AN IMAGING STUDY OF WORKING MEMORY: THE EFFECTS OF CONCURRENT ARTICULATION ON PHONOLOGICAL TASKS AND THE CEREBELLUM'S ROLE

by

David A. Raboy

BPhil, University of Pittsburgh, 2010

Submitted to the Faculty of

University Honors College and the School of Arts and Sciences in partial fulfillment

of the requirements for the degree of

Bachelor of Philosophy

University of Pittsburgh

2010

UNIVERSITY OF PITTSBURGH

University Honors College

This thesis was presented

by

David A. Raboy

It was defended on

April 21, 2010

and approved by

Natasha Tokowicz, Professor, Department of Psychology

Mark Wheeler, Professor, Department of Psychology

Lori Holt, Professor, Department of Psychology

Thesis Advisor: Julie Fiez, Professor, Department of Psychology

AN IMAGING STUDY OF WORKING MEMORY: THE EFFECTS OF CONCURRENT ARTICULATION ON PHONOLOGICAL TASKS AND THE CEREBELLUM'S ROLE

David A. Raboy, BPhil

University of Pittsburgh, 2010

Recent work has shown that cerebellar patients have difficulty with particular types of rhyme judgments (pairs with phonological and orthographic mismatch), as well as working memory tasks (Ben-Yehudah and Fiez, 2008). Both working memory and rhyme judgment tasks can be disrupted by concurrent articulation (Gathercole and Baddeley, 1994; Besner 1987), indicating a possible set of common regions in the cerebellum. In a review investigating the effects of concurrent articulation on phonological judgment tasks, Besner (1987) found differential effects for rhyme judgments compared to homophone and non-word homophone judgments. Interestingly, there may be differences even within rhyme judgments where word pairs with mixed phonological and orthographic (visual) similarity are more affected by concurrent articulation (Johnston and McDermott, 1986). We performed a behavioral experiment (Experiment 1) to replicate the effects found by both Besner and Johnston and McDermott. Our behavioral experiment found similar results. Concurrent articulation decreased the accuracy of rhyme judgments but not homophone and non-word homophone judgments; within the rhyme judgment task, word pairs with mixed phonology and orthography were the most affected. In order to elucidate the potential role of the cerebellum in these tasks, we designed a neuroimaging experiment (Experiment 2) with both a working memory component and a phonological tasks component. We identified a set of ten regions that were positively active during the working

memory task and used this set of regions to explore potential regions of overlap between working memory and rhyme judgment, but not homophone and non-word homophone judgments. Of the ten regions active for the phonological tasks, only one bilateral region in the superior cerebellum showed a significant task effect. Counter to what we had hypothesized, it showed greater activation for the homophone and non-word homophone judgments than the rhyme judgments. While our results show a separation of the tasks in this bilateral region, further study is necessary to help explain why we saw lower activation for rhyming in this region and why we were unable to identify any rhyme specific areas within the cerebellum.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

I owe sincere gratitude to Corrine Durisko who committed much time and effort in guiding me through all the steps leading up to this thesis. Heartfelt thanks are also due to Dr. Julie Fiez who gave me the opportunity to call this project my own and whose intellectual pursuits motivated and helped to shape this work.

1.0 INTRODUCTION

The cerebellum has long been known for its important role in motor control. Besides its role in movement, more recent studies have begun to elucidate a role for the cerebellum in what are considered to be higher order cognitive functions, such as language. (Stoodley and Schmahmann, 2009; Stoodley and Schmahmann, 2008; Strick, Dum, and Fiez, 2009; Schmahmann, 1996). These studies have found many connections between the cerebellum and cognition, revealing a more complicated role for the cerebellum than what was long thought.

A study by Ben-Yehudah and Fiez (2008) compared cerebellum lesion patients and controls on reading tasks to determine the relationship between cerebellar function and reading. Patients did not differ from controls on basic reading skills such as word identification, comprehension, and fluency. However, the patients were significantly worse at deciding if a pair of words with mismatched orthography and phonology rhymed (ex. *thigh* and *fly*, *fear* and *bear*). Patients with anterior and superior cerebellar lobular damage had severe difficulty on this task whereas patients with damage in the inferior lobules performed normally. In verbal working memory tasks, patients displayed memory spans equivalent to controls on words and digits recalled in the order of presentation but had difficulty with recalling digits in reverse order and non-words. The authors propose that verbal working memory and rhyme judgment are both impaired in patients because they rely on a common articulatory monitoring process in the anterior and superior lobules of the cerebellum.

In examining behavioral studies to find a common articulatory process for rhyming and verbal working memory, the work with concurrent articulation in working memory emerged as a possible explanation. The seminal model of working memory proposed by Alan Baddeley provides one theoretical perspective. At its core, the model posits three key components necessary for maintaining and manipulating information in working memory: the visuo-spatial sketchpad that serves as a temporary store with limited capacity for visual and spatial features of a stimuli, the phonological loop that executes a similar function for verbal information, and a control system known as the central executive that is a flexible coordinator of the maintenance systems, responsible for shifting attention and binding all of the information into a working representation (Baddeley, 2003). The phonological loop is further divided into two parts: a short term store (the phonological store) which holds phonological information of the to-be-remembered items, and an articulatory rehearsal mechanism that acts to prevent the decay of verbal information in the phonological store by keeping it active through a repetitive, silent inner speech process (Gathercole and Baddeley, 1994). In other words, through an inner speech like mechanism, the phonological loop functions to maintain stimuli in working memory.

In order to demonstrate the validity of his model, Baddeley used concurrent articulation, the repetitive utterance of irrelevant material such as counting digits or repeatedly saying the same word. Having participants concurrently articulate while trying to remember a short list of words decreased performance. Baddeley attributed this finding to the fact that concurrent articulation occupies the needed articulatory rehearsal mechanism, thus preventing items in the store from being refreshed (Gathercole and Baddeley, 1994).

In a series of experiments, Baddeley and Lewis (1981) applied the concepts they developed in the domain of verbal working memory to the study of reading. Using a variety of non-word stimuli to prevent subjects from using any existing lexical information, the authors did not find an expected impairment in reading performance when participants engaged in concurrent articulation. This result is difficult to reconcile with Baddeley's model of working memory which posits that all phonological tasks should be impaired by concurrent articulation since articulation should prevent stimuli from reaching the phonological store. In order to make sense of their results, the authors conclude that there must be several information stores involved in reading. However, Baddeley has never updated his model of working memory to account for his own findings. Even in a review of his most salient findings 22 years later, Baddeley (2003) wrote of only a singular phonological store for all phonological information.

Other groups of researchers specifically interested in what underlies reading processes looked at concurrent articulation effects to see if phonology must always be accessed (Besner, 1987; Johnston and McDermott, 1986). Their work provides reason to question Baddeley's ideas. In a review examining the widely held conclusions of concurrent articulation literature at the time, Besner (1987) reviewed experiments that explored participants' responses to homophones to determine if there is a general phonological code for all similar reading tasks or possible differences between superficially similar phonological tasks. Besner included the Baddeley and Lewis (1981) study, in which participants were asked to decide whether a pair of non-words sounded the same with and without concurrent articulation. After introducing the various studies, Besner concluded that only rhyme judgments are affected by concurrent articulation while homophone and non-word homophone judgments are not. Besner therefore argued that there must be different underlying mechanisms responsible for the varying impact of concurrent articulation, and that the widely held conclusion that concurrent articulation affects all phonological decisions is unjustifiably generalized. To explain these differential effects, Besner suggested that rhyme judgments require post-assembly phonemic segmentation and deletion processes that are affected by concurrent articulation and which are not necessary for other phonological decisions such as homophones.

