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Experience-Specific and Domain-General Effects on Simple and Complex Meter Processing

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EXPERIENCE-SPECIFIC AND DOMAIN-GENERAL EFFECTS ON

SIMPLE AND COMPLEX METER PROCESSING

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Abstract

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Our ability to process rhythmic patterns is constrained by the complexity of its interval structure. The goal of the present study was to explore the cognitive demands and neural mechanisms for processing simple and complex meters, and the extent to which they are modulated by culture-specific experience. The first experiment explored the argument that perception of rhythm is guided by a domain-general ability to process quantity, and that processing simple and complex meter rhythms requires different cognitive strategies. Rhythm perception was assessed by testing listeners' ability to detect disruptions in simple and complex meter melodies. Proficiency with numerosity judgments was measured by using visual and auditory enumeration tasks. Results showed that individual performance on simple meter trials correlated with: performance on the more automatic enumeration of small quantities (the "subitizing range") *and* with performance on the more effortful enumeration of larger quantities (the "counting range"). In contrast, performance on complex meter trials only correlated with performance in the counting range, and with working memory capacity.

The second experiment used electroencephalography (EEG) to measure brain responses as listeners were asked to mentally place a beat on one of two positions (subjective accents), with rhythms varying in metrical complexity. To assess the role of prior experience on rhythm perception, Non-Western listeners (from India and Bulgaria) and Western listeners (from North America) were tested separately. Western music consists of metrical subdivisions predominantly associated by simple ratios, but music from cultures like India and Bulgaria frequently contains complex ratio meters. N1 response amplitude pointed to differences in simple and complex meter processing, even in those for whom they are equally familiar, with larger amplitudes at the start of the trial and smaller amplitudes subsequently within a trial. The results from the two experiments reveal greater cognitive demands on complex meter processing, and an effect of culture on attenuating (instead of causing) these constraints.

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CHAPTER 1

Introduction

Music from around the world is comprised of sequences of durations. The organization of these durations forms the rhythm of the musical piece. For instance, a rhythm can be composed of a series of alternating short and long intervals of 250 ms and 500 ms respectively. Similar to these durational contrasts, other surface features, such as grouping and intensity changes (Povel & Essens, 1985) act as accents that can shape perception of the musical events. While these exogenous factors shape rhythmic structure, the interaction between these exogenous variables and the endogenous interpretations of the rhythm by the listener, forms the meter (Hannon, Snyder, Eerola & Krumhansl, 2004). Thus, meter can be defined as the abstract temporal structure inferred from periodic regularities in the music (Palmer & Krumhansl, 1990). Within a meter, note onsets or events (such as clapping, or the sounding of a drum) tend to occur on the strong positions, known as downbeats, instead of on the weak positions, known as upbeats.

In inferring the meter, listeners attend to the metrical hierarchy, which at its most fundamental level is comprised of equally spaced isochronous beats, and additional higher levels which subdivide or multiply this fundamental beat level. Within this higher-level of hierarchy, the nested levels of periodic structure in Western music are typically composed of durations that are related by simple integer ratios, such as 1:2 and 1:3 (Lerdahl & Jackendoff, 1983; Trehub & Hannon, 2006), named duple and triple meters respectively. In perceiving these meters, the listener typically perceives certain beats as being more accented than others are. For instance, a listener perceives a duple meter with a **ONE-**two-**ONE-**two pattern, as in a march, and a triple meter with a **ONE-**two-three-**ONE-**two-three pattern, as in a waltz.

Unlike these simple meters, complex meters consist of unequal subdivisions, with adjacent intervals related in more complex ratios, such as 2:3. One of the theories in music perception is that simple meters and rhythms, having multiple coinciding pulse levels, are easier to perceive and produce (Fraisse, 1982; Snyder, Hannon, Large, & Christiansen, 2006) than complex meters. In an early study, Fraisse (1982) focused on the importance of simple integer ratios in perceiving rhythms and meters, and described the tendency for more complex ratios to migrate towards these simpler ratios. Similar results are found in a categorical rhythm perception task, where listeners are required to notate the metrical component of metrical and non-metrical stimuli. Even in the absence of a metrical context, participants are most likely to interpret the stimuli as having a duple meter, pointing to the bias towards simple meter processing (Desain & Honing, 2003).

Likewise, when presented with a rhythm with either a small (5:13 = 0.38) or large (6:7 = 0.86) ratio between the intervals, listeners have trouble detecting timing perturbations that bring the ratio closer to a 1:2 simple ratio (Repp, London, & Keller, 2008). That is, for the large ratios, temporal changes that reduce the ratio are not as easily detected as changes that increase the ratio (bring it further away from the preferred 1:2 ratio). On the other hand, for small ratios, changes that *increase* the ratio (thus bringing it closer to 1:2) are not as easily detected. These findings suggest that listeners prefer to perceive the pattern as if composed of a simple ratio despite perceivable temporal changes in the stimulus (Clarke, 1987). Clarke (1987) theorizes that listeners first extract the rhythmic structure in terms of simple integer ratios, with any deviation from this simple ratio perceived as expression or stress.

Similar to the findings from perception, production tasks also highlight the constraints for simple integer ratios. Complex meters are produced and reproduced less accurately (mean distance of tap from beat) and less precisely (more variability across successive taps) than simple meters. For instance, when participants are asked to produce any rhythmic pattern without specific instructions or rhythmic templates, they tend to be produced in a long-short pattern with a 1:2 ratio (Povel, 1981). Even when participants are presented with a specific two-interval pattern to synchronize with and continue tapping the pattern, if the pattern conforms to a complex interval ratio such as 2:3, participants tend to produce a ratio ranging between the given complex ratio, and a simple 1:2 ratio (Repp, London, & Keller, 2008). That is, two-interval rhythms are most accurately produced and reproduced when the interval ratios are closest to 1:2 (Povel, 1981; but see Repp, London & Keller, 2011, 2012). The ratio towards which produced intervals are distorted is referred to in the literature as an *attractor ratio* (Fraisse, 1946, 1956; Summers, 1986, 1989). For ratios larger than this attractor, the rhythm is reproduced by *increasing* the durational contrast between successive intervals, and for smaller ratios, the rhythm is reproduced by *decreasing* the contrast, thus drawing the ratio closer to the attractor in both cases.

This process of assimilation towards the simple ratio is more pronounced during the continuation phase, that is, in the absence of any auditory background tones, than during the synchronization phase, that is, along with an auditory template. This tendency to distort reproduced intervals in the direction of a simple 1:2 ratio is observed while reproducing interval ratios ranging in complexity from 1:3 and 1:4 to more complex ratios such as 3:4 and 4:5 (Povel, 1981). When adjacent intervals have a larger contrast (such as 1:4 or 0.25), the durational contrast is decreased during reproduction, assimilating the ratio closer to 1:2. On the other hand, when adjacent intervals have a smaller contrast (such as 4:5 or 0.80), the duration contrast is increased during reproduction (Repp, London, & Keller, 2010). These results are observed regardless of music training (Repp, London, & Keller, 2005; Summers, Bell, & Burns, 1989; Summers, Hawkins, & Mayers, 1986), and despite receiving visual feedback about performance accuracy (Collier & Wright, 1995)

Assimilation towards simple meter ratios is observed even when participants synchronize with complex ratio meters in the presence of a musical melody (Snyder, Hannon, Large, & Christiansen, 2006). In this study, participants were presented with a rhythm comprised of three intervals, two short and one long, with the short and long intervals related in a 2:3 ratio, and accompanied by a drum pattern in a complex 7/8 meter. Participants were instructed to synchronize with the drum pattern (synchronization phase), and then continue tapping the same pattern in the absence of the drum pattern (continuation phase). Although the participants did not completely assimilate to the simple ratio, they produced intervals ratios ranging between the given 2:3 ratio and a simple 1:2 ratio.

Evidence also points to the increased cognitive load in processing complex meters, as measured by differential brain responses while processing rhythms of varying metrical complexity (Lewis, Wing, Pope, Praamstra, & Miall, 2004; Sakai, et al., 1999). In one such instance, participants were instructed to produce patterns containing either simple (1:2:3 or 1:2:4) or complex (1:2.5:3.5) duration ratios (Sakai, et al, 1999). Functioning magnetic resonance imaging (fMRI) scans pointed to separate brain areas being activated for simple versus complex ratio patterns, with simple ratios activating the left premotor and parietal areas, and the complex ratio rhythms activating the right prefrontal, premotor, and parietal areas. The increased prefrontal activation is likely to result from the increased role of memory required to process the complex ratio patterns. Interestingly, participants who drifted towards the simple ratio while asked to produce complex patterns, exhibited brain responses resembling those observed during the simple ratio trials.

These results make it tempting to conclude that constraints for processing meters with simple integer ratios are universal and innate. However, two lines of evidence challenge this viewpoint. Firstly, musical styles from cultures such as Africa, Asia, and the Balkan Peninsula frequently use rhythms and meters that violate these simple ratio constraints (London, 1995). Despite the complexity in these ratios, adults and children familiar with music from these cultures continue to dance and sing along with these rhythmic structures, unlike adults unfamiliar with complex meters (Rice, 1995; Singer, 1973).

For instance, when Western listeners are presented with simple and complex meter melodies, they are easily able to detect disruptions in the metrical structure in Balkan melodies with simple meters, but they show considerable difficulty in noticing metrical disruptions in Balkan melodies with complex meters. On the other hand, individuals of Balkan origin detect metrical disruptions equally well in both the simple and complex meter melodies (Hannon & Trehub, 2005a). Interestingly, this advantage for complex meter processing is not driven merely by familiarity with the specific music and meters from one's own culture. Instead, familiarity with complex meters in one culture facilitates processing of complex meters even in unfamiliar musical contexts, and with unfamiliar musical meters. For instance, when adults familiar with complex meters in Indian music are presented with unfamiliar Turkish melodies, they are equally proficient at detecting disruptions in both simple and complex meters, despite the specific meters being unfamiliar to them (Kalendar, Trehub, & Schellenberg, 2013).

Individuals familiar with complex ratio meters also show comparable performance while synchronizing with simple and complex meters, unlike adults unfamiliar with complex patterns. Indian adults, for instance, are equally accurate and fast to synchronize with both simple and complex meters, whereas American adults, whose experience was limited to simple meters, are significantly more accurate and faster to synchronize with simple meters. Further, the metrical framework for simple and complex meters appears to be equally strong for Indian adults, as evidenced by comparable disruption in performance following an abrupt switch away from either a simple, or a complex meter (Ullal-Gupta, Hannon, & Snyder, 2014).

Studies on young infants offer a second line of evidence in support of the argument that biases for simple meter processing might be experience-driven. Since infants are naïve to culture-specific experience, any differences observed in their performance on simple versus complex meter processing should stem from innate biases. As discussed earlier, Western adults show considerable difficulty in perceiving complex meter structures prevalent in music from other cultures. On the other hand, Western infants who have had minimal exposure to music from any one culture, show no such bias (Hannon & Trehub, 2005a; 2005b). Specifically, 6-month-old infants just as readily respond to structure-disrupting alterations in complex meter patterns as they do to simple meter patterns (Hannon & Trehub, 2005a). By 12 months of age, however, Western infants start showing adult-like responses, in that they are significantly better at detecting disruptions in simple meter patterns than they are at complex meter patterns (Hannon & Trehub, 2005b), presumably due to passive exposure to culture-specific rhythms and meters. Unlike adults, however, the infants' biases are less resistant to change, as demonstrated by the 12-month-olds showing improvement in performance on the complex meter trials following brief at-home exposure to complex meter music.

While these studies suggest that preferences for simple meters might be entirely learned, other evidence suggests that the bias might be caused by interaction between innate constraints and culture-specific learning (Hannon, Soley, & Levine, 2011). For instance, although 5 and 7 month-old infants show culture-general performance in perceiving disruptions in complex meters, they are unable to detect disruptions in highly complex ones (e.g., 4:7 ratios). Thus, while preference for simple versus complex meters might be experience driven, at least some of the bias for simple meters might be innate. Even among the cultures that do use complex meters (e.g., 2:3 ratios), there is a limit on the degree of complexity of ratios. Listeners from these cultures show similar constraints on highly complex meters. For instance, when presented with simple, complex, and highly complex meters, Western adults perform significantly better on the simple meter trials, but show no difference between their performance on the complex and highly complex meters. Turkish adults, on the other hand, perform comparably on the simple and complex meter task, but significantly worse with the highly complex meters (Hannon, Soley, & Ullal, 2012).

Taken together, this corpus of evidence strongly suggests that the innate bias for the simpler meters which is present in early infancy is overcome by extensive experience with the more complex patterns. Further, it is plausible that preference for simple ratios is the cause for, and not a consequence of, the use of simple meter ratios in every studied culture around the world, including those cultures that have a large presence of complex meters in their music. While several cultures exclusively use simple meter ratios in their music, no known musical culture uses exclusively complex meter ratios. Thus, it is entirely plausible that simple meters and complex meters are processed differently and recruit different brain mechanisms, even among those that are familiar with them.

If complex meter rhythms are difficult and unfamiliar, it is possible that listeners employ counting strategies to locate the beat level and find periodicities at other levels (London, 1995). Further, the processing of complex rhythmic patterns requires the ability to estimate unequal durations, an individual might use strategies such as counting. Thus, the ability to accurately perceive disruptions in complex meter rhythms plausibly correlates with a domain general ability to process quantity. Towards this aim, the first experiment in this dissertation examines individual differences in simple and complex meter perception, and the association with processing numerosity in both, the visual and auditory modalities. Additionally, this dissertation examines relationships between an individual's rhythm processing abilities and their working memory capacity. Given the increased cognitive load in processing complex meters (Lewis, et al, 2004; Sakai, et al, 1999), it is imperative to ensure that any relationship observed between complex meter processing abilities and enumeration abilities are not driven by differences in working memory alone.

The second study tests the nature of neural activity in response to simple (familiar to both groups) and complex (familiar to one group) meters. In listening to music, extrinsic factors, such as physical accents and spacing between beats, interact with the intrinsic interpretation to create a metrical percept. The strength of the intrinsic representations depends on the ease of processing of the patterns, which in turn is shaped by experience with the meters in question. While the extrinsic factors are equally available to all listeners, differences in the intrinsic representation create different mental percepts of the same pattern, as evidenced by neural activity. This experiment examines the role of extrinsic factors in processing rhythms, and how this ability is affected by implicit experience with culture-specific rhythms. This study uses an EEG paradigm to measure brain activity in response to various rhythms that conform to simple and complex meters, and the role of culture-specific experience in shaping the brain activity patterns.

CHAPTER 2

Processing of Quantity in Time and Number

Introduction

The association between music and mathematics has been studied since the days of the ancient Chinese, Indians, Greek, and Egyptians, who searched for the mathematical principles of sound. They expressed musical scales and rhythms as being composed of mathematical ratios, with the theory that the two domains were associated at a fundamental level of their composite elements. In the more recent past, however, popular media has linked music and mathematics in a different vein. Namely, because the processing of rhythmic structures involves an understanding of mathematical ratios, there is an assumption that music training confers an advantage in mathematical processing. A third association between the two domains is in the predominant use of *counting* in learning musical rhythms. For instance, children learning a new song might often be taught to think of it as “CLAP-two-three-four-CLAP-two-three-four…”. The interesting question is whether this association between music and mathematics translates into measurable behavioral outcomes. Specifically, is there a relationship between an individual’s performance on a music task and their performance on a mathematical task?

One of the important theories in studies of animal and human timing is the Scalar Expectancy Theory (SET) (Gibbon, Church, & Meck, 1984). According to this model, at the start of an interval of interest, a “switch” opens, allowing an internal pacemaker to generate and send pulses to an accumulator. At the end of the interval, the switch closes, upon which the accumulator counts the number of pulses. This number is compared to previous memory traces, held in long-term memory, after which a decision is made regarding the length of the interval. Given the central role that numerosity takes in this model, a relevant question is the extent to which number processing abilities are related to the processing of temporal patterns.

Although a common theory linking various dimensions of magnitude (of time and number, for instance) was not formally defined until quite recently (Walsh, 2003), evidence pointing towards this has been present for much longer. Some of the earliest evidence in favor of a generalized magnitude system comes from studies in non-human animals. In their classic study, Church & Gibbon (1982) used a temporal generalization procedure to present rats with an auditory or light signal between 2 and 8 seconds in durations. The rats were trained to press the lever only upon the 4-second signal. The results showed an increase in the probability of a lever press as the signal was closest to the 4-second target, pointing to the ability of rats to estimate time intervals.

Further studies suggest that in addition to their sensitivity to duration, rats appear to pay attention to the number of events as well (Church & Meck, 1984). Rats were trained on one of two sequences, in a paradigm similar to the temporal discrimination design described above. However, in addition to varying the duration, in this task, the number of events was controlled for. The rats were trained to discriminate between a melody consisting of two tones that lasted two seconds, and another consisting of eight tones and lasting eight seconds. Although the rats rapidly learned to discriminate between the two melodies, given that the two dimentions were confounded, it was unclear as to which dimension the rats were paying attention to. Thus, to tackle this questions, the rats were presented with certain trials where one of the two dimensions was fixed while the other varied. The results showed that rats were equally proficient at generalizing across either of the dimensions, and the subjective midpoint was identical across both. Further, discrimination in one dimension was transferred to the other, without additional training, suggesting that rats can abstract modality-general information from these stimuli (Meck & Church, 1983).

Some of the most direct behavioral evidence in humans in favor of this model comes from interference effects of dual tasks or Stroop tests. Dual tasks measure the effects of interference, referring to a disruption in one task, while participants perform a demanding secondary task. In studies testing the effects of dual tasks on duration, results typically point to a lengthening of perceived time. This usually leads to shorter verbal estimates and reproductions, or longer productions (Block, Hancock, & Zakay, 2010). Listeners may be presented with a Stroop task to assess the degree of interference between numerical and temporal tasks, with one of the tasks acting as the distractor task. If common mechanisms underlie both processes, performance on the numerical task should be influenced by the irrelevant numerical distractor task, and vice versa.

When listeners are presented with a task requiring them to judge whether the duration of a test stimulus is longer or shorter than a previously presented reference, results show that merely looking at number symbols biases their duration judgment (Olivieri, et al., 2008). Specifically, looking at small digits (such as 1) leads to underestimation of duration, and looking at large digits (such as 8) leads to overestimation of the perceived duration. Not surprisingly, there is no such biasing effect of looking at letters of the alphabet instead of numbers. Likewise, when participants are asked to make duration judgments on stimuli that vary in size, luminance, and numerosity, increasing the magnitude on any one of these non-temporal domains leads participants to make longer temporal judgments (Xuan, Zhang, He, & Chen, 2007). Similar results have been observed in children in both implicit (Rousselle & Noel, 2008) and explicit (Levin, 1979) temporal judgment tasks.

While these studies assess the interfering effects of non-temporal dimensions on temporal judgment, the converse has also been explored; namely whether temporal tasks interfere with non-temporal (particularly, numerical) tasks. In one such study, participants were presented with two series of flashing dots with a rectangle separating the two series, and were assigned to one of two tasks (Dormal, Seron, & Pesenti, 2006). In the numerosity comparison, they were asked to decide which series has more dots, and in the duration comparison, they were asked to decide which series lasts longer. Thus, one of the two dimensions (number or duration) acts as the dimension of focus, while the other acts as the irrelevant distractor. The duration and numerosity were manipulated to create congruent (series with more dots last longer) and incongruent (series with fewer dots last longer) conditions. The results show that numerical cues interfere with the duration, such that incongruent trials were slower and more error-prone than congruent trials. However, surprisingly, temporal cues appear not to interfere with the numerosity judgments, with no difference between congruent and incongruent conditions. The authors interpreted these results to suggest that while numerosity is processed automatically, duration processing is not. These findings replicate results from an earlier study (Droit-Volet, Clement, & Fayol, 2003) testing children aged 5 and 8, and adults on a similar Stroop task.

The unidirectional nature of these interference effects have been explained using a theory of "attentional load". Whereas duration is a continuous variable, numerosity is discrete. Due to the continuous nature of duration, there is greater amount of noise introduced in the variable (Gallistel & Gelman, 2000), which the authors argue, requires more attention than that of number. Hurewitz, Gelman, & Schnitzer (2006) suggest that this hierarchy of magnitudes from continuous to discrete suggests that while time tasks are easily disrupted by a numerical task, they themselves do not act as good disrupters (but see Brown, 1997). These studies suggest automaticity of number processing, but do not provide any conclusive evidence in support of a common mechanism for temporal and numerical processing.

Evidence in favor of a common neural substrate for temporal and numerical processing also comes from findings in neuropsychology. The right inferior parietal cortex has been shown to be central to time perception tasks, as evident from imaging (Rao, Mayer, & Harrington, 2001) and electrophysiological (Mohl & Pfurtscheller, 1991) findings. Animal studies corroborate these findings, with monkeys' time judgment correlating with the response of the neurons in the inferior parietal cortex (Leon & Shadlen, 2003). Likewise, patients with damage to the right inferior parietal cortex (but not left) show substantial deficits in their time perception abilities (Battelli, Cavanaugh, Martini, & Barton, 2003; Harrington, Haaland, & Knight, 1998). Evidence from transcranial magnetic stimulation (TMS) also elucidates these findings (Alexander, Cowey, & Walsh, 2005). Specifically, when the right posterior parietal cortex is disrupted via TMS, participants show slower reaction time in making time discrimination, but show no corresponding deficit in pitch discrimination tasks. However, stimulation of the left posterior parietal cortex shows no such deficit in either of the tasks. Lewis & Miall (2003) highlight the role of the parietal cortex and its role in automatic temporal processing, in contrast to the implication of the dorsolateral prefrontal cortex involved in cognitive timing and working memory.

Besides having neurons specified for time processing, the parietal cortex is also known to have neurons that respond to numerosity (Walsh, 2003). However, unlike in temporal processing which shows activation only in the *right* parietal region, numerical processing has been shown to activate the bilateral parietal cortex. Imaging studies have shown the involvement of the bilateral intraparietal sulcus during various numerical tasks, all the way from the mere detection of number symbols (Eger, Sterzer, Russ, Giraud, & KLeinschmidt, 2003) and number estimation (Cohen & Dehaene, 1996), to complex arithmetic (Ansari & Dhital, 2006; Chochon, Cohen, van de Moortele, & Dehaene, 1999; Prado, et al., 2011). Interestingly, the activity of the intraparietal sulcus appears to be directly proportional to the difficulty of the numerical task (Pinel, Dehaene, Riviere, & LeBihan, 2001).

Although the activation is bilateral, activation in the right hemisphere has been found to be associated with the understanding of the approximate number system (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Holloway, Price, & Ansari, 2010; Piazza, Mechelli, Price, & Butterworth, 2006; Prado, et al., 2011). One of the explanations for this finding is that the right parietal sulcus is perhaps involved in the more abstract, pre-lingual number sense, and might act as the basis for other, more precise numerical processing that depends on language. In support of this theory, it has been found that infants and children show a greater right parietal activation in response to a numerosity adaptation task (Cantlon, Brannon, Carter, & Pelphrey, 2006; Izard, Dehaene-Lambertz, & Dehaene, 2008). Since infants and young children have likely not yet developed an understanding of the exact number system, these results provide further evidence that the right parietal cortex is involved in basic numerical abilities upon which future math skills can be built.

Given the role of the right inferior parietal sulcus in the processing of both time and numerical magnitude, an important question is the extent to which the two processes share common mechanisms. One of the major developments in the area is a review of a large corpus of data on numerical and temporal processing, which supports the idea of a generalized magnitude system for the processing of time, size, quantity and space, located in the parietal cortex (Walsh, 2003). Several lines of evidence support this notion. For instance, applying TMS to the parietal cortex has been shown to interfere with various forms of magnitude judements, including the judgment of time, size and number (Göbel, Walsh, & Rushworth, 2001; Hodinott-Hill, Thilo, Cowey, & Walsh, 2002). Likewise, single-cell studies in primates have pointed to the implication of the parietal neurons in numerical (Sawamura, Shima, & Tanji, 2002) and duration estimation tasks (Leon & Shadlen, 2003).

If duration and number tasks rely on similar mechanisms, then this might imply that musical abilities should be related to numerical abilities. Theoretically, there should be several areas of overlap between musical and mathematical processing. Music, for instance, uses several mathematical constructs in its chords and time sequences. Musical tones are composed of a fundamental frequency and harmonics which are equivalent to integer multiples of the fundamental frequency. Likewise, mathematical ratios between frequencies and durations form the bases for consonant intervals and simple meters, respectively. Behavioral findings, however, show inconclusive evidence in favor of associations between musicality (the ability to perceive and recall music) and musicianship (the ability to perform and create music), and mathematical abilities. Further, when testing musicality (music perception and music memory) and musicianship (music performance and music creation), mathematicians are no more proficient than are literature and language scholars (Haimson, Swain & Winner, 2011). However, this study used a web-based approach and a self-report design, making it difficult to assess the validity of the results. Further, this study examined musical abilities in mathematicians, instead of the converse.

