

2014

Determining Shared Working Memory Systems for Rhythmic Incongruities in Music and Language using functional Near-Infrared Spectroscopy

Jackson T. Mathews
jtmathew@uvm.edu

Follow this and additional works at: <http://scholarworks.uvm.edu/hcoltheses>

Recommended Citation

Mathews, Jackson T., "Determining Shared Working Memory Systems for Rhythmic Incongruities in Music and Language using functional Near-Infrared Spectroscopy" (2014). *UVM Honors College Senior Theses*. Paper 55.

This Honors College Thesis is brought to you for free and open access by the Undergraduate Theses at ScholarWorks @ UVM. It has been accepted for inclusion in UVM Honors College Senior Theses by an authorized administrator of ScholarWorks @ UVM. For more information, please contact donna.omalley@uvm.edu.

Determining Shared Working Memory Systems for Rhythmic Incongruities in Music and
Language using functional Near-Infrared Spectroscopy

Jackson Mathews

University of Vermont

Abstract

Rhythmic organization of auditory information is used differently in the retention of music and spoken language. However, similar areas of the prefrontal cortex (PFC) have been implicated in the retention of unusual rhythmic patterns. This study investigated the degree of PFC activation using functional near-infrared spectroscopy (fNIRS) during three rhythmic pattern manipulation working memory tasks. In addition the normalized pairwise variability index (NPVI) was tested as a measure of rhythmic accuracy. Of the 6 participants considered, 3 demonstrated greater activation of the right PFC in response to the Rhythmic Motor task, a manipulation of musical rhythms. Similar activation was observed for the Stress Speech task, which altered stress patterns in natural speech. No changes in activation were observed in the Rhythmic Speech task, which paired speech with metric patterns. The NPVI values did not reflect task performance. Refinement is needed to determine if the current procedure accurately measures rhythmic working memory.

Introduction

Rhythm in Musical Contexts

Rhythm refers to a set pattern of regular temporal information. This regularity of information exists in music and speech and serves different roles in our understanding of the mediums. There are both similarities and differences in the ways rhythmic patterns influence the processing and understanding of auditory information for speech and music.

It has been proposed that rhythm perception arises from regular oscillatory neuronal activity in groups of neurons (Large & Snyder, 2009). Physiological evidence from EEG studies indicates distinct activity spikes in time with rhythmic patterns, supporting this hypothesis (Jomori, Uemura, Nakagawa & Hoshiyama, 2011, Nozaradan, Peretz, Missal & Mouraux, 2011). Perception of rhythmic patterns is biased towards regularly alternating, or binary meters (Abecasis, Brochard, Granot & Drake, 2005), so much so that listeners will often perceive accents on alternating beats when no such accent exists in the stimuli (Potter, Fenwick, Abecasis & Brochard, 2009). The presence of a regularly structured alternating rhythmic pattern can help facilitate the detection of differences in other factors, such as the pitch or loudness (Brochard et al, 2003, Grube & Griffiths, 2009). This suggests rhythmic regularity plays an important role in the processing of musical information, perhaps being the default approach to musical information processing.

Rhythm in Linguistic Contexts

Early discussions on the issue of rhythm in language divided languages in rhythmic groups based on the prevalence and order of accented, or stressed, syllables in each language

(Paines-Bertrán, 1999). Languages such as English and German were dubbed “stress-timed” languages, as they contained regular alternating durations in their syllables. Languages such as French and Spanish were categorized as “syllable-timed” languages, as each syllable is roughly the same length. This rhythmic distinction between stress-timed and syllable-timed languages, however, does not appear to exist at the level of typical speech. Mathematical analyses of repetitive speech have found that stresses are created via alternating variations in loudness rather than in duration (Kochanski & Orhpanidou, 2008). Most evidence collected and metrics used in support of distinct stress categories has been confounded by inter-speaker and inter-material variation within languages (As reviewed by Arvaniti, 2009, Arvaniti, 2012). Finally the ability to distinguish between languages has been shown to be more dependent on durational cues rather than stress patterns (White, Mattys & Wiget, 2012).

While strict stress categories do not seem to exist, there is evidence to suggest that humans are capable of attending to varying levels of rhythmic complexity in stress-timed speech (Lidji, Palmer, Peretz & Morningstar, 2011). In addition when individuals were asked to repeatedly produce sentences in conjunction with a set meter, words with prominent stress become synchronized to clear metrical subdivisions (Cummings & Port, 1998). The presentation of words in a rhythmically consistent manner also reduces reaction time for the identification of specific speech sounds (Quené & Port, 2005). This suggests that there exists a basic sensitivity to regular stresses in speech, regardless of duration, intensity, or other more salient elements of speech.

Rhythmic Processing in the Brain

Preliminary fMRI investigations into the neural correlates of rhythmic processing identified distinct neural engagement in the retention and reproduction of metric and non-metric

rhythms (Sakai et al. 1999). Retaining and reproducing metric rhythms were shown to activate the left premotor and parietal cortex, and right cerebellum, while non-metric rhythms invoked activation of the right premotor, parietal and prefrontal cortices. Further studies demonstrated the activation of right hemispheric structures, including the right inferior frontal cortex (RIFG), during passive non-metric rhythm perception (Horváth et al, 2011). The involvement of the RIFG may be due to increased cognitive demands of processing non-metric rhythms. With regards to working memory the retention and use of rhythmic information has been shown to activate both cerebellar hemispheres, as well as the anterior insular and anterior cingulate cortices (Jerde et al, 2011). Working memory for both rhythmic and melodic information activated the left inferior frontal gyrus (LIFG), an area commonly implicated auditory working memory (Schneiders et al, 2012).

Several recent studies (Jomori & Hoshiyama, 2009, Rothermich, Schmidt-Kassow & Kotz, 2012, Rothermich & Kotz, 2013, Bohn, Knaus, Wiese & Domas, 2012) have investigated the sensitivity to the rhythmic component of speech stresses. Bohn et al. (2012) demonstrated that disturbing a regularly alternating stress pattern by either placing prominent syllables next to or far apart from each other produced a distinct event related potential (ERP) pattern, known as mismatch negativity (MMN). Jomori & Hoshiyama (2009) observed an increase in negative ERPs when unexpected silences were inserted between syllables, distorting stress patterns in an unexpected manner. Two studies conducted by Rothermich & Kotz (2012, 2013) which used the same stress detection protocol, found distinct activation for unexpected stressed using both EEG and fMRI. EEG results demonstrated a MMN response for unexpected stresses and an earlier detection of semantic incongruities when stress patterns were regular. fMRI results linked the detection of unexpected stresses to both the left and right IFGs and superior temporal gyri (STGs). This evidence suggests that we are sensitive to expectations in relation to a regular

pattern of speech stress that facilitate processing, as violations of regular stress produce distinct neural responses.

Reliance on rhythmic stability in processing and memory encoding appears to be minimal, as studies that included rhythmic variation report that unexpected rhythms have little effect on comprehension (Rothermich et al, 2012, Rothermich & Kotz, 2013). The only instances when rhythmic consistency plays an essential role in language processing are when distinguishing information in nonsense languages (Cason & Schön, 2012) and interpreting sentences with lexically ambiguous words when the speech signal is compromised (Mattys, Brooks & Cook, 2009). In both of these cases semantic information is either lost or compromised, suggesting linguistic content takes precedent to rhythmic variation in normal speech. At this time, however, no studies have investigated the specific neural correlates of rhythmic regularity with regards to a working memory task. An understanding of this relationship would further advance our knowledge of the specific nature of musical processing and memory.

Evidence from neuroimaging studies suggests that a number of cortical areas are involved in aspects of both music and language processing. Increased activity in the rostral portion of the LIFG, corresponding to Brodmann's area 47, has been demonstrated when listening to and producing polyrhythmic patterns (Vuust et al, 2006, Vuust et al, 2011). Polyrhythms are defined as rhythms where a conflicting meter is presented against a primary meter (e.g. 4/4 over 3/4). The activation of BA 47 was observed during the production of both the primary and conflicting meter against the opposite meter. Evidence from studies of linguistic processing show a similar pattern of complex information activating BA 47 (See Uddén & Bahlmann, 2012). In the context of linguistic information, as processing tasks progress from phonetic to syntactic to semantic processing, changes in cortical activation moved from the caudal end of the LIFG (BA 44) to BA

47. Taken together this evidence suggests a multimodal role of the LIFG as it is involved in both musical working memory tasks, as well as the processing of complex information in both musical and linguistic contexts with explicit memory use.

Only recently have studies directly compared the involvement of rhythmic regularity in both music and language. The first theoretical framework for studying music and language comparatively in the brain came from Patel (2003), who proposed the shared syntactic integration resource hypothesis (SSIRH). This hypothesis suggested that basic temporal components of music and language may be processed in similar areas of the brain. Abrams et al. (2011) tested the SSIRH using fMRI by reorganizing musical and speech segments to remove distinct units of meaning and clear rhythms. Both reorganized musical and linguistic information resulted in activation of the IFG and STG, although fine spatial analysis demonstrated slight differences in the extent of overlap in processing locations. Ystad et al. (2007) specifically manipulated rhythmic structure in musical and linguistic information to produce single incongruities. Musical rhythmic incongruities produced more negative ERPs compared to the normal stimuli, while linguistic rhythmic incongruities were not significantly different. Overall this evidence suggest that the same areas of the brain, IFG and STG, are involved in the detection of rhythmic variation, but the response to variation in music is greater than it is in language.

The presence of clear rhythmic structure in musical context can help facilitate the retention of information, while rhythmic consistency only plays a prominent role in language processing under specific circumstances. To this date no studies have directly compared the effect of musical and linguistic rhythmic variations on memory encoding. If the importance of rhythm is different between musical and linguistic domains then rhythmic variations should have distinct effects on working memory encoding between these mediums. In turn if rhythmic

structure has the same importance for both mediums then its effects on working memory should be similar. The primary goal of this study was to determine the difference in prefrontal cortex activation in response to the unique roles of rhythmic variation in musical and linguistic working memory contexts.

It has been known for some time that areas of the prefrontal cortex play an important role in working memory (As reviewed by Carpenter, Just & Reichle, 2000). In particular areas of the left PFC have been shown to activate in response to short term manipulations of information in comparison to information stored in long-term memory (Braver et al, 2001). This area in the left PFC has been shown to activate in response to retention of auditory information in multiple contexts, including manipulations of both rhythm and melody (Jerde et al, 2011). It is likely then that is area of the PFC is not sensitive to the context of the information, but rather is activated during manipulations of multiple forms of information. As such it is likely that LPFC activation would be observed for both musical and linguistic working memory tasks.

Functional Near-Infrared Spectroscopy

For this study we measured changes in prefrontal cortex activity using functional near-infrared spectroscopy (fNIRS). fNIRS devices emit light into the brain and indirectly assess changes in neuronal activation based on the refraction pattern returned to the sensors. Because the refraction pattern of light shone on tissue will vary depending on the concentrations of oxygen bound to hemoglobin in the blood, the refraction pattern can be used to measure if certain areas of the brain are using more oxygen (as reviewed by Ferrari & Quaresima, 2012). fNIRS was first used to study changes in cortex activity in 1992, and it is a fairly new measure of neural activity compared to EEG and fMRI. fNIRS has been used extensively to study issues concerning speech production and perception (as reviewed by Dieler, Tupak & Fallgatter, 2012),

and has been shown to produce stable results over time for verbal working memory tasks (Schecklmann, Ehli, Plichta & Fallgatter, 2008).

Several studies have been published using fNIRS devices to assess neural responses to music. These studies have often focused on emotional responses to music (Moghimi, Kushki, Guerguerian & Chau, 2012), some have assessed differences in passive and active listening (Remijin & Kojima, 2013), while some have simply determined that different overall activation patterns occur during arithmetic tasks versus musical imagery tasks (Power, Falk & Chau, 2010). Alba & Okanoya (2008) used fNIRS to investigate neural activation for tonal working memory, observing activation of the LIFG and STG. While it has yet to be used to study rhythmic working memory, fNIRS will likely prove effective as it possesses good temporal resolution, being able to detect changes in hemoglobin concentration in intervals less than 10 seconds (Alba & Okanoya, 2008).

Present Study: Rhythmic Manipulation Tasks

In order to evaluate the relation of rhythmic variation to working memory (WM) in musical and linguistic contexts, we used one previously documented protocol and developed two novel tasks. Each task contained a simple and complex sub-condition to assess the influence of variation within mediums. The first task, dubbed the Rhythmic Motor task (RM), follows the metric interval protocol used by Sakai et al. (1999) to assess the possible influence of metrical rhythmic regularity on working memory. Since no previous research has investigated linguistic rhythmic variation against music in working memory contexts, we developed two novel tasks to directly compare aspects of the RM task to a linguistic context. The second task, dubbed the Rhythmic Speech task (RS), applies lexical information to the metric rhythms from RM to evaluate the influence of metric rhythms on linguistic WM. For this task the simple sentences

were spoken normally, while the complex sentences were spoken such that each syllable coincided with the timing of a rhythmic pattern determined in same manner as the RM simple stimuli. The third task, dubbed the Stressed Speech task (SS), altered the stress pattern of the sentences with no direct regard to metric rhythms but produced sentences with unnatural and unusual stress patterns. Both the simple and complex sentences were longer than those used in RS, but the complex sentences consisted of equally spaced syllables with syllables shortened in conjunction with the locations of beats from RM stimuli.