A study by Johnston and McDermott (1986) looking at the effect of concurrent articulation on different types of rhyme decisions provides evidence that even Besner (1987) may be over generalizing. Johnston and McDermott created four types of rhyming word pairs by mixing phonological and orthographic (visual) similarity. Type 1 pairs were visually similar, non-rhyming words (e.g. *bone, none*). Type 2 pairs were visually similar rhyming words (e.g. *full, pull*). Type 3 pairs were dissimilar non-rhyming words (e.g. *chair, reel*). Type 4 pairs were visually dissimilar rhyming words (e.g. *dare, hair*). Using these four types of word pairs, the authors performed four experiments manipulating the speed of articulation and stimuli presentation mode. Concurrent articulation required participants to count from one to eight at a pace of 3 per second or as quickly as possible. Word pairs were presented either simultaneously with one word above the other or successively with the second word displayed 1500 ms after the first word display ended. These two conditions of each variable were mixed to create the four experiments. Johnston and McDermott found that concurrent articulation affected the accuracy of responses regardless of the mode of presentation or articulation speed. This effect was greatest for the type 1 (*bone, none*) word pairs. Participants also had more errors on the type 4 (*dare, hair*) word pairs compared to the type 2 (*full, pull*) and type 3 (*chair, reel*). Overall, participants performed much worse on type 1 (*bone, none*) pairs than type 4 (*dare, hair*) pairs. The authors concluded that type 1 (*bone, none*) pairs would most benefit from encoding the words into an articulatory form, a process blocked by concurrent articulation. This finding calls into question the conclusion by Besner (1987), in which all rhyme decisions are treated similarly.

The current literature leaves us wondering what common mechanism might explain a common contribution of the cerebellum for rhyme decisions and verbal working memory tasks. This study aims to test and validate the findings of Johnston and McDermott (1986) that different rhyme judgments are differentially affected by concurrent articulation and to examine the cerebellum's role in various phonological and working memory tasks. The methods and results from Experiment 2 (using simultaneous presentation and rapid articulation) in Johnston and McDermott's study were used to motivate the present experimental design, which included the four types of rhyme word pairs in the rhyming task of this study. Also, this study incorporates a non-word homophone task that is similar to the task used by Baddeley and Lewis (1981) The conclusion of Besner (1987), that rhyme judgments are affected by concurrent articulation, but other phonological judgments (such as homophone and non-word homophone) are not affected, was combined with the evidence from Ben-Yehudah and Fiez (2008) which indicated a common region for rhyme and recall in the cerebellum to generate specific predictions. Based on the results of Ben-Yehudah and Fiez, we hypothesize that control participants should have similar activation patterns for rhyming and working memory tasks in the cerebellum whereas homophone and non-word homophone tasks should have different activation sites.

2.0 EXPERIMENT 1 – BEHAVIORAL EXPERIMENT

2.1 METHODS

2.1.1 Participants

Twenty undergraduate students (8 females, 12 males) enrolled in an introductory psychology course at the University of Pittsburgh served as participants for the behavioral portion of the experiment. All of the participants were native English speakers and given credit for participation. All subjects provided informed consent on a University of Pittsburgh consent form approved by the Institutional Review Board.

2.1.2 Stimuli

The stimuli for the rhyme component were 80 pairs of words of four different types (20 word pairs of each type). Type 1 (*bone, none*) word pairs look alike but do not rhyme, type 2 (*full, pull*) word pairs look alike and do rhyme, type 3 (*chair, reel*) word pairs do not look alike and do not rhyme, and type 4 (*dare, hair*) word pairs do not look alike but do rhyme (see Appendix A.1).

Three tasks comprised the multi-task component, a rhyme judgment task, a homophone judgment task, and a non-word homophone judgment task. Each of these tasks had 64 pairs of words. In the rhyme judgment task, word pairs were split into the same four types as the rhyme component (see Appendix A.2). For the homophone and non-word homophone tasks, there were 64 word triplets (see Appendix A.3, A.4). Each of these triplets had a "main" word that was either paired with a word that created a homophone match half of the time or a word that did not make a homophone match the other half. The non-word homophone stimuli also consisted of 64 word triplets of non-real words. Words for this task were created by morphing the words from the homophone task using the following rules; only one letter could be added to a word, only two letters in a word could be changed, and the vowel sounds had to stay constant. These non-words were created to avoid creating homophones of actual words while maintaining the construction of a real English word by avoiding unusual sequences of letters.

All of the stimuli were single syllable words/non-word and presented in all capital letters. All stimuli were matched for frequency, word length, number of phonemes, and number of phonological and orthographic neighbors. There was a practice phase for each component of the experiment. All stimuli for the practice were completely different than those used in the main experiment.

2.1.3 Procedure

The behavioral experiment was designed using E-Prime software (Schneider et al., 2002). It consisted of two parts; a rhyme only component that consisted only of rhyme judgments, and a "multi-task" component that consisted of rhyme judgments as well as homophone and non-word homophone judgment tasks. The order of presentation for these two components and all tasks within the multi-task component were presented randomly. During a portion of each component, subjects were asked to perform a secondary task, concurrent articulation (e.g. repeating the word “the” out loud as quickly as possible). Rapid articulation was used in this study because it was easier for participants to maintain. During the task epochs when no secondary task was performed, subjects made word pair judgments without any distraction.

Participants were provided with both detailed written instructions and verbal instructions and any additional questions were addressed before the study began. For both components, subjects were presented with a 3 s instruction screen and a preparatory 1500 ms fixation screen. The fixation screen was followed by a block of eight trials. Each trial consisted of a word pair display screen for 500 ms and a 2500 ms response screen. The stimuli were presented one above the other at the center of the screen with a fixation cross in between the two words (see Figure 1). During the response screen, the fixation cross remained in the center of the screen. Participants were instructed to press “1” if the word pair rhymed or were a homophone pair or “2” if the word pair did not rhyme or form a homophone pair. Responses were to be made as quickly as possible and were valid if made both during word presentation as well as during the response screen afterwards. To mimic the imaging experiment, a 15 sec fixation baseline screen was displayed which had an asterisk at the center of the screen. All presentation screens had a white background with black, bold, Courier New, size 18 font (see Figure 1). A button press began the next block so that participants could rest in between if they wished (see Figure 2 for block design)

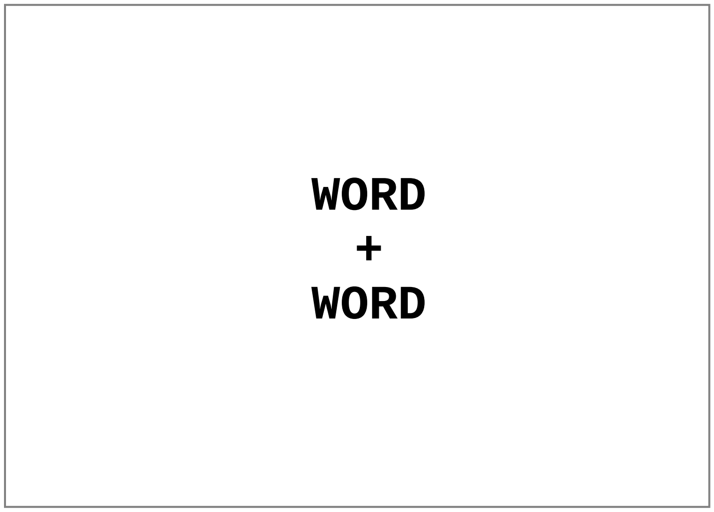

Figure 1. Format of Presentation Screens for Experiment 1

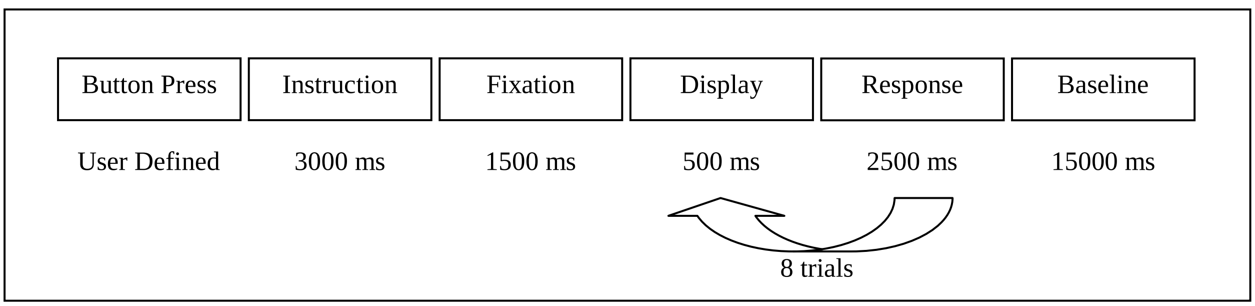

Figure 2. Block design for Experiment 1

The rhyme only component consisted of 10 blocks, 5 with articulation and 5 with no articulation, with the blocks presented in random order. The instruction screen for the articulation blocks said “Articulation” in the center of the screen and for the no articulation blocks it said “No Articulation”. In the articulation trials, participants were to articulate from the instruction screen until the baseline screen. For each block, two of each of the four rhyme pair types were presented in random order in each block. Participants were to press “1” if the pair of words rhymed and “2” if they did not as quickly as possible.