Another study reports that mathematical performance *does* correlate with musicality, but only in certain areas, specifically in pattern recognition and symbol usage (Bahr & Christensen, 2000). For instance, a longitudinal training study which assigned children to music lessons reports better performance on mathematical and visuospatial abilities (Rauscher & Hinton, 2011). Other studies, however, have not been able to find this correlation between musical abilities and pattern recognition (Helmbold, Rammsayer & Altenmüller, 2005). In testing the causal relationship between music training and math achievement, one study tests children's abilities to use fractions and proportional math while being trained on a spatial-temporal math video game with randomly assigned to either concurrent piano lessons, or no music training. The findings suggest that second-grade children who are given piano instruction in addition to the video game training perform significantly better than those trained on the video game alone (Graziano, Peterson, & Shaw, 1999). However, a meta-analysis consolidating findings from mathematical achievement in musicians and nonmusicians reports only a modest positive association between the two domains (Vaughn, 2000).

At the outset, these results suggest no real link between music and math performance. However, while these studies look for *expertise* in math and music, a fundamental question that remains unanswered was whether the two domains share common mechanisms at a more fundamental level of processing. Specifically, the goal of the present study is to examine the extent to which an individual's performance on a musical task predicts his/her performance on a fundamental numerosity task.

These findings lead to the question regarding the role of explicit counting in performing temporal tasks. To assess the extent to which we use counting mechanisms while processing musical rhythms, individual abilities in the domains of music and mathematical processing was measured. One of the central theories in music perception is that the ratio between time intervals of successive notes is an important factor in determining ease of processing of these patterns. Musical patterns whose intervals are related in simple ratios, such as 1:2, are easier to perceive and produce (Fraisse, 1978; Fraisse, 1982; Snyder, Hannon, Large & Christiansen, 2006) than more complex ratios such as 3:2. Further, differential brain response patterns are observed while processing simple versus complex ratio patterns, pointing to the increased role of cognitive resources in processing complex patterns (Sakai, et al, 1999). Thus, in exploring links between numerical and rhythmic processing, this study assessed participants' ability to process simple and complex meter rhythms, and examined relationships to numerical processing.

Methods

Ethics Statement. All procedures were approved by UNLV's Institutional Review Board for Human Subjects Research (Social/Behavioral), and complied with the ethical guidelines of the Office of Research Integrity. Written informed consent was obtained from all participants.

Participants. Participants were college students from Las Vegas, Nevada, USA, (*N*=48, *M* = 22.2 years, 22 male, 26 female) recruited from the Subject Pool, and were offered 1 credit for their participation. Their music training ranged from 0 years to 13 years (*M*=1.92, *SD*=3.56), with 28 participants reporting 0 years of music training. All participants were asked about their performance on the math subsection of the SAT exam, however, only 7 participants reported it (*M*=648, *SD*=50).

Task and Stimulus. In describing the relationship between the numerical and musical tasks in this study, the first step is to tease apart the effects of other factors that could affect performance on these tasks. Towards the aim, each individual's score on a scale of math anxiety and their performance on a working memory task, were measured and are described below.

Mathematics Anxiety. An often-described relationship exists between mathematics anxiety and numerical processing (e.g., Maloney, Risko, Ansari, & Fugelsang, 2010). Mathematics anxiety is described as a condition where the individuals experience unusual negative emotions while performing numerical and mathematical tasks. Since the present study explored the relationship between numerical and rhythm processing, an important consideration was to examine the association between math anxiety and the various tasks of numerical processing, and how this translated into performance on the rhythm tasks. Importantly, mathematics anxiety is said to affect mathematical processing by occupying working memory, which would otherwise be used to perform the mathematical tasks (Ashcraft, 2002; Ashcraft & Faust, 1994). This is particularly relevant to the present study, given the importance of working memory in processing durations (Miyake, Onishi, & Pöppel, 2004) and rhythms (Sakai, et al, 1999) in music. To obtain a measure of mathematics anxiety, the Abbreviated Math Anxiety Scale (AMAS; Hopko, Mahadevan, Bare, & Hunt, 2003) was used. The test consisted of 9 questions that asked the participant about their level of anxiety (on a scale of 1-5) on a range of mathematical scenarios.

Working Memory. The role of working memory is critical in tasks of rhythm and numerical processing. It is important, therefore, to ensure that any relationship observed between an individual's performance on a rhythm and enumeration task is not solely driven by their working memory capacity. To measure working memory, the three subtests of digit span from the Wechsler Adult Intelligence Scale IV (WAIS-IV; Wechsler, 2008) were used in the study: digit span forward, digit span backward, and digit span sequencing. The digit span task measures auditory short-term memory and sequential processing, and assesses a range of cognitive variables including working memory, memory span, rote memory, immediate auditory recall, numerical ability, and attention (Sattler & Ryan, 2009).

In all three subtests, which were presented in separate blocks, participants heard a series of digits presented once, at approximately one item per second. In digit span forward, participants were asked to repeat the digits back in the same order that they were presented in. In digit span backward, participants were asked to repeat the digits backwards. In digit span sequencing, participants were asked to repeat the digits in sequence, starting with the lowest number. In all three subtests, there were two practice trials, with feedback. In the test trials, there were two trials for each digit length with the digit length increasing incrementally (i.e., two trials of two digits, followed by two trials of three digits, etc.). Each subtest was administered until the participant got both trials of a certain length (i.e., both trials five digits in length) incorrect. Each subtest was scored based on the longest number of items recalled correctly, yielding three separate scores: Longest Digit Span Forward (Digit Forward), Longest Digit Span Backward (Digit Backward), and Longest Digit Span Sequencing (Digit Sequencing).

Rhythm and Meter Perception. The primary test of rhythm and meter in this study used a perceptual judgment task to assess listeners' ability to detect a variety of disruptions in isochronous and nonisochronous meters. The aim of this task was to assess individual differences in simple and complex meter performance, and to observe how this correlates with the individual's performance on the numerical tasks. This task presented listeners with a standard stimulus, followed by a comparison stimulus that was either unaltered ("unaltered" condition, altered but meter preserved ("meter preserved" condition), or altered with a disruption in meter ("meter disrupted" condition). Participants were asked to make similarity judgments comparing the two melodies. The melodies in the "meter preserved" condition maintained the original metrical structure, while changing the rhythm. The melodies in the "meter disrupted" condition caused a change in the meter of the melody. The "unaltered" melody included novel instrument timbre compared to the standard, while maintaining the pitch, rhythm, and meter of the original.

Stimuli. All the stimuli were drawn from, and used with permission from Hannon & Trehub (2005) and Hannon, Vanden Bosch der Nederlanden, & Tichko (2012). As in the original study, the standard stimuli were comprised of four traditional Balkan songs, two in an isochronous 4/4 meter (simple), and two in a non-isochronous 7/8 meter (complex). The melodies were accompanied by one of two drum patterns: they alternated either between 1000 and 500 msec (2:1 ratio; simple condition) or between 750 and 500 msec (3:2 ratio; complex condition). Each of the four standard stimuli was edited to create the stimuli that either preserve or disrupt the original meter. For the "meter preserving" conditions, one stimulus was "unaltered", maintaining the rhythm and pitch, while changing the timbre, and the other was "structure preserving", with 250 ms eighth notes inserted into each measure and adjacent note durations reduced. For the "meter disrupting" conditions, one was "structure disrupting" with 250 msec eighth notes inserted into each measure but no corresponding adjacent note reduction, and the other was "severely disrupting", with pseudorandom insertions of 250-500 msec notes one to three times per measure.

Procedure. This experiment began with a brief practice session, with the song "Mary had a little lamb" used as the standard stimulus, and four altered stimuli created as described in the prior section. Participants first listened to the standard stimulus, during which the label "*Here is a new song*" was presented on the screen. Then, they listened to the four test stimuli, with the label "*Here is a version of the same song*". Following each test song, the participant was instructed to rate the songs on how similar it was to the original standard melody, on a scale of 1 (very similar) to 5 (very different). Participants only received feedback during the practice block.

All similarity ratings were analyzed per condition, separately for the simple meter and complex meter trials, collapsed across the “meter preserving: conditions (mean of structure-preserving and unaltered) and the “meter disrupting” conditions (mean of structure-disrupting and severely disrupting). From these similarity ratings, a difference score was computed as a measure of sensitivity to change (accuracy), by subtracting the similarity rating of the meter preserving condition from those of the meter disrupting condition. A larger difference score corresponds to a higher sensitivity score.

Key perception. The principal goal of this task was to examine the relationship between melodic processing and processing of numerosity. In particular, this task allowed us to observe if any relationship between music and mathematical processing was confined to the rhythmic aspects of music alone, or if the link was present even for the more global processing of music. The test was based on the rules of pitch structure governing key membership and implied harmony in Western music, and assessed listeners’ ability to detect various melodic changes.

Western tonal music is typically written in a particular key, with all the notes within the melody belonging to the scale associated with that key. Out of key changes are more easily detected by listeners that within-key changes (Trainor and Trehub, 1994). Further, for within-key changes, out-of-harmony changes are more easily detected than within-harmony changes.

In this task, participants were tested on their ability to detect these changes in melody. Three of these included a change in one of the pitches relative to the other notes: within-harmony and within-key, out-of-harmony but within-key, or out-of-key. In addition, a subsection of the melodies were transposed such that the tonic will be varied across conditions. Research has shown that listeners attend more to relative pitch information than they do to absolute pitch. By transposing the melodies, it ensures that listeners are using their memory for relative pitch information, rather than attending to absolute pitch changes for the notes. Thus, the fourth condition included a transposition of the entire melody, with the relative pitches maintained.

Stimuli. The standard melody, adapted from Trainor and Trehub (1994), consisted of 10 notes in the key of E major, consisting of the following sequence of notes: E4, Ab4, B4, A4, Gb4, C3, F4, Ab4, Gb4, and E4 ("standard" condition). The standard melody was transposed to two other keys, G major and B major ("no change" condition). The tones were 75 dB sine waves 400 msec in duration with 10 msec rise and fall times. In addition to the "no change" condition, the 6th note in the transposed melodies was either raised one semitone ("out of key" condition), raised two semitones ("out of harmony" condition), or raised four semitones ("within harmony" condition).

Procedure. This experiment commenced with a practice phase comprised of four trials. The participant listened to one rendition of the standard melody, followed by one of the other melodies ("no change", "out of key", "out of harmony", or "within harmony"), and was asked to press a key indicating if they noticed a change in the melody. During this phase, participants received feedback for their response. The second melody was always be in a different key in relation to the first, regardless of whether there was a change in the relative pitches or not. Following the practice session, the test phase began, where participants were not provided with feedback. In the test phase, there were 12 trials, with the "no change" condition presented 6 times, and each of the change conditions ("out of key", "out of harmony", and "within harmony") presented twice each. Thus, there were the same number of change and no change trials. The standard melody was first played with the label "*Here is the first melody*", followed by one of the other melodies and the label "*Here is the second melody*". Participants were instructed to press a key to indicate a change in the melody as soon as they noticed it (counted as a "response").

Test of music aptitude. The Advanced Measures of Music Audiation (AMMA) is a music aptitude test that tests for music abilities (rhythm and tonality) independent of music training and experience (Gordon, 1989). In the current study, this test was used to examine the extent to which music aptitude correlates with performance on simple and complex meter perceptual tasks. AMMA has been used extensively to predict music performance achievement of university students, and has reliability scores of 0.84 for the tonal section, 0.85 for the rhythm section, and 0.88 for the composite score (Gordon, 1990; 1991).

Stimuli and Procedure. This test consisted of thirty questions ("trials"), and three additional practice questions with feedback. Each trial began with a short piano melody ("musical statement") approximately five seconds in length, followed by a brief two-second pause, and a comparison piano melody ("musical answer") approximately five seconds in length. The participant was asked to decide if the musical statement was the same as, or different from the musical answer. If different, the participant was asked if the two melodies differed on tonality or rhythm. If different, the melodies only differed on one of the two dimensions. At the completion of the test, the scores were automatically tallied for rhythm, tonal, and composite scores to give raw and percentile rank scores.

Numerosity tasks. When asked to enumerate rapidly the number of objects presented, response time data show a clear "dog leg" function. That is, sets consisting of less than 4 objects are enumerated faster, almost automatically, with the reaction time increasing very slowly, typically at around 50-80 milliseconds per item. On the other hand, larger sets show a steeper increase in reaction time with increasing number of objects, typically increasing at a rate of about 200 milliseconds per additional item (Mandler & Shebo; Trick & Pylyshyn, 1993). This difference in slope of counting for small numbers and larger numbers has led to discussion of two separate processing in enumerating small and large numbers. Enumerating small numbers appears to be effortless, innate (Butterworth, 1999) and precise (Feigenson, Dehaene, & Spelke, 2004), and is referred to as subitizing, from the Latin word *subitus,* or sudden. The special aspect of subitizing is the seemingly automatic manner in which it occurs, almost akin to apprehending color or shape. In contrast, enumerating large items can either be counted – a time consuming and accurate process, or estimated - a rapid and error-prone process (Kaufman, Lord, Reese, & Volkmann, 1949). Numerosity discrimination studies show a constant Weber fraction of 25% (Ross, 2003). That is, when the relative difference between subsequent numerosities drops below 25%, participants should have a more difficult time enumerating rapidly or accurately. Consequently, when participants had to rate how similar two sets of items were, they rated two small number sets as being less similar to each other than two large number sets (Logan & Zbrodoff, 2003). For set sizes larger than 4, the relative difference between subsequent numerosities drops below 25%, which could explain the transition from subitizing to counting. A relevant question is the extent to which each of these enumeration processes is involved in temporal processing.

The present study tested participants' performance in the subitizing and counting ranges, and explored relationships between these processes and their performance on the music tasks. Most studies in the realm of numerical processing use exclusively visual stimuli, thus testing visual enumeration. However, the present study tests individuals' temporal processing abilities. Thus, it is important to measure their enumeration abilities in the auditory modality in addition to the visual one, by presenting individuals with tones, in addition to dots. This would also answer two additional questions; firstly about the extent to which an individual's performance on a visual enumeration task is correlated with their performance on an auditory task, and secondly, whether the overall pattern of results are comparable across the two modalities. Further, enumeration tasks in the visual modality typically consist of dots presented simultaneously, while the individual was asked to estimate or count them. However, objects typically unfold sequentially while processing rhythms. Thus, in this experiment, the auditory tasks of enumeration consist of tones presented sequentially. To ensure that similar tasks are being used in both modalities to the greatest extent possible, in addition to dots being presented simultaneously, they will also be presented in rapid succession, to mimic the auditory tasks of enumeration.

The enumeration of items (presented simultaneously) and events (presented sequentially) have been shown to have different ranges of accuracy (Taubman, 1950b) and to require different cognitive resources. For instance, in an articulatory suppression task, where participants were asked to repeat the words "the the the" during enumerating either items or events, the suppression task had an effect on the sequential event enumeration much earlier than it did for the simultaneous item enumeration task (Logie & Baddeley, 1987). Specifically, whereas simultaneous enumeration was intact until the set size reached seven items, articulatory suppression disrupted sequential enumeration even at 1 event. However, no study so far has presented identical stimuli both spatially (simultaneous), and temporally (sequential), and tested enumeration in the visual and auditory modalities.

Visual Simultaneous Enumeration.

Stimuli and Procedure: The stimuli and procedure were similar to the ones used in prior studies (see Mandler & Shebo, 1982 for review). Participants were presented with an array of dots on the screen, and asked to say aloud the number of dots. The stimuli consisted of between 1 and 9 dots per display. In creating the stimuli, the display was partitioned by the use of an imaginary 6X8 grid, with the dot appearing in the middle of the cell. Dots less than 4 have easily recognizable canonical patterns (point, line, and triangle for 1, 2, and 3 dots respectively). For dots above 4, any arrangements that will lead to a recognizable pattern (e.g., rectangle, pentagon) were discarded from use. From this collection of all stimuli, 27 were used in this study (3 per number), with an additional set of 9 from which the practice trials were drawn.

The experiment began with a practice block consisting of 3 trials, during which participants received feedback for their answers. The test phase consisted of 27 trials with arrays ranging from 1-9 dots, in a randomly presented order. Each trial began with a black fixation point presented for 500 ms, on a white screen. The display containing the dots was presented until a voice response was detected. The voice response triggered the next screen during which time the experimenter recorded the participant's answer. Trials where the first voice response was not detected, where the participant changed the answer once the response was detected, or where the voice response was detected prior to the participant saying the answer, were coded as "0" by the experimenter, and excluded from further analyses.

Sequential enumeration. This paradigm is an extension of the simultaneous enumeration task described above. Dots (for the visual modality) or tones (for the auditory modality) ranging from 1 to 9 were presented sequentially and were modified from Piazza, et al (2006). For the visual modality, red and green dots were presented on a white background one at a time. The location of the dot varied and was pseudorandomized, based on the grid described in the prior section. In the auditory modality, high-pitched and low-pitched tones (1200 Hz and 400 Hz) were used, with a blank white screen. The brightness of the dots and the intensity of the tones were assigned by testing five volunteers to assess the subjective equi-luminance and equi-loudness values, respectively. Each stimulus (dot or tone) lasted for 90 ms, with inter-stimulus interval randomly varying between 90 ms and 180 ms, to avoid the stimuli being presented isochronously. Each trial began with a black fixation point presented for 500 ms, on a white screen, followed by the sequence of stimuli, and finally a black screen to denote the end of the trial. Similar to the simultaneous enumeration task, there were 27 trials (per modality). The participants were instructed to say the number of dots or tones aloud in the microphone. The experiment commenced with a practice block with 3 trials (per modality) during which the participant received feedback for their response. Given the lack of a priori hypothesis about data trends, in addition to reaction time and accuracy, deviance measures (expected response – given response) were calculated and are reported below.

Results

Results on Individual Measures.

Math Anxiety

Math anxiety scores in the task used in this study range from 9 to 45, with a higher score being indicative of a higher level of mathematics anxiety. In this particular participant group, the scores ranged from 9 to 34 (*M*=22.45, *SD*=5.90).

Working memory

Results showed that participants' individual performance on each of the subtests correlated with each other, but surprisingly did not correlate with the scores on the math anxiety scale (See Table 1 below). Since the three subtests of the digit span task were correlated with each other, a composite working memory measure (WMC) was obtained, comprising the average of the three subtests.

Table 1: Correlation Coefficients between the subsections of the Digit Span Task and Math Anxiety Scores

		Digit Forward	Digit Backward	Digit Sequencing	Math Anxiety
Correlation	Digit Forward	1.00			
	Digit Backward	.38**	1.00		
	Digit Sequencing	.29*	.57***	1.00	
	Math Anxiety	.01	-.15	-.07	1.00

Note. N = 48
* $p < .05$. ** $p < .01$. *** $p < .001$.

Rhythm and Meter Perception

As seen in Figure 1, participants were more sensitive to change (higher difference score) in the simple meter trials than in the complex meter trials. A one-way repeated measures analysis of variance (ANOVA) revealed a main effect of Meter, $F(1,47)=12.17$, $p<.01$, $\eta_p^2=.21$ with a higher difference score in the simple meter trials (M=1.49, *SD*=0.20) than in the complex meter condition (M=0.79, *SD*=0.17). These results replicate the findings from the Hannon, et al (2012) study, which found higher levels of sensitivity in the simple, versus in the complex meter conditions.

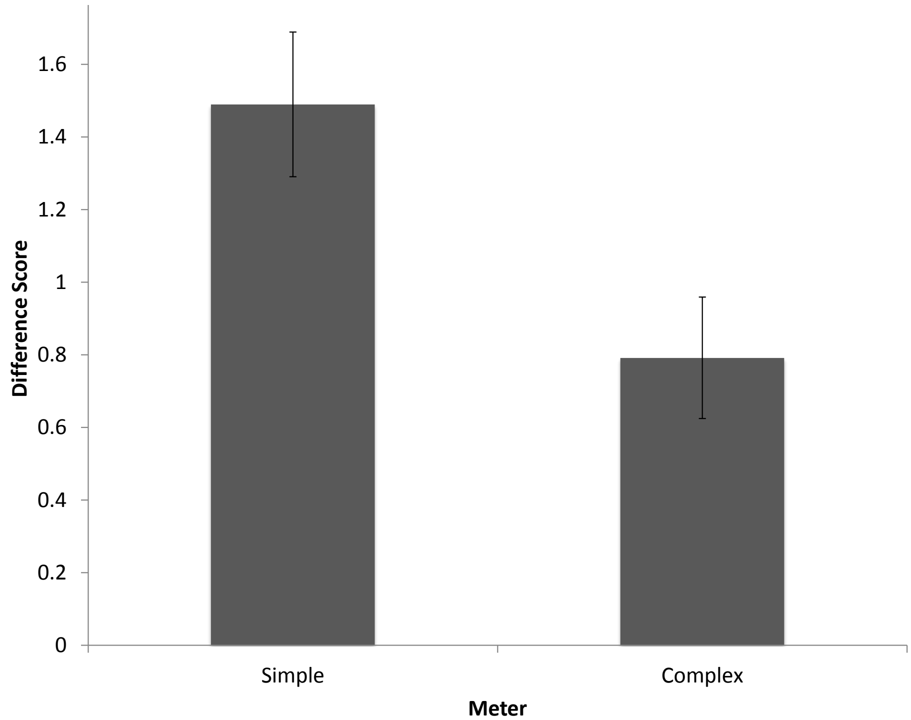


Figure 1: Difference scores in the simple and complex meter condition (larger difference score denotes higher sensitivity to change)

Test of Key Perception

Results were analyzed for each change condition separately by calculating the proportion of response on the change trials (hits) and no-change trials (false alarms). These proportions were transformed by adding 0.5 to the total number of responses made, and dividing by the total number of trials + 1, to yield a transformed d' from a table of signal detection theory. This transformation ensured that there are no proportions of 0 or 1. Chance performance is represented by a d' of 0.

A repeated measures ANOVA revealed a main effect of Change Type, $F(2,47)=2.87$, $p=.10$, $\eta_p^2=.071$. Bonferroni corrected paired sample t-tests revealed no significant difference in performance between out-of-key and out-of-harmony changes: $t(47)=.33$, $p=.74$, a marginally higher performance on the within-harmony changes than on the out-of-key changes, *t*(47)=2.00, *p*=.051, and significantly higher performance on the within-harmony changes than the out-of-harmony changes: *t*(47)=2.17, *p*<.05 (see Figure 2). These results contradict those found by Trainor & Trehub (1994), who reported that within-harmony change trials showed the *lowest* level of performance, with no significant difference between out-of-key and out-of-harmony changes.

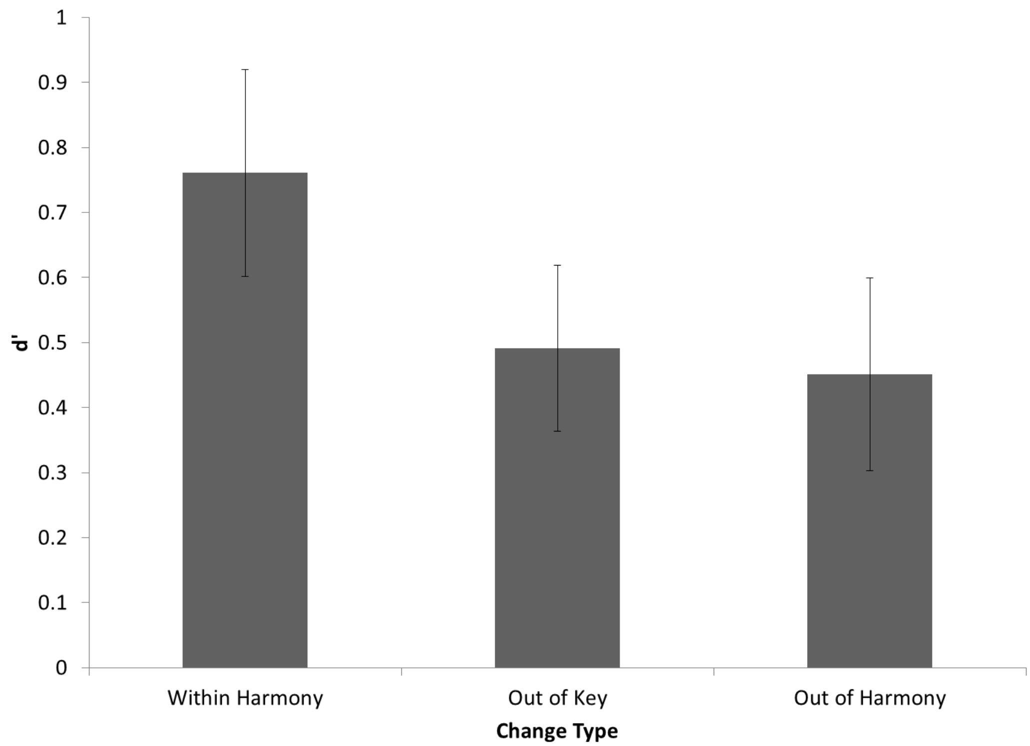


Figure 2: Performance on task of melody for different change types

In both, the original (Trainor & Trehub, 1994) and the present study, the within-harmony changes had the largest change (four semitones), out-of-harmony (two semitones) and out-of-key (one semitone). However, the major difference between the two studies is in the larger number of trials per condition and the presentation of the trials in a block-design fashion in the original study. Thus, in the present study, given the few number of trials, it is possible that listeners were merely attending to the degree of change in semitones, instead of attending to the overall melody. The original study avoided this problem by using a block-design (all within-harmony changes presented in one block, for instance), but the low number of trials in the present study did not allow for this design consideration.