For the RM task we expect to see similar activation of the RIFG in response to non-metric complex rhythmic stimuli. While no activation of the LIFG was observed by Sakai, fMRI evidence from Jerde et al. (2011) suggests LIFG activation for both metric and non-metric information may be observed. While retaining a sentence that follows a distinct metrical beat may be an unusual occurrence, the presence of clear semantic information in the RS condition will likely reduce activation of the left and right IFG in comparison to the rhythmic motor task. The unnatural variation present in the SS task will likely result in either equal or greater activation patterns compared to the rhythmic motor condition, as not only will supportive stress cues be missing but the distortions may also require more working memory resources.

As such three primary hypotheses are proposed. We hypothesize that the complex sub-conditions in the RM, RS and SS tasks will all result in activation of the right PFC in comparison the simple stimuli. Because of the difference in importance of rhythmic variation for musical and linguistic stimuli, we also hypothesize that the degree of right PFC activation will be smaller for the two linguistic tasks. Finally, we hypothesize that there will be greater activation of both the right and left lateral PFC for the SS task compared to the RS task, as the application of a metric rhythm to speech in RS stimuli will require fewer resources to process in comparison to the changes in stress pattern applied in the SS task.

Materials and Methods

Participants

Participants were recruited through announcements to college organizations, communication science and neuroscience classes, and by word of mouth. Nine participants (7 female, 2 male) were recruited for this study. Of those nine, the first participant was excluded due to subsequent changes to stimuli placement in the protocol. Additionally two participants were excluded due to a lack of fluctuation in and oversaturation of fNIRS data, respectively. Of the six remaining participants, behavioral data from one participant only consists of the RM task, due to a malfunction in the audio recorder.

Stimuli Generation

All audio stimuli were created using the Audacity audio editing software. Stimuli for the RM task were generated using the “Generate tone” and “Generate silence” tools, while all sentences for RS and SS stimuli were spoken by the primary investigator. Stimuli for the RM task were created following a modified version of the protocol used by Sakai et al (1999). RM task stimuli consisted of seven tones at 440Hz lasting 30ms, separated by six gaps with a base gap interval of 235ms. Stimuli for the RM simple condition followed an interval ratio of 1:2:4, with two 235ms, two 470ms, and two 940ms gaps. Stimuli for the RM complex condition followed a 1:2.5:3.5 interval ratio, with two 235ms, two 587.5ms, and two 822.5ms gaps. Total length of each stimuli was 3500ms. The order of these gaps was rearranged to ten simple and ten complex rhythmic patterns, five of each which were used in each condition. Examples of simple and complex RM stimuli are displayed in figure 1.

To match the seven tones and six gaps used in the RM task, sentences containing seven syllables were used in the RS task. Twenty seven-syllable sentences were created, ten of which

were selected for use in the five RS simple and five RS complex stimuli. RS simple stimuli were spoken such that the sentence lasted approximately 3.5 seconds to match the length of RMs stimuli. No other changes were made in stress or pronunciation from the speaker's typical speech. For RS complex stimuli the sentences were spoken such that they matched a rhythmic pattern with a 1:2:4 interval ratio as used in the RM simple stimuli. To ensure the accuracy of the pattern the speaker listened to the rhythmic pattern on a set of headphones while recording the stimuli.

For the SS stimuli sentences containing fifteen syllables were used. This was done to match the total number of interval units in each RM stimulus. Twenty fifteen-syllable long sentences were created and randomly assigned to either the SS simple or SS complex condition, five of each which were used in the procedure. Sentences in the SS simple condition were recorded in the speaker's typical voice, with no changes in length or stress pattern. Sentences in the SS complex condition were spoken one syllable at a time with gaps in between each syllable. The sentences were then edited such that the gap in between each syllable was approximately identical. Stress patterns were created by using the "Change tempo" tool to shorten seven syllables. These seven syllables were chosen by following the interval patterns used in the RM stimuli.

Stimuli Presentation

Stimuli were presented using PowerPoint software (Microsoft Corporation, Redmond Washington) . Transitions between slides were automated to occur following a set amount of time with a one second delay between slides. The tasks were presented starting with RM, followed by RS and finally SS. Each task followed the same structure; an instructional slide was presented to inform participants of how to perform the upcoming task, followed by a practice

stimulus. Participants were then presented with the five simple stimuli for the task, followed by a 15 second relaxation cross, then the five complex stimuli, then another 15 relaxation cross. Each stimulus was played twice. Participants were then required to retain the stimulus for 10 seconds. Following a slide transition, participants then had seven seconds to repeat the previous stimulus.

For the RM task participants were instructed to repeat the pattern either producing a clicking sound or the syllable “Da” depending on their preference. For the RS and SS tasks participants were instructed to pay attention to the tone and pacing of the stimulus and recreate it as accurately as possible. Each stimulus presentation / retention / reproduction cycle lasted 32 seconds, while an entire task, including simple and complex stimuli as well as rests and instructions, lasted seven minutes 46 seconds.

Procedure

Participants were brought into a small office containing the fNIRS device and a computer displaying the stimulus presentation slideshow. Following informed consent participants filled out a short questionnaire collecting basic demographic information. For this study the fNIR100A (Biopac systems, inc., Goleta, CA) was used to collect hemodynamic data. The fNIR100A measures changes in the hemodynamic response using a headband containing 4 light sources and 10 sensors, dividing the forehead into 16 voxels. The headband covers the anterior portion of the PFC (BA 10, parts of BA 9) as well as the anterior portions of the left and right IFG (parts of BA 11, 46, and 47). Figure 2 provides an image of the BIOPAC fNIR100, as well as of the location of Brodmann’s areas. The fNIRS headband was applied to the forehead and further secured using gauze. During establishment of the fNIRS baseline measures participants were instructed to relax. When the participant indicated readiness the stimulus presentation slideshow was started.

Performance on the tasks was measured using an audio recording device. From beginning to end the procedure lasted approximately 35 minutes.

Data Processing

Behavioral data was extracted from audio recordings using PRAAT software (Boersma & Weenik, University of Amsterdam, version 5.3.85). Task performance was evaluated by measuring gaps in between tones / syllables depending on the task. Gaps were measured from the functional end of a sound to the beginning of the next. Because speech production does not always result in clearly defined spaces between sounds, a set of criteria was developed to define and identify functional sound length in PRAAT. For the RM task data the end of a sound was defined as either the peak intensity of the sound or as the beginning of vowel production, depending on whether the participant used clicking or “Da” sounds, respectively. For RS and SS task data the length of a sound was designated as the vowel nucleus, which was measured from the beginning of vowel production to the beginning of the fourth pulse. Figure 3 shows examples of the sound duration identification process.

The lengths of gaps in between sounds were then recorded in Excel. Accuracy in reproducing and understanding rhythmic patterns was assessed using the Normalized Pairwise Variability Index (NPVI). Developed by Grabe and Low (2002), the NPVI measures the relationship of durational variation in a set of sequential values. NPVI has been used to both study temporal patterns in linguistic (Grabe & Low, 2002) and musical (Patel & Daniele, 2003) contexts. The NPVI is calculated using the following formula:

$$nNPVI = 100 \times \left[\sum_{k=1}^{m-1} \left| \frac{d_k - d_{k+1}}{(d_k + d_{k+1})/2} \right| / (m - 1) \right]$$

Whereby m is the total number of items and d_k is the duration of the k th item. The mean, standard deviation, coefficient of variation (CoV; defined as standard deviation/mean), and NPVI value for each stimuli's gaps were calculated using an online NPVI calculator (http://www.nsi.edu/~ani/npvi_calculator.html).

In order to test the difference between participant performance and target productions, the mean and standard deviations of the target stimuli NPVI and CoV values were used to set the population values for comparison via one-sample t-test. The average NPVI and CoV values for each participant were compared against the population values using JMP (SAS Institute, Cary, NC). Because changes in NPVI have not yet been used as a measure of task accuracy, a measure of general success during the RM conditions was obtained as a reference point. General success was assessed by the principal investigator by listening to each stimuli reproduction and assigning a value of "Correct" or "Incorrect" to each reproduction. Incorrect reproductions were identified based on accuracy in the number of tone produces, or noticeable deviations from the expected gap length. This measure was not meant to serve as an absolute measure of accuracy, but to provide a metric to compare NPVI values against. Measures of general success were not obtained from the RS or SS conditions, as it was believed that the presence of accurate semantic information (i.e. correctly reproducing the words) could bias perception of rhythmic accuracy (i.e. not detecting incorrect rhythmic patterns).

fNIRS data were extracted to an excel spreadsheet using fNIRSoft (Biopac systems, inc, Goleta, CA). Average percent HbO change for baseline was taken from all stimuli in each condition. The 16 fNIR voxels were further averaged into four regions, corresponding to left lateral, left medial, right medial and right lateral PFC. The lateral left and lateral right groups contain the anterior portions of the LIFG and RIFG that are of interest in this study

Observational comparisons were made between simple and complex conditions of each task, as well as between RM, RS, and SS tasks overall.

Results

Demographic Data

Table 1 lists demographic data collected from each participant. Participant age ranged from 19 to 22. All participants listed student as their primary occupation, although JM04 and JM05 also worked as tutors. Of those participants with musical training or performance skills, years of experience ranged between 4 and 19 years. Only one participant, JM08 had no previous musical training or experience. JM03, in addition to having the most years of musical experience, was a native speaker of Japanese. JM08 was fluent in both English and Polish. JM07 was a native speaker of British English. This was noted, as personal correspondence with JM07 following the protocol illustrated that, unbeknownst to the investigator, several words used in the RS and RM conditions were American English colloquialisms.

Table 1- Demographic data

Participant Identifier	Included in Analysis	Age	Gender	Handedness	Musical Experience	Primary Language	Occupation
JM01	No	19	Male	Right	"A long time"	English	Student
JM02	Yes	21	Female	Right	13 years	English	Student
JM03	Yes	22	Female	Right	19 years	Japanese	Student
JM04	No	20	Female	Right	4 years	English	Student/Tutor
JM05	No	22	Female	Right	15 years	English	Student/Tutor
JM06	Yes	22	Female	Right	15 years	English	Student
JM07	Yes	21	Female	Right	5 years	British English	Student
JM08	Yes	19	Female	Right	None	English / Polish	Student
JM09	Yes	21	Male	Right	7 years	English	Student

Behavioral Data: Task Performance

The general perception of task accuracy for the RM conditions is listed in table 2. In general accuracy was poor for both the simple and complex RM conditions. Participants correctly reproduced between one and three out of the five stimuli for each condition. One participant, JM06, did not correctly reproduce any of the complex stimuli. Several participants, including JM03, JM08, and JM09, had more correct reproductions in the complex RM condition compared to the simple. Stimuli number 2 and 5 from RM simple were only correctly reproduced once each, while stimulus 4 from RM complex was never correctly reproduced. This suggests that these particular stimuli may have been too unfamiliar or difficult to be correctly reproduced in this protocol. In summary these data demonstrate a low level of accuracy amongst participants in the RM conditions.

Table 2 - General performance evaluation for all subjects on Rhythmic Motor tasks

Stimulus Category	Stimulus Number	Participant General Success					
		JM02	JM03	JM06	JM07	JM08	JM09
RM_s							
	1	C	C	C	I	I	I
	2	I	I	I	C	I	I
	3	I	C	I	I	C	I
	4	C	I	I	C	C	C
	5	I	I	I	I	I	C
RM_c							
	1	I	I	I	C	C	C
	2	I	C	I	I	C	I
	3	I	C	I	C	C	C
	4	I	I	I	I	I	I
	5	C	C	I	I	I	C

Note: C = Correct, I = Incorrect

Behavioral Data: NPVI and CoV

Tables 3 and 4 demonstrate NPVI and CoV values, respectively, for each participant's reproduction of each stimulus. Data from JM02 for all RS and SS conditions was not available

due to malfunction of the audio recorder. Data from JM03 for the SS complex condition was not considered due to incorrect recall of semantic information for all stimuli.

Because the NPVI is determined by the relationship between neighboring items, NPVI values can vary when the same group of numbers is rearranged. This can be seen in the NPVI and CoV values for the RM conditions, where the CoV values are identical for each stimulus within a condition. Because CoV values for all RS and SS conditions were taken from gaps extracted from the original stimuli, they are subject to variations in speech production, and are thus not identical.