The multi-task component consisted of four sets of six blocks each. Each set had two blocks of a rhyme task, two blocks of a homophone task, and two blocks of a non-word homophone tasks. Each task had one block with articulation and one block with no articulation. All of the blocks in each set were presented in random order. The instruction screen for each block consisted of the type of block and either “articulation” or “no articulation” written in the center of the screen (e.g. “Homophone No Articulation”). For rhyme task blocks, the block proceeded exactly as described above with two words from each of the four types presented in random order. For the homophone and non-word homophone trials, a main word (or non-word) was paired with two possible items, either the word (or non-word) which made a homophone or the word (or non-word) making a non-homophone pair. Half of all trials in the task resulted in “1” responses and half “2” responses, with the order of the trials randomized. Participants were instructed to press “1” if the pair of words rhymed or were homophones and “2” if they were not.

The participants first completed a practice experiment which was a shortened version of the main experiment to become familiar with the protocol. The word stimuli used in the practice session were different than those used in the main experiment, but the procedure and timing of the blocks were identical to the main experiment. The same written and verbal instructions were given and participants were encouraged to ask any questions just as in the main experiment. The rhyme component and multi-task component were presented in random order. The practice session of the rhyme component consisted of two blocks, articulation and no articulation, presented in random order. The practice multi-task component consisted of one set of the six blocks presented randomly.

2.2 RESULTS

2.2.1 Reaction Time

Only correct trials were used to calculate average response times for each subject. A main effect of rhyme pair type, $F(3,57) = 37.0$, $p<0.000001$ was found for reaction time (see Table 1). Responses for type 1 (*bone*, *none*) pairs were significantly slower than for all other pair types, $p<.0001$. Also, responses to type 4 (*dare, hair*) pairs were significantly slower than for type 2 (*full, pull*) and type 3 (*chair, reel*) pairs, $p<.005$. No significant main effect was found for concurrent articulation in the rhyme component, $F(1,19) = 0.577$, $p<0.46$. However, there was a significant interaction between pair type and articulation, $F(3,57) = 4.07$, $p<0.01$.

There was a main effect of task type on reaction time in the multi-task component, $F(2,38) = 8.95$, $p<0.001$ with participants responding significantly slower for non-word homophone trials than rhyme or homophone (see Table 2). No main effect of concurrent articulation on reaction time was found between the tasks in the multi-task component, $F(1,19) = 0.797$, $p<0.38$. There was no significant interaction between task type and articulation, $F(2,38) = 2.27$, $p<0.12$.

Table 1. Reaction Time±SE for Rhyme Component

	Type 1	**Type 2**	**Type 3**	**Type 4**
Overall	1241.07±21.82	991.72±12.83	1022.52±14.51	1090.33±12.21
Articulation	1202.27±25.20	1005.88±22.56	1010.55±18.63	1089.25±19.89
No Articulation	1270.74±27.54	977.24±14.14	1036.34±19.55	1089.09±17.98

Table 2. Reaction Time±SE for Multi-Task Component

	Homophone	Non-Word Homophone	Rhyme
Overall	1042.79±7.10	1103.57±10.80	1054.39±8.10
Articulation	1030.40±10.46	1085.73±14.04	1058.13±13.44
No Articulation	1052.88±14.65	1119.35±17.75	1050.43±11.73

2.2.2 Accuracy

There was a main effect of pair type on the percent error (percentage of incorrect responses) in the rhyme component, $F(3,57) = 26.2$ $p<0.000001$ (see Table 3). Comparing pair types using paired t-tests, participants missed significantly more rhyme judgments of type 1 (*bone, none*) pairs compared to all other pair types, $p<.0005$. In addition, participants performed significantly worse on the type 4 (*dare, hair*) pairs compared to the type 2 (*full, pull*) and type 3 (*chair, reel*) pairs, $p<.03$. More errors also occurred for type 2 pairs than type 3 pairs, $p<.01$. Looking at the effects of concurrent articulation, a main effect of articulation was found between pair types, $F(1,19) = 13.5$ $p<0.002$. Using paired t-tests, only type 1 (*bone, none*) pairs showed a significant effect of articulation with more errors occurring in the concurrent articulation condition, $t(19)=2.98$ $p< 0.01$. However, there was not a significant interaction between pair type and articulation, $F(3,57) = 1.86$, $p<0.15$.

No main effect was found for task type in the multi-task component, $F(2,38) = 1.99$, $p<0.15$ (see Table 4). However, participants responded less accurately on the non-word homophone task than on the homophone task, $p< 0.05$. A main effect of articulation was also found for the multi-task component, $F(1,19) = 4.83$ $p<0.05$. Again, rhyme decisions were significantly more effected by concurrent articulation, $p< 0.01$. There was no interaction between task type and articulation, $F(2,38) = 2.32$, $p<0.11$.

Table 3. Percent Error±SE for Rhyme Component

	Type 1	Type 2	Type 3	Type 4
Overall	31.04±3.15	7.51±1.82	2.29±1.31	12.61±1.72
Articulation	35.29±4.10	9.56±2.69	2.67±1.66	13.50±2.31
No Articulation	26.72±2.68	5.50±1.46	2.00±1.70	11.75±1.88

Table 4. Percent Error±SE for Multi-Task Component

	Homophone	Non-Word Homophone	Rhyme
Overall	9.87±0.98	13.29±1.01	12.60±1.14
Articulation	10.81±1.29	13.97±1.74	15.67±1.83
No Articulation	8.95±1.34	12.58±1.12	9.55±1.19

2.3 DISCUSSION

Our results support the argument by Besner (1986) that concurrent articulation impairs rhyme judgments but not homophone and non-word homophone judgments. While the reaction times for all three tasks were not significantly affected by concurrent articulation, articulation significantly increased errors for the rhyme task without affecting the other tasks.

Furthermore, the results mostly verify the findings by Johnston and McDermott in Experiment 2 (1987). We similarly found type 1 (*bone*, *none*) pairs resulted in the slowest responses. Whereas Johnston and McDermott only found significantly slower responses for type 1 pairs compared to type 2 (*full*, *pull*) and 3 (*chair*, *reel*) pairs and type 4 (*dare, hair*) pairs compared to type 2 pairs, we found type 1 pairs to be significantly slower than all other types and significantly slower responses for type 4 pairs compared to type 2 and 3 pairs. Our finding that reaction time was not significantly affected by concurrent articulation also matches Johnston and McDermott's results. We also replicated their finding that significantly more errors occurred for type 1 and 4 pairs than on type 2 and type 3. However, only type 1 (*bone*, *none*) words showed a significant effect of articulation on accuracy in our study whereas Johnston and McDermott found this effect for type 2 (*full, pull*) and type 4 (*dare, hair*) word pairs as well. While our results demonstrated this pattern (see Table 3), the differences were not significant.

These results verify the findings by Johnston and McDermott (1987) and Besner (1986) which intimate that different processes are involved in rhyme judgments compared to homophone and non-word homophone judgments and that there are differences even within rhyme judgments. Replicating their results gives us confidence that our imaging results for the multi-task component can be used to look at areas involved in a possible articulatory mechanism even when no concurrent articulation is used, using the basic logic that tasks that are disrupted by concurrent articulation are likely to share a common neural substrate within the cerebellum.

3.0 EXPERIMENT 2 – NEUROIMAGING EXPERIMENT

3.1 METHODS

3.1.1 Participants

Twenty participants took part in the neuroimaging experiment. Because of a scanning error resulting in poor cerebellar coverage, four participants were excluded from the analysis. The remaining participants (11 females, 5 males) were between the ages of 18 and 38 (average of 23.5) and were native English speakers. They received monetary compensation for participating.