In addition, unlike in the original study, music training did not correlate with any of the measures [within-harmony: $r(47)$=.020, p=.90; out-of-harmony: $r(47)$=-.078, p=.60; out-of-key: $r(47)$=-.089, p=.55], likely once again, due to the small number of trials.

Test of Music Aptitude (AMMA)

As expected, the scores for the tonal and rhythm subsections of AMMA positively correlated with each other, $r(47)$=.72, p<.0001, and each correlated positively with the composite score [tonal: $r(47)$=.93, p<.0001; rhythm: $r(47)$=.93, p<.0001]. Furthermore, each measure correlated positively with number of years of music training [tonal: $r(47)$=.48, p<.01; rhythm: $r(47)$=.48, p<.0001; composite: $r(47)$=.52, p<.0001].

Tests of Enumeration

Visual simultaneous enumeration

The data are presented below for accuracy, reaction time (after omitting the incorrect responses), and slope of reaction time for the subitizing and the counting ranges. Figure 3 presents the accuracy score, calculated for each trial based on whether the response was correct or incorrect.

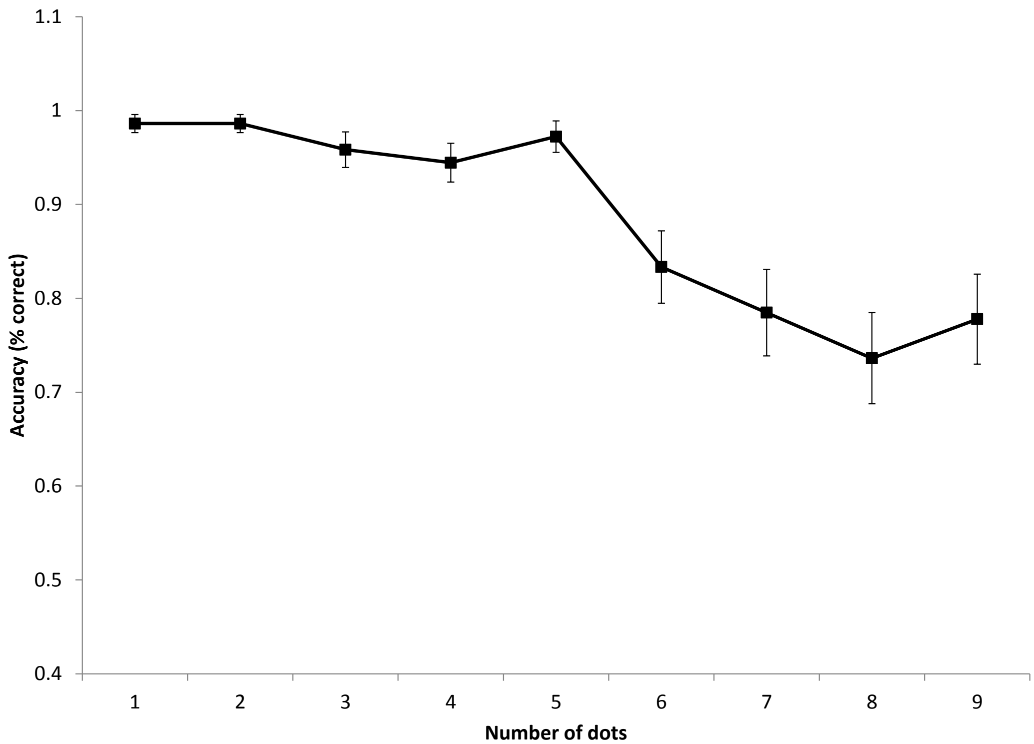


Figure 3: Accuracy (% correct) of responses for simultaneous presentation of visual stimuli

As can be seen, accuracy decreased as the number of dots increased. The slopes corresponding to the accuracy scores for consecutive numbers of dots (e.g., between 1 and 2, between 2 and 3, etc.) were computed, and paired-sample t-tests were used to explore differences in accuracy for adjacent numerosities. The results showed a significant difference between the numerosities corresponding to the slope between 4 and 5 dots, and between 5 and 6 dots, $t(47)=3.29$, $p<.01$. This is also evident in Figure 4 which depicts a steady rate of accuracy between 1 and 5 dots, followed by a dramatic decline in accuracy beyond 5 dots.

Next, in order to observe the effects of increasing numerosity on response times, the response time values for the correct responses were calculated. These values were first submitted to a data trimming procedure, to test for outliers which fell outside of 2.5

standard deviations of the mean in each cell (Maloney, Risko, Ansari, & Fugelsang, 2010). There were no outliers in the present dataset. As observed in Figure 4, there was an increase in response time from 1 through 9 dots.

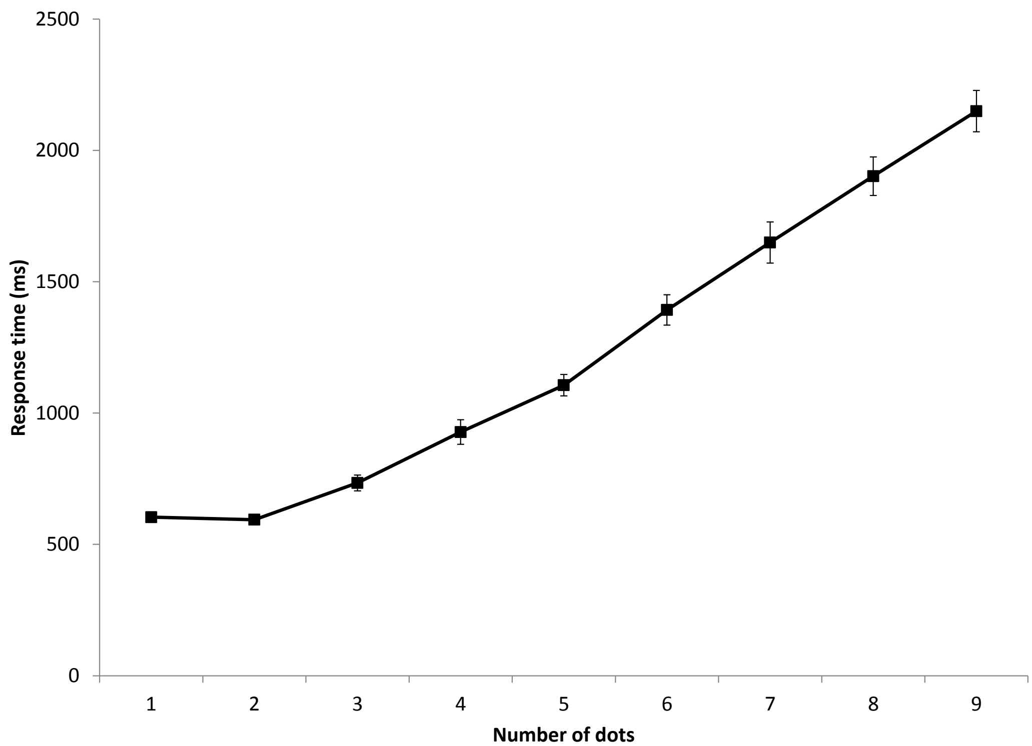


Figure 4: Response time of correct responses for simultaneous presentation of visual stimuli

The slopes corresponding to the response times for consecutive numbers of dots (e.g., between 1 and 2, between 2 and 3, etc.) were computed, and paired-sample t-tests were used to explore differences in rates of change in response time for adjacent numerosities. The results showed a significant difference between the numerosities corresponding to the slope between 1 and 2 dots, and between 2 and 3 dots, $t(47)=4.43$, $p<.001$. There were no other significant differences between any of the other adjacent pairs. This suggests that based on the response time measures from the present dataset, the subitizing range extends only up to 2 dots, with the counting range extending from 3-9 dots.

Based on these data, the accuracy measures suggested a distinct process beyond 5 dots, and the response time measures suggested a distinct process beyond 2 dots, making it difficult to use these trends to decide a suitable subitizing and counting range. This disparity in findings is likely due to the small number of trials used in this study compared to other studies in the literature on enumeration. Therefore, to ensure an unbiased method of separating the subitizing range from the counting range, (Atkinson, Campbell, & Francis, 1976) data from prior studies in the literature (e.g., Atkinson, Campbell, & Francis, 1976, Mandler & Shebo, 1982, Trick, 1992) were used to determine that the subitizing range extends from 1-4 dots, and counting range extends beyond 4 dots. Further, as is typically done in the literature, the reaction time associated with 9 dots was omitted from analyses, since any number beyond 8 can be apprehended as being 9, without having to count the additional dot.

Next, the accuracy and response time measures were averaged over the subitizing (1-4 dots) and counting ranges (5-8 dots), and submitted to a one-way repeated measures ANOVA with Range [Subitizing, Counting] as the within subjects variable. Both, the accuracy and response time measures revealed a main effect of Range [accuracy: $F(1,47)=21.29$, $p<.001$, $\eta_p^2=.31$; response time: $F(1,47)=323.92$, $p<.001$, $\eta_p^2=.87$] with the accuracy decreasing, and response time increasing between the subitizing and the counting ranges.

Visual Sequential Enumeration. Figure 5 presents the accuracy score associated with each numerosity. As can be seen, accuracy decreased as the number of dots increased.

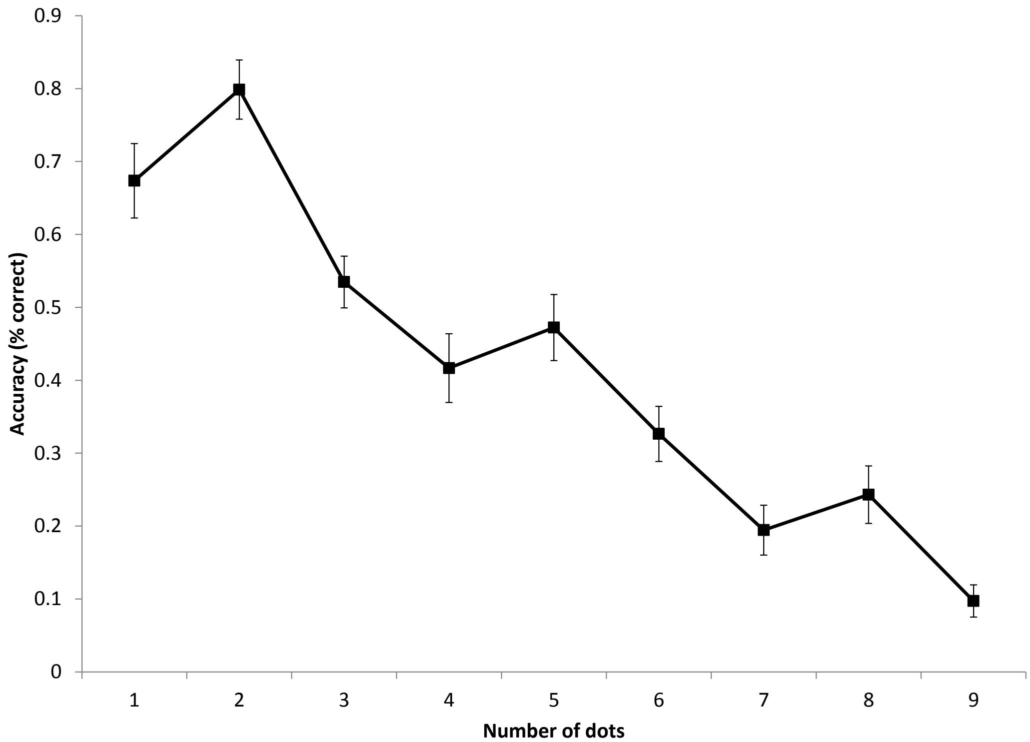


Figure 5: Accuracy (% correct) of responses for sequential presentation of visual stimuli

The slopes corresponding to the accuracy scores for consecutive numbers of dots (e.g., between 1 and 2, between 2 and 3, etc.) were computed, and paired-sample t-tests were used to explore differences in accuracy for adjacent numerosities. There was a significant difference between the numerosities corresponding to the slope between 1 and 2 dots, and between 2 and 3 dots, $t(47)=4.60$, $p<.001$. In addition, there was a difference between the slope between 6 and 7 dots, and between 7 and 8 dots, $t(47)=2.33$, $p<.05$, and between the slope between 7 and 8 dots, and between 8 and 9 dots, $t(47)=2.53$,

p<.05. Thus, based on these effects and the trends seen in Figure 6, there was a decline in accuracy beyond 2 dots, but an unexpected increase (and subsequent decline) in accuracy after 7 dots. The *increase* in accuracy between 1 and 2 dots, occurred presumably because with the single flashing dot, participants inaccurately counted the number of events (dot appearing, dot disappearing) as two, instead of one. The spike in accuracy associated with 8 dots might have occurred because with the increasing number of flashes, participants might have merely regressed to the strategy of responding with "8", as an average of 7 and 9 flashing dots.

Since this sequential presentation of items was largely exploratory in nature, a deviance measure was calculated, to observe the difference between the expected response and the given response. As seen in Figure 6, beyond 2 dots, participants underestimated the number of items, and there was a general increase in deviance beyond 5 dots.

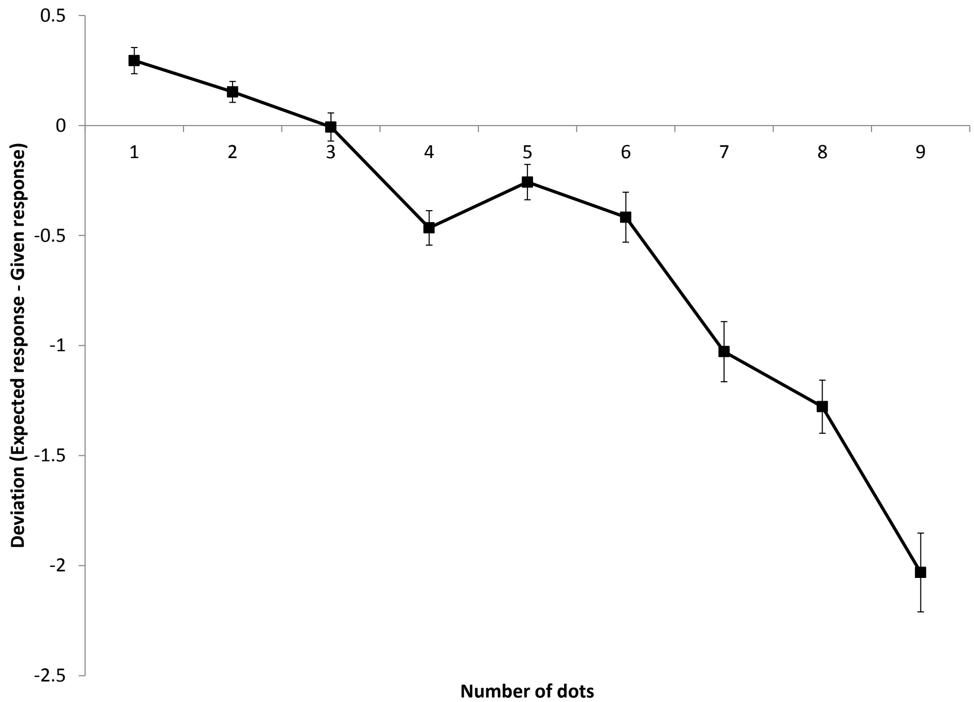


Figure 6: Deviance measure for sequential presentation of visual stimuli

Next, the response times associated with the different numerosities were computed. 2.32% of response times were discarded as outliers. As observed in Figure 7, there was no steady increase in response time. Instead, there was a peak in response time for 3 and 7 dots, with response time decreasing on both sides of these number sets, and a drop in response time associated with 5 dots.

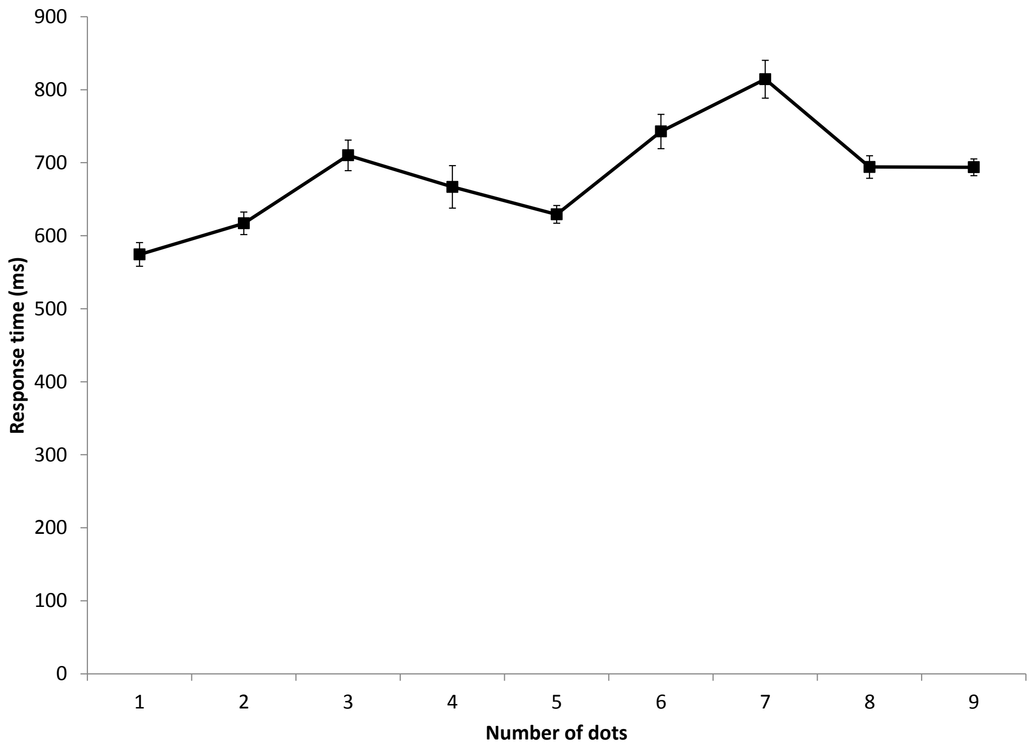


Figure 7: Response time for sequential presentation of visual stimuli

The slopes corresponding to the response times for consecutive numbers of dots were computed, and Bonferroni-corrected paired-sample t-tests were used to explore differences in rates of change in response time for adjacent numerosities. The results showed a significant difference between the numerosities corresponding to the slope between 4 and 5 dots, and between 5 and 6 dots, $t(47)=3.92$, $p<.001$.

The data from the accuracy and the response time measures depict different trends, with unclear patterns of where the subitizing and counting ranges exist. On the one hand, the results from the response time measures suggest that the distinction might occur around 5 events. However, the data from the accuracy measures suggest that this happens much earlier, perhaps after 2 events. Although much of the literature on enumeration focuses on spatial enumeration, those that do discuss temporal enumeration use error rates as their primary dependent variable, because events unfold over time making it difficult to determine when timing should start (Trick, 2005). Therefore, for the purposes of this study, based on the accuracy measures and prior literature (Taubman, 1950b; Trick, 1992), the subitizing range in temporal visual enumeration was determined to extend up to 2 events, with counting extending from 3-8 events.

Next, the accuracy and response time measures were averaged over the subitizing (1-2 dots) and counting ranges (3-8 dots), and submitted to a one-way repeated measures ANOVA with Range [Subitizing, Counting] as the within subjects variable. Both, the accuracy and response time measures revealed a main effect of Range [accuracy: $F(1,47)=71.54$, $p<.001$, $\eta_p^2=.60$; response time: $F(1,47)=13.36$, $p<.001$, $\eta_p^2=.22$] with accuracy decreasing, and response time increasing between the subitizing and the counting ranges.

Auditory Enumeration. Figure 8 depicts the accuracy scores in the auditory enumeration task. As can be seen, the accuracy measure showed a steady decline with increasing numbers of tones.

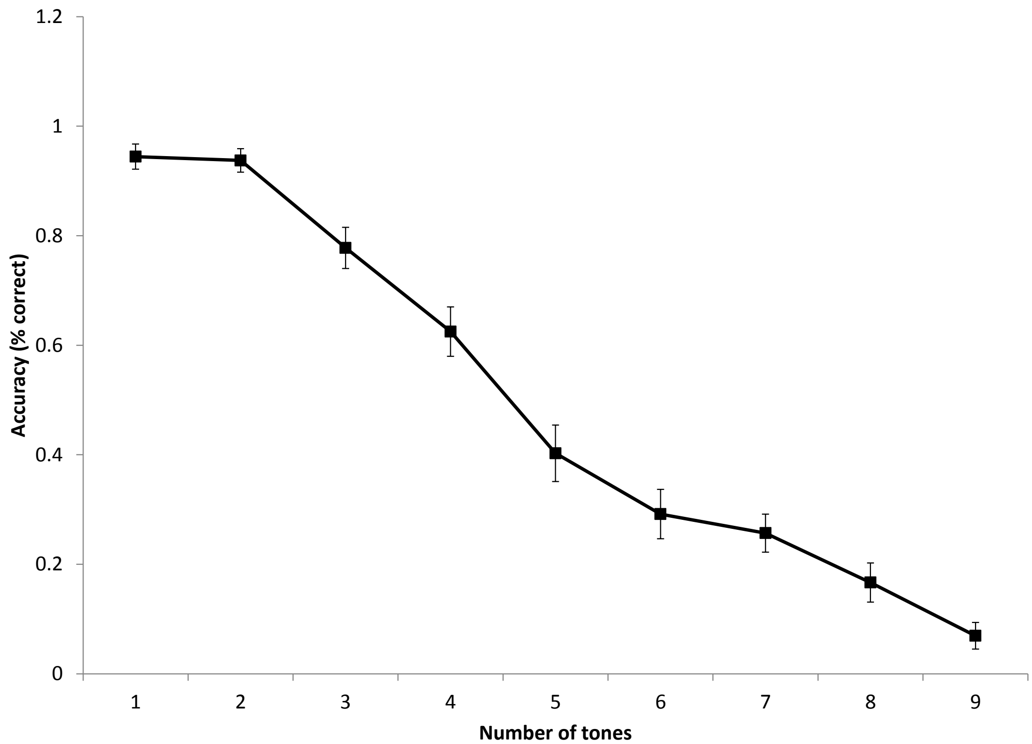


Figure 8: Accuracy (% correct) of responses for auditory stimuli

Similar to the analyses from the visual enumeration tasks, the slopes corresponding to adjacent accuracies were computed, and compared using paired-sample t-tests. The findings replicated those found in the simultaneous visual enumeration task, namely, there was a significant difference in the rate of change between 1 and 2 tones, and between 2 and 3 tones, $t(47)=2.91$, $p<.01$. Unlike in the simultaneous visual enumeration task, there were no other significant differences between adjacent pairs. These data make it evident that there exists a break in the accuracy measure beyond 2 auditory events, suggesting a subitizing range for 1 and 2 tones, with a counting range for 3 tones and beyond. Similar to the analyses from the visual sequential enumeration task, a deviance measure was calculated, to observe the difference between the given response and the expected response. As seen in Figure 9, participants underestimated the number of items, with an increase in this underestimation as the number of events increased, replicating findings from earlier studies (Repp, 2007).