Although they have not been measured in a statistical manner, the NPVI and CoV for the complex SS condition trend towards lower values than all other conditions. This is likely due to the controlled process by which the complex SS stimuli were created, resulting in similarly long inter-syllable gaps.

Table 3 - Individual NPVI values for all stimuli and conditions

Stimulus Category	Stimulus Number	Participant NPVI Values						
		Target NPVI	JM02	JM03	JM06	JM07	JM08	JM09
RM s								
	1	26.67	32.50	33.76	30.33	41.76	43.48	45.04
	2	88.00	54.64	45.03	44.00	71.97	90.10	78.48
	3	74.67	56.44	90.48	68.31	67.99	67.70	58.66
	4	40.00	38.76	53.58	43.31	44.26	52.44	41.54
	5	50.67	46.75	74.11	52.45	88.64	77.99	58.05
RM c								
	1	56.51	75.31	90.10	53.30	79.57	79.74	83.76
	2	23.81	38.79	26.09	36.09	68.47	30.19	54.93
	3	74.92	68.63	76.56	54.42	65.15	70.27	78.93
	4	40.95	54.78	95.33	37.44	79.67	96.75	48.66
	5	46.03	44.29	49.75	53.19	50.81	51.31	78.11
RS s								
	1	52.66		87.62	70.31	65.90	78.93	39.81
	2	68.71		89.46	60.23	54.65	82.46	91.81
	3	72.93		69.19	70.25	76.08	82.01	93.80
	4	57.16		99.71	50.39	76.79	93.78	81.10
	5	75.72		94.65	86.87	80.71	80.71	76.99
R Sc								
	1	56.42		64.77	45.08	42.76	46.48	34.67
	2	55.51		45.08	48.32	79.83	57.95	56.16
	3	80.05		48.32	56.25	80.84	62.21	95.53
	4	30.52		97.62	45.61	78.47	55.80	26.72
	5	67.58		32.89	79.70	61.07	59.72	70.51
SS s								
	1	50.64		72.92	62.76	49.75	39.77	50.85
	2	64.81		59.98	59.27	66.23	65.14	65.09
	3	60.99		74.10	38.77	53.90	58.94	56.64
	4	33.77		58.44	56.11	55.97	46.47	42.56
	5	48.27		61.31	54.61	40.25	47.22	43.26
SS c								
	1	38.08			62.76	45.41	36.32	19.78
	2	44.55			29.84	57.02	45.27	38.95
	3	29.66			51.64	36.02	34.28	18.99
	4	28.11			58.26	49.56	57.10	35.46
	5	37.10			22.99	23.25	40.98	29.89

Table 4 - Individual coefficients of variation for all stimuli and conditions

Stimulus Category	Stimulus Number	Participant CoV Values						
		Target CoV	JM02	JM03	JM06	JM07	JM08	JM09
RM s								
	1	0.5855	0.5774	0.5997	0.6029	0.5157	0.6082	0.6232
	2	0.5855	0.4013	0.4928	0.3216	0.4637	0.7125	0.6310
	3	0.5855	0.4152	0.5735	0.4027	0.5839	0.6726	0.3456
	4	0.5855	0.6199	0.4918	0.4696	0.6351	0.5970	0.5028
	5	0.5855	0.5720	0.6863	0.7513	0.6676	0.6871	0.5765
RM c								
	1	0.4823	0.6284	0.5365	0.3508	0.5572	0.5662	0.5793
	2	0.4823	0.4262	0.4561	0.3239	0.4582	0.4762	0.3755
	3	0.4823	0.5582	0.4898	0.3981	0.4307	0.4859	0.5330
	4	0.4823	0.4279	0.5632	0.2581	0.6215	0.5485	0.5265
	5	0.4823	0.5091	0.4770	0.4370	0.5333	0.4878	0.5265
RS s								
	1	0.5039		0.6733	0.6646	0.5651	0.6430	0.5577
	2	0.4803		0.6914	0.3901	0.3956	0.5863	0.6667
	3	0.4984		0.7037	0.5432	0.4981	0.5240	0.6543
	4	0.4420		0.7113	0.4389	0.4070	0.5707	0.5513
	5	0.5702		0.5641	0.5744	0.6383	0.5460	0.6320
RS c								
	1	0.5770		0.5472	0.4119	0.4406	0.3654	0.3187
	2	0.6290		0.4162	0.5241	0.5297	0.5479	0.5220
	3	0.6414		0.7231	0.5740	0.6128	0.6305	0.6051
	4	0.6358		0.5437	0.5211	0.5310	0.4535	0.5281
	5	0.5475		0.5703	0.5574	0.5963	0.4664	0.5547
SS s								
	1	0.4001		1.3154	0.6262	0.4366	0.4074	0.4581
	2	0.8850		0.8943	0.8404	0.6896	0.6815	0.8081
	3	0.7040		0.8110	0.5488	0.8105	0.7370	0.5930
	4	0.3881		0.9070	0.5068	0.5301	0.4964	0.4721
	5	0.3416		0.8175	0.4195	0.2979	0.3512	0.4209
SS c								
	1	0.2602			0.6262	0.3759	0.3298	0.2098
	2	0.3421			0.2248	0.5477	0.3472	0.3232
	3	0.2655			0.4550	0.3317	0.2678	0.2234
	4	0.2554			0.5114	0.5660	0.4728	0.2833
	5	0.2724			0.2032	0.2042	0.3572	0.3146

Figures 4 and 5 show the average NPVI and CoV values, respectively, for each condition compared against the stimuli average for that condition. A statistically significant difference ($p < 0.05$) from the stimuli average was considered an indication of poor overall task performance. Tables 5 and 6 summarize the results of figures 4 and 5, respectively.

When compared to the general success measures the NPVI and CoV results do not appear to reflect general success. While no participants reproduced more than two stimuli correctly in

the simple RM condition, only one value, the CoV for JM08, was shown to be significantly different than the target stimuli. Participants JM08 and JM09 both reproduced three stimuli correctly during the complex RM, while JM06 incorrectly reproduce all stimuli. However, the NPVI values for JM08 and JM09 for RMc were significantly different than the average, while the NPVI for JM06 was not. Taken together this suggests that the observed changes in average NPVI and CoV for each participant compared to the target stimuli do not accurately reflect task performance.

For the simple and complex RS conditions, JM03, JM08 and JM09 showed significantly different NPVI and CoV values from the target average. Because both values were significantly different it is possible the NPVI and CoV values may have accurately assessed poor task performance. However with no reference point on RS accuracy it is not possible to confirm this accuracy. Interestingly, the NPVI values averages for all participants in the complex SS condition were significantly different compared to the target stimuli. This suggests that NPVI was able to discern some difference between the target stimuli. The nature of this difference will be discussed later.

Table 5 - Summary of significantly different NPVI values

Task Condition	JM02	JM03	JM06	JM07	JM08	JM09
RMs						
RMc		X		X	X	X
RSs	N/A	X			X	X
RSc	N/A					
SSs	N/A	X				
SSc	N/A	N/A	X	X	X	X

Note: X = significantly different, N/A = no data available

Table 6 - Summary of significantly different CoV values

Task Condition	JM02	JM03	JM06	JM07	JM08	JM09
RMs					X	
RMc			X			
RSs	N/A	X			X	X
RSc	N/A		X		X	
SSs	N/A	X				
SSc	N/A	N/A			X	

Note: X = significantly different, N/A = no data available

fNIRS Data

Figure 6 shows percent change in oxygenated hemoglobin (HbO) in each task compared to the baseline measure. For both the simple and complex RM conditions participants JM02, JM03 and JM07 showed greater increase in HbO in the lateral right PFC in comparison to the rest of the areas. Participants JM06, JM08 and JM09 showed greater increases in both left and right medial PFC, though the trend appears to be not as pronounced. No major differences in percent HbO change were observed between the simple and complex RM conditions. This suggests the simple and complex RM conditions, as they were presented in this protocol, may have been processed similarly.

With the exception of participant JM07 during the complex RS task condition, all participants showed a decrease in HbO compared to baseline. Participant JM02 exhibited a greater decrease in HbO for the lateral right PFC compared to the other three divisions for both simple and complex RS tasks. Participant JM03 showed a similar trend in lateral right HbO for simple RS, but not for complex RS. Participants JM07, JM08 and JM09 showed minimal change in HbO from baseline for both simple and complex RS conditions. In summary this data suggests that the area of the PFC measured via fNIRS was likely not involved in the processing of RS stimuli.

For the simple SS condition four out of six participants showed either minimal change in HbO from baseline, or a slight decrease in HbO. Participant JM02 showed an increase in HbO for all four areas, with a greater increase exhibited in the lateral right PFC. In contrast for the complex SS conditions five participants demonstrated a trend towards greater change in HbO in the lateral right PFC. For participants JM02, JM03, JM08, this greater increase in HbO in the lateral right PFC was pronounced. This suggests a trend in the complex SS condition towards greater increases in HbO in the later right PFC, similar to what was seen in the simple and complex RM conditions.

Discussion

fNIRS Results: Implications of Right Prefrontal Cortex Activity

This study sought to investigate patterns of prefrontal cortex activation using fNIRS in response to manipulation of rhythmic patterns in musical and linguistic memory contexts. To test this activity three tasks were developed; Rhythmic Motor, which manipulated interval patterns in a purely musical setting, Rhythmic Speech, which required reproduction of sentences set to an interval-based rhythmic pattern, and Stressed Speech, which manipulated stress patterns in sentences by shortening inter-syllable spaces. Each task contained a simple and complex condition, where the simple condition contained more typical stimuli (i.e. binary intervals, non-manipulated sentences) and the complex condition contained the manipulation of interest. It was hypothesized that the RIFG would show a greater increase in activation in the complex condition for all three tasks. The results of this study, however, only partially support this hypothesis, as only the SS conditions demonstrated a greater increase in right PFC activity during the complex condition.

This first hypothesis was proposed because of previous research demonstrating RIFG activation in response to non-metric rhythms (Sakai et al, 1999), as well as several other memory-related processes. These include attending to the semantic category of words (MacLeod et al, 1998), recalling episodic memories, and retaining task-specific rules (Shi et al, 2010). Interestingly, this area of the right PFC has been shown to significantly decrease in activity during improvisational verse generation in comparison to recitation of a memorized verse, further implying a memory-specific role for this area (Liu et al, 2012). Taken together this information suggests the right PFC is involved in a number of general memory processes with a focus on manipulating verbal memories.

Following this theoretical framework, the question becomes why did Sakai et al (1999) observe an increase in RIFG activation in response to non-metric compared to metric rhythms, despite extensive familiarization with each rhythm type? It is possible that retaining non-metric rhythmic patterns requires recruitment of a more general memory system, as these rhythms cannot be placed within a regular, binary oscillating pattern. Thus the right PFC is recruited while retaining a non-metric rhythmic pattern rather than the left premotor and parietal cortices.

If this argument were correct, then we would expect to see increased activation of the RIFG during only the complex RM task, which followed the same non-metric rhythmic intervals as Sakai et al (1999). This trend towards RIFG activation, however, was observed in both the simple metric and complex non-metric RM stimuli. These results at first glance contradict the first hypotheses, as well as the argument that the right PFC is only recruited to process complex, non-metric rhythms.

This contradiction assumes that the RM tasks would be accurately performed, so that any observed change in activation would reflect rhythmic processing only. The general performance data for both simple and complex RM tasks, however suggests this was not the case. In general

participants performed worse in the simple RM task than the complex, and overall participants did not accurately reproduce more than 3 stimuli in the complex condition. This suggests that the RM sub-conditions may not have been able to fully distinguish between simple and complex rhythms, as both were difficult to reproduce. Instead the current data more accurately reflect recruitment of the right PFC in response to the increased effort needed to retain information in a difficult memory task, rather than memory specifically for rhythm.

In comparison to the RM task data, the majority of participants showed either a decrease or minimal change in activity of the right PFC during both the simple and complex RS tasks. These results provide some support for the second hypothesis, that the RS and SS tasks would elicit lesser degrees of RIFG activation compared to the RM tasks. The hypothesis is only partially supported, however, as only two participants demonstrated greater decreases lateral right PFC activation. This data more likely reflects a lack of recruitment of the PFC in the RS task.

It was also suggested that the LIFG might play a role in processing during the RS task. Previous research has suggested an involvement of the LIFG, corresponding to Brodmann's area 47, in response to manipulations of rhythmic meter in speech (Rothermich & Katz, 2013). This area, however, is located in the posterior region of the LIFG, next to the anterior portion of the lateral fissure, placing it out of range of the fNIRS device used in this study. That is not to say this area was not activated by the RS task, but rather it was impossible to measure it. Future research involving manipulations such as the RS or SS task should employ fNIRS devices that can measure more posterior regions of the PFC.