3.1.2 Stimuli

All of the stimuli used in the rhyme and multi-task components were identical to those used in Experiment 1. In addition, a third component involving a working memory task was added to the experimental design. For this task, the items on each trial were drawn from a pool of nine words and nine letters (see Appendix A.5). The letters were all dissimilar sounding consonants. The words were one-syllable, four letter, dissimilar words, each beginning with a different consonant which were matched for frequency.

3.1.3 Procedure

The neuroimaging portion of the experiment used an adapted version of the behavioral experiment with necessary timing modifications for use in the scanner. The scanning sessions included a rhyme-only task component, but because of a design oversight, details of this component will not be discussed further. A working memory portion of the experiment was also added. There were no articulation trials in the neuroimaging experiment, but the number of trials and stimuli for each task remained the same. As with the behavioral experiment, participants first completed a practice experiment. Participants were provided with both written and verbal instructions before each component in the practice experiment. To minimize brightness in the scanner, all presentation screens had a grey background with white text. The text remained bold, Courier New, size 18 font (see Figure 3).

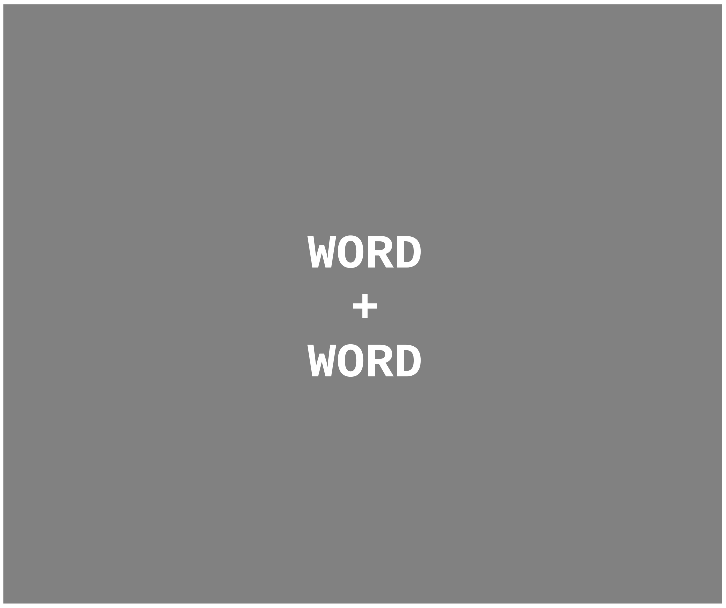

Figure 3. Format of Presentation Screens for Experiment 2

In the main experiment conducted in the scanner, participants were given one of eight counterbalanced experimental designs, in which the order of presentation for the rhyme component and multi-task component was mixed. The working memory component was always presented after the rhyme and multi-task components because of movement concerns.

A start screen first notified participants which component was about to begin. Following the trigger pulse, a two second fixation cross at the center of the screen was displayed. This was followed by a set of six blocks for the multi-task component and five blocks for the working memory component. The design of a block for the multi-task component (see Figure 4) was the same as in the behavioral experiment with the following exceptions: There were no concurrent articulation blocks. In the multi-task component, the instruction screen lasted for 2000 ms. The fixation before each block was 2000 ms instead of 1500 ms so that it would take up 1 TR. The baseline was changed from 15 sec to 14 sec so that it would also take up an even number of TRs. Each block progressed automatically after the baseline screen without a button press by the participant. Responses were recorded using a response glove attached to the participants' hand.

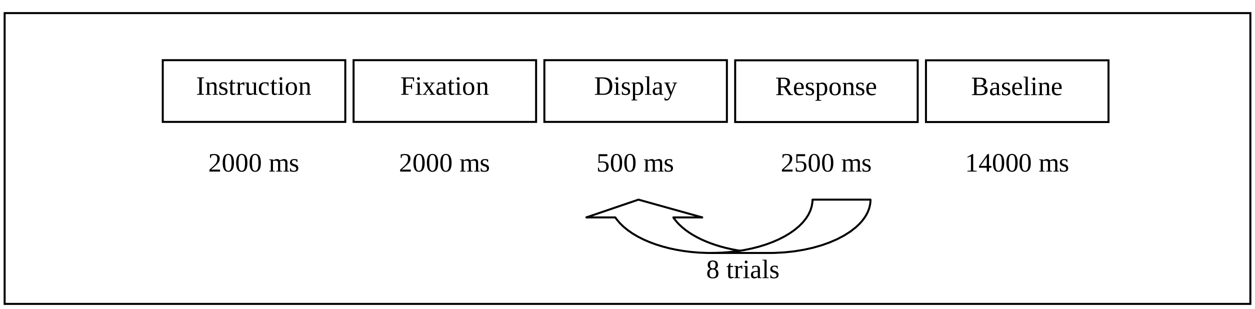

Figure 4. Block Design for Multi Task Component in Experiment 2

The multi-task component consisted of four sets of six blocks each. Each set had two blocks of a rhyme task, two blocks of a homophone task, and two blocks of a non-word homophone tasks. All of the blocks in each set were presented in random order. Participants were instructed to press the button attached to their index finger when the pair of words rhymed or were homophones and their middle finger when the words were not a rhyming or homophone pair.

The working memory component consisted of four counterbalanced sets of trials, across which the type of stimuli (words, letters) and output modality (written, spoken) was varied. Each set consisted of five blocks each. All sets began with a four second instruction screen which said the set type in the center of the screen. Then, the trigger pulse was followed by a two second fixation cross in the center of the screen. This was followed by the five trials in the set. Each trial consisted of the presentation of six stimuli, with stimulus presented in all capital letters at the center of the screen for 750 ms, followed by a 250 ms fixation cross in the center of the screen followed by the. Once all six stimuli were presented, there was a ten second delay with five pound signs in the center of the screen. The delay period was followed by a six second response period indicated by five question marks at the center. A 12 second baseline then concluded each block (see Figure 5 for block design).

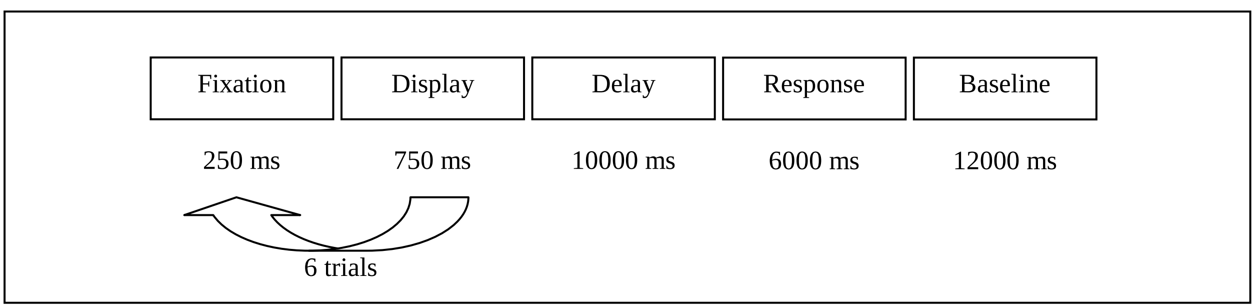

Figure 5. Block Design for Working Memory Component in Experiment 2

For written sets, one of the investigators went into the scanning room to take off the response glove and put a pad of paper on the participant's stomach and a pen in the participant's hand. The investigator put the participant's hand with the pen in the proper starting position on the page. Before going into the scanner, participants were told to write the six words or letters of each block across the page and then move their hand down a little bit on the page for the next trial. When participants finished one of the written runs, the investigator turned the page on the writing pad and again placed the participant's hand with the pen at the top of the page. For spoken trials, participants were instructed to speak normally into a microphone that was attached to headphones.

The practice experiment was performed on a computer outside of the scanner in order for the participants to become familiar with the procedure and timing of the tasks. All of the timing was the same as for the scanning experiment besides the removal of the 2 s fixation screen which followed the trigger pulse. The stimuli used in the practice were all completely different than those used in the main experiment. All participants first practiced the rhyme component, then the multi-task component, and finally the working memory component. Participants were provided detailed written and verbal instructions before each task and were asked if they had any questions. To mimic using the response glove, they were instructed to respond using their index finger if the word pair rhymed or were a homophone pair and their middle finger if the word pair did not rhyme or form a homophone pair.