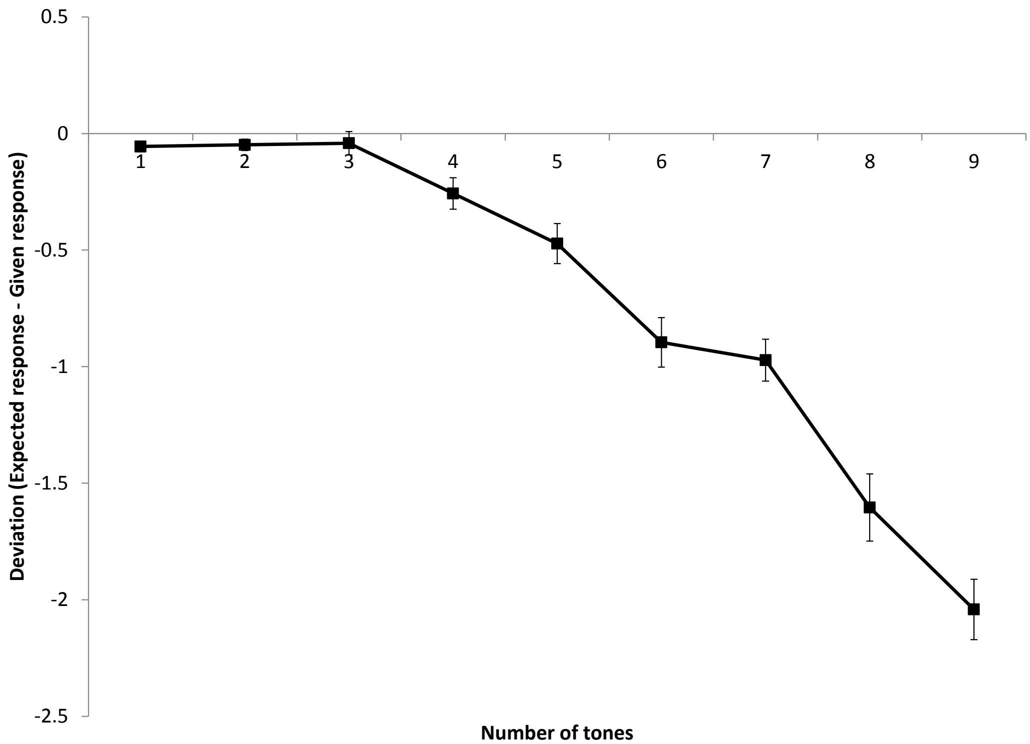


Figure 9: Deviance measure for sequential presentation of auditory stimuli

The response time measures were also computed, with 1.67% of response time values discarded as outliers. The trends were remarkably similar to those seen with the accuracy measures, with a significant difference in the slopes between 4 and 5 tones, and between 5 and 6 tones, as seen in Figure 10, and confirmed by Bonferroni corrected paired-sample t-tests, $t(47)=2.74$, $p<.01$.

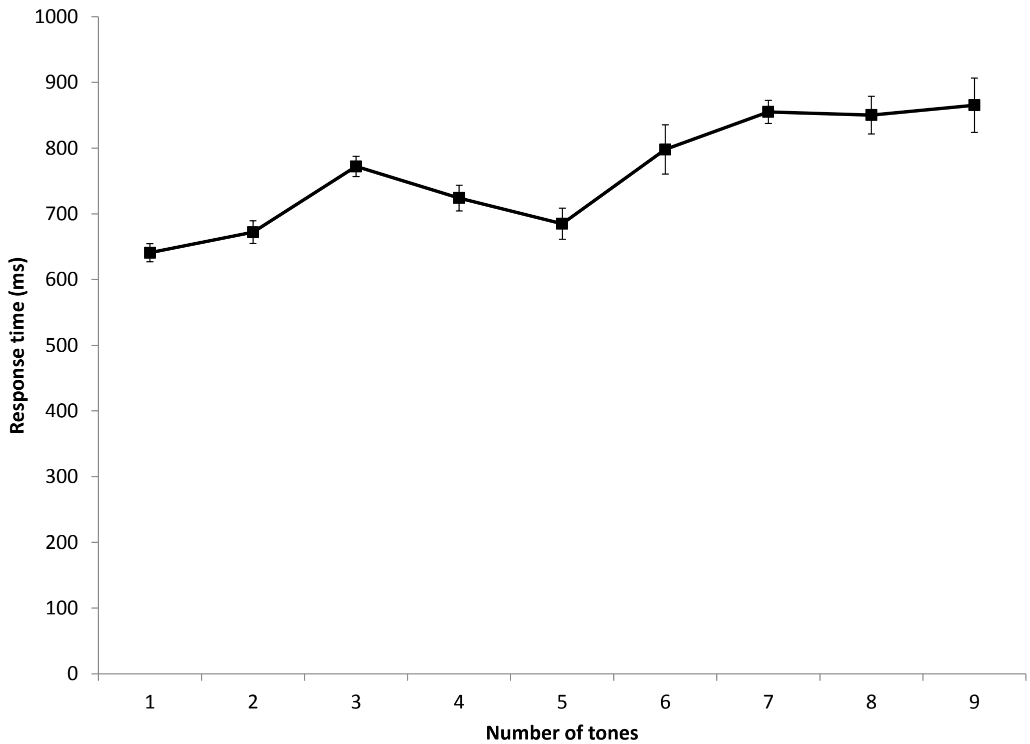


Figure 10: Response time for sequential presentation of auditory stimuli

Since the trends in accuracy and response time measures paralleled those from the sequential visual enumeration task, the same numerosity ranges were used to calculate the subitizing (1-2 tones) and counting (3-8 tones) averages. These values were submitted to a one-way repeated measures ANOVA with Range [Subitizing, Counting] as the within subjects variable. Both the accuracy and response time measures revealed a main effect of Range [accuracy: $F(1,47)=317.13$, $p<.001$, $\eta_p^2=.87$; response time: $F(1,47)=54.02$, $p<.001$, $\eta_p^2=.54$] with the accuracy decreasing, and response time increasing between the subitizing and the counting ranges.

Association between enumeration and Working Memory and Math Anxiety

Visual simultaneous enumeration

There was no correlation between math anxiety scores and the two dependent measures in either the subitizing [accuracy: $r(47)$=-.16, p=.28; response time: $r(47)$=.26, p=.16] or the counting [accuracy: $r(47)$=-.14, p=.34, response time: $r(47)$=.22, p=.18] ranges. These results contradict those found in prior studies (Maloney, Risko, Ansari, & Fugelsang, 2010), which found that math anxiety negatively affected performance in the counting range. However, while the prior study deliberately recruited participants who had the highest and the lowest math anxiety scores, the present study did not. Thus, it is likely that the limited range of math anxiety scores in the present study prevented any correlation between math anxiety and accuracy measures to be revealed. There was also no correlation between working memory and accuracy in the subitizing [Digit Forward, $r(47)$=.20, p=.16; Digit Backward, $r(47)$=.079, p=.59; Digit Sequencing, $r(47)$=-.13, p=.39] or counting [Digit Forward, $r(47)$=-.094, p=.52; Digit Backward, $r(47)$=.24, p=.11; Digit Sequencing, $r(47)$=.23, p=.10] ranges, or between working memory and response time in the subitizing [Digit Forward, $r(47)$=-.11, p=.45; Digit Backward, $r(47)$=.006, p=.97; Digit Sequencing, $r(47)$=.58, p=.70] or counting [Digit Forward, $r(47)$=-.27, p=.067; Digit Backward, $r(47)$=-.10, p=.49; Digit Sequencing, $r(47)$=.044, p=.76] ranges.

Visual Sequential Enumeration

Similar to the findings from the simultaneous enumeration, there was no correlation between math anxiety scores and the two dependent measures in either the subitizing [accuracy: $r(47)$=-.032, p=.83; response time: $r(47)$=-.024, p=.87] or the counting [accuracy: *r(47)*=-.11, *p*=.47, response time: *r(47)*=.047, *p*=.75] ranges. There was also no correlation between working memory and accuracy in the subitizing [Digit Forward, *r(47)*=-.067, *p*=.65; Digit Backward, *r(47)*=-.21, *p*=.16; Digit Sequencing, *r(47)*=.17, *p*=.25] or counting [Digit Forward, *r(47)*=.023, *p*=.88; Digit Backward, *r(47)*=.043, *p*=.77; Digit Sequencing, *r(47)*=-.11, *p*=.44] ranges, or between working memory and response time in the subitizing [Digit Forward, *r(47)*=.16, *p*=.27; Digit Backward, *r(47)*=.097, *p*=.51; Digit Sequencing, *r(47)*=-.077, *p*=.60] or counting [Digit Forward, *r(47)*=.098, *p*=.51; Digit Backward, *r(47)*=.078, *p*=.60; Digit Sequencing, *r(47)*=-.21, *p*=.14] ranges.

Auditory Enumeration.

There was no correlation between math anxiety scores and response time in the subitizing, *r(47)*=.023, *p*=.87, or the counting, *r(47)*=.091, *p*=.54 ranges, or between math anxiety scores and accuracy in the counting range, *r(47)*=-.19, *p*=.21. There was, however, a significant *negative* correlation between math anxiety and the accuracy in the subitizing range, *r(47)*=-.35, *p*<.01, such that as math anxiety increased, there was a decline in accuracy.

There was no correlation between working memory and response time in the subitizing [Digit Forward, *r(47)*=.13, *p*=.37; Digit Backward, *r(47)*=.18, *p*=.22; Digit Sequencing, *r(47)*=-.12, *p*=.43] or counting [Digit Forward, *r(47)*=.21, *p*=.15; Digit Backward, *r(47)*=.17, *p*=.25; Digit Sequencing, *r(47)*=.035, *p*=.81] ranges. Likewise, there was no correlation between working memory and accuracy in the subitizing range [Digit Forward, *r(47)*=.11, *p*=.45; Digit Backward, *r(47)*=.01, *p*=.96; Digit Sequencing, *r(47)*=-.08, *p*=.59]. In the counting range, however, there was a significant *positive* correlation between Digit Backward and accuracy, *r(47)*=.34, *p*<.05, and between Digit Sequencing and accuracy, *r(47)*=.35, *p*<.05, but none between Digit Forward and accuracy, *r(47)*=.043, *p*=.77. That is, as digit span increased, so did accuracy, but only in the counting range, paralleling the findings from math anxiety, which showed a decline in accuracy with increased anxiety.

Math anxiety has been shown to occupy working memory (Ashcraft & Faust, 1994; Ashcraft, 2002), and to affect performance in counting, but not in subitization tasks, mediated by load on working memory (Maloney, Risko, Ansari, & Fugelsang, 2010). However, the present finding is novel in that it extends these effects to auditory enumeration, and to sequential enumeration of events, instead of on simultaneous visual enumeration.

Association between rhythmic and numerical processing

The central question in this study is the extent to which individual performance on the rhythm task (measured by the difference scores on the simple and complex meter rhythm task) correlates with performance on the tasks of enumeration. Tests of multicollinearity indicated that a low level of multicollinearity was present across all variables (*VIF*<5). Next, to select the specific variables to enter into the regression analysis, a correlation analysis was performed between the outcome variables and each of the independent variables (Table 2).

Table 2: Correlation between simple and complex meter performance and each independent variable

	MT	WMC	MA	VSim % Sub	Vsim % Count	Vsim R Sub	Vsim R Count	Vseq % Sub	Vseq % Count	Vseq R Sub	VSeq R Count	Aseq % Sub	Aseq % Count	Aseq R Sub	Aseq R Count	WH	OK	OH	Tonal	Rtm
Simple	0.58**	0.28	-.040	-.16	-.22	-.33*	-.33*	-.08	-.05	.12	-.14	.07	.14	-.30*	.09	.00	.00	0.08	0.40**	0.56**
Complex	.43**	.40**	.016	-.21	.016	-.077	-.098	-.11	-.10	.15	.057	.033	.36*	-.075	-.030	.21	.11	.20	.27	.40**

Note: N=48, * $p < .05$. ** $p < .01$. *** $p < .001$.

Acronym	**Variable Name**
MT	Number of years of music training
WMC	Composite working memory score
MA	Math Anxiety score
VSim%Sub	Accuracy on Visual Simultaneous Enumeration – Subitizing Range
VSim%Count	Accuracy on Visual Simultaneous Enumeration – Counting Range
VSimRSub	Response Time on Visual Simultaneous Enumeration – Subitizing Range
VSimRCount	Response Time on Visual Simultaneous Enumeration – Counting Range
VSeq%Sub	Accuracy on Visual Sequential Enumeration – Subitizing Range
VSeq%Count	Accuracy on Visual Sequential Enumeration – Counting Range
VSeqRSub	Response Time on Visual Sequential Enumeration – Subitizing Range
VSeqRCount	Response Time on Visual Sequential Enumeration – Counting Range
ASeq%Sub	Accuracy on Auditory Sequential Enumeration – Subitizing Range
ASeq%Count	Accuracy on Auditory Sequential Enumeration – Counting Range
ASeqRSub	Response Time on Auditory Sequential Enumeration – Subitizing Range
ASeqRCount	Response Time on Auditory Sequential Enumeration – Counting Range
WH	Score on Within Harmony trials
OK	Score on Out of Key trials
OH	Score on Out of Harmony trials
Tonal	Score on Tonal Subtest of AMMA
Rtm	Score on Rhythm Subtest of AMMA

The number of years of music training and music aptitude (both rhythm, and tonality) correlated positively (p<.05) with performance on the simple meter trials. That is, as number of years of music training or music aptitude increased, so did the scores on the simple meter tasks. Interestingly, however, in addition to the effects of music aptitude and music training, the following predictor variables correlated *negatively* with performance on the simple meter trials: response time on the visual simultaneous enumeration task (subitizing range: $r(47) = -.33$, $p < .05$; counting range: $r(47) = -.33$, $p < .05$), and response time on the auditory enumeration task in the subitizing range, $r(47) = -.30$, $p < .05$. That is, as response times on these enumeration tasks increased, accuracy on the simple meter task decreased.

Based on these significant correlations, a series of hierarchical multiple regression analyses was performed to assess whether the performance on the enumeration tasks predicted performance on the simple meter tasks *independently* of the influence of music training and music aptitude. To do so, in the first step, all the predictor variables that correlated significantly with performance on the simple meter trials were entered into the model, including the music training and music aptitude variables. This full model was significant; $R(47)$=.71, adjusted R^2 = 4.39, $F(6.41)$=7.12, p<.001. In the next step, the effects of music aptitude were removed from the hierarchical regression analysis. Removal of these variables (performance on both, the rhythm and tonal subtests) significantly diminished the effectiveness of the model, R^2 change=-.083, F=3.47, p<.05, suggesting that music aptitude was an important factor in predicting performance on the simple meter trials. In the final step, the effects of music training were removed from the resulting regression model, leaving only the response time on the enumeration tasks in the equation. Removal of music training also diminished the model's predictability significantly, R^2 change=-.26, F=19.23, p<.001. Further, given that music training was removed last from the analysis, the model highlights the role of music training *beyond* any role of music aptitude.

The effects of music training and music aptitude on simple meter perception are not surprising. The essential question is how well individual performance on an enumeration task can predict simple meter perception *after* removing the effects of music training and aptitude. The individual models at each step of the hierarchical regression analysis suggest that even when the effects of music training and aptitude are removed from the model, response time on the enumeration tasks can still effectively predict performance on the simple meter trials, $F(3,44)=3.03$, $p<.05$.

In looking at the complex meter trials, besides the significant associations with music training and performance on the rhythm subtest, individual performance correlated positively with their performance on the working memory task, and with accuracy in the counting range of the auditory enumeration task. Similarly to the analyses with the simple meter trials, hierarchical multiple regression analyses were performed, with the full model including all of the variables that correlated significantly with performance on the complex meter trials. This full model significantly predicted performance on the complex meter trials, R(47)=.57, adjusted R^2=.26, $F(4,43)=5.08$, p<.01. In the next two steps, working memory, and performance on the rhythm subtest of AMMA were hierarchically removed in that order. Neither of these steps diminished the effectiveness of the full model, R^2 change<2.02, F<5.96, p>.16, *n.s.* Removal of music training in the final step, however, significantly reduced R^2, R^2 change=-.14, $F(1,46)=8.25$, F<.01. Interestingly, the reduced model with accuracy in the auditory counting task acting as the only predictor, still resulted in a significant model, R(47)=.36, adjusted R^2=.11, $F(1,46)$=6.62, $p<.05$.

Taken together, the findings from the simple and complex meter tasks suggest that an individual's enumeration abilities predict their performance on a rhythm perception task even after effects of music training, music aptitude, and working memory are controlled for. The specific enumeration tasks and the strength of their effects differ depending on whether the rhythms involve simple, isochronous meters, or complex, non-isochronous meters.

Discussion

The primary goal of this study was to examine the elusive link between music and mathematics. Before exploring the link between the two domains, it was important to assess the association between auditory and visual processing, since the domain of mathematics is predominantly based on the visual system, whereas music is based on the auditory system.

Prior studies that have compared enumeration abilities in the visual and auditory modalities report similar trends across both in terms of response time and accuracy (Camos & Tilmann, 2008). Specifically, results from both, vision and audition, support a discontinuity between enumerating small versus large sets, with response times increasing and accuracy decreasing linearly for larger sets, but staying constant within the smaller sets. Likewise, in both vision and audition, brain imaging studies have argued for the role of the left hemisphere in subitization (Piazza, Mechelli, Price, & Butterworth,

2006) and the right hemisphere in counting (Pasini & Tessari, 2001). However, no study to date compared individual performance across the two modalities. The results from the present study revealed a high level of correlation between an individual's performance on the auditory and visual enumeration tasks, as seen in Table 2, with an additional interesting and unexpected finding – an individual's performance on the visual and auditory numerosity tasks are correlated, but only within the subitizing range. This novel finding suggests that at the subitizing level, the mechanism for enumeration might be similar across modalities, but might diverge for larger set sizes. This lends support to the argument in the literature that subitizing is a more basic skill, and acts as a precursor to counting (Klahr & Wallace, 1976; Schaeffer, Eggleston, & Scott, 1974). Prior research suggests that unlike counting, subitizing abilities emerge in very early infancy and existing across both, vision and audition (Klein & Starkey, 1988).

The central question of study measured the extent to which the domains of music and mathematics are correlated within individuals. The test used the basic enumeration task across vision and audition to measure mathematical abilities, and an ecologically valid measure of rhythm perception to assess musical ability. Specifically, the rhythm consisted of repeating patterns of events, with durations related in either simple or complex integer ratios. The results from this study revealed a novel and important finding. Namely, whereas simple meter processing correlated with performance on enumeration in the subitizing and counting ranges, complex meter processing correlated with performance only within the counting range, but not within the subitizing range, as seen in Table 2. Further, whereas performance on the complex meter task correlated significantly with working memory capacity, performance on the simple meter task did not.

These findings add strength to the theory that there may be fundamental differences in terms of processing of simple versus complex meter rhythms, and that this difference might be associated with the processing of quantity in general. Further, whereas processing of simple meter rhythms might be akin to processing small quantities – automatic and innate, processing of complex meter rhythms might be dependent on greater cognitive resources. In processing simple versus complex meter rhythms, one of the theories in the literature is that while simple meter processing is automatic and implicit, the processing of complex meters requires explicit strategies (Sakai, et al., 1999). Specifically, whereas simple integer (or “metrical”) rhythms easily map on to an internal clock, the more complex ones do not (Povel & Essens, 1985). Thus, rhythms comprised of simple integer ratios have been shown to be easier to perceive than simple meters (Desain & Honing, 2003; Repp, London, & Keller, 2010).

Evidence also points to the increased cognitive load in processing complex meters, as measured by differential brain responses while processing rhythms of varying metrical complexity (Lewis, et al, 2004; Sakai, et al, 1999). In turning towards the literature on enumeration, a small number of items are enumerated almost instantly and automatically, both in the visual (Mandler & Shebo, 1982) and in the auditory modalities (Repp, 2007), whereas enumeration of larger quantities is effortful, deliberate, and requires learning (Starkey & Cooper, 1980). The results from this study reveal that automatic perception of intervals in simple meter rhythms borrows on some of the same mechanisms as does apprehending visual or auditory quantities. In contrast, complex meter rhythms, being more effortful, might require active strategies, including counting. In particular, the counting involved in processing complex integer ratios presumably involves enumerating events that unfold over time (sequential, instead of simultaneous enumeration) in the auditory modality.

Taken together, the present study adds to the theory that the domains of mathematics and music are both governed by the ability to process quantity – that of number in mathematics, and that of time in music. Theories for a common mechanism for processing quantity in the dimensions of time and number have been proposed (Walsh, 2003) and supported by behavioral (Olivieri, et al., 2008) and neurophysiological (Rao, Mayer, & Harrington, 2001) data. The present study highlights not just an association between numerical and musical processing, but a distinction between the processing of simple versus complex meters in music.

Beyond the links between music and mathematics, the results from the present study add to the existing literature on limits of enumeration. One of the current debates in the field of mathematical cognition is why small and large numbers are treated differently. That is, why is there a distinct subitizing range that is both qualitatively and quantitatively different from the counting range? A density-based argument points out that larger numbers of items are more densely packed in the same space than are smaller numbers of items. Atkinson, Campbell, & Francis (1976) theorize that special neural units are sensitive to low numbers of items. In contrast, they speculate that there are no corresponding units specialized for larger spatial frequencies. The second argument is a pattern-based one that suggests that whereas 1 dot forms a point, 2 dots form a line, and 3 dots form a triangle, larger numbers of dots do not produce recognizable canonical patterns. Thus, pattern stops being a useful cue with increasing numbers of items. The third major theory is a working-memory based one argues that when the number of items to enumerate exceeds the memory capacity, it requires the participant to make successive "trips" to the display (Klahr, 1973).

While these theories are all plausible with simultaneously presented displays of items, the use of sequentially presented events, as in the present study, offers a strong argument against both, the density-based and the pattern-based theories. Items presented sequentially cannot be apprehended by means of a predictable pattern. In terms of the density-based theory, although the sequential presentation offers an additional cue in terms of total duration (since more items take longer to be presented), they do not offer information in terms of density. Furthermore, in the present study, the interval between events was manipulated so that total duration could not be used as a direct cue.

Instead, the working-memory based model stands as a plausible theory to explain the decline in accuracy and increase in response time for both, sequentially *and* simultaneously presented items. Larger sets have to be held in memory for longer, while participants store the number of items that have already been presented, and add newly presented items to this total. In their hallmark study, Trick & Pylyshyn (1994) argue that when participants are asked to enumerate a set of items larger than can be processed in the visual preattentive state, they use counting strategies, which involves keeping track of where their attention was last focussed, planning where to move their focus to, and inhibiting previously viewed information. Prior studies have found a clear effect of an individual's working memory and their performance in the counting range, but not in the subitizing range (Maloney, Risko, Ansari, & Fugelsang, 2010; Tuholski, Engle, & Baylis, 2001). Other studies found a difference in performance in the counting range, but only as a factor of spatial visual memory capacity (Shimomura & Kumada, 2011). The present study did not find significant correlations between any of the enumeration measures and working memory scores, except with accuracy in the auditory counting task, where accuracy increased with an increase in working memory (see Appendix A). One possible reason is that all the reviewed studies that found differences due to working memory, recruited participants on the highest and lowest extremes of the working memory scale.

From this experiment on simple and complex meter processing, an unanswered question is the extent to which the processing of these simple and complex meters are driven by different neural mechanisms. The next study examines neural responses as participants listen to rhythms composed of either simple or complex meters. Further, given the large corpus of data that suggest that ease of metrical processing is driven by culture-specific familiarity with these meters, the study tests two groups of listeners: American participants who should be familiar with simple meters exclusively, and Non-American (Indian/Bulgarian) participants who should be equally familiar with both types of meters.

CHAPTER 3

Neural correlates of Simple and Complex Meter Rhythm Processing

Introduction

In perceiving a metrical structure, listeners develop an anticipatory mechanism that allows them to predict the onset of regularly occurring events. Electrophysiological studies have measured this anticipatory response, known as a slow anticipatory potential, which occurs prior to an expected event (Brunia, 1999). When presented with an isochronous sequence of tones, an occasionally omitted tone elicits similar brain responses as a physically present one.

Prior studies have explored the relationship between brain activity and mental percepts of the rhythmic patterns. For instance, Snyder and Large (2005) present listeners with metric rhythms that were comprised of alternating loud and soft tones. In one subset of the trials, there was an occasionally omitted tone, with the loud tone being omitted in half of these trials, and the soft tone being omitted in the other half of these trials. While induced and evoked gamma band (20-60 Hz) activity was observed near tone onsets (particularly for loud tones), induced activity shows additional peaks even while the tone was occasionally omitted, with the highest amplitude observed in the 20-30 Hz range. In evoked activity, the individual bursts of energy are phase-locked to the stimulus onset and the latency overlap over trials, with activity following stimulus events. In induced activity, on the other hand, the amplitude (but not the phase) is time-locked to the stimulus onset (Tallon-Baudry & Bertrand, 1999), and activity can occur at various latencies. These results are taken to suggest that non-phase locked gamma band activity may represent rhythmic expectancy and the cognitive aspects of auditory perception (Tallon-Baudry & Bertrand, 1999).