The third hypothesis of this study predicted that the complex SS condition would show greater levels of activation in both the LIFG and RIFG compared to complex RS. This hypothesis supported in part, due to an increase in lateral right PFC activation during the

complex SS. In general, activation during the complex SS was greater in all areas than in complex RS, which showed mostly decreases in activation compared to baseline. This greater activation in the SS complex condition, however, showed no bias towards the left PFC, suggesting no specific recruitment of the observable areas of the LIFG. Interestingly, the increases in activation observed in the complex SS task appear to be similar to those seen in the simple and complex RM conditions. It is important to note that differences in participant NPVI values, which were considered as measure of task accuracy, were significantly different from the target mean for every participant in the complex SS condition. This suggests that overall understanding of the rhythmic manipulations in the complex SS condition may have been low, and that the SS task was difficult for participants to complete. Furthermore this similar right PFC activation and poor performance in both RM tasks as well as the complex SS condition suggest that the right PFC was activated in response to the difficulty of the task rather than as a component of rhythmic memory processing.

NPVI: Reliability as Accuracy Measure?

In order to evaluate the behavioral performance of participants in this study, the normalized pairwise variability index was used as measure of accuracy in reproducing stimuli. Early research using the NPVI demonstrated differences in NPVI values between stress-timed and syllable-timed languages (Grabe & Low, 2002), suggesting that the NPVI could be used as a measure of rhythmic variation in languages. Furthermore Patel and Danielle (2003) compared NPVI values for both British English and French speech to the NPVI values of rhythms from music motifs of English and French composers. Their results indicated not only greater NPVI values for English, a variable stress-timed language, compared to French, but also similar NPVI values between both English and French compared to their rhythmic motifs. Recent evidence,

however has called the validity of stress categorization in languages into question (Arvaniti, 2009; White, Mattys, & Wiget, 2012). In addition the NPVI has been shown to fluctuate due to inter and intra speaker linguistic productions, suggesting the NPVI may not be reliable for detecting overall rhythmic trends in languages (Arvaniti, 2012). Similar unreliability has been documented with regards to reflecting the rhythmic complexity of short patterns from a wide range of musical styles (Toussant, 2011).

These previous studies, however, have not used NPVI values to determine the accuracy of rhythmic productions, that is, they have not measured the NPVI values of a target rhythm against the NPVI value of an individual's reproduction. While the NPVI may be sensitive to inter-speaker variation when speaking under normal conditions, this variation may be less pronounced when the goal of speech production is to replicate a specific speech pattern or rhythm. Furthermore when used as a measure of task accuracy NPVI need only be sensitive to substantial differences between the target stimuli and reproductions, thus unreliability in qualitative measures of rhythmic complexity may not affect this result.

It is impossible, given the limited current data, to declare conclusively that NPVI cannot be used as a useful measure for determining task accuracy across musical and linguistic rhythmic variations. In this study only five stimuli were presented in each condition. In addition, when selecting the order of interval patterns for stimuli, the subsequent NPVI values were not controlled, thus some conditions featured a wide range of NPVI values (e.g. 26.67 to 88 in RMs). It is possible that the significantly different reproductions in the complex SS condition were detected due to the smaller range of NPVI values between stimuli. As such creating rhythmic and speech stimuli with a smaller range of NPVI values could possibly make the NPVI more sensitive to differences due to inaccurate reproductions. To conclusively determine the validity

of NPVI as a measure of task accuracy, future research should include more stimuli and reduce the range of NPVI values.

Conclusion

This sought to identify the similarities and difference of prefrontal cortex activation in response to the retention of rhythmic variations in musical and linguistic contexts using fNIRS. However, given the small number of participants recruited and stimuli presented it was not possible to conclusively determine the nature of this activation. General trends indicated greater activation of the right PFC occurred in several participants for both RM conditions, as well as for the complex SS condition. While the right PFC has been associated with verbal memory and retention of complex rhythms, the poor performance on these tasks suggest this activation general effort to retain the information. In addition the NPVI, a measure of intra-rhythmic variability, did not reliably indicate task performance in this protocol. These tasks may be prove useful and accurate in future studies of rhythmic memory processing, however significant refinements should be made to the protocol to ensure accurate measurements.

Acknowledgments

I would like to thank Dr. Michael Cannizzaro for his extensive advice and guidance in executing this study, as well as Gabe Stine for his assistance in operating the fNIRS device for all participants.

References

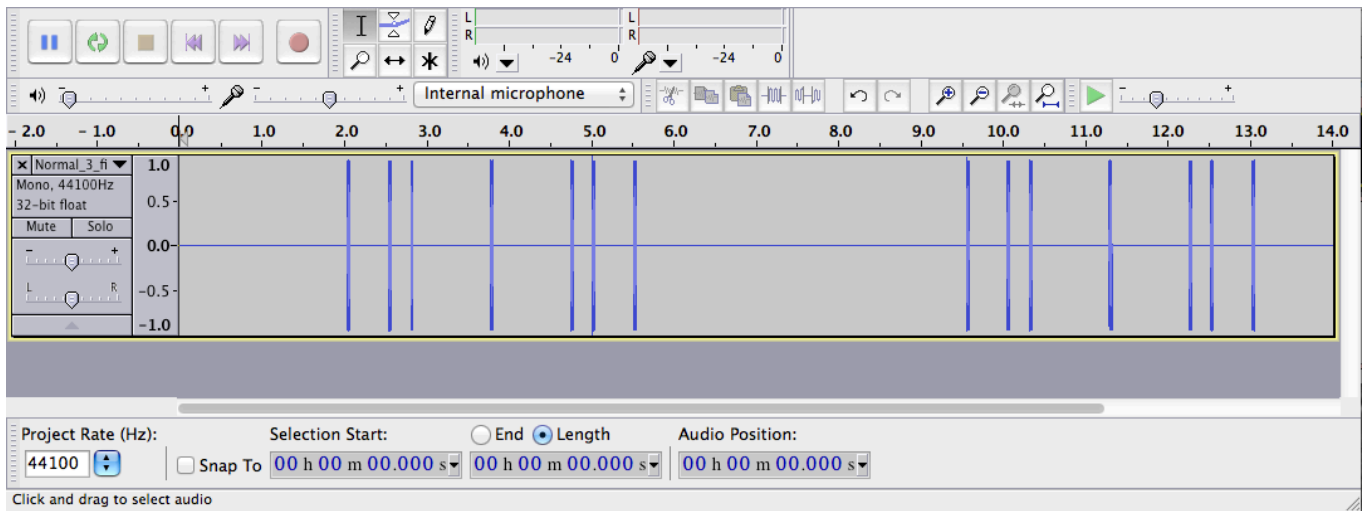
- Abecasis, D., Brochard, R., Granot, R., & Drake, C. (2005). Differential Brain Response to Metrical Accents in Isochronous Auditory Sequences. *Music Perception, 22*(3), 549–562.
- Abrams, D. a, Bhatara, A., Ryali, S., Balaban, E., Levitin, D. J., & Menon, V. (2011). Decoding temporal structure in music and speech relies on shared brain resources but elicits different fine-scale spatial patterns. *Cerebral cortex, 21*(7), 1507–18.
- Abla, D., & Okanoya, K. (2008). Statistical segmentation of tone sequences activates the left inferior frontal cortex: a near-infrared spectroscopy study. *Neuropsychologia, 46*(11), 2787–95.
- Arvaniti, A. (2009). Rhythm, timing and the timing of rhythm. *Phonetica, 66*(1-2), 46–63.
- Arvaniti, A. (2012). The usefulness of metrics in the quantification of speech rhythm. *Journal of Phonetics, 40*(3), 351–373.
- Ayaz, H., Shewokis, P. a, Bunce, S., Izzetoglu, K., Willems, B., & Onaral, B. (2012). Optical brain monitoring for operator training and mental workload assessment. *NeuroImage, 59*(1), 36–47.
- Bohn, K., Knaus, J., Wiese, R., & Domahs, U. (2013). The influence of rhythmic (ir)regularities on speech processing: Evidence from an ERP study on German phrases. *Neuropsychologia, 51*(4), 760–71.
- Braver, T. S., Barch, D. M., Kelley, W. M., Buckner, R. L., Cohen, N. J., Miezin, F. M., Snyder, a Z., et al. (2001). Direct comparison of prefrontal cortex regions engaged by working and long-term memory tasks. *NeuroImage, 14*(1 Pt 1), 48–59.
- Brochard, R., Abecasis, D., Potter, D., Ragot, R., & Drake, C. (2003). THE “ TICKTOCK ” OF OUR INTERNAL CLOCK : Direct Brain Evidence of Subjective Accents in Isochronous Sequences, *14*(4), 362–366.
- Carpenter, P. a, Just, M. a, & Reichle, E. D. (2000). Working memory and executive function: evidence from neuroimaging. *Current opinion in neurobiology, 10*(2), 195–9.
- Cason, N., & Schön, D. (2012). Rhythmic priming enhances the phonological processing of speech. *Neuropsychologia, 50*(11), 2652–8.
- Dieler, a C., Tupak, S. V., & Fallgatter, a J. (2012). Functional near-infrared spectroscopy for the assessment of speech related tasks. *Brain and language, 121*(2), 90–109.

- Ferrari, M., & Quaresima, V. (2012). A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application. *NeuroImage*, *63*(2), 921–35.
- Grabe, E., & Low, E. L. (2002). Durational variability in speech and the rhythm class hypothesis. *Papers in laboratory phonology*, *7*(515-546)
- Grube, M., & Griffiths, T. D. (2009). Metricality-enhanced temporal encoding and the subjective perception of rhythmic sequences. *Cortex; a journal devoted to the study of the nervous system and behavior*, *45*(1), 72–9.
- Horváth, R. a, Schwarcz, a, Aradi, M., Auer, T., Fehér, N., Kovács, N., Tényi, T., et al. (2011). Lateralisation of non-metric rhythm. *Laterality*, *16*(5), 620–35.
- Jerde, T. a, Childs, S. K., Handy, S. T., Nagode, J. C., & Pardo, J. V. (2011). Dissociable systems of working memory for rhythm and melody. *NeuroImage*, *57*(4), 1572–9.
- Jomori, I., & Hoshiyama, M. (2009). Auditory brain response modified by temporal deviation of language rhythm: an auditory event-related potential study. *Neuroscience research*, *65*(2), 187–93.
- Jomori, I., Uemura, J., Nakagawa, Y., & Hoshiyama, M. (2011). Event-related potential study of frontal activity during imagination of rhythm. *Journal of clinical neuroscience : official journal of the Neurosurgical Society of Australasia*, *18*(12), 1687–9.
- Kochanski, G., & Orphanidou, C. (2008). What marks the beat of speech? *The Journal of the Acoustical Society of America*, *123*(5), 2780–91.
- Large, E. W., & Snyder, J. S. (2009). Pulse and meter as neural resonance. *Annals of the New York Academy of Sciences*, *1169*, 46–57.
- Lidji, P., Palmer, C., Peretz, I., & Morningstar, M. (2011). Listeners feel the beat: entrainment to English and French speech rhythms. *Psychonomic bulletin & review*, *18*(6), 1035–41.
- Liu, S., Chow, H. M., Xu, Y., Erkkinen, M. G., Swett, K. E., Eagle, M. W., Rizik-Baer, D. a, et al. (2012). Neural correlates of lyrical improvisation: an fMRI study of freestyle rap. *Scientific reports*, *2*, 834.
- Macleod, A. K., Buckner, R. L., Miezin, F. M., Petersen, S. E., & Raichle, M. E. (1998). Right Anterior Prefrontal Cortex Activation during Semantic Monitoring and Working Memory, *48*(7), 41–48.
- Mattys, S. L., Brooks, J., & Cooke, M. (2009). Recognizing speech under a processing load: dissociating energetic from informational factors. *Cognitive psychology*, *59*(3), 203–43.
- Moghimi, S., Kushki, A., Guerguerian, A. M., & Chau, T. (2012). Characterizing emotional response to music in the prefrontal cortex using near infrared spectroscopy. *Neuroscience letters*, *525*(1), 7–11.