For the multi-task component, participants practiced one block of the rhyme task, one block of the homophone task, and one block of the non-word homophone task. The three blocks were presented in random order. They then practiced one block for each type of the working memory component in the following order: written words, written letters, spoken words, and spoken letters. In order to simulate the testing conditions of the scanner, participants were instructed to hold the writing pad across their stomach and write their responses while looking at the screen.

3.1.4 fMRI Data Acquisition

All fMRI data were collected using a 3.0T Siemens Magnetom Allegra (Siemens AG, USA) head-only research scanner with a circularly polarized transmit/receive head coil and a projection mirror at the Brain Imaging and Research Center (University of Pittsburgh, Pittsburgh, Pa). Prior to the functional scans, high resolution and T2-weighted in-plane (38 slice) structural scans using Echo-planar imaging pulse sequence were obtained. For the functional scanning, 38, 3.2 mm thick, oblique slices were taken parallel to the plane of the anterior commissure and posterior commissure (TR time = 2000ms, echo time = 25 ms, flip angle = 70, field of view = 200). The scanning slice prescription was changed based on subject anatomy to cover the entire cerebellum. While activations in all covered brain regions were obtained, only activations in the cerebellum were analyzed in the current study.

3.1.5 fMRI Data Pre-processing

The scanning data were reconstructed and preprocessed using Neuroimaging Software Package, NIS 3.6 (University of Pittsburgh, Princeton University) and an in-house software package called Fiswidgets (Functional Imaging Software Widgets, Fissell et al., 2003). After performing quality checks, the data were corrected for motion with Automated Image Registration, AIR 3.0.8 (Woods et al., 1993) Data from tasks in which movement in any direction exceeded four mm or degrees was excluded from analysis. Data were then corrected for linear trends adjusting for any possible scanner drift. A reference brain was chosen from among the subjects, and all extraneous matter was removed each subject's T2 structural image. The stripped structural scans were co-registered to the first functional scan, and then transformed into the reference brain space. Functional images were scaled to a global mean and then smoothed using a three dimensional Gaussian filter (8 mm full width at half maximum). The reference brain and all functional data were then converted into Talairach space (Talairach and Tournoux, 1988) using AFNI (AFNI_2008_07_18_1710, Cox, 1996) in order to perform statistical analysis.

3.1.6 fMRI Localizer

In order to localize regions associated with working memory, we performed a voxel-wise analysis of variance (ANOVA) on the data from the working memory component. We identified two sets of regions that were active during the encoding and retrieval epochs of the working memory component. In order to obtain BOLD (blood oxygen level depending) signal in each epoch, a portion of the task window was contrasted with baseline fixation. For the encoding epoch, we contrasted the last 2 s of encoding and the first 4 s of the maintenance interval versus the last 4 s of baseline. For the retrieval epoch, we contrasted the last 2 s of retrieval and the first 4 s of baseline with the last 4 s of baseline. We used a threshold criterion of $p = .005$ and a voxel contiguity threshold of three voxels. From this localizer, we were able to identify a set of 18 regions in the cerebellum (9 from each working memory epoch).

3.1.7 Regions of Interest Analysis

The set of 18 regions was then applied to the multi-task component using a time series analysis. Of these 18 regions, 8 (5 from the encoding epoch, 3 from the retrieval epoch) showed negative patterns of activation for both the working memory component as well as the multi-task component. These eight regions are noted in Table 5 and will not be discussed further. For the remaining 10 regions (Figure 6, Table 6), data from the time series analysis were used to calculate percent signal change in the regions during the multi-task component. To compute percent signal change, we calculated the average activation across the 24 sec of each task (rhyme, homophone, non-word homophone) minus the average activation for the last four seconds of baseline across all three tasks, and then divided this value by the average activation across each task and then multiplied the resulting number by 100. We then performed a repeated-measures ANOVA to look at differences between the tasks in each ROI.

Table 5. ROIs with Negative Activation

Regions with negative activation for encoding versus baseline and response versus baseline in the working memory component at p = 0.005, voxel contiguity = 3.			
Contrast	Hemisphere	Talairach coordinate	Cerebellar region
Working Memory Retrieve	L	-39, -55, -44	VIIIB
	L	-26, -33, -47	VIIIB
	R	23, -74, -40	CRI/CRII
Working Memory Encode	L	-16, -45, -50	IX
	R	-26, -46, -44	IX
	R	23, -39, -54	VIIIB
	R	-26, -32, -43	X
	R	-20, -36, -29	IV

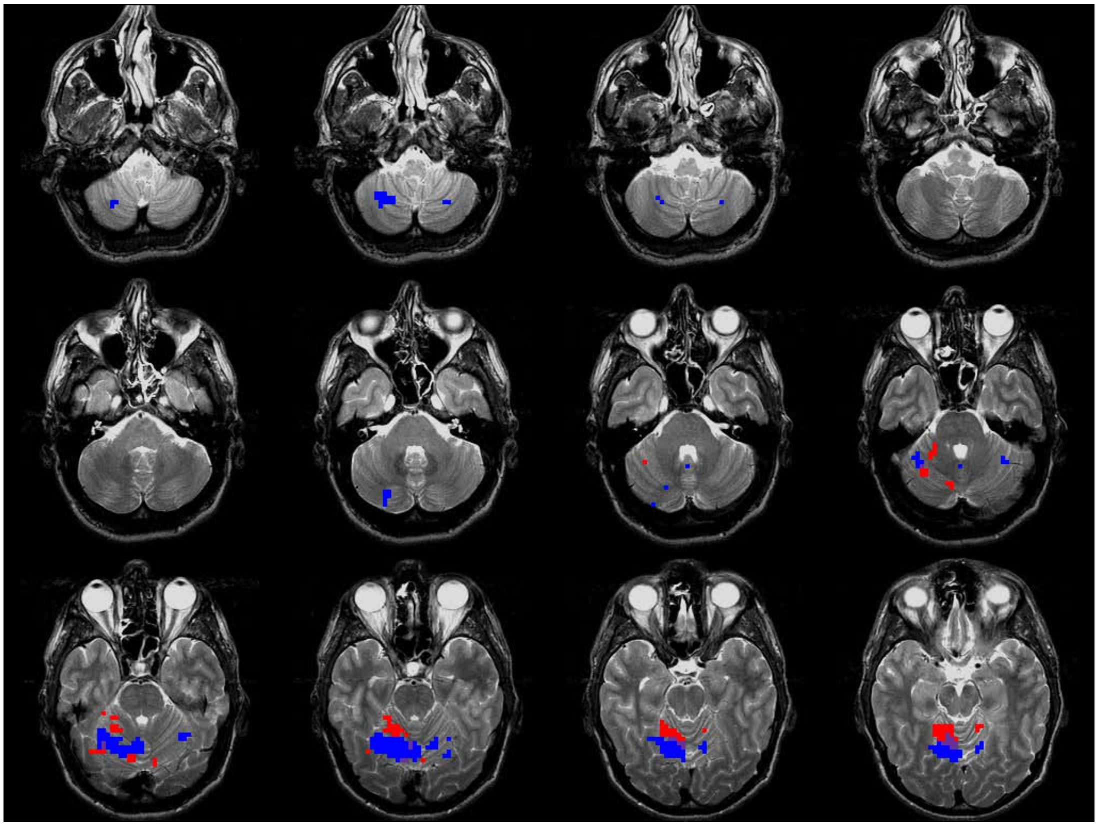

Figure 6. 10 Regions from Working Memory Component with Positive Activation

(Blue=Retrieve, Red=Encode, Purple=Overlap)

Table 6. ROIs with Positive Activation

Regions with positive activation for encoding versus baseline and response versus baseline in the working memory component at p = 0.005, voxel contiguity = 3.				
Contrast	Hemisphere	Talairach coordinate	Task Effect?	Cerebellar region
Working Memory Retrieve	L	-26, -56, -47	No	VIIIA
	R	19, -56, -50	No	VIIIA
	L	-26,-58, -22	No	VI
	L	-32, -43, -29	No	VI
	L	-13, -55, -18	No	V
	R	13, -58, -18	No	V
Working Memory Encode	L	-7, -65, -22 (ROI 1)	Yes	VI
	R	6, -61, -29 (ROI 2)	Yes	VI/VIII
	R	36, -58, -26	No	VI
	R	13, -45, -15	No	IV

3.2 RESULTS

3.2.1 Behavioral Results

As with Experiment 1, there was a main effect of task type for the response time in the multi-task component, $F(2,30) = 6.49$ $p<0.005$. Participants responded significantly slower on non-word homophone judgments than homophone judgments, $p< 0.004$. Unlike Experiment 1, this effect was not significant for non-word homophone versus rhyme judgments. Also, rhyme judgments were performed significantly more slowly than homophone judgments, $p< 0.04$ (see Table 7).