Interestingly, the sensitivity of brain activity to accents is observed even when the accents are merely subjective (Brochard, Abecasis, Ragot, Potter, & Drake, 2003). In this study, participants were presented with a metronomic sequence of tones, where every odd-numbered tone was typically perceived as sounding accented. There were occasional deviant tones (reduced amplitude from the standard tones), occurring on either the odd-numbered or even-numbered tones. Event-related potential (ERP) responses showed significantly larger amplitudes when the deviant tone was at an odd-numbered position, than at an even-numbered position. Specifically, the differences were observed in the late P3b component, which was interpreted as being associated with top-down modulation of attentive and cognitive processes on metrical processing.

Similar results were observed when the metrical structure was "objective" instead of "subjective" (Abecasis, Brochard, Granot, & Drake, 2005). When there was a deviant tone, larger ERP amplitudes were observed in positions corresponding to strong beats, as induced by phenomenal accents, in both a binary (long-short) and ternary (long-short-short) condition. Further, similar to the findings from the Brochard, et al. (2003) study, the findings confirmed the findings that listeners predominantly employ a binary metrical structure, and show better processing of the first (accented) event within each perceptual group.

In addition to perception of accents being shaped by the position of, and phenomenal accents on the tones themselves, metrical interpretation can also be manipulated by means of a physical cue at the start of each sequence (Iversen, Repp &

Patel, 2009). In this study, listeners were presented with a repeating pattern of two tones followed by a rest. Each sequence started with an induction phase with a physical accent on one of the two beats. Listeners were instructed to continue to imagine the accent on that beat once the induction phase ends. This yielded two possible metrical interpretations; a **short**-long-**short**-long or a **long**-short-**long**-short percept, with the subjective accent being perceived on the short or the long interval respectively. The brain responses showed an increase in evoked amplitude in the 20-30 Hz range corresponding to the accented tone, and a comparable increase when the tone was merely *imagined* to be the beat. Based on these findings, a subsequent study found increased N1/P2 amplitudes in physically accented versus subjectively accented events, a larger amplitude in subjectively accented versus unaccented events, and an early positive deflection in the first unaccented event compared to the last unaccented event (Schaefer, Vlek, & Desain, 2011).

Taken together, these preceding studies explore the nature of metrical representations and the corresponding patterns of brain activation for physically accented, subjectively accented, and different kinds of unaccented events. The present study attempts to examine the moderating effects of culture-specific experience on metrical interpretations of ambiguous rhythms. By varying the durational ratio between adjacent tones, the underlying rhythms conformed to either a simple or a complex meter pattern.

Methods

Ethics Statement. All procedures were approved by UNLV's Institutional Review Board for Human Subjects Research (Social/Behavioral), and complied with the ethical guidelines of the Office of Research Integrity. Written informed consent was obtained from all participants.

Participants. Participants for the "Western Group" were college students from Las Vegas, Nevada, USA, who were born in and spent a majority of their lives in North America (Group: *N*=20, *M* = 24.4 years, 10 male, 10 female) recruited using word-of-mouth. Their music training ranged from 0 years to 25 years (*M*=7.38, *SD*=10.97), with 5 participants reporting 0 years of music training. A majority of them spoke English as their first language (*N*=14), with the others speaking Italian (*N*=1), Spanish (*N*=4), and English/Spanish bilingually (*N*=1). A large majority was right handed (*N*=19). Participants in the "Non Western Group" were college students from Las Vegas, Nevada, who were from India (*N*=18) or Bulgarian (*N*=2), recruited using word-of-mouth (Group: *N*=20, *M* = 27 years, 12 male, 8 female). Their music training ranged from 0 years to 8 years (*M*=0.9, *SD*=2.47), with 17 participants reporting 0 years of music training. First language learned included Telugu (*N*=11), Bulgarian (*N*=2), Hindi (*N*=2), Tamil (*N*=2), English (*N*=1), Kannada (*N*=1), and Urdu (*N*=1). A large majority was right handed (*N*=19) with the remainder (*N*=1) being ambidextrous.

Task and Stimulus. The basic task consisted of a repeating sequence of three tones (T) followed by a rest (0) and was adapted from Iversen, et al (2009). The tones were 1 KHz pips 45 ms in duration with 5 ms rise and fall times. The tones were organized in a TTT0 format, with several possible rhythmic percepts. Specifically, there were three possible rhythmic combinations, depending on where the initial beat was perceived (highlighted beat): **T**TT0, T**T**T0/**T**T0T and TT**T**0/**T**0TT. Of these three rhythms, two rhythms were used in the present study: **T**TT0 and **T**0TT. Listeners were asked to adopt one of the two rhythmic interpretations for each trial, leading to the percept of SHORT-short-long (SSL) and LONG-short-short (LSS) respectively.

In order to facilitate this process, each trial began with five cycles of the sequence, with a physical accent (2X amplitude) on the tone that was intended to be heard as the initial beat (referred to as "accented period"). The specific amplitude accent was selected to replicate the design of the Iversen, et al, 2009 study. It was important to point out, however, that several cues, including temporal accents, dynamic accents and pitch changes (Hannon, Snyder, Eerola, & Krumhansl, 2004) could have been used to change the rhythmic percept during the induction phase.

Following this induction period, the trial continued with 15 cycles of the sequence, with no physical accents (referred to as "unaccented period"). During this unaccented period, listeners were instructed to continue to mentally place the beat at the same location, thus continuing the rhythmic percept from the accented period. Thus, despite having two different rhythmic percepts, the unaccented periods were physically identical across all trials. Figure 11 presents a schematic of the basic stimulus.

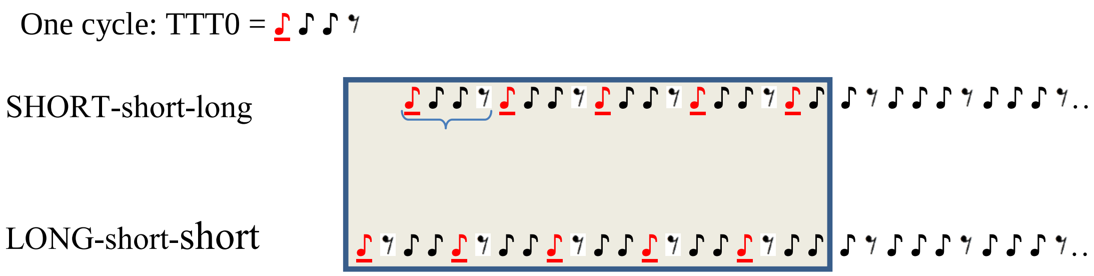


Figure 11: Schematic of basic stimulus
The stimulus consists of a repeating sequence of three tones followed by a rest. Depending on the position of the physical accent (on the first tone or the last tone), the stimulus was heard either as SHORT-short-long (first tone accented) or LONG-short-short (last tone accented). After five cycles of the induction phase (accented period: highlighted), the stimulus was identical across the two rhythmic conditions. The red note denotes a physically accented tone, and the black note denotes an unaccented tone. The shaded box denotes the induction phase.

In addition to the different rhythms, two different meters were used in this study. The inter-onset intervals and the duration of the rest were manipulated to give rise to two types of meters: simple and complex. In the simple meter trials, the rest was twice (2X) as long as the inter-onset interval between two successive tones, to create a simple 1:2 ratio between the long and the short durations. In the complex meter trials, the rest was one and a half times (1.5X) longer than the inter-onset interval between two successive tones, to create a more complex 2:3 ratio between the long and the short durations.

Further, two different tempi were used for each of the meters. First, one-half of the simple meter trials and one-half of the complex meter trials had the same duration for each cycle of the sequence. By doing so, the overall duration was maintained but the durations of the short and long intervals were different across the two meters. The second manipulation addressed this concern, by maintaining the same durations of the short intervals, but with a different overall duration for the sequence. Figure 12 highlights these different tempi for the simple and complex meters.

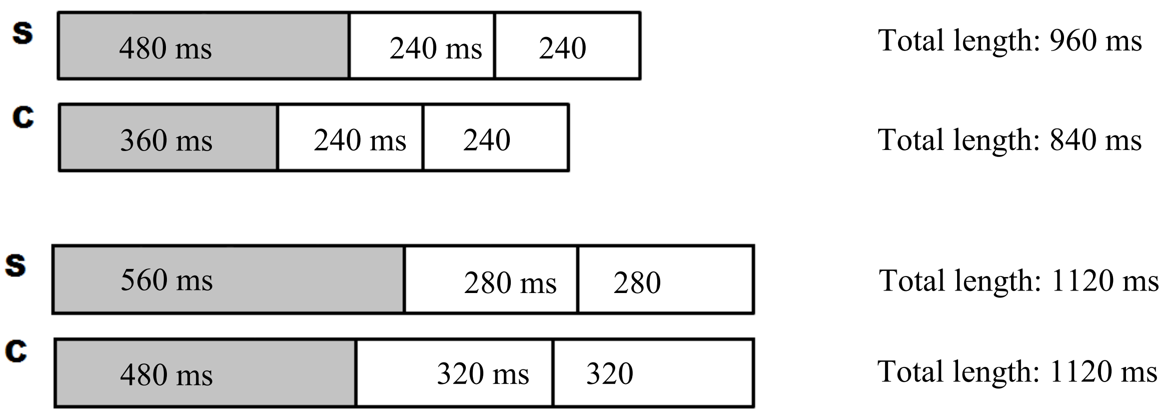


Figure 12: Tempi across simple and complex meter conditions. The shaded boxes denote the long intervals, which are twice the length of the short intervals (unshaded boxes) in the simple meter conditions (S), and 1.5 times the length of the short intervals in the complex meter conditions (C).

After accounting for the two rhythms (LONG-short-short and SHORT-short-long), the two meters (simple and complex), and the two tempi per meter (slow and fast), there were 8 different conditions. During the experiment, participants were presented with 8 blocks of trials, with 4 consecutive simple meter blocks, and 4 consecutive complex meter blocks. The order of presentation of the simple and complex meter blocks were predetermined and counterbalanced among participants. Each block consisted of the same 20 trials presented in a pseudorandom order (with different trials for the simple and complex meter blocks). Each trial consisted of the accented period followed by the unaccented period. After the unaccented period ended, the participants were asked if they mostly heard the unaccented period as "1- long-short-short" or as "2 - short-short-long", and make their response by pressing one of two buttons (labeled "1- long-short-short" and "2 - short-short-long").

When participants were asked to make their decision, they were presented with one cycle of an accented LONG-short-short sequence (with the label "1- long-short-short") and one cycle of an accented SHORT-short-long sequence (with the label "2-short-short-long"). A schematic of one trial is presented in Figure 13 below.

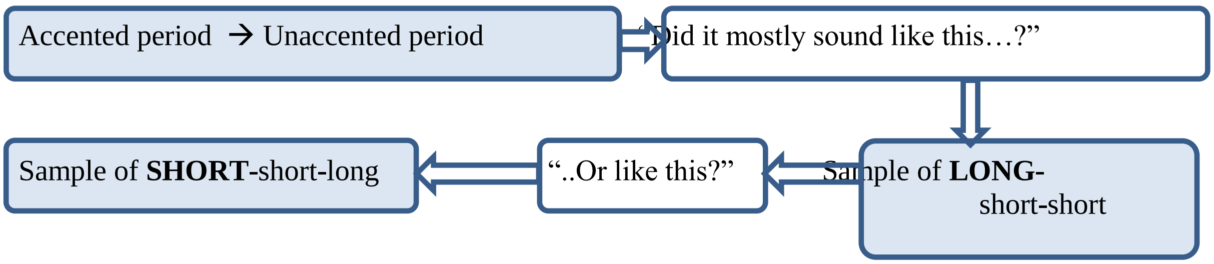


Figure 13: Schematic of an entire trial. Highlighted sections denote an auditory stimulus being played.

The experiment began with an induction phase, where participants listened to one accented period (5 cycles) of LONG-short-short and SHORT-short-long with the appropriate labels, followed by four practice trials. Participants were also asked to press and hold down a button when they felt like they lost the intended rhythmic organization. These trials were excluded from further analysis, similar to the procedure used by Iversen, Repp & Patel (2009). Participants were not explicitly told about the two types of meters (simple and complex) or the different tempi.

Recording and analyses of brain responses. Participants were seated in a comfortable chair in a sound-attenuated booth. They listened to the stimuli using E.A.RTone 3A insert earphones (E.A.R Auditory System, AudioMed, Inc, Jackson, MS). Listeners were asked to avoid closing their eyes, or making any movements during presentation of the stimuli, except to press a button to indicate if they lost the rhythmic organization. Electroencephalography (EEG) was recorded during the entire experiment, using a sampling rate of 512 Hz and a bandwidth of 104 Hz. A total of 72 Ag-AgCl electrodes are used, including two ground electrodes, 64 electrodes placed on a Biosemi electrode cap, and 8 electrodes placed below the hair line (two each of mastoids, pre-auricular points, outer canthus of each eye, and inferior orbit of each eye). Prior to EEG recording, voltage offsets are measured to ensure that it was below 40 mV, and all electrodes were periodically checked to ensure that they were all in normal working condition. During the EEG recording phase, any electrodes that were noted to be noisy were interpolated prior to further analyses.

EEG was recorded and saved on a PC computer using an Actiview System, and all off-line analyses were conducted using Brain Electrical Source Analysis software (BESA; MEGIS Software GmbH, Grafelfing, Germany) and Matlab (The Mathworks, Inc., Natick, MA). The raw EEG data was corrected for ocular artifacts using a horizontal ocular amplitude threshold (for saccades and smooth movements) of 150 µV and a vertical ocular amplitude threshold (for blinks) of 250 µV. An amplitude criterion of 150 µV was used for artifact rejection, and any epochs that have less than 50% of accented trials were omitted from further analyses.

The averaging epoch was determined by visually inspecting the data for the start position. The end position varies by condition, and depends on the length of one stimulus: 960 ms and 1120 ms for the fast and slow tempi in the simple meter condition, 840 ms and 1120 ms for the fast and slow tempi in the complex meter condition. In addition, baseline definition was determined by averaging the period between -100 and 0 ms in relation to the start of the trigger.

All epochs were aligned to the start of the "Long" in the LONG-Short-Short/SHORT-Short-Long sequence. Epochs were averaged separately for each condition (simple and complex meter, LONG-Short-Short and SHORT-Short-Long rhythm, and fast and slow tempo). In addition, each unaccented period (containing 15 unaccented cycles) was separated into three measures containing five cycles each, in order to observe any changes in the activity over the course of a trial. Therefore, each trial was divided into four measures (one accented and 3 unaccented). Mean amplitude and time frequency analyses were performed separately for each trial type.

Mean amplitudes for ERP data were calculated over each interval (long and short), within each trial type. Based on the location of the interval, some of the intervals were accented (either physically or subjectively). The mean amplitude analyses were used to observe differences in brain responses to physically versus subjectively accented intervals, and subjectively accented versus unaccented intervals. Further, these analyses were used to study the effects of metrical complexity on brain activity to subjective accents, and the moderating effects of culture-specific experience. Within each interval, the ERP mean amplitudes were calculated in time ranges showing maximal differences in the grand averaged waveforms between conditions of interest. The time ranges used in the different conditions are highlighted in Table 3.

Table 3: Time ranges used for different conditions

Simple Meter		
	Total length: 960 ms	Total length: 1120 ms
Long interval	N1: 95 ms to 137 ms P2: 162 ms to 229 ms (Baseline → 110 to 210 ms)	N1: 95 ms to 137 ms P2: 162 ms to 229 ms (Baseline → 110 to 210 ms)
First short interval	N1: 580 ms to 625 ms P2: 632 ms to 685 ms (Baseline → 590 to 690 ms)	N1: 660 ms to 700 ms P2: 705 ms to 760 ms (Baseline → 670 to 770 ms)
Complex Meter		
	Total length: 840 ms	Total length: 1120 ms
Long interval	N1: 91 ms to 136 ms P2: 156 ms to 200 ms (Baseline → 110 to 210 ms)	N1: 94 ms to 143 ms P2: 157 ms to 213 ms (Baseline → 110 to 210 ms)
Short interval	N1: 461 ms to 500 ms P2: 517 ms to 665 ms (Baseline → 470 to 570 ms)	N1: 570 ms to 617 ms P2: 633 ms to 695 ms (Baseline → 590 to 690 ms)

Prior to performing analyses on the EEG data, behavioral analyses were performed. These data consist of participant responses for what the unaccented section mostly sounded like (LONG-short-short or SHORT-short-long). Based on participant responses, a behavioral measure of "accuracy" was obtained, such that a trial where the physical accent pattern matches the participant's percept in the unaccented section was marked as being "accurate". For instance, if a trial cues a **LONG**-short-short pattern during the induction phase, and the participant responds that they mostly perceived the unaccented phase as being **SHORT**-short-long, then this trial will be marked as being "inaccurate". Only the accurate trials were used in the EEG analyses, to explore associations between brain responses and endogenous rhythmic percepts.

Results and Discussion

Behavioral Results. Participants' responses were analyzed to calculate the extent to which they reported perceiving the rhythm in the same manner as the rhythm presented in the induction phase. This measure of "accuracy" was calculated separately over the simple and the complex meter trials and provided an estimate of how well participants were able to hold on to the rhythm they heard during the induction phase. Figure 14 presents accuracy over the simple and complex meter trials for the Western and Non-Western participants.

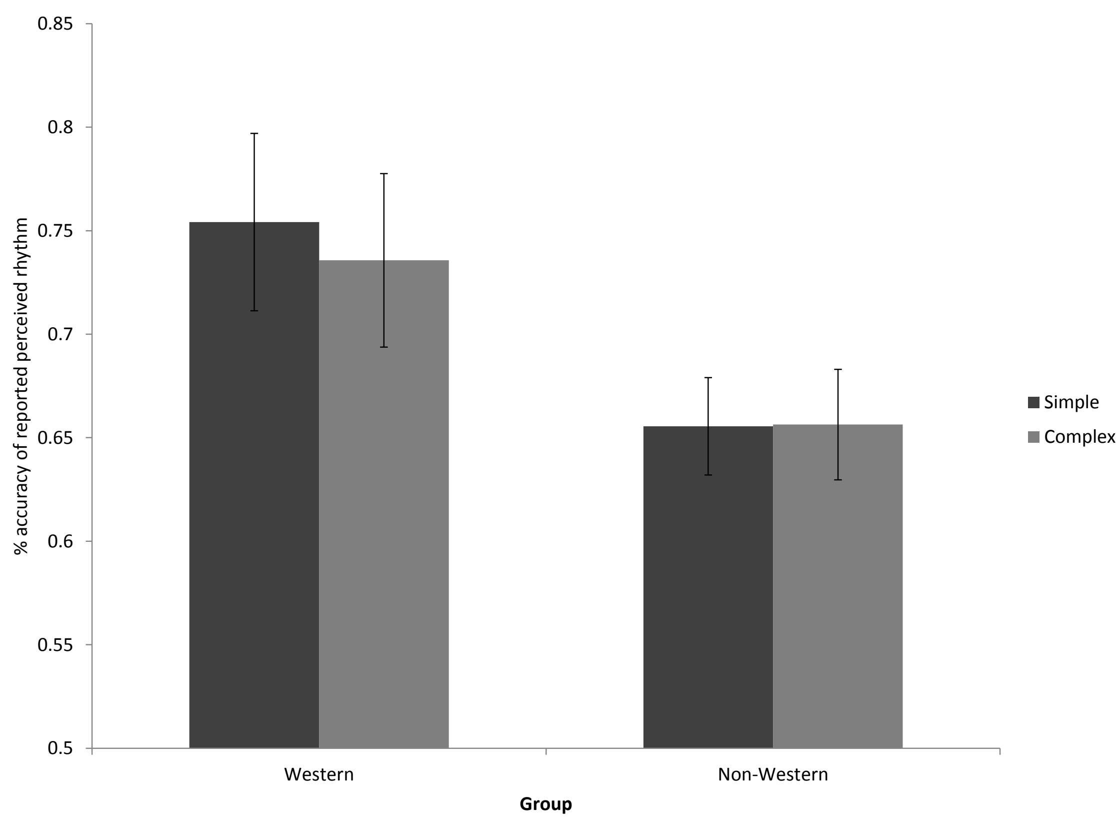


Figure 14: Accuracy for simple and complex meter trials for the Western and Non-Western participants

There was a general trend for the Western group to have higher overall accuracy (*M*=.76, *SD*=.17) than the Non-Western group (M=.66, SD=.11). However, when the accuracy scores were submitted to a 2 x 2 (Meter [simple, complex] within-subjects, x Nationality [Western, Non-Western] between subjects) mixed-design ANOVA, with Music Training (in years) entered as a covariate[1], there was no main effects of Nationality, $F(1,37)=1.24$, $p=.27$, η2=.032. In addition, there were no significant main effects of Music Training, $F(1,37)=2.87$, $p=.10$, $\eta_p^2=.071$ or Meter, $F(1,37)=.002$, $p=.97$, $\eta_p^2<.001$, and no significant interaction between Meter and Nationality, $F(1,37)=.088$, $p=.77$, $\eta_p^2=.002$, but a significant interaction between Music Training and Nationality, $F(1,37)=87.13$, $p<.05$, $\eta_p^2=.25$.

In addition to the measures of accuracy, the behavioral data were used to point to any biases to perceive the rhythms as either SHORT-short-long or LONG-short-short. To do so, the proportions of the given responses for SHORT-short-long vs. LONG-short-short were compared against the induced rhythms (Figure 15).

[1] Because the Western group had significantly more music training than the Non-Western group, this covariate was used to account for any potential effects of music training on the dependent measures.

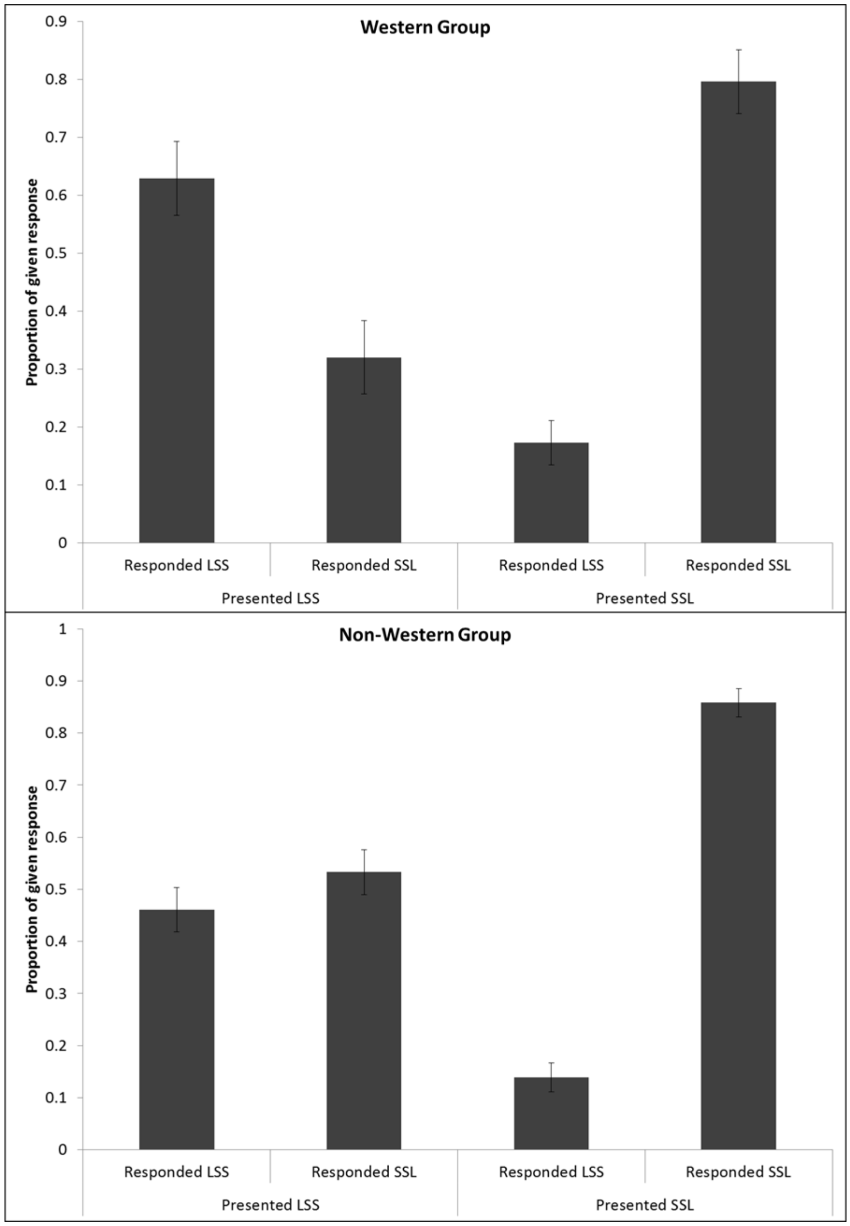


Figure 15: Proportions of each perceived rhythm for different induced rhythms

Overall, participants were more likely to report perceiving the rhythm as SHORT-short-long (roughly 63% of the time). Paired-sample t-tests performed separately for the proportion of SHORT-short-long responses over each group indicated that this bias to perceive the rhythms in the SHORT-short-long pattern existed for both groups: Western group, $t(19)=2.25$, $p<.05$, Non-Western group, $t(19)=7.14$, $p<.001$. These results replicate the general findings from prior studies on rhythmic grouping confirming that when listeners are presented with tones that alternate in duration, the longer sounds tend to mark the end of the group (Woodrow, 1909). Further analyses comparing the proportion of SHORT-short-long responses for the two groups suggested that the bias was stronger for the Non-Western group (M=.70, SD=.12) than the Western group (M=.55, SD=.17; $t(38)=2.99$, $p<.01$).