- Nozaradan, S., Peretz, I., Missal, M., & Mouraux, A. (2011). Tagging the neuronal entrainment to beat and meter. *The Journal of neuroscience : the official journal of the Society for Neuroscience*, *31*(28), 10234–40.
- Pamines Bertrán, A. (1999). Prosodic Typology: On the Dichotomy between Stress-Timed and Syllable-Timed Languages. *Language Design*, (2), 103–130.
- Patel, A. D. (2003). Language, music, syntax and the brain. *Nature neuroscience*, *6*(7), 674–681.
- Patel, A. D., & Daniele, J. R. (2003). An empirical comparison of rhythm in language and music. *Neurosciences*, *87*.
- Potter, D. D., Fenwick, M., Abecasis, D., & Brochard, R. (2009). Perceiving rhythm where none exists: event-related potential (ERP) correlates of subjective accenting. *Cortex*, *45*(1), 103–9.
- Power, S. D., Falk, T. H., & Chau, T. (2010). Classification of prefrontal activity due to mental arithmetic and music imagery using hidden Markov models and frequency domain near-infrared spectroscopy. *Journal of neural engineering*, *7*(2), 26002.
- Quené, H., & Port, R. F. (2005). Effects of timing regularity and metrical expectancy on spoken-word perception. *Phonetica*, *62*(1), 1–13.
- Remijn, G. B., & Kojima, H. (2013). Active versus passive listening to auditory streaming stimuli: a near-infrared spectroscopy study. *Journal of biomedical optics*, *15*(3), 037006.
- Rothermich, K., Schmidt-Kassow, M., & Kotz, S. a. (2012). Rhythm's gonna get you: regular meter facilitates semantic sentence processing. *Neuropsychologia*, *50*(2), 232–44.
- Rothermich, K., & Kotz, S. a. (2013). Predictions in speech comprehension: fMRI evidence on the meter-semantic interface. *NeuroImage*, *70*, 89–100.
- Sakai, K., Hikosaka, O., Miyauchi, S., Takino, R., Tamada, T., Iwata, N. K., & Nielsen, M. (1999). Neural representation of a rhythm depends on its interval ratio. *The Journal of neuroscience : the official journal of the Society for Neuroscience*, *19*(22), 10074–81.
- Schecklmann, M., Ehlis, A.-C., Plichta, M. M., & Fallgatter, A. J. (2008). Functional near-infrared spectroscopy: a long-term reliable tool for measuring brain activity during verbal fluency. *NeuroImage*, *43*(1), 147–55.
- Schneiders, J. a, Opitz, B., Tang, H., Deng, Y., Xie, C., Li, H., & Mecklinger, A. (2012). The impact of auditory working memory training on the fronto-parietal working memory network. *Frontiers in human neuroscience*, (6), 1-14.

- Shi, Y., Zhou, X., Müller, H. J., & Schubert, T. (2010). The neural implementation of task rule activation in the task-cuing paradigm: an event-related fMRI study. *NeuroImage*, *51*(3), 1253–64.
- Toussaint, G. T. (2012). The pairwise variability index as a tool in musical rhythm analysis. *Proceedings of the 12th International Conference on Music Perception and Cognition (ICMPC), and 8th Triennial Conference of the European Society for the Cognitive Sciences of Music (ESCOM)*, 1001-1008.
- Uddén, J., & Bahlmann, J. (2012). A rostro-caudal gradient of structured sequence processing in the left inferior frontal gyrus. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, *367*(1598), 2023–32.
- Vuust, P., Roepstorff, a, Wallentin, M., Mouridsen, K., & Østergaard, L. (2006). It don't mean a thing... Keeping the rhythm during polyrhythmic tension, activates language areas (BA47). *NeuroImage*, *31*(2), 832–41.
- Vuust, P., Ostergaard, L., Pallesen, K. J., Bailey, C., & Roepstorff, A. (2009). Predictive coding of music--brain responses to rhythmic incongruity. *Cortex; a journal devoted to the study of the nervous system and behavior*, *45*(1), 80–92.
- White, L., Mattys, S. L., & Wiget, L. (2012). Language categorization by adults is based on sensitivity to durational cues , not rhythm class. *Journal of Memory and Language*, *66*(4), 665–679.
- Ystad, S., Magne, C., Farner, S., Pallone, G., Aramaki, M., Besson, M., & Kronland-Martinnet, R. (2007). Electrophysiological Study of Algorithmically Processed Metric/Rhythmic Variations in Language and Music. *EURASIP Journal on Audio, Speech, and Music Processing*, *2007*, 1–13.

1.a



1.b

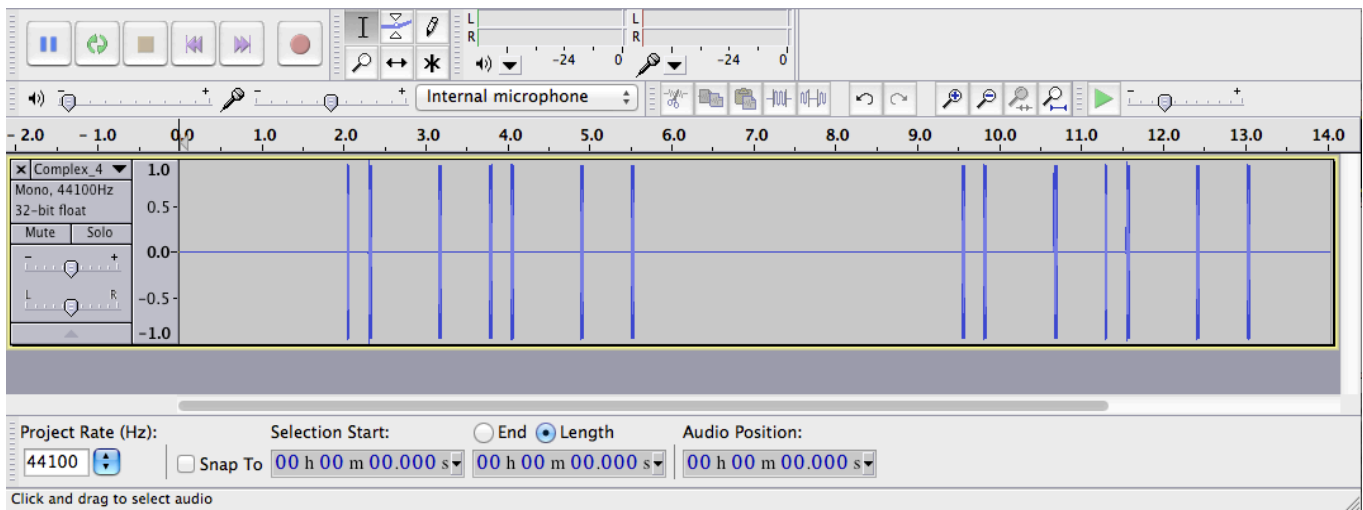
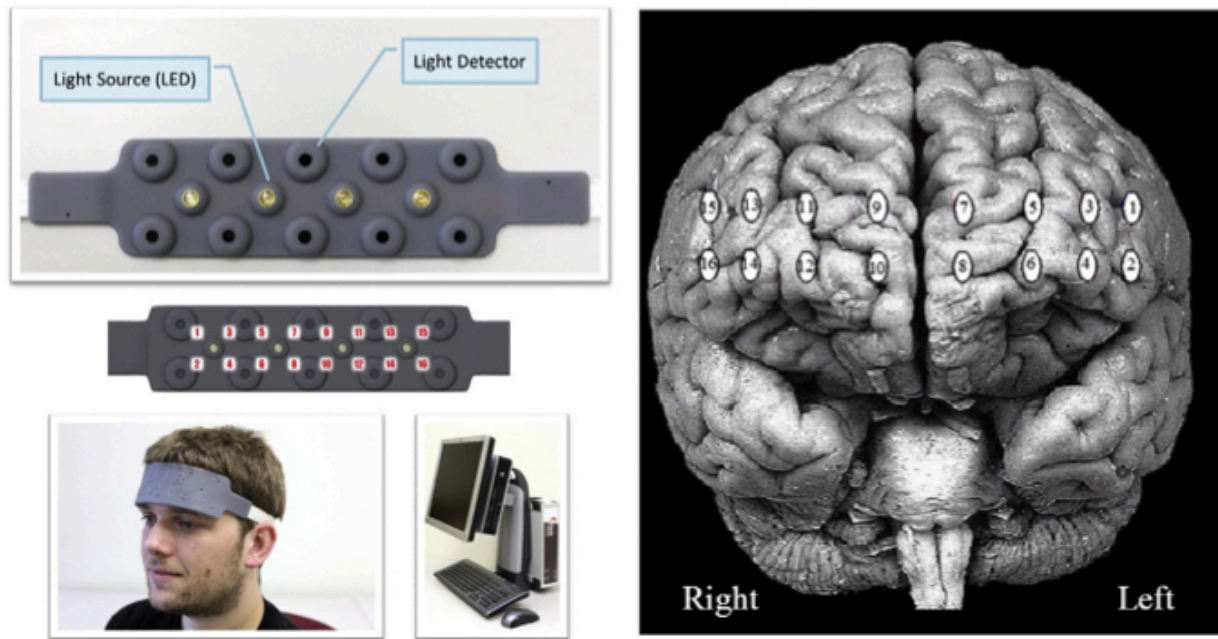


Figure 1, examples of simple and complex Rhythmic Motor stimuli. a) timeline of simple RM stimuli following a 2|1|4|1|2 interval pattern. b) Timeline of a complex RM stimuli following a 1|3.5|2.5|1|3.5|2.5 interval pattern. Each stimuli was repeated twice following a four second delay. Images captured from Audacity.

2.a



2.b

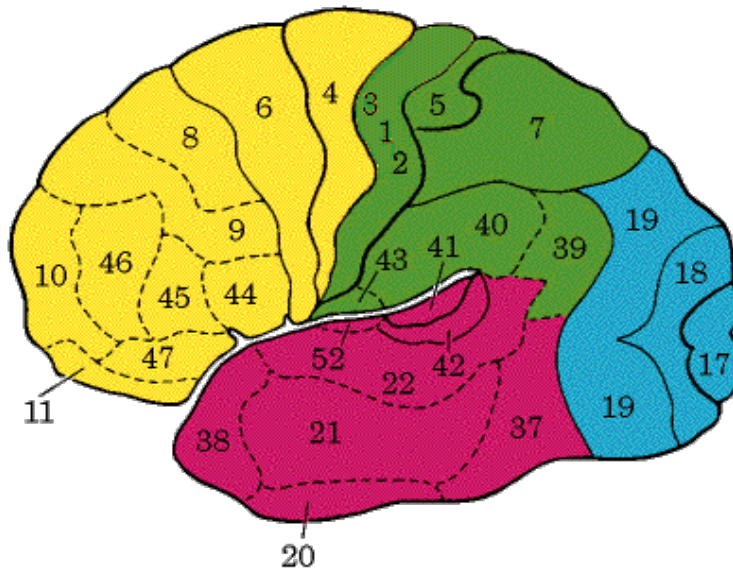
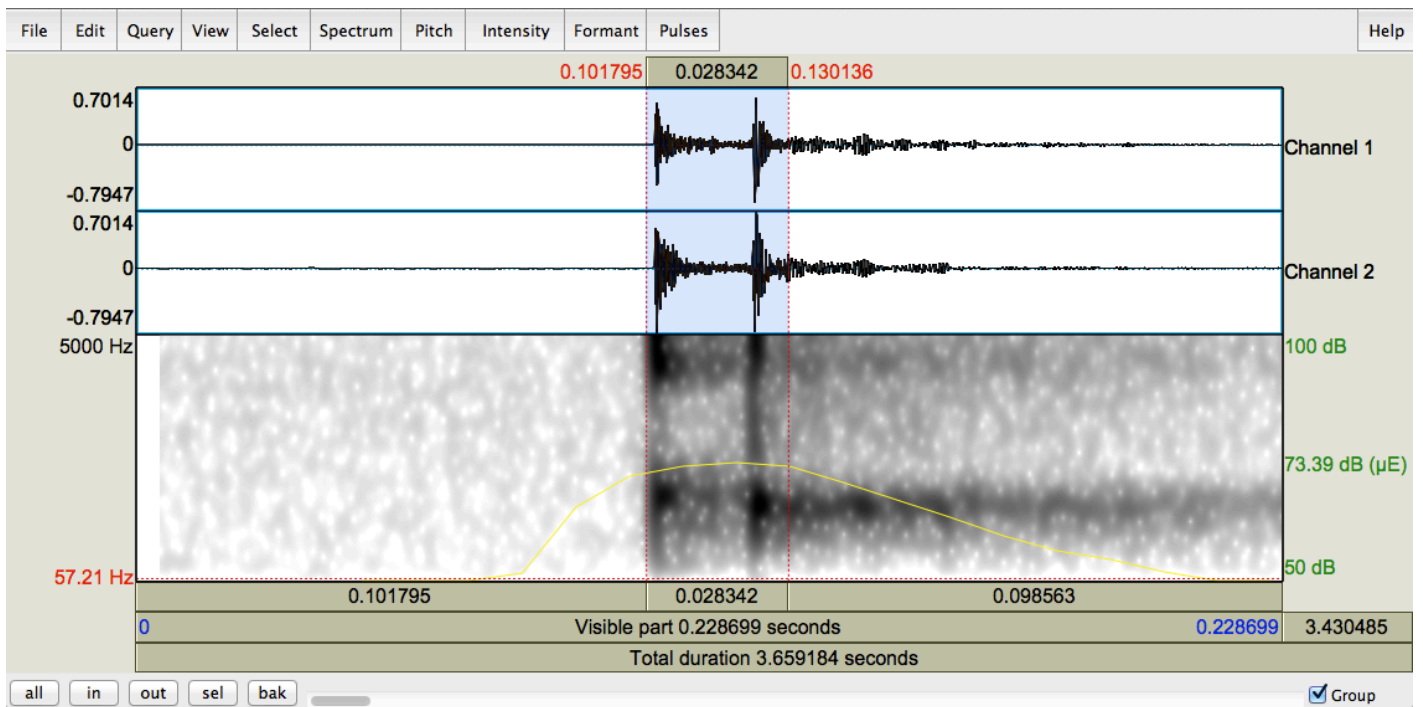


Figure 2, Visual references. a) BIOPAC fNIR100A device, including demonstration of proper headband application, as well as voxels and their corresponding locations on the prefrontal cortex. Image source: Ayaz et al. (2012). b) Diagram of Brodmann's areas. Image source: <http://www.umich.edu/~cogneuro/jpg/Brodmann.html>.