Table 7. Reaction Time±SE for Multi-Task Component in Experiment 2

Homophone	Non-Word Homophone	Rhyme
1122.70±9.64	1213.40±18.74	1156.78±14.24

Also coinciding with the results from Experiment 1, there was no significant main effect of task type on accuracy for the multi-task component $F(2,30) = 2.82$ $p<0.08$. However, non-word homophone judgments were responded to incorrectly significantly more than homophone judgments, $p< 0.05$ (see Table 8).

Table 8. Percent Error±SE for Multi-Task Component in Experiment 2

Homophone	Non-Word Homophone	Rhyme
7.39±1.01	10.93±0.79	8.73±0.79

3.2.2 Imaging Results

Of the 10 ROIs analyzed, only two showed a significant main effect of task type (rhyme vs. homophone vs. non-word homophone) for percent signal change. These bilateral regions were both active in the encoding contrast. The ROI at Tailarach coordinates -7, -65, -22 (from now on referred to as ROI 1) ($F(2,30) = 5.01$ $p<0.02$) was significantly more active for the non-word homophone task than the rhyme task, $p< 0.0006$ (Figure 7). The ROI at coordinates 6, -61, -29 (from now on referred to as ROI 2) ($F(2,30) = 6.04$ $p<0.006$) was significantly more active for the homophone ($p< 0.02$) and non-word homophone ($p< 0.02$) tasks compared to the rhyme task (Figure 8).

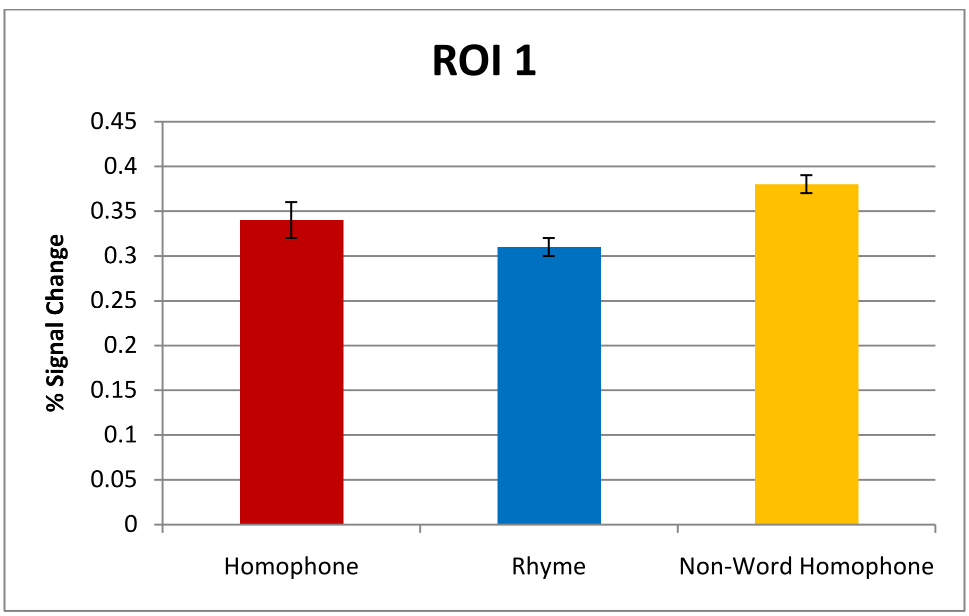

Figure 7. Percent Signal Change by Task in ROI 1

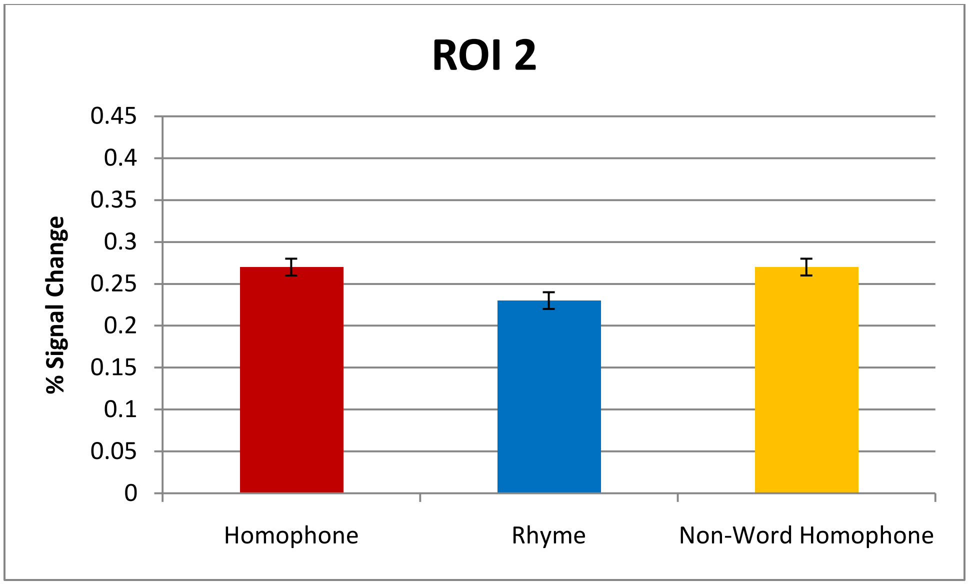

Figure 8. Percent Signal Change by Task for ROI 2

3.3 DISCUSSION

The results are opposite what we had expected and difficult to explain. Regions identified as active for the working memory component showed the most activation for homophone and non-word homophone tasks. Results from the study by Ben-Yehudah and Fiez (2008) suggest that we should have found the opposite effect, with common activity for recall and rhyming tasks.

There are a number of reasons why we may not have gotten the result that we expected. In the working memory task, patients with cerebellar damage in Ben-Yehudah and Fiez (2008) performed within the range of intact controls for digits and words recalled in the order of presentation. Their deficit was evident on tasks with non-word recall and backwards recall of digits. In our study, participants recalled words and stimuli in the order of presentation. It is possible that only more difficult working memory tasks recruit cerebellar areas that are common with rhyme judgments tasks. We might not have found significant percent signal change for the rhyme task in the ROIs for this reason.

It may also be that collapsing across multiple recall modalities (written and spoken) and stimulus types (letters and words) in the working memory component to identify ROIs cancelled out the activation of some cerebellar regions involved in working memory. However, we did identify regions that were found by Durisko and Fiez (2010) in a study specifically meant to identify cerebellar regions involved in working memory. Interestingly, one of the regions in which we found a significant effect of task type on percent signal change (ROI 1) was identified by Durisko and Fiez as a region involved in overt speech but not working memory. In our study, activation in this ROI may have been particularly boosted by the spoken recall sets (the Durisko and Fiez study used only written recall). It is possible that participants anticipated a spoken response and began to internally practice this output while the stimuli were being encoded. Using a paired t-test, we found a significant effect of recall mode in ROI 1 with significantly more activation for the spoken blocks, $t(16)=98.24$ $p< 0.0001$. The associated bilateral region, ROI 2, also showed this same effect, $t(16)=84.61$ $p< 0.0001$.

Another possibility is that activation was influenced by the difficulty of the tasks. The behavioral results support this. The non-word homophone task, which displayed the most signal change in ROIs 1 and 2, had the slowest response times in both Experiments. Specifically, responses for the non-word homophone task were significantly slower compared to both the rhyme and homophone tasks in Experiment 1, but only significantly slower than the homophone task in Experiment 2. Accuracy was also significantly worse on the non-word homophone task compared to the homophone task in Experiment 2 and this same effect approached significance in Experiment 1. In Experiment 2 however, responses for the rhyme task were significantly slower than the homophone task although the homophone task showed a greater percent signal change in ROI 2. Also, despite the higher percent signal change for the non-word homophone task compared to the rhyme task, there was no significant difference of accuracy between these tasks. This task difficulty explanation cannot account for all of the effects seen between the tasks or how the increased activation for the homophone and particularly non-word homophone tasks relate to the working memory component used to identify the ROIs.