Effect of Rhythmic Percept on Brain Responses.

Mean Amplitude. Mean amplitudes were averaged across a small number of electrodes where ERP differences were most pronounced for each participant. Based on visual inspection, the central electrodes (Cz, C1, FC1, FCz, FC2, C2, CP1, CPz, and CP2) were averaged. From this, the mean amplitudes were extracted within the time ranges specified in Table 3, to yield an N1 and P2 response over these central electrodes. Brain responses to the TTT0 stimulus were measured separately based on the rhythm in the induction sequence (SHORT-short-long vs. LONG-short-short), further separated by meter (simple vs. complex) and tempo (fast vs. slow). All the mean amplitude comparison figures are presented in Appendix B.

One of the questions was whether participants would continue to perceive the subjective accents even in the absence of physical accents, and whether their ability to perceive these subjective accents was easier immediately following the conclusion of the induction phase. In other words, is there a change in amplitude among the three subsequent measures of the unaccented period?

The mean N1 and P2 amplitudes corresponding to the long interval and the first short interval for each of the three unaccented sections were submitted to separate 2 x 2 x 2 x 3 x 2 x 2 (Meter [simple, complex], within-subjects, x Tempo [fast, slow], within-subjects, x Rhythm [LONG-short-short, SHORT-short-long], within-subjects, x Measure [unaccented 1, unaccented 2, unaccented 3], within-subjects, x Temporal Position [long, short], within-subjects, x Nationality [Western, Non-Western], between subjects) mixed design ANOVAs, with music training as a covariate. There was no main effect of Measure on the N1, $F(2,74)=2.103$, $p=.129$, $\eta_p^2=.054$, or the P2, $F(2,74)=2.208$, $p=.117$, $\eta_p^2=.054$ amplitudes (see Figure 16). That is, unlike in prior studies in the literature (Schaefer, Vlek, & Desain, 2011), there was no change in amplitude with trial progression. Hence, the mean amplitudes were collapsed across the three sections of the unaccented period for subsequent analyses and compared to the accented period.

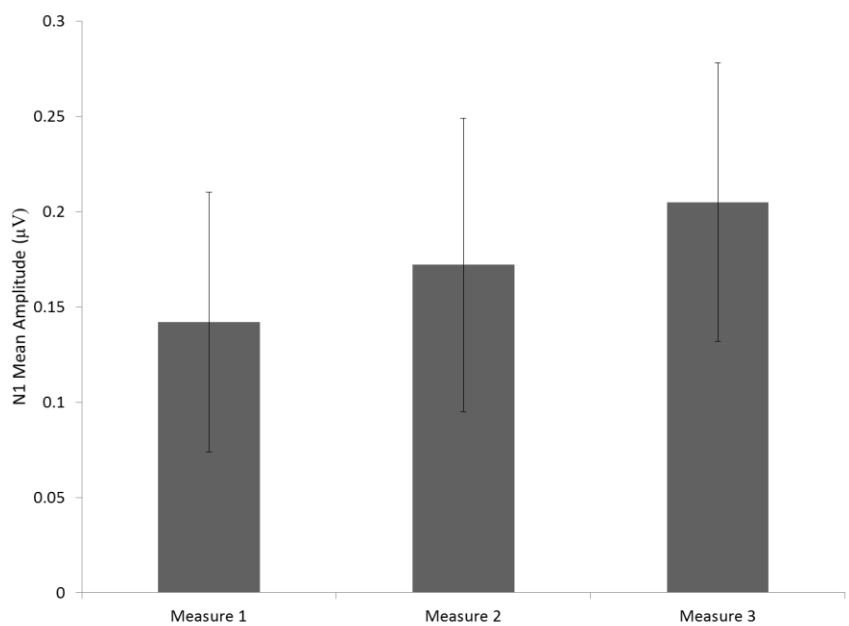


Figure 16: N2 mean amplitudes associated with each measure

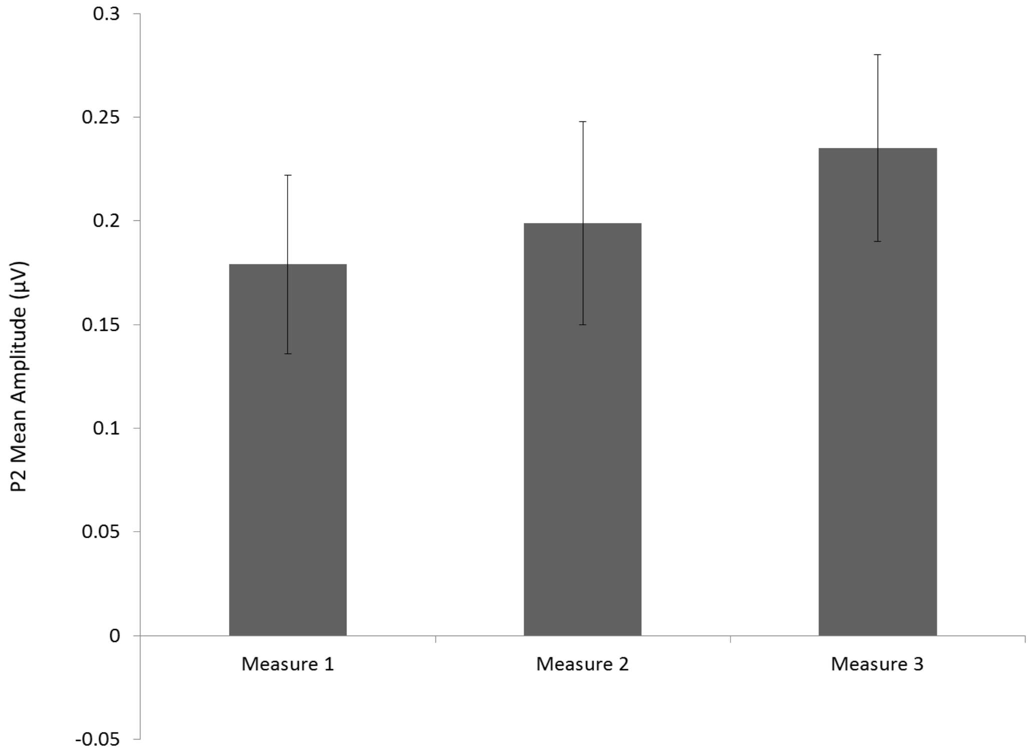


Figure 17: P2 mean amplitudes associated with each measure

The next question was whether there was a difference in amplitude in response to the physical (labelled “accented”) versus subjective accents (labelled “unaccented”). The N1 and P2 mean amplitudes associated with the physically or subjective accented events (long interval in the LONG-short-short rhythms, and short interval in the SHORT-short-long rhythm) were analyzed separately for each induced rhythm, by means of a 2 x 2 x 2 x 2 x 2 (Meter [simple, complex], within-subjects, x Tempo [fast, slow], within-subjects, x Accent [accented, unaccented], within-subjects, x Nationality [Non-Western, Western], between subjects) mixed design ANOVA, with music training as a covariate.

There was a significant main effect of Accent on the N1 and P2 for both the LONG-short-short, [N1: $F(1,37)=31.30$, $p<.001$, $\eta p2=.46$, P2: $F(1,37)=9.04$, $p<.01$,

$\eta_p^{\,2}$=.20] and the SHORT-short-long rhythms, [N1: $F(1,37)=28.97$, $p<.001$, ηp2=.44. P2: $F(1,37)=6.95$, $p<.05$, $\eta_p^{\,2}$=.13]. That is, across both rhythms, physically accented events were associated with larger amplitudes than subjectively accented events (see Figure 18 and Figure 19), replicating findings from prior studies (Schaefer, Vlek, & Desain, 2011).

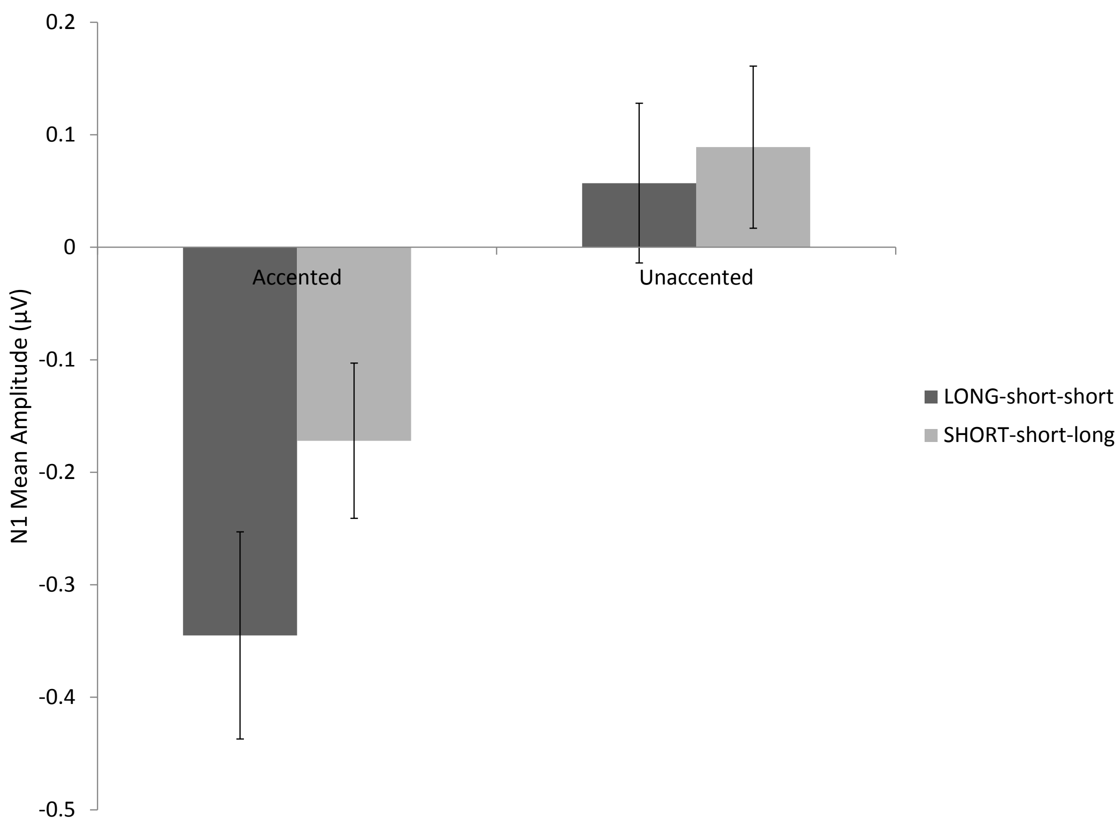


Figure 18: N1 mean amplitudes comparing the physically accented versus subjectively accented events for each rhythm

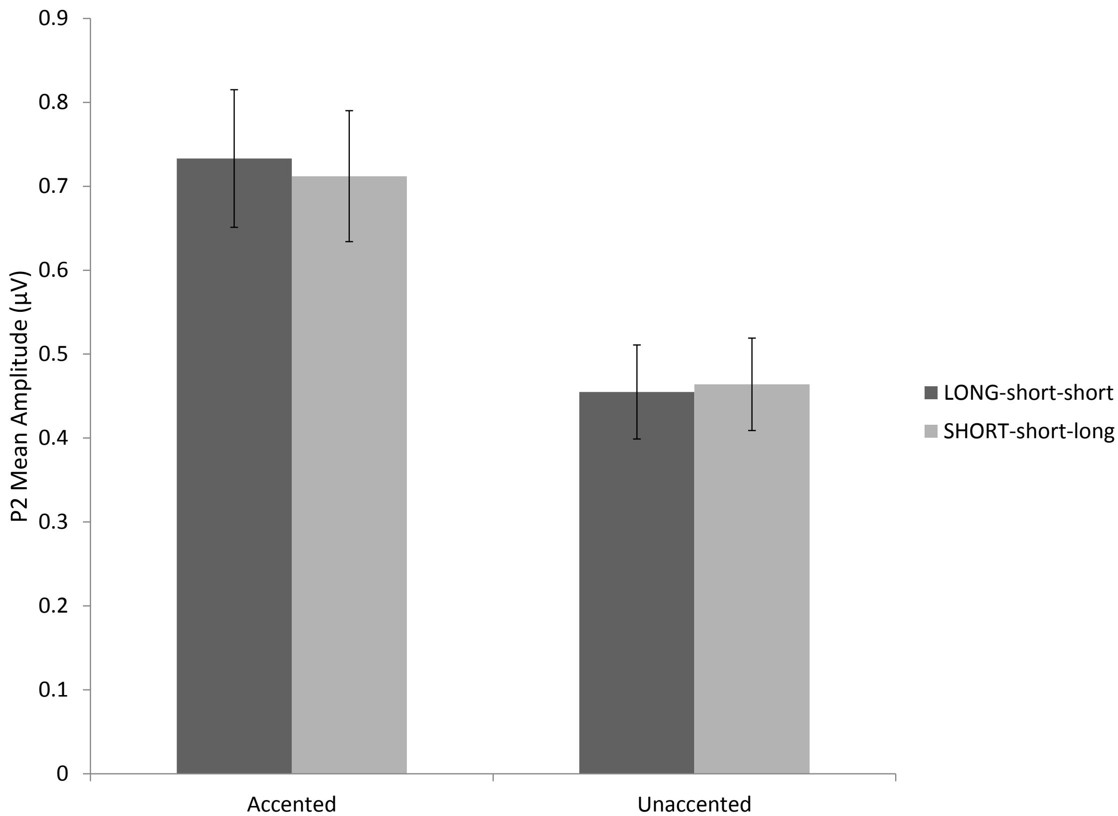


Figure 19: P2 mean amplitudes comparing the physically accented versus subjectively accented events for each rhythm

To examine the pattern of amplitudes associated with the physically accented events, the mean amplitudes for the long and short intervals for the induction sequence were analyzed separately for each rhythm by means of a 2 x 2 x 2 x 2 (Meter [simple, complex], within-subjects, x Tempo [fast, slow], within-subjects, x Temporal Position [long, short], within-subjects, x Nationality [Non-Western, Western], between subjects) mixed design ANOVA, with music training as a covariate. Due to the effect of the physical accents, the start of the long interval should be associated with larger amplitudes than the short interval, in the LONG-short-short rhythm. Likewise, the short interval should be associated with larger amplitudes than the long interval in the SHORT-short-long rhythms.

For the LONG-short-short rhythms, there was a significant main effect of Temporal Position, for both the N1, $F(1,37)= 24.31$, $p<.001$, $\eta_p^2=.40$, and P2, $F(1,37)=20.78$, $p<.001$, $\eta_p^2=.36$, amplitudes, with significantly larger amplitudes associated with the start of the long (physically accented) interval. Likewise, for the SHORT-short-long rhythms, there was a significant main effect of Temporal Position, for both the N1, $F(1,37)= 3.76$, $p<.05$, $\eta_p^2=.10$, and P2, $F(1,37)= 32.83$, $p<.001$, $\eta_p^2=.36$, amplitudes, with significantly larger amplitudes associated with the start of the short interval. That is, across both rhythms, when a tone was physically accented, it was associated with larger amplitudes than when it was unaccented, as seen in Figure 20 and 21.

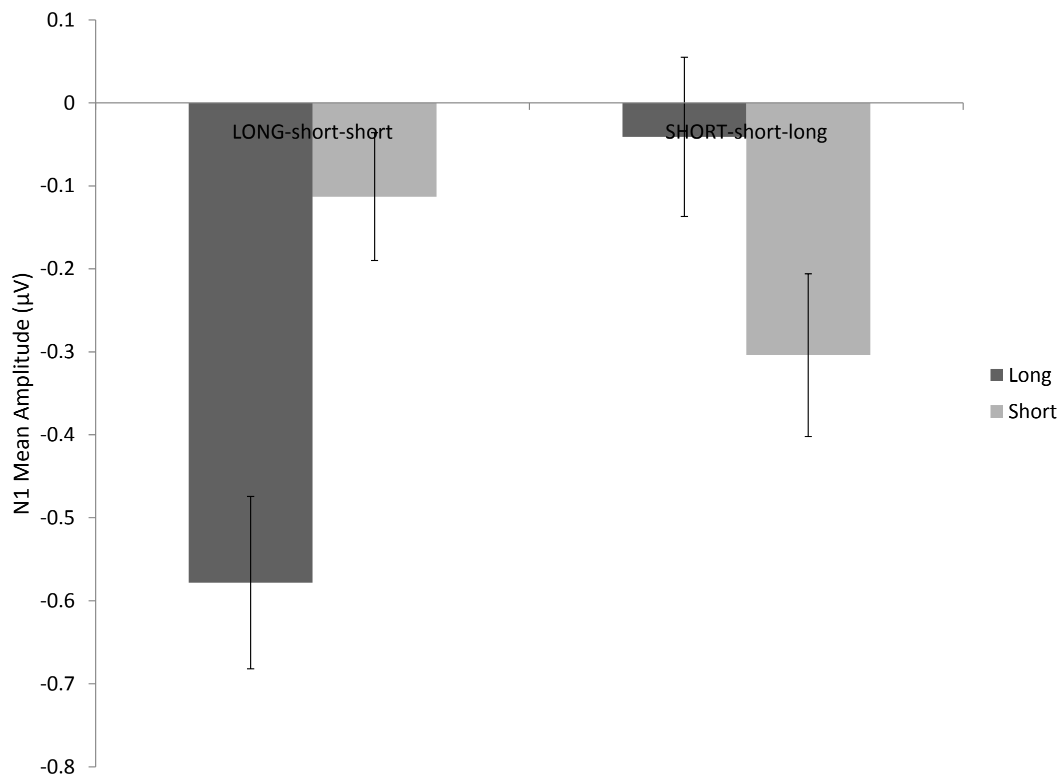


Figure 20: N1 amplitudes for the accented versus unaccented events in the physically accented section. The long interval in the LONG-short-short rhythm and the short interval in the SHORT-short-long rhythm are accented.

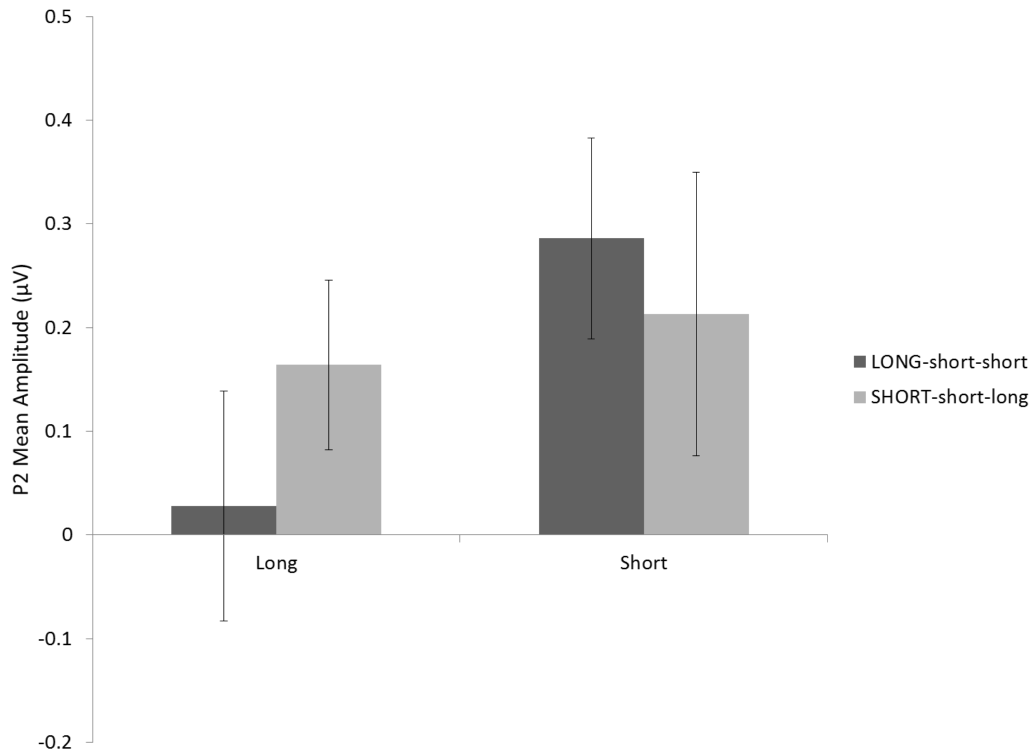


Figure 21: P2 amplitudes for the accented versus unaccented events in the physically accented section. The long interval in the LONG-short-short rhythm and the short interval in the SHORT-short-long rhythm are accented.

Based on prior studies (Iversen, Repp, & Patel, 2009; Schaefer, Vlek, & Desain, 2011), when a tone is merely imagined to be the beat, it should still lead to comparable increases in N1 and P2 amplitudes. Thus, the next question assessed the role of subjective accents on the N1 and P2 mean amplitudes for the unaccented period. Since the unaccented periods themselves are identical across both rhythms, any difference in amplitude should be driven by the perception of subjective accents. Thus, the long interval in the LONG-short-short rhythm, and the short interval in the SHORT-short-long rhythm, should have the perceived accent, and therefore, a corresponding increase in amplitude, similar to that observed with the physical accents.

The mean amplitudes for the unaccented period were analyzed separately for each rhythm by means of a 2 x 2 x 2 x 2 (Meter [simple, complex], within-subjects, x Tempo [fast, slow], within-subjects, x Temporal Position [long, short], within-subjects, x Nationality [Non-Western, Western], between subjects) mixed design ANOVA, with music training as a covariate. For the SHORT-short-long rhythms, there was a main effect of Temporal Position on the N1, $F(1,37)= 7.07$, $p<.05$, $\eta_p^2=.16$, and the P2, $F(1,37)= 20.47$, $p<.001$, $\eta_p^2=.36$ amplitudes, with the short (subjectively accented) interval associated with larger amplitudes than the long interval, as expected. For the LONG-short-short rhythm, there was a main effect of Temporal Position, for both the N1, $F(1,37)= 5.80$, $p<.05$, $\eta_p^2=.14$, and P2, $F(1,37)= 20.47$, $p<.001$, $\eta_p^2=.36$, amplitudes. However, contrary to expectation, while the subjective accents should have been perceived at the start of the long interval, larger amplitudes were associated with the short (subjectively unaccented) interval than the long interval (see Figure 22 and 23). This is also evident in the mean amplitude figures in Appendix B, with larger N1 and P2 responses following the start of the short intervals.

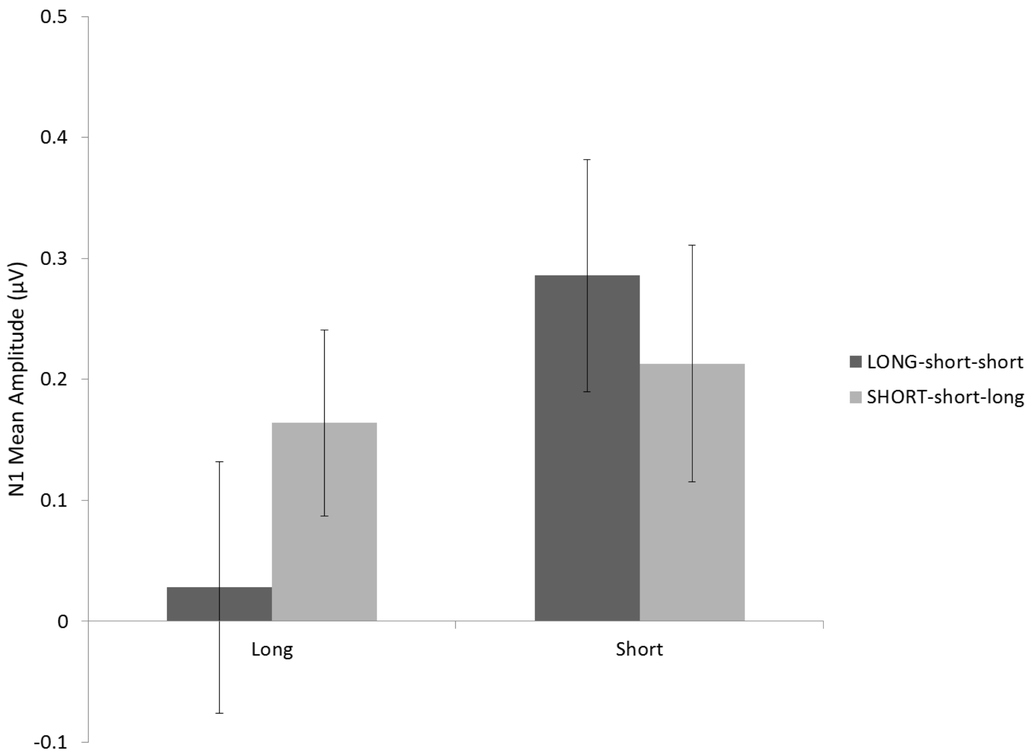


Figure 22: N1 amplitudes for the subjectively accented versus unaccented events. The long interval in the LONG-short-short rhythm and the short interval in the SHORT-short-long rhythm are subjectively accented.