3.a



3.b

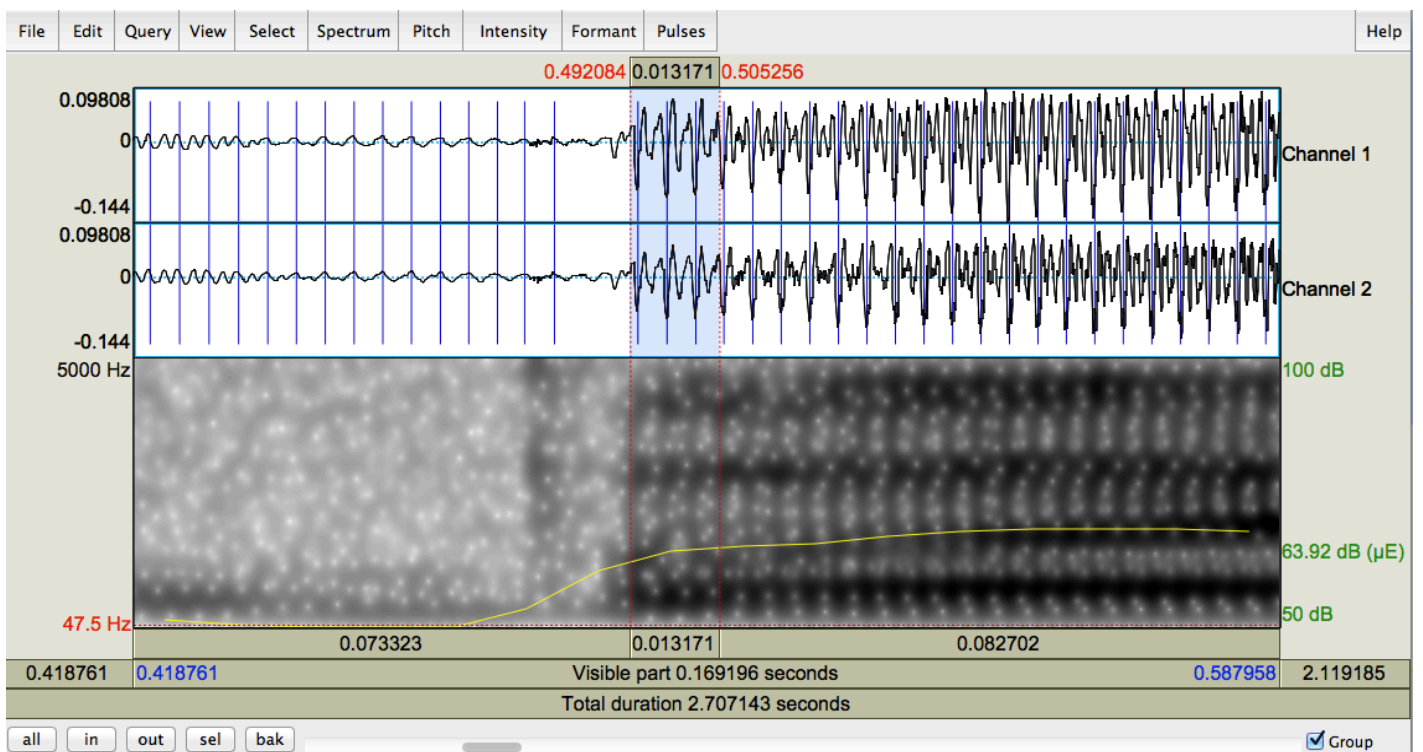


Figure 3, identifying sound duration in PRAAT. a) Sound length measured for clicking noise produced by JM02 during RMs stimuli #4. Sound length was defined from the beginning of the sound to peak intensity, indicated by the yellow line. b) Sound length measured for syllable produced by JM07 during RSs stimuli #3. Sound length was defined from the beginning of the vowel vocalization to the beginning of the fourth pulse.

4.a

JM02_RMs NPVI	
Summary Statistics	
Mean	45.817088
Std Dev	10.229566
Std Err Mean	4.5748011
Upper 95% Mean	58.518772
Lower 95% Mean	33.115404
N	5
Test Mean	
Hypothesized Value	56
Actual Estimate	45.8171
DF	4
Std Dev	10.2296
Sigma given	25.0865
z Test	
Test Statistic	-0.9076
Prob > z	0.3641
Prob > z	0.8180
Prob < z	0.1820

JM03_RMs NPVI	
Summary Statistics	
Mean	59.39199
Std Dev	22.801164
Std Err Mean	10.196991
Upper 95% Mean	87.703374
Lower 95% Mean	31.080605
N	5
Test Mean	
Hypothesized Value	56
Actual Estimate	59.392
DF	4
Std Dev	22.8012
Sigma given	25.0865
z Test	
Test Statistic	0.3023
Prob > z	0.7624
Prob > z	0.3812
Prob < z	0.6188

JM06_RMs NPVI	
Summary Statistics	
Mean	47.678652
Std Dev	13.980578
Std Err Mean	6.2523044
Upper 95% Mean	65.037832
Lower 95% Mean	30.319472
N	5
Test Mean	
Hypothesized Value	56
Actual Estimate	47.6787
DF	4
Std Dev	13.9806
Sigma given	25.0865
z Test	
Test Statistic	-0.7417
Prob > z	0.4583
Prob > z	0.7709
Prob < z	0.2291

JM07_RMs NPVI	
Summary Statistics	
Mean	62.923971
Std Dev	19.778107
Std Err Mean	8.8450383
Upper 95% Mean	87.481734
Lower 95% Mean	38.366208
N	5
Test Mean	
Hypothesized Value	56
Actual Estimate	62.924
DF	4
Std Dev	19.7781
Sigma given	25.0865
z Test	
Test Statistic	0.6172
Prob > z	0.5371
Prob > z	0.2686
Prob < z	0.7314

JM08_RMs NPVI	
Summary Statistics	
Mean	66.341599
Std Dev	18.829491
Std Err Mean	8.4208045
Upper 95% Mean	89.721501
Lower 95% Mean	42.961698
N	5
Test Mean	
Hypothesized Value	56
Actual Estimate	66.3416
DF	4
Std Dev	18.8295
Sigma given	25.0865
z Test	
Test Statistic	0.9218
Prob > z	0.3566
Prob > z	0.1783
Prob < z	0.8217

JM09_RMs NPVI	
Summary Statistics	
Mean	56.354845
Std Dev	14.53545
Std Err Mean	6.500451
Upper 95% Mean	74.402991
Lower 95% Mean	38.3067
N	5
Test Mean	
Hypothesized Value	56
Actual Estimate	56.3548
DF	4
Std Dev	14.5355
Sigma given	25.0865
z Test	
Test Statistic	0.0316
Prob > z	0.9748
Prob > z	0.4874
Prob < z	0.5126

4.b

JM02_RMc NPVI	
Summary Statistics	
Mean	56.359913
Std Dev	15.54205
Std Err Mean	6.9506161
Upper 95% Mean	75.657917
Lower 95% Mean	37.061909
N	5
Test Mean	
Hypothesized Value	48.4444
Actual Estimate	56.3599
DF	4
Std Dev	15.542
Sigma given	18.9396
z Test	
Test Statistic	0.9345
Prob > z	0.3500
Prob > z	0.1750
Prob < z	0.8250

JM03_RMc NPVI	
Summary Statistics	
Mean	67.566421
Std Dev	29.14089
Std Err Mean	13.032202
Upper 95% Mean	103.74962
Lower 95% Mean	31.383227
N	5
Test Mean	
Hypothesized Value	48.4444
Actual Estimate	67.5664
DF	4
Std Dev	29.1409
Sigma given	18.9396
z Test	
Test Statistic	2.2576
Prob > z	0.0240*
Prob > z	0.0120*
Prob < z	0.9880

JM06_RMc NPVI	
Summary Statistics	
Mean	46.888096
Std Dev	9.2642572
Std Err Mean	4.1431018
Upper 95% Mean	58.39119
Lower 95% Mean	35.385001
N	5
Test Mean	
Hypothesized Value	48.4444
Actual Estimate	46.8881
DF	4
Std Dev	9.26426
Sigma given	18.9396
z Test	
Test Statistic	-0.1837
Prob > z	0.8542
Prob > z	0.5729
Prob < z	0.4271

JM07_RMc NPVI	
Summary Statistics	
Mean	68.734021
Std Dev	11.949535
Std Err Mean	5.3439944
Upper 95% Mean	83.571328
Lower 95% Mean	53.896714
N	5
Test Mean	
Hypothesized Value	48.4444
Actual Estimate	68.734
DF	4
Std Dev	11.9495
Sigma given	18.9396
z Test	
Test Statistic	2.3954
Prob > z	0.0166*
Prob > z	0.0083*
Prob < z	0.9917

JM08_RMc NPVI	
Summary Statistics	
Mean	65.653783
Std Dev	25.741727
Std Err Mean	11.51205
Upper 95% Mean	97.616358
Lower 95% Mean	33.691207
N	5
Test Mean	
Hypothesized Value	48.4444
Actual Estimate	65.6538
DF	4
Std Dev	25.7417
Sigma given	18.9396
z Test	
Test Statistic	2.0318
Prob > z	0.0422*
Prob > z	0.0211*
Prob < z	0.9789

JM09_RMc NPVI	
Summary Statistics	
Mean	68.879077
Std Dev	15.89736
Std Err Mean	7.1095155
Upper 95% Mean	88.618256
Lower 95% Mean	49.139897
N	5
Test Mean	
Hypothesized Value	48.4444
Actual Estimate	68.8791
DF	4
Std Dev	15.8974
Sigma given	18.9396
z Test	
Test Statistic	2.4126
Prob > z	0.0158*
Prob > z	0.0079*
Prob < z	0.9921

4.c

JM03_RSs NPVI	
Summary Statistics	
Mean	88.125855
Std Dev	11.589754
Std Err Mean	5.1830958
Upper 95% Mean	102.51644
Lower 95% Mean	73.735274
N	5
Test Mean	
Hypothesized Value	65.4342
Actual Estimate	88.1259
DF	4
Std Dev	11.5898
Sigma given	10.0528
z Test	
Test Statistic	5.0474
Prob > z	<.0001*
Prob > z	<.0001*
Prob < z	1.0000

JM06_RSs NPVI	
Summary Statistics	
Mean	67.607503
Std Dev	13.566696
Std Err Mean	6.0672108
Upper 95% Mean	84.45278
Lower 95% Mean	50.762225
N	5
Test Mean	
Hypothesized Value	65.4342
Actual Estimate	67.6075
DF	4
Std Dev	13.5667
Sigma given	10.0528
z Test	
Test Statistic	0.4834
Prob > z	0.6288
Prob > z	0.3144
Prob < z	0.6856

JM07_RSs NPVI	
Summary Statistics	
Mean	70.82754
Std Dev	10.569745
Std Err Mean	4.7269335
Upper 95% Mean	83.951612
Lower 95% Mean	57.703468
N	5
Test Mean	
Hypothesized Value	65.4342
Actual Estimate	70.8275
DF	4
Std Dev	10.5697
Sigma given	10.0528
z Test	
Test Statistic	1.1997
Prob > z	0.2303
Prob > z	0.1151
Prob < z	0.8849

JM08_RSs NPVI	
Summary Statistics	
Mean	83.577889
Std Dev	5.8637126
Std Err Mean	2.622332
Upper 95% Mean	90.85865
Lower 95% Mean	76.297128
N	5
Test Mean	
Hypothesized Value	65.4342
Actual Estimate	83.5779
DF	4
Std Dev	5.86371
Sigma given	10.0528
z Test	
Test Statistic	4.0358
Prob > z	<.0001*
Prob > z	<.0001*
Prob < z	1.0000

JM09_RSs NPVI	
Summary Statistics	
Mean	76.706087
Std Dev	21.800505
Std Err Mean	9.7494823
Upper 95% Mean	103.77499
Lower 95% Mean	49.637184
N	5
Test Mean	
Hypothesized Value	65.4342
Actual Estimate	76.7061
DF	4
Std Dev	21.8005
Sigma given	10.0528
z Test	
Test Statistic	2.5072
Prob > z	0.0122*
Prob > z	0.0061*
Prob < z	0.9939