4.0 GENERAL DISCUSSION

The current data are difficult to make sense of within the framework of concurrent articulation and models of working memory. One possibility is that our localizer did not accurately identify areas involved in working memory for some of the reasons mentioned above. Instead, it seems that ROI 1 and 2 are likely regions identified because of their strong activation for spoken recall. We found that both ROIs in this bilateral region were significantly more active for spoken recall in the working memory component after realizing that ROI 1 is the same region labeled by Durisko and Fiez (2010) as an area for overt speech. Therefore, the higher activation in these regions for homophone and non-word homophone judgments may indicate that these tasks require more internal verbal practice in anticipation of verbal recall than the rhyme task. This would seem particularly true for the non-word homophone task which requires participants to make phonological decisions for stimuli with no existing lexical information. Interestingly, non-word homophone judgments had the most activation in the region corresponding to Durisko and Fiez' overt speech area (ROI 1). Further analysis might want to parse out the activation for spoken and written recall in the working memory component to see if this finding is consistent even in the ROIs which did not show a significant task effect.

Due to the difficulty of non-word homophone judgments, why is this task not affected by concurrent articulation? In both Experiment 1 and 2 of our study, non-word homophone judgments resulted in the slowest and least accurate responses. Consistent with previous studies

(Besner 1987), we found that despite the apparent difficulty of the task, there are no effects of concurrent articulation on responses. It may be that concurrent articulation does not affect non-word homophone judgments because there are no existing phonological representations to disrupt when the unfamiliar stimuli are first presented. Therefore, an effect of concurrent articulation would likely be found in responses to subsequent presentations of the non-words. In other words, participants should have greater difficulty with non-word homophone judgments for stimuli that were first presented during concurrent articulation since this distracting task should prevent participants from creating a phonological representation of the new stimuli. This process should not be disrupted for non-word homophone pairs that were presented without concurrent articulation and these stimuli should therefore be responded to more accurately on subsequent presentations.

Another consistent finding for the effects of concurrent articulation is its effect on accuracy but not reaction time (Johnston and McDermott, 1986; Baddeley, Eldridge, and Lewis, 1981; Baddeley and Lewis, 1981). This effect is obvious for the rhyme judgments in Experiment 1. In the multi-task component, the average reaction time for the rhyme task is almost the same with and without concurrent articulation but there is a large effect of articulation on the percent error. Also, type 1 pairs (*bone, none*) in the rhyme component displayed a significant effect of articulation on accuracy but were actually responded to quicker with concurrent articulation. The idea of an articulatory monitoring process proposed by Ben-Yehudah and Fiez (2008) can help to explain this effect. Articulatory monitoring would benefit phonological decisions with conflict such as the type 1 (*bone, none*) and 4 rhyme pairs which mix orthographic and phonological similarity (*dare, hair*). If concurrent articulation affects the articulatory monitoring process, difficult phonological decisions such as these should suffer from decreased accuracy due to the inability to check for errors in pronunciation. However, occupying this monitoring process should not influence the reaction time. In fact, the quicker responses for type 1 pairs during concurrent articulation in Experiment 1 might be due to the disruption of the monitoring process removing a step of processing leading up to a response. The articulatory monitoring process should also help for unfamiliar stimuli such as in the non-word homophone task since participants have no previous experience with the stimuli. In fact, the cerebellar patients in the study by Ben-Yehudah and Fiez did have difficulty with recalling non-words in a working memory task.

Looking for activation of these difficult tasks may help to locate a site of the articulatory monitoring process in the cerebellum. Future studies could look at the overlap of activation for backwards recall, which cerebellar patients had difficulty with (Ben-Yehudah and Fiez (2008), non-word homophone judgments, and rhyme judgments using rhyme pairs with mixed orthography and phonology (type 1 and 4). In the current study, it is possible that pulling out the effects of these difficult rhyme judgments may result in different effects.

It would also be beneficial to look at active areas across the brain rather than a focus in the cerebellum given the complicated pattern of results. Although opposite in direction from what we had expected, we do see a separation of activation for the rhyme task versus the other tasks in the multi-task component. The percent signal change for the rhyme task is significantly different in ROI 1 (Figure 7) then the homophone and non-word homophone tasks. While the effect is puzzling, it is worth further attention. It may be that the decreased activation for rhyme judgments in the cerebellum corresponds with an increase in the cortex. A widened search could help to clarify this possibility.

APPENDIX

STIMULI

STIMULI FOR RHYME COMPONENT

Type1		Type2		Type3		Type4	
BONE	NONE	PITCH	DITCH	CHAIR	REEL	NUDE	LEWD
BARN	WARN	CRANK	DRANK	LEAVE	TORCH	BIRD	HERD
DOUGH	ROUGH	CREAM	DREAM	THREE	TWICE	GOAL	ROLL
BOOT	FOOT	FULL	PULL	GIRL	SHEET	DARE	HAIR
FOUL	SOUL	PLAN	CLAN	SALT	JUMP	LOAN	TONE
HINT	PINT	BAKE	LAKE	RAIN	FARM	SOAK	POKE
WAND	HAND	BATCH	LATCH	DIME	THINK	REIGN	TRAIN
DEAF	LEAF	TEND	MEND	BROWN	DIRT	PAIN	LANE
LONE	GONE	FLAME	BLAME	GRANT	SHELL	NOTE	COAT
TOUR	SOUR	YIELD	FIELD	SNOW	THING	CARE	WEAR
FREAK	BREAK	RING	WING	PIPE	FERN	SOLE	COAL
COWL	BOWL	COIL	BOIL	SAND	GALE	FLAIR	STARE
DRIVE	GIVE	BURN	TURN	BRAIN	BROOM	NEWS	LOSE
CASTE	TASTE	NOISE	POISE	EIGHT	WHARF	SHARE	STAIR
CASH	WASH	BRACE	TRACE	MIND	WALL	MOOSE	JUICE
CLOVE	GLOVE	FLOCK	CLOCK	LIST	BRAN	TALE	RAIL
CATCH	WATCH	SOUND	POUND	WHOLE	STORE	WART	SORT
BOTH	MOTH	NUMB	DUMB	SHIRT	WITCH	GREAT	TRAIT
BLOWN	CLOWN	BLOT	CLOT	SLUG	SOUP	BUNK	MONK
TOLL	DOLL	LOAD	TOAD	BEAT	ROAD	PHONE	KNOWN

STIMULI FOR RHYME TASK IN MULTI TASK COMPONENT

Type1		**Type2**		**Type3**		**Type4**	
GOLF	WOLF	BRIBE	TRIBE	WEAN	FAWN	FLOAT	QUOTE
SAID	PAID	ROOT	LOOT	CHAIN	SING	SHOE	VIEW
GROWN	CROWN	PAST	LAST	DINE	BOAT	NAIL	PALE
BEAD	DEAD	FADE	MADE	VEIL	GLASS	HEIGHT	BITE
GASP	WASP	VAULT	FAULT	MEAT	PANT	WANE	MAIN
CARD	WARD	RAKE	TAKE	PLATE	MARCH	SHOOT	FRUIT
WORSE	HORSE	DAMP	LAMP	HURT	STEAM	DIAL	MILE
DOVE	ROVE	HOUSE	MOUSE	STORM	ROAST	HAIL	SALE
LOVE	MOVE	HOST	POST	BLESS	CASE	FUME	ROOM
WORD	LORD	RUNG	SUNG	BOOK	NOUN	TOOL	RULE
YOUTH	SOUTH	CRUSH	BRUSH	FORM	TINT	BLUE	KNEW
BEARD	HEARD	HOLD	BOLD	WALK	LEFT	ROAM	HOME
WHOSE	THOSE	BARGE	LARGE	ROSE	COST	CUTE	NEWT
CROW	BROW	MIGHT	TIGHT	BANK	SURE	CLOAK	SPOKE
HOOD	FOOD	FALL	TALL	EAST	SWIM	RATE	BAIT
HUSH	BUSH	COLD	TOLD	CLOUD	PEACH	WRITE	LIGHT