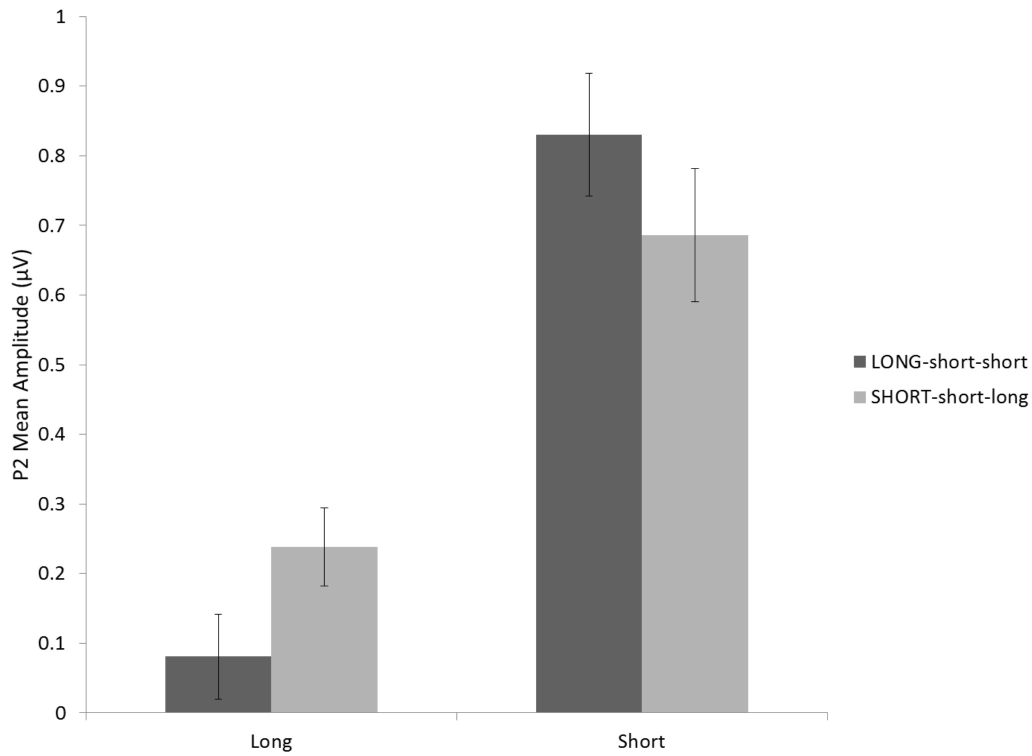


Figure 23: P2 amplitudes for the subjectively accented versus unaccented events. The long interval in the LONG-short-short rhythm and the short interval in the SHORT-short-long rhythm are subjectively accented.

The most obvious explanation for this is the decrease in response to successive identical tones due to adaptation (Budd, Barry, Gordon, Rennie, & Michie, 1998; Grill-Spector, Henson, & Martin, 2006). Specifically, in any TTT0 rhythm, the first tone following the long interval should have maximal response, followed by a decline in response to successive (identical tones). In the analysis of brain responses, only the “correct” trials from the behavioral responses (i.e., listeners’ report of perceived rhythm matched induced rhythm) were used. Thus, the larger amplitude at the start of the short interval occurred even when listeners actually reported perceiving the beat at the start of the long interval. This explanation likely accounts for some of this response. Further, this might account for the trend in the behavioral data which suggested that once the physical accents are removed, participants were more likely to perceive the rhythms as being SHORT-short-long, regardless of what the induced rhythm was.

The next question assessed whether this effect differed based on metrical complexity. That is, are accented events associated with larger amplitudes regardless of metrical complexity? To answer this question, the N1 and P2 amplitudes in response to the accented events were compared across both meters, separately for physically accented and subjectively accented events by submitted the amplitude data to a 2 x 2 x 2 x 2 (Meter [simple, complex], within-subjects, x Tempo [fast, slow], within-subjects, x Rhythm [LONG-short-short, SHORT-short-long], within-subjects, x Nationality [Non-Western, Western], between subjects) mixed design ANOVA, with music training as a covariate. Specifically, the N1 and P2 amplitudes in response to the long interval in the LONG-short-short and to the short interval in the SHORT-short-long were used.

In response to the physical accents, there were larger N1 amplitudes in the simple meter condition, as evidenced by a significant main effect of Meter, $F(1,37)=5.22$, $p<.05$, $\eta_p^2=.12$. However, there was no Meter X Group interaction, $F(1,37)=.39$, $p=.54$, $\eta_p^2=.010$, suggesting that the effect was not moderated by culture-specific experience with simple meters. There was no effect of meter on the P2 amplitudes, in response to physical accents, $F(1,37)=.049$, $p=.83$, $\eta_p^2=.001$.

In response to the subjective accents, however, the trends were quite different. Namely, there was still a significant main effect of Meter on the N1, $F(1,37)=6.16$, $p<.05$, $\eta_p^2=.14$, amplitudes and no significant effect on the P2 amplitudes, $F(1,37)=2.17$, $p=.081$, $\eta_p^2=.08$, or significant Meter X Group interactions on the ERP amplitudes [N1: $F(1,37)=.041$, $p=.84$, $\eta_p^2=.001$; P2: $F(1,37)=3.18$, $p=.082$, $\eta_p^2=.79$]. However, unlike with the physical accents, the subjective accents in the simple meter trials were associated with *smaller* N1 amplitudes than the subjective accents in the complex meter trials. The effects of physical and subjective accents on mean amplitudes are summarized in Figures 24 and 25.

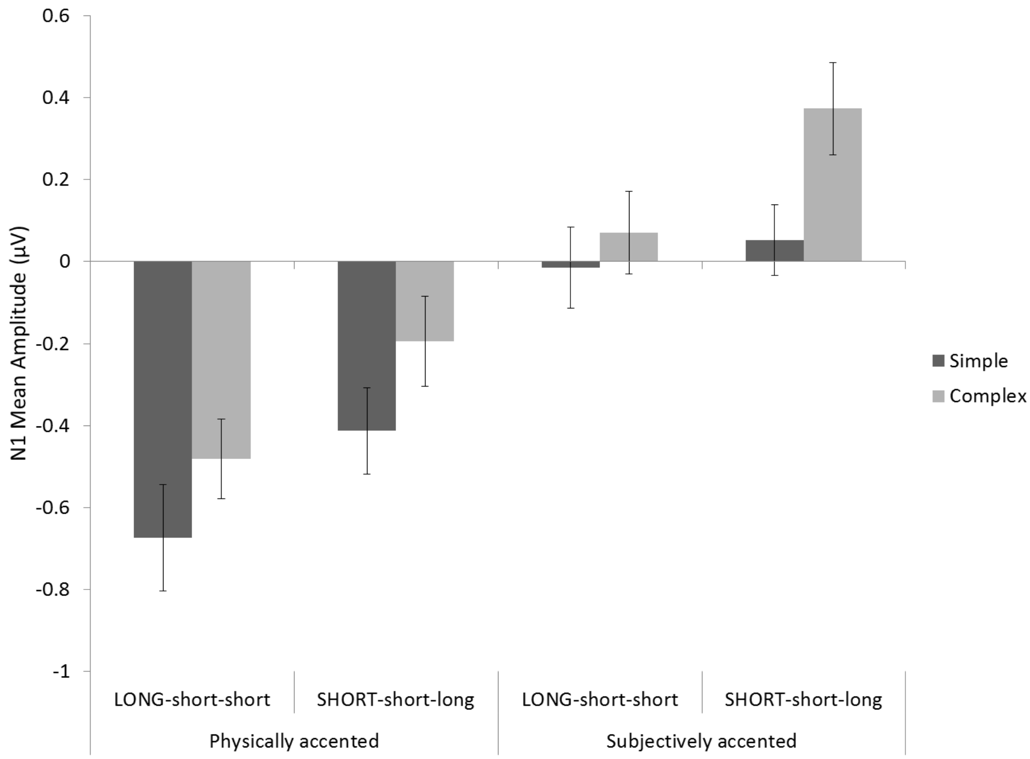


Figure 24: Mean N1 amplitudes for the physically accented and subjectively accented events for each rhythm, compared across simple and complex meters

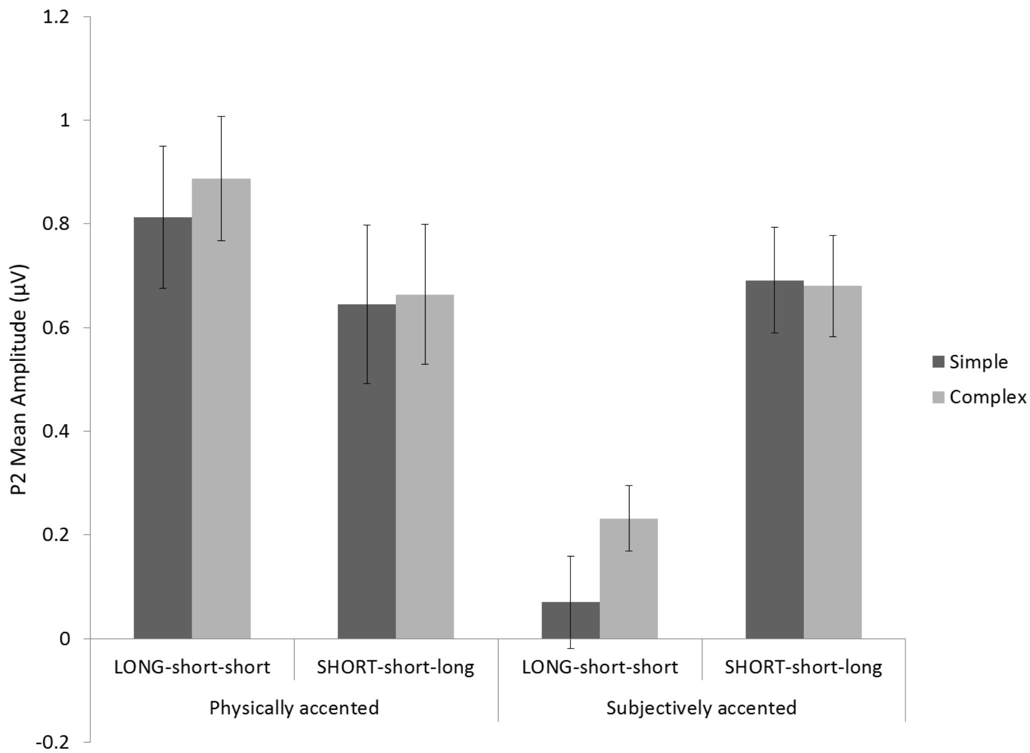


Figure 25: Mean P2 amplitudes for the physically accented and subjectively accented events for each rhythm, compared across simple and complex meters

Overall, there were some important trends within the N1 and P2 mean amplitude data. Firstly, the N1 and P2 amplitudes showed an effect of physical accents, with the physically accented section producing larger amplitudes, replicating findings from earlier studies (Schaefer, Vlek, & Desain, 2011). Further, they showed rhythm-specific patterns of activation, such that for the LONG-short-short rhythms, the start of the long (physically accented) interval was associated with larger amplitudes, and for the SHORT-short-long rhythms, the start of the short interval was associated with larger amplitudes.

Surprisingly, there was no change in amplitude through the course of a trial, with the first unaccented events showing no difference from the last unaccented events. This suggests that participants were proficient at imagining the accents through the entire course of the trial (irrespective of whether the position of the accent was what was implied based on the physical accents in the induction sequence). This stands in contrast to other studies (Iversen, Repp, & Patel, 2009; Schaefer, Vlek, & Desain, 2011) which reported that the first unaccented event was more like an accented event than the last unaccented event.

In terms of continuing to perceive the accents in the absence of physical accents, the N1 and P2 responses were larger at the start of the short interval, regardless of the actual induced rhythm. This replicates the behavioral findings, which showed that listeners were biased to report that they perceived the rhythms as being SHORT-short-long.

Another important question was the extent to which perception of these rhythms, and in particular, the ability to continue to perceive the subjective accents, was determined by metrical complexity. The results from this study revealed some novel findings. Firstly, when the beat was physically accented, the associated N1 responses were larger in the simple meter condition, than in the complex meter condition. In contrast, when the beat was only imagined to be the beat, the associated N1 responses were larger in the complex meter condition.

Prior studies have shown that *attending* to a stimulus at a certain point in time yields *enhancement* of the N1 response (Hillyard, Hink, Schwent, & Picton, 1973; Lange, Kramer, & Roder, 2006; Lange, Rosler, & Roder, 2003). It has been argued that this evidence supports the sensory gating mechanism for attention, with selective inhibition of unattended stimuli (Hillyard, 1981; Hillyard, Hink, Schwent, & Picton, 1973).

On the other hand, *prediction* has been shown to *suppress* the N1 response (Lange, 2013). For instance, when participants knew when an auditory stimulus was going to occur, ther resulting N1 response had significantly smaller amplitude than when participants did not know the timing of the stimulus (Lange, 2009; Schafer, Amochaev, & Russell, 1981). In perceiving a rhythmic stimulus, bottom-up sensory information is compared to top-down predictive information. With improving prediction, the sensory information will match the top-down predictive information, which has been shown to yield a smaller "error signal", and a suppressed N1 response (Baldeweg, 2007).

This distinction between attention and prediction (see Lange, 2013 for review) and their contrasting effects on the N1 amplitudes, can perhaps be used to explain the findings from the present study. Namely, there was presumably greater attention being drawn to the accented tones in the simple meter condition, yielding larger N1 responses. This argument is also supported by the dynamic attending theory which postulates that selective enhancement of neuronal activity allow the listener to form expectations about the occurrence of the beat (Jones & Boltz, 1989). Besides being physically accented, the induction sequence was also at the start of each trial. Thus, while there was greater attention, it is possible that the short induction sequence was not sufficient to allow the listener to reliably predict the location of the beat. As the trial progresses, the listener is better able to make predictions about the occurrence of the beat, yielding smaller error signals, and suppressed N1 responses. Thus, while attention and prediction are described as opposing processes, it is likely that they merely occur at different points in processing: with greater attention yielding better prediction, in a rhythmic, predictable stimulus.

Unexpectedly, however, these findings did not differ based on listeners' experience with complex meters. One of the possibilities is that simple and complex meters are processed differently, even by those to whom they are familiar. Certainly a large corpus of evidence supports this theory. For instance, even in a culture where complex meters are common, individuals have difficulty processing highly complex metrical ratios (Hannon, Soley & Ullal, 2012). Likewise, whereas infants can detect disruptions in some complex meters just as well as they can with simple meters, they too show difficulty in processing highly complex (egg: 4:7 ratio) meters.

Oscillatory Responses. Time frequency data were analyzed to study stimulus-driven oscillatory synchronization, for the gamma (35-50 Hz) frequency range, over the central electrodes. This specific frequency range was selected based both on prior literature (Iversen, Repp, & Patel, 2009), and from the visual inspection of brain responses which showed a peak of activity centered around this frequency range, which corresponded to the onset of the three tones: long, short1 and short2. The time frequency representations were analyzed for both evoked and induced activity. Averaged evoked and induced activity figures are depicted in Appendix C and Appendix D respectively.

Similar to the analyses on the mean amplitude data, the unaccented period was analyzed in three separate sections ("Measures"), in order to observe any possible differences in activity within each trial. The evoked and induced time frequency data were separately submitted to 3 x 2 x 2 x 2 x 2 x 2 x 2 (Meter [simple, complex] within-subjects, x Tempo [slow, fast] within-subjects, x Rhythm [SHORT-short-long, LONG-short-short] within-subjects, x Measure [1, 2, 3], within-subjects, x Temporal Position [long, short] within-subjects, x Nationality [Western, Non-Western] between subjects) mixed-design ANOVAs, with Music Training (in years) entered as a covariate. As depicted in Figure 26 and 27, neither the evoked, nor the induced gamma band activity showed significant main effects of Measure [Evoked: $F(2,74)=.388$, $p=.680$, $\eta_p^2=.010$;

Induced: $F(2,74)=1.92$, $p=.154$, $\eta_p^2=.049$]. Thus, the three sections of the unaccented portion were combined.

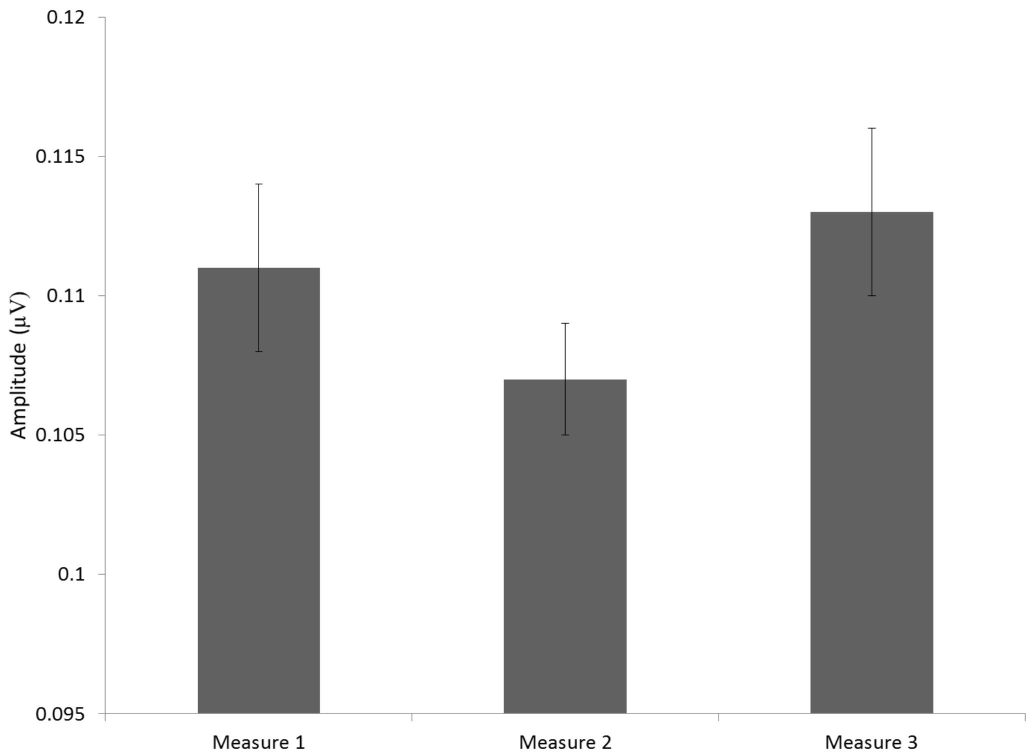


Figure 26: Evoked activity for each measure

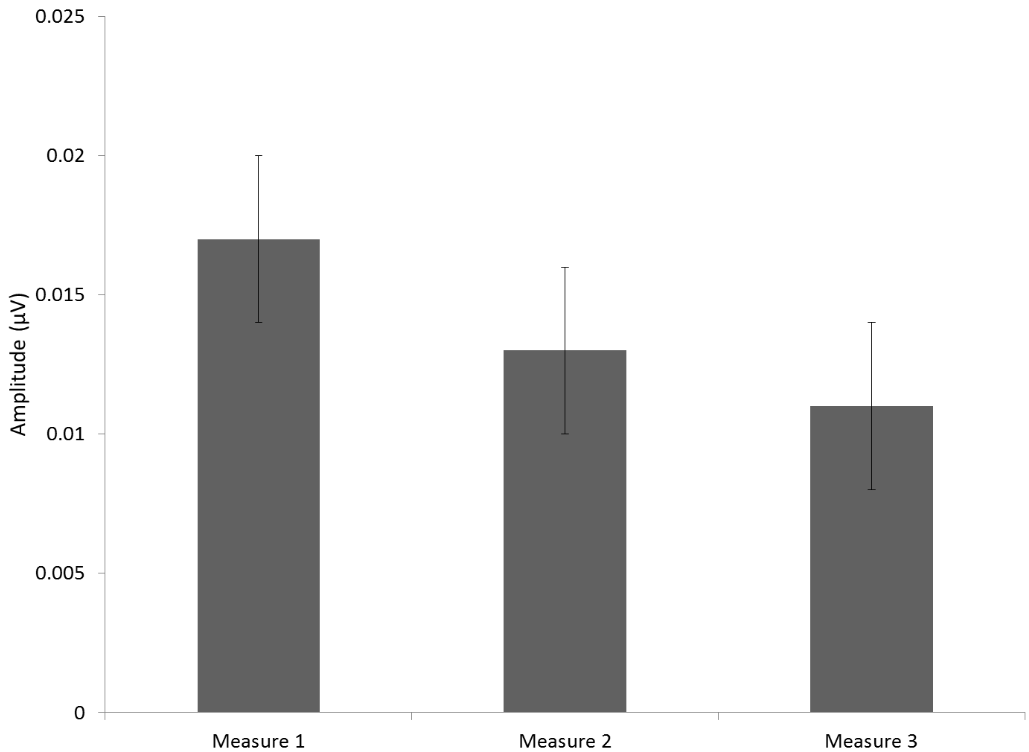


Figure 27: Induced activity for each measure

Next, to assess the effect of physical accents versus subjectively, the evoked and induced activity in response to the physical accents were compared to that of the average unaccented period separately for each rhythm by means of 2 x 2 x 2 x 2 x 2 (Meter [simple, complex], within-subjects, x Tempo [fast, slow], within-subjects, x Accent [accented, unaccented], within-subjects, x Nationality [Non-Western, Western], between subjects) mixed design ANOVA, with music training as a covariate. There was no effects of physical accented for either of the rhythms in the evoked [LONG-short-short: $F(1,39)=.28$, $p=.60$, $\eta_p^2=.007$; SHORT-short-long: $F(1,39)=.38$, $p=.54$, $\eta_p^2=.01$] or induced [LONG-short-short: $F(1,39)=.21$, $p=.65$, $\eta_p^2=.006$; SHORT-short-long: $F(1,39)=.008$, $p=.93$, $\eta_p^2<.001$] gamma band activity (see Figure 28 and Figure 29). That is, the induced and evoked activity did not differ as a consequence of physical accents, contrary to predictions based on prior research (Iversen, Repp, & Patel, 2009).