4.d

JM03_RSc NPVI		JM06_RSc NPVI		JM07_RSc NPVI		JM08_RSc NPVI		JM09_RSc NPVI	
Summary Statistics		Summary Statistics		Summary Statistics		Summary Statistics		Summary Statistics	
Mean	57.738684	Mean	54.994205	Mean	68.595706	Mean	56.431572	Mean	56.717106
Std Dev	25.031174	Std Dev	14.51357	Std Dev	16.567228	Std Dev	6.0399491	Std Dev	27.763461
Std Err Mean	11.194281	Std Err Mean	6.4906659	Std Err Mean	7.4090897	Std Err Mean	2.7011474	Std Err Mean	12.416197
Upper 95% Mean	88.818992	Upper 95% Mean	73.015183	Upper 95% Mean	89.166637	Upper 95% Mean	63.931159	Upper 95% Mean	91.189995
Lower 95% Mean	26.658376	Lower 95% Mean	36.973227	Lower 95% Mean	48.024775	Lower 95% Mean	48.931984	Lower 95% Mean	22.244216
N	5	N	5	N	5	N	5	N	5
Test Mean		Test Mean		Test Mean		Test Mean		Test Mean	
Hypothesized Value	58.0168	Hypothesized Value	58.0168	Hypothesized Value	58.0168	Hypothesized Value	58.0168	Hypothesized Value	58.0168
Actual Estimate	57.7387	Actual Estimate	54.9942	Actual Estimate	68.5957	Actual Estimate	56.4316	Actual Estimate	56.7171
DF	4	DF	4	DF	4	DF	4	DF	4
Std Dev	25.0312	Std Dev	14.5136	Std Dev	16.5672	Std Dev	6.03995	Std Dev	27.7635
Sigma given	18.3152	Sigma given	18.3152	Sigma given	18.3152	Sigma given	18.3152	Sigma given	18.3152
z Test		z Test		z Test		z Test		z Test	
Test Statistic	-0.0340	Test Statistic	-0.3690	Test Statistic	1.2916	Test Statistic	-0.1935	Test Statistic	-0.1587
Prob > z	0.9729	Prob > z	0.7121	Prob > z	0.1965	Prob > z	0.8465	Prob > z	0.8739
Prob > z	0.5135	Prob > z	0.6439	Prob > z	0.0983	Prob > z	0.5767	Prob > z	0.5630
Prob < z	0.4865	Prob < z	0.3561	Prob < z	0.9017	Prob < z	0.4233	Prob < z	0.4370

4.e

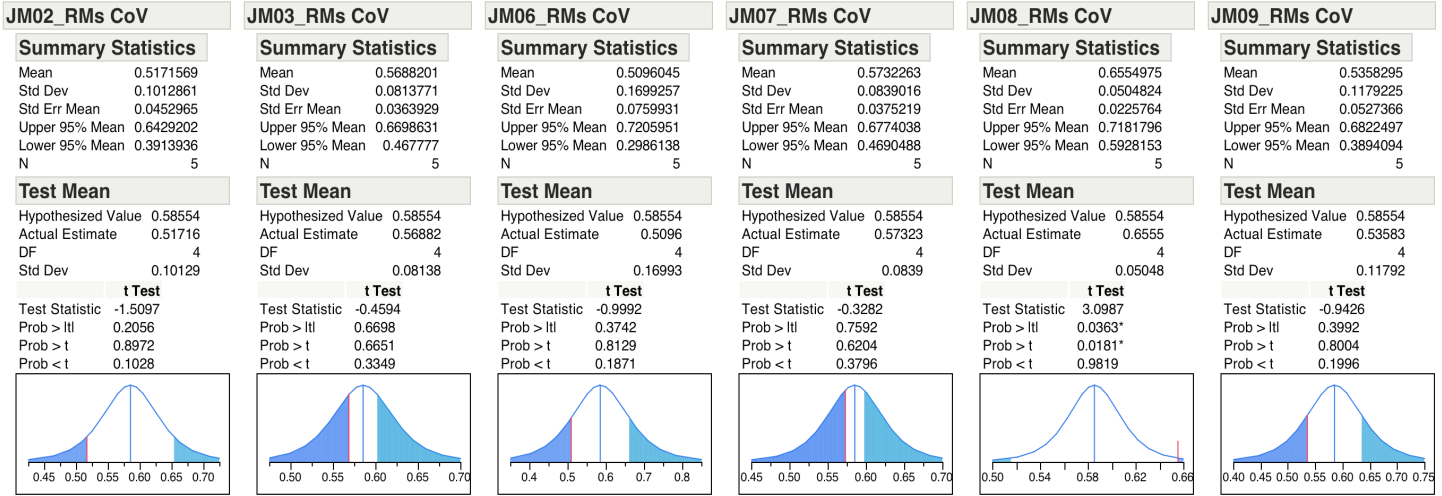
JM03_SSs NPVI		JM06_SSs NPVI		JM07_SSs NPVI		JM08_SSs NPVI		JM09_SSs NPVI	
Summary Statistics		Summary Statistics		Summary Statistics		Summary Statistics		Summary Statistics	
Mean	65.350447	Mean	54.30495	Mean	53.218076	Mean	51.507324	Mean	51.679199
Std Dev	7.5290727	Std Dev	9.2306781	Std Dev	9.4551054	Std Dev	10.278842	Std Dev	9.4747395
Std Err Mean	3.3671037	Std Err Mean	4.1280847	Std Err Mean	4.2284517	Std Err Mean	4.596838	Std Err Mean	4.2372323
Upper 95% Mean	74.699025	Upper 95% Mean	65.766351	Upper 95% Mean	64.95814	Upper 95% Mean	64.270193	Upper 95% Mean	63.443642
Lower 95% Mean	56.001868	Lower 95% Mean	42.84355	Lower 95% Mean	41.478012	Lower 95% Mean	38.744456	Lower 95% Mean	39.914756
N	5	N	5	N	5	N	5	N	5
Test Mean		Test Mean		Test Mean		Test Mean		Test Mean	
Hypothesized Value	51.6958	Hypothesized Value	51.6958	Hypothesized Value	51.6958	Hypothesized Value	51.6958	Hypothesized Value	51.6958
Actual Estimate	65.3504	Actual Estimate	54.305	Actual Estimate	53.2181	Actual Estimate	51.5073	Actual Estimate	51.6792
DF	4	DF	4	DF	4	DF	4	DF	4
Std Dev	7.52907	Std Dev	9.23068	Std Dev	9.45511	Std Dev	10.2788	Std Dev	9.47474
Sigma given	12.1729	Sigma given	12.1729	Sigma given	12.1729	Sigma given	12.1729	Sigma given	12.1729
z Test		z Test		z Test		z Test		z Test	
Test Statistic	2.5082	Test Statistic	0.4793	Test Statistic	0.2796	Test Statistic	-0.0346	Test Statistic	-0.0031
Prob > z	0.0121*	Prob > z	0.6317	Prob > z	0.7798	Prob > z	0.9724	Prob > z	0.9976
Prob > z	0.0061*	Prob > z	0.3159	Prob > z	0.3899	Prob > z	0.5138	Prob > z	0.5012
Prob < z	0.9939	Prob < z	0.6841	Prob < z	0.6101	Prob < z	0.4862	Prob < z	0.4988

4.f

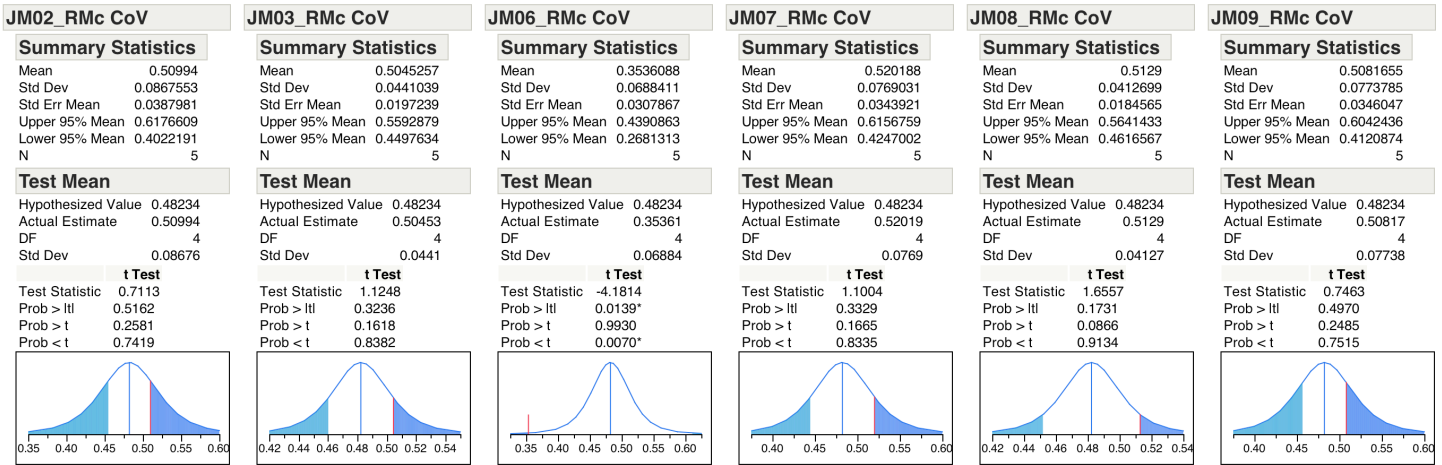
JM06_SSc NPVI		JM07_SSc NPVI		JM08_SSc NPVI		JM09_SSc NPVI	
Summary Statistics		Summary Statistics		Summary Statistics		Summary Statistics	
Mean	45.097731	Mean	42.252079	Mean	42.789857	Mean	28.611984
Std Dev	17.674621	Std Dev	13.053045	Std Dev	9.0640865	Std Dev	9.0266324
Std Err Mean	7.9043307	Std Err Mean	5.8374992	Std Err Mean	4.0535827	Std Err Mean	4.0368327
Upper 95% Mean	67.043671	Upper 95% Mean	58.459575	Upper 95% Mean	54.044407	Upper 95% Mean	39.820029
Lower 95% Mean	23.151791	Lower 95% Mean	26.044583	Lower 95% Mean	31.535307	Lower 95% Mean	17.40394
N	5	N	5	N	5	N	5
Test Mean		Test Mean		Test Mean		Test Mean	
Hypothesized Value	35.4992	Hypothesized Value	35.4992	Hypothesized Value	35.4992	Hypothesized Value	35.4992
Actual Estimate	45.0977	Actual Estimate	42.2521	Actual Estimate	42.7899	Actual Estimate	28.612
DF	4	DF	4	DF	4	DF	4
Std Dev	17.6746	Std Dev	13.053	Std Dev	9.06409	Std Dev	9.02663
Sigma given	6.70337	Sigma given	6.70337	Sigma given	6.70337	Sigma given	6.70337
z Test		z Test		z Test		z Test	
Test Statistic	3.2018	Test Statistic	2.2526	Test Statistic	2.4320	Test Statistic	-2.2974
Prob > z	0.0014*	Prob > z	0.0243*	Prob > z	0.0150*	Prob > z	0.0216*
Prob > z	0.0007*	Prob > z	0.0121*	Prob > z	0.0075*	Prob > z	0.9892
Prob < z	0.9993	Prob < z	0.9879	Prob < z	0.9925	Prob < z	0.0108*

Figure 4, one sample z-tests for average NPVI values for each condition. a) NPVI for RMs, b) RMc, c) RSs, d) RSc, e) SSs, f) SSc.