STIMULI FOR HOMOPHONE TASK IN MULTI TASK COMPONENT

Main	Word 2	Word 3	Main	Word 2	Word 3
AIL	ALE	APE	GRAZE	GRAYS	GRABS
AIR	HEIR	SIR	HAIL	HALE	HAVE
ARC	ARK	ART	HAIR	HARE	HATE
BAIL	BALE	BALD	HAUL	HALL	HALT
BAIT	BATE	BANE	HERTZ	HURTS	HUNTS
BAWL	BALL	BULL	LACKS	LAX	LAP
SEAM	SEEM	TERM	MAID	MADE	MAZE
BARE	BEAR	BEER	MAIL	MALE	MAKE
BEAT	BEET	BEER	MAIN	MANE	MARE
BYTE	BITE	BITS	MEET	MEAT	MEAN
BILLED	BUILD	BUILT	MOWED	MODE	MORE
BLUE	BLEW	BLOW	PASTE	PACED	PAVED
BORE	BOAR	BOAT	PAIL	PALE	PAVE
BORED	BOARD	BEARD	PAIN	PANE	PARE
CHOOSE	CHEWS	CHOWS	PAIR	PEAR	PEAS
CHORD	CORD	CURD	PAUSE	PAWS	PADS
SIGHT	CITE	CUTE	PIECE	PEACE	PLACE
CLAUSE	CLAWS	CLAPS	PLAIN	PLANE	PLATE
CRUDE	CREWED	CROWED	QUART	COURT	COUNT
CRUISE	CREWS	CROWS	ROAD	RODE	ROPE
DAYS	DAZE	DARE	ROLL	ROLE	RULE
DEAR	DEER	DEED	SEEN	SCENE	SCONE
YOLK	YOKE	YORE	SIGHS	SIZE	SIDE
PHASE	FAZE	FATE	SYNC	SINK	SANK
FEET	FEAT	FEAR	SOAR	SORE	SURE
FLAIR	FLARE	FLAKE	STAKE	STEAK	SPEAK
FLEA	FLEE	FLEX	STAIR	STARE	STORE
FLU	FLEW	FLAW	TACKS	TAX	TOP
GAIT	GATE	GALE	THRU	THREW	THREE
JEAN	GENE	GONE	THYME	TIME	TAME
GRAYED	GRADE	GRACE	WAIT	WEIGHT	HEIGHT
GRATE	GREAT	GREET	WORN	WARN	WARE

STIMULI FOR NON-WORD HOMOPHONE TASK IN MULTI TASK COMPONENT

Main	Word 2	Word 3	Main	Word 2	Word 3
AIF	AFE	ANE	VRAZE	VRAYS	VRABS
JAIR	JARE	JIR	CHAIL	CHALE	CHAVE
SARC	SARK	SART	ZAIR	ZARE	ZATE
BAIP	BAPE	BAVE	JAUL	JALL	JALT
QUAIT	QUATE	QUANE	MERTZ	MURTS	MUNTS
SAWL	SAUL	SOOL	NACKS	NAX	NAF
SEAB	SEEB	TERB	TAID	TADE	TAFE
SARE	SAIR	SAIP	LAIL	LALE	LAPE
BEAV	BEEV	BEEG	NAIN	NANE	NADE
BYFE	BIFE	BIFS	ZEET	ZEAT	ZEAN
BILLN	BUILN	BUILF	POAD	PODE	POTE
PLUE	PLEW	PLOE	JASTE	JACED	JAVED
CLORE	CLOAR	CLOAT	ZAIL	ZALE	ZAVE
DORED	DOARD	DEARD	HAIN	HANE	HAPE
CHOOM	CHEWM	CHOWM	YAIR	YARE	YEAS
KORP	CORP	CURP	PAUM	PAWM	PAMS
PIGHT	PITE	PUTE	FIECE	FEACE	FLACE
PLAUSE	PLAWS	PLAPS	KLAIN	KLANE	KLATE
GRUDE	GREWED	GRAWED	BOART	BORTE	BOUNT
PRUSE	PREWS	PRAWS	HOAD	HODE	HOKE
KAYZ	KAZE	KABE	ZOLL	ZOLE	ZULE
DEAV	DEEV	DEEC	SEEF	SEAF	SOFE
ZOAK	ZOKE	ZORE	MIGHS	MIZE	MIDE
PHOSE	FOZE	FOTE	SYNT	SINT	SANT
FEEM	FEAM	FEAD	JOAR	JORE	JURE
PLAIR	PLARE	PLAKE	SMAKE	SMAIK	SKAIK
VLEA	VLEE	VLEX	STAIF	STAFE	STOFE
FLOOM	FLEWM	FLAWM	DACKS	DAX	DOP
VAIT	VATE	VAVE	PHRU	PHREW	PHREE
JEAM	GEME	GOME	VYME	VIME	VAME
CRAYED	CRADE	CRACE	YAIT	YATE	YETE
BRAIT	BRATE	BREET	FORN	FORNE	FARNE

STIMULI FOR WORKING MEMORY COMPONENT

Recall Letters	Recall Words
B	NOSE
F	RAIN
H	MEAL
K	SHIP
L	TREE
M	CAKE
Q	HILL
R	GOLD
S	LUCK

BIBLIOGRAPHY

Baddeley, A. D. (2003). Working memory: Looking back and looking forward. *Nature Reviews Neuroscience, 4,* 829-839.

Baddeley, A., Eldridge, M., & Lewis, V. (1981). The role of subvocalisation in reading. *The Quarterly Journal of Experimental Psychology, 33,* 439 – 454.

Baddeley, A. & Lewis, V. (1981). Inner active processes in reading: The inner voice, the inner ear and the inner eye. In A. M. Lesgold and C. A. Perfetti (Eds.), *Interactive processes in reading* (pp. 107-129). Hillsdale, N.J.: Lawrence Erlbaum Associates.

Ben-Yehudah, G. & Fiez, J. A., (2008). Impact of cerebellar lesions on reading and phonological processing. *Annals of the New York Academy of Sciences, 1145,* 260-274.

Besner, D. (1987). Phonology, lexical access in reading, and articulatory suppression: A critical review. *The Quarterly Journal of Experimental Psychology, 39*, 467-478.

Cox, R.W. (1996). AFNI: Software for analysis and visualization of functional magnetic resonance neuroimages. *Computers and Biomedical Research*, *29*, 162-173.

Durisko, C., & Fiez, J.A. (2010) Functional activation in the cerebellum during working memory and simple speech tasks. *Cortex*, doi:10.1016/j.cortex.2009.09.009.

Fissell, K., Tseytlin, E., Cunningham, D., Iyer, K. Carter, C.S., Schneider, W., et. al., (2003). Fiswidgets: a graphical computing environment for neuroimaging analysis. *Neuroinformatics*, *1*, 111– 125.

Gathercole, S.E., & Baddeley, A.D. (1994). *Working Memory and Language*. Hove, UK: Lawrence Erlbaum Associates, Ltd .

Johnston, R. S., & McDermott, E. A. (1986). Suppression effects in rhyme judgement tasks. *The Quarterly Journal of Experimental Psychology*, *38A*, 111-124.

Schmahmann, J. D. (1996). From movement to thought: Anatomic substrates of the cerebellar contribution to cognitive processing. *Human Brain Mapping, 4,* 174-198.

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

Stoodley, C. J., & Schmahmann, J. D. (2009). Functional topography in the human cerebellum: A meta-analysis of neuroimaging studies. *NeuroImage, 44*, 489-501.

Stoodley, C. J., & Schmahmann, J. D. (2009). The cerebellum and language: Evidence from patients with cerebellar degeneration. *Brain and Language, 110*, 149-153.

Strick, P. L., Dum, R. P., & Fiez, J. A. (2009). Cerebellum and nonmotor function. *Annual Review of Neuroscience, 32*, 413-434

Talairach, J., & Tournoux, P. (1988). *Co-planar stereotaxic atlas of the human brain: 3-dimensional proportional system: An approach to medical cerebral imaging.* Stuttgart, Germany: Thieme Medical Publishers.

Woods R.P, Mazziotta J.C., & Cherry, S.R. (1993). MRI-PET registration with automated algorithm. *Journal of Computer Assisted Tomography, 17*, 536-546.