Results:

L *Healthy Mild Moderate Severe Profound*

R *Healthy Mild Moderate Severe Profound*

Vision:

Glasses/contacts prescribed? YES NO

Glasses/contacts worn? YES NO

ZEISS Online Vision Screening Results (with glasses or contacts):

Visual Acuity: *Optimal* *Less than Optimal*

Contrast Vision: *Optimal* *Less than Optimal*

Color Vision: *Optimal* *Less than Optimal*

Handedness ("which hand do you use for the following activities?")

Writing	R	L	Either
Throwing	R	L	Either
Cutting with scissors	R	L	Either
Holding a toothbrush	R	L	Either
Drawing	R	L	Either
Eating with a spoon	R	L	Either
Hold a match while striking it	R	L	Either

Concussion History Questionnaire

Adapted from the University of Kansas Medical Center Concussion History Survey

Has a healthcare provider told you you've had a concussion? ☐ *yes* ☐ *no*

If yes, what is your best estimate of when you had your most recent concussion?

___ ___ / ___ ___ ___ ___ (mm/yyyy)

If you have had a concussion, when did you return to activities like school, work, driving?

☐ *within one week* ☐ *within 1 month* ☐ *eventually (>1 month)*

If you have had a concussion, what were your symptoms? *(check all that apply)*

☐ Headache	☐ Dizziness	☐ More emotional
☐ "Didn't feel right"	☐ Confusion	☐ Sensitivity to noise
☐ Drowsiness	☐ Blurred vision	☐ Irritable
☐ Difficulty concentrating	☐ Loss of consciousness	☐ Feeling slowed down
☐ Neck pain	☐ "Pressure in head"	☐ Sadness
☐ Difficulty remembering	☐ Balance problems	☐ Feeling "like in a fog"
☐ Nausea or vomiting	☐ Trouble with sleeping	☐ Nervous or Anxious
☐ Fatigue or low energy	☐ Sensitivity to light	☐ Other: _______________

If you had a concussion, how long did your symptoms last?

☐ Less than 24 hours
☐ 1 to 3 days
☐ 4 to 6 days
☐ 1 week to 3 months
☐ more than 3 months

Do these same symptoms occasionally return now?

☐ *No* ☐ *Yes, when I do this:* ____

If you lost consciousness, how long did it last?

☐ 0-30 minutes ☐ >30 min and <24 hours ☐ >24 hours

If you have had a concussion, what treatment(s) did you have? *(check all that apply)*

☐ Acetaminophen (Tylenol)
☐ Aspirin
☐ Ibuprofen (Advil, Motrin, others)
☐ Anti-nausea medicine
☐ Brain rest (no television screens, computers, phones, texting, *etc.*)
☐ Shortened or modified school day or work day
☐ Followed a "Return to Play" or a "Return to Learn" program
☐ Avoiding physical exertion
☐ Avoided alcohol
☐ Concussion or other rehabilitation therapy
☐ Other(s): ______________________