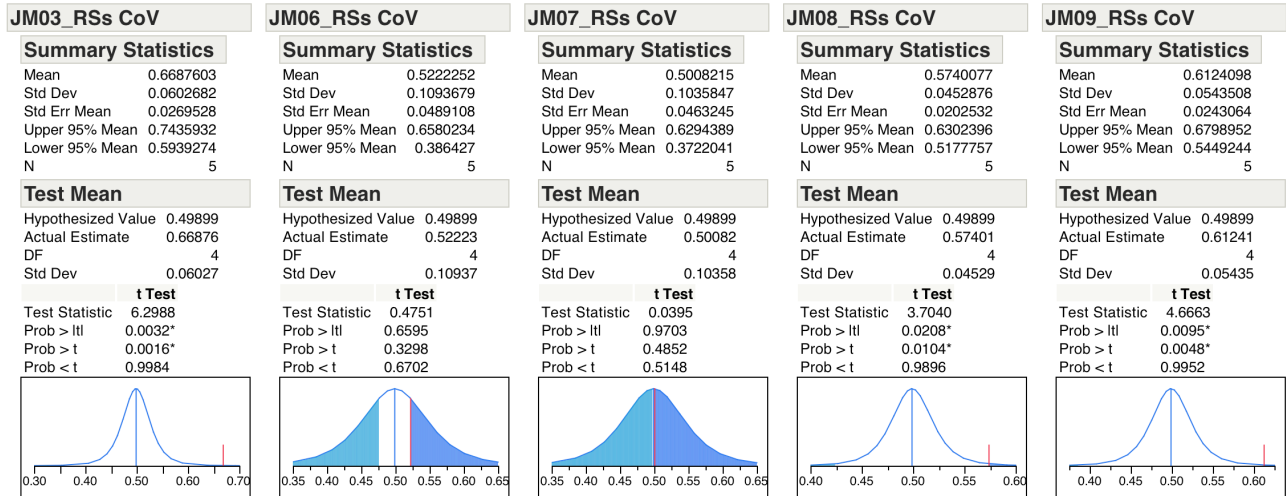
5.a



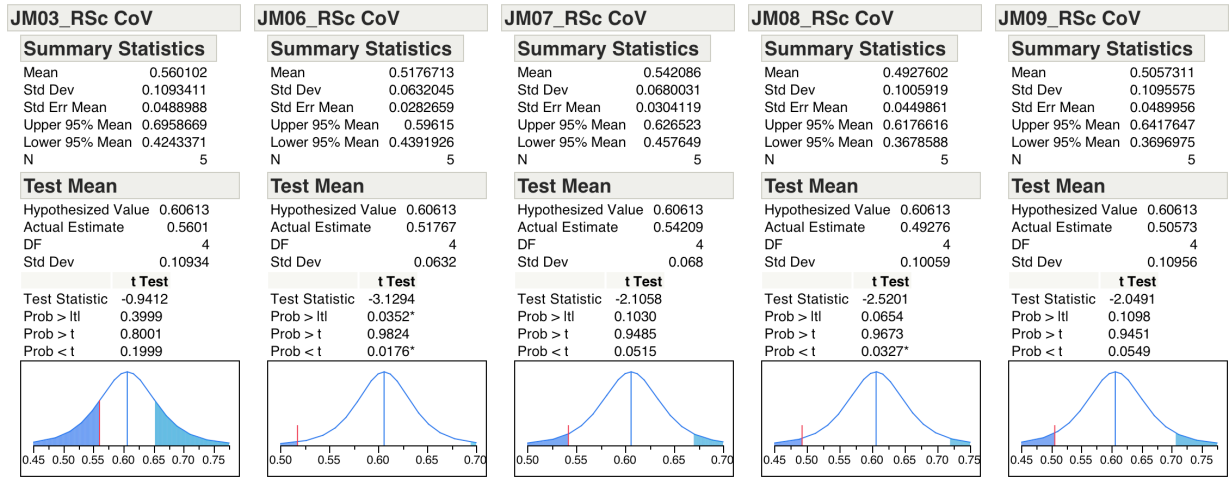
5.b



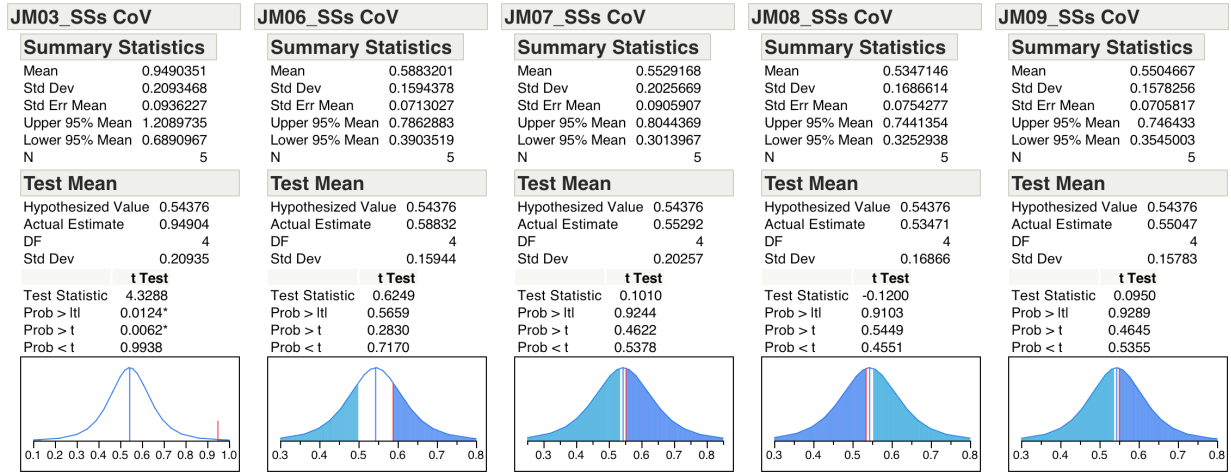
5.c



5.d



5.e



5.f

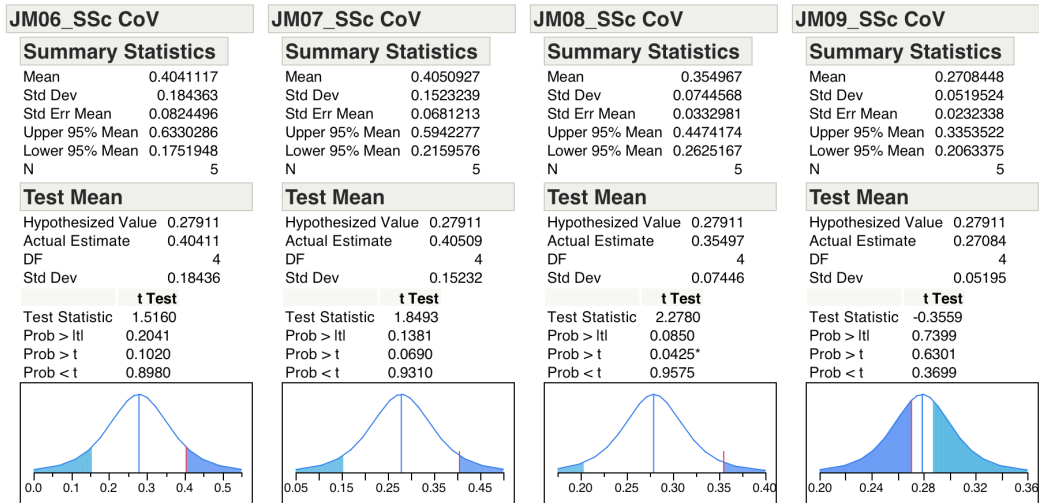


Figure 5, one sample t-tests for average CoV values for each condition. a) CoV for RMs, b) RMc, c) RSs, d) RSc, e) SSs, f) SSc.

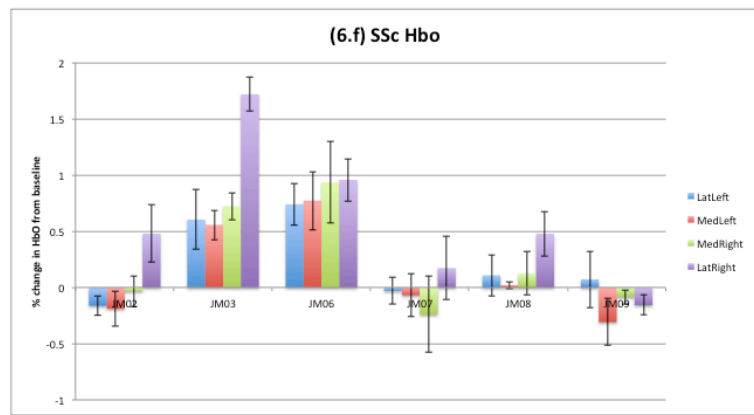
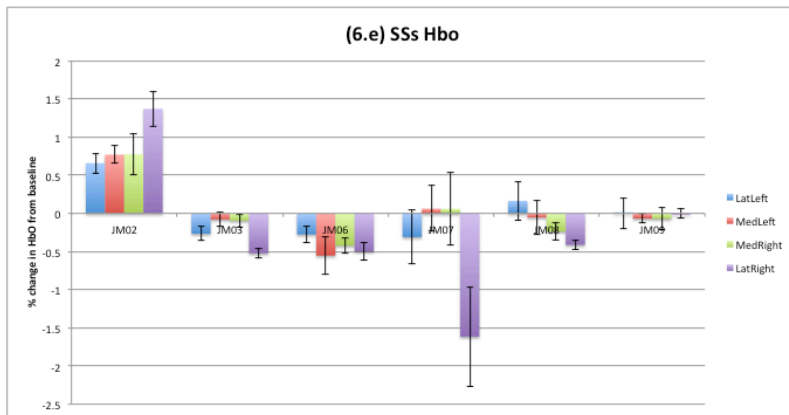
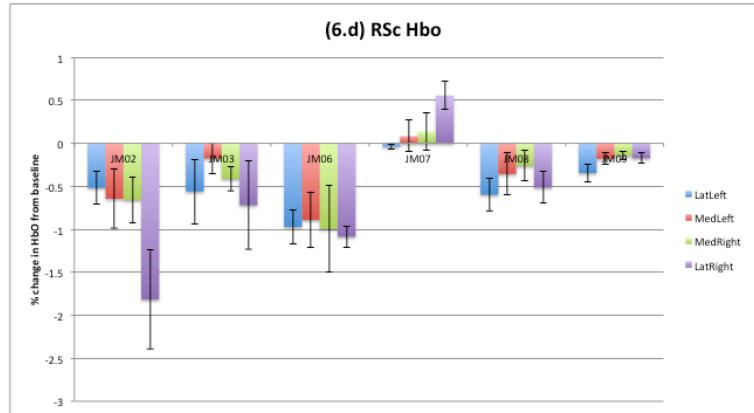
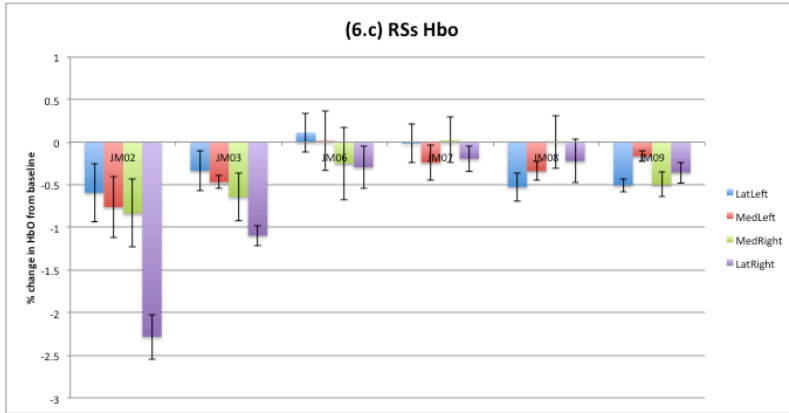
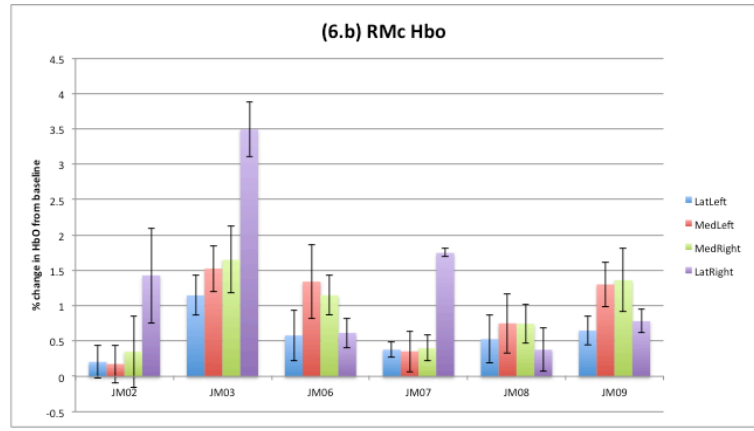
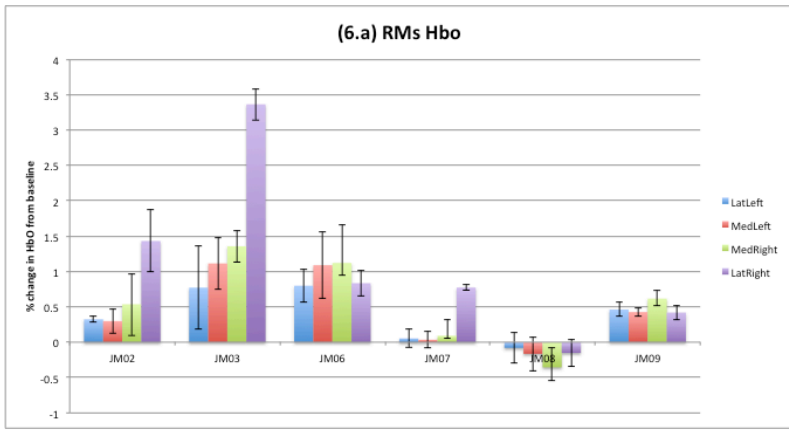


Figure 6, Percent change in HbO levels compared to baseline. a) HbO change during RMs, b) RMc, c) RSs, d) RSc, e) SSs, f) SSc. Bars represent standard deviation for all condition stimuli.