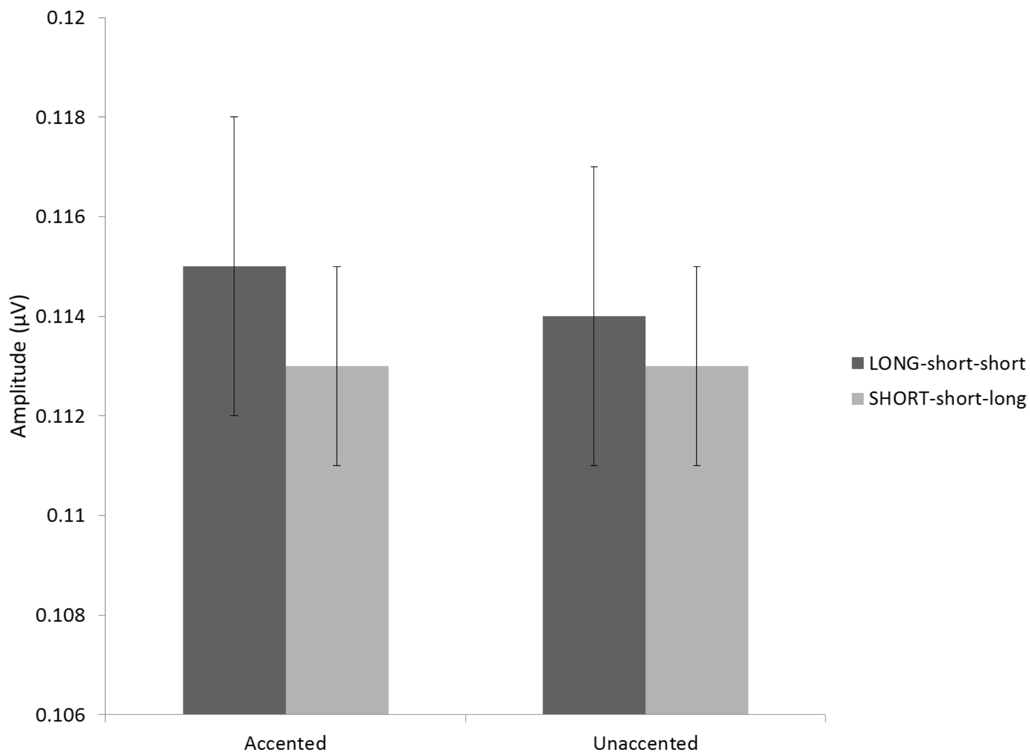


Figure 28: Evoked activity for the physically accented and unaccented (subjectively accented) events for each rhythm

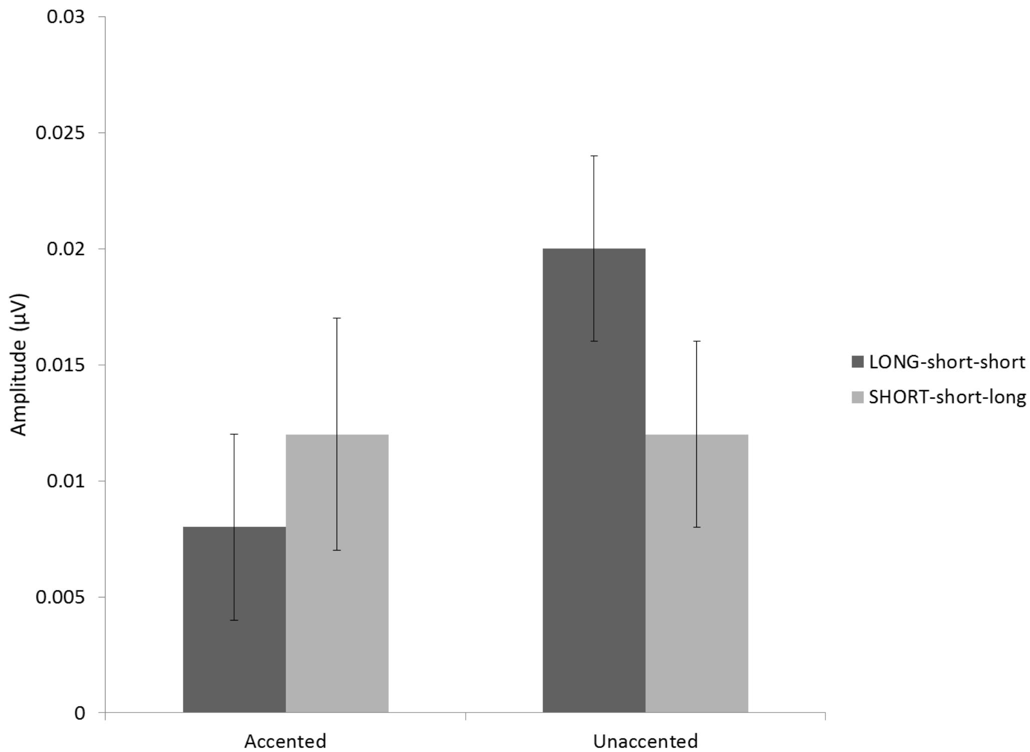


Figure 29: Induced activity for the physically accented and unaccented (subjectively accented) events for each rhythm

Next, to examine the pattern of induced and evoked activity in response to subjective accents, the long and short intervals for the induction sequence were analyzed separately for each rhythm by means of a 2 x 2 x 2 x 2 (Meter [simple, complex], within-subjects, x Tempo [fast, slow], within-subjects, x Temporal Position [long, short], within-subjects, x Nationality [Non-Western, Western], between subjects) mixed design ANOVA, with music training as a covariate.

There was no effect of temporal position on either the evoked or the induced data. That is, despite the physical accent being present at the start of the long interval in the LONG-short-short rhythms, and at the start of the short interval in the SHORT-short-long rhythms, there was no significant difference in activity between the start of the long versus the short interval in either of the rhythms [LONG-short-short – evoked:

$F(1,39)=2.92$, $p=.095$, $\eta_p^2=.068$; SHORT-short-long – evoked: $F(1,39)=2.43$, $p=.13$, $\eta_p^2=.057$; LONG-short-short – induced: $F(1,39)=3.99$, $p=.053$, $\eta_p^2=.093$; SHORT-short-long – induced: $F(1,39)=3.21$, $p=.081$, $\eta_p^2=.076$], as seen in Figures 30 and 31.

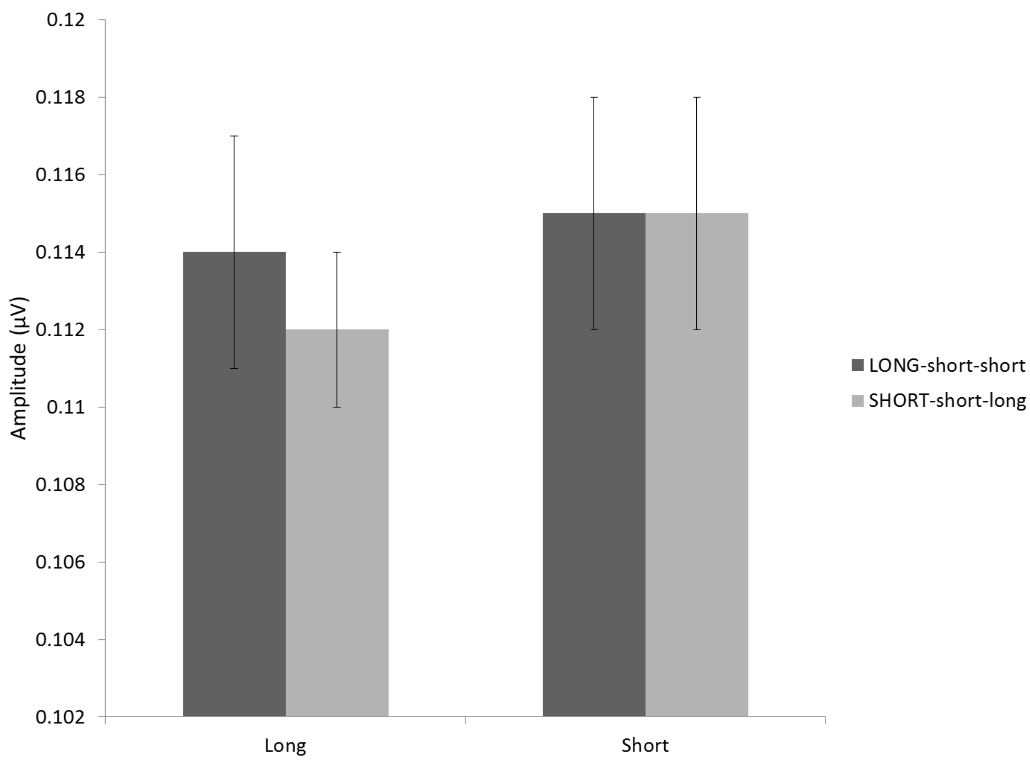


Figure 30: Evoked activity for the physically accented versus unaccented events. The long interval in the LONG-short-short rhythm and the short interval in the SHORT-short-long rhythm are accented.

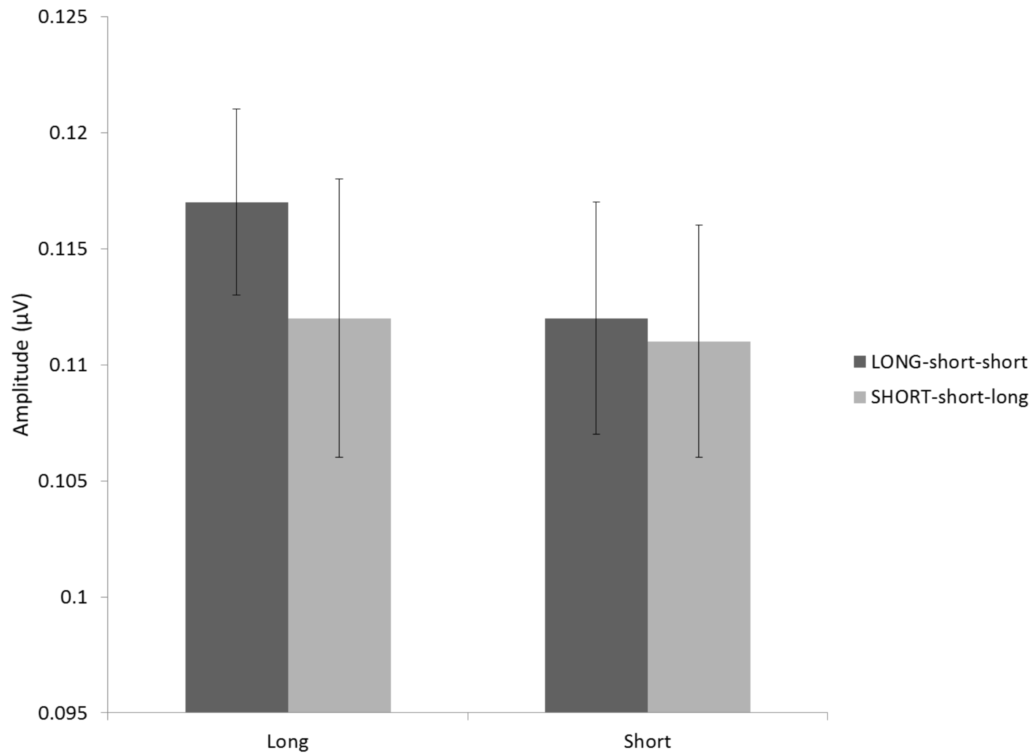


Figure 31: Induced activity for the physically accented versus unaccented events. The long interval in the LONG-short-short rhythm and the short interval in the SHORT-short-long rhythm are accented.

Similar to the effects of physical accents, there was no significant difference between the subjectively accented and subjectively unaccented tones on the evoked, $F(1,39)=2.02$, $p=.16$, $\eta_p^2=.048$, or induced, $F(1,39)=3.82$, $p=.058$, $\eta_p^2=.087$ gamma responses. That is, the start of the subjective accented interval showed no significant difference from the subjectively unaccented interval (See Figure 32 and Figure 33).

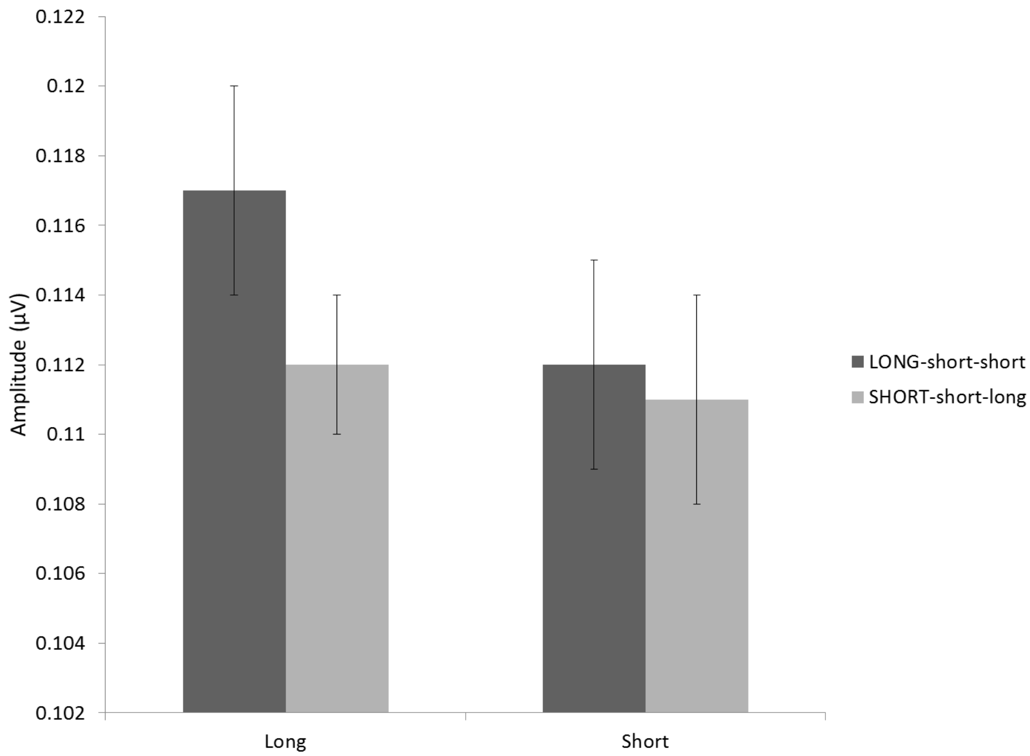


Figure 32: Evoked activity for the subjectively accented versus unaccented events. The long interval in the LONG-short-short rhythm and the short interval in the SHORT-short-long rhythm are accented.

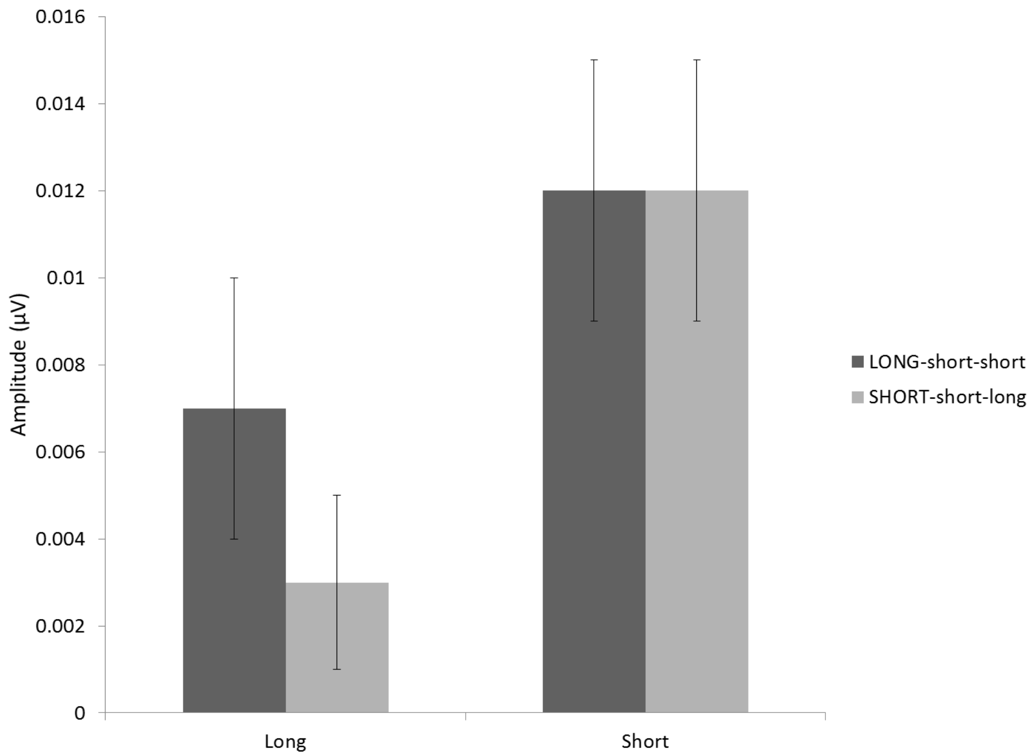


Figure 33: Induced activity for the subjectively accented versus unaccented events. The long interval in the LONG-short-short rhythm and the short interval in the SHORT-short-long rhythm are accented.

Finally, to answer the central question, namely, the effect of metrical complexity on oscillatory responses, the induced and evoked gamma band data were submitted to a 2 x 2 x 2 x 2 (Meter [simple, complex], within-subjects, x Tempo [fast, slow], within-subjects, x Rhythm [LONG-short-short, SHORT-short-long], within-subjects, x Nationality [Non-Western, Western], between subjects) mixed design ANOVA, with music training as a covariate, separately for the physical accents and subjective accents. In response to the physical affects, there was no significant main effect of Meter on evoked, $F(1,37)=.068$, $p=.79$, $\eta_p^2=.002$, or induced, $F(1,37)=.020$, $p=.89$, $\eta_p^2=.001$, activity. There was also no Meter X Group interaction on either the evoked,

$F(1,37)=.016$, $p=.90$, $\eta_p^2<.001$, or induced, $F(1,37)=.67$, $p=.42$, $\eta_p^2=.018$, gamma band activity.

Findings were similar in response to subjective accents. That is, there was no significant main effect of Meter on either the evoked, $F(1,37)=2.91$, $p=.096$, $\eta_p^2=.073$, or induced, $F(1,37)=3.38$, $p=.074$, $\eta_p^2=.084$, gamma band activity. Likewise, there was no significant Meter X Group interaction on either the evoked, $F(1,37)=.028$, $p=.87$, $\eta_p^2=.001$, or induced, $F(1,37)=.51$, $p=.48$, $\eta_p^2=.014$, gamma band activity (see Figure 34 and Figure 35).

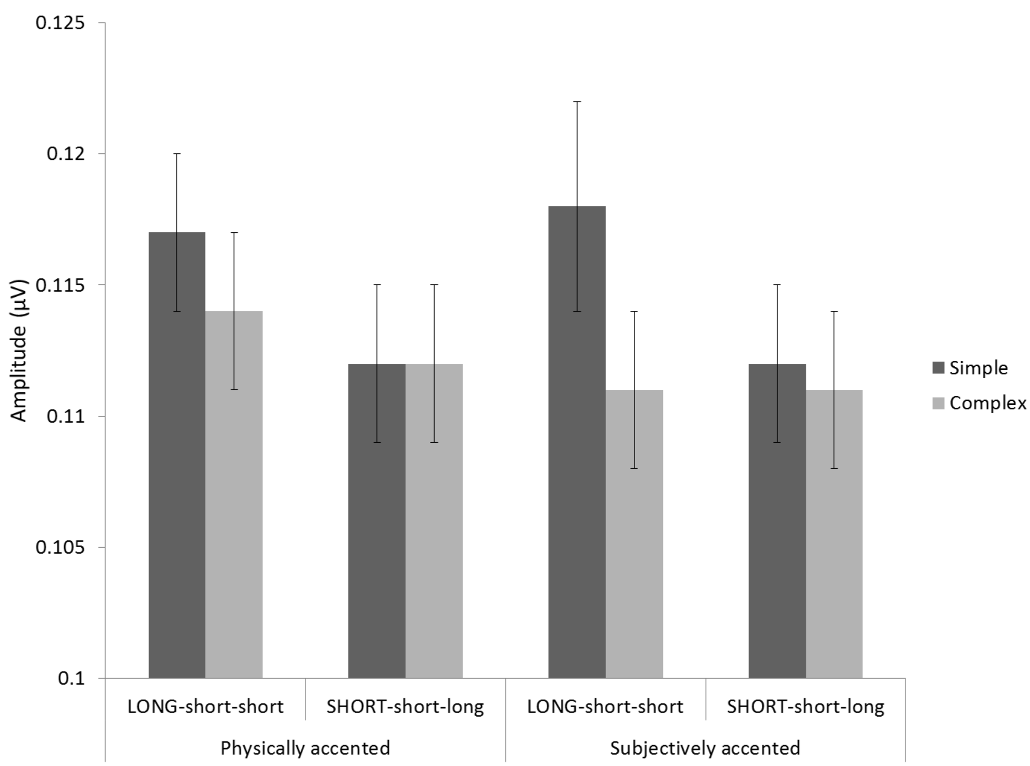


Figure 34: Evoked activity for the physically accented and subjectively accented events for each rhythm, compared across simple and complex meters

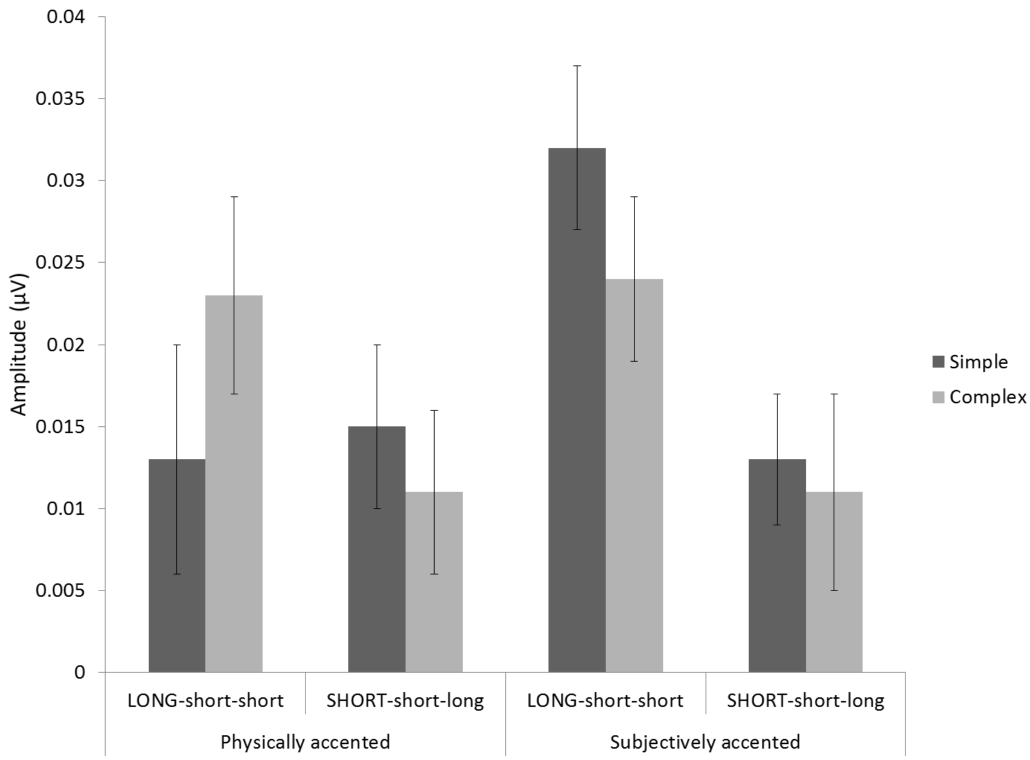


Figure 35: Induced activity for the physically accented and subjectively accented events for each rhythm, compared across simple and complex meters

Discussion

The present study used an ambiguous rhythm which could be interpreted differently by imagining a subjective accent on one of two locations. The goal of the study was to examine how the top-down interpretation of the different rhythms coupled with prior experience with meters of varying complexity drives neural response, by means of event related potentials, and evoked and induced oscillatory responses.

The early ERP responses showed an increase in N1 and P2 amplitudes when a tone was physically accented. Subjective accents were expected to cause a similar increase in amplitude, with larger amplitudes associated with the tones imagined to be the beats. Instead, results revealed a bias to perceive the beat at the start of the short interval (thus perceiving the rhythm as SHORT-short-long), regardless of the actual induced rhythm. There are two possible theories for this result. Firstly, it has been noted that when listeners are presented with a sequence of durations, the long durations tend to mark the end of sequences (Woodrow, 1909). Secondly, with successive identical tones, there is a decline in neural activity. Given the repeating sequence of tones, organized as TTT0, the second and third tones should presumably cause a decline in activity, being identical to the first tone.

The next set of analyses measured oscillatory activity in response to rhythm perception. Evoked gamma band responses typically have been shown to follow tone onsets, whereas induced gamma band responses precede them, suggesting anticipatory activity. In the present study, the beats in the rhythm modulated oscillations in the gamma frequency range, with a clear increase in evoked gamma amplitude in response to tone onsets. However, there was no difference in evoked gamma responses between physical and imagined accents. Further, there was no difference in the gamma band responses as a factor of rhythmic percept. One possible explanation for this is that there are two different mechanisms for subjective accents in place. Firstly, there are the accents induced by the initial induction phase, which should be expected to cause stronger gamma on the accented tone (long in the LONG-short-short and short in the SHORT-short-long). Secondly, there are the effects of grouping, which should be expected to cause stronger gamma at the start of the first short interval, regardless of the induced rhythm. Thus, it is plausible that the size of the gamma enhancement caused by the induction phase is cancelled out by the gamma enhancement caused by the grouping effect.

Beyond the phase-locked evoked gamma band activity, prior studies have found that non phase-locked induced gamma activity precedes tone onset, and occurs even with tone omission (Snyder & Large, 2005), and has been theorized to be related to anticipation and attention (Sokolov, Pavlova, Lutzenberger, & Birbaumer, 2004; Zanto, Large, Fuchs, & Kelso, 2005). In addition, it has been theorized that when tones occur at a time of maximal induced activity, there is a larger evoked response following the tone, presumably due to a larger group of responsive neurons (Iversen, Repp, & Patel, 2009). In the present study, however, there was no evidence of induced gamma responses in any of the conditions. One possible explanation for this is that induced gamma band activity has been shown to be modulated by music training, and by specific auditory experience (Shahin, Roberts, Chau, Trainor, & Miller, 2008). Additionally, listeners might have adopted different listening strategies during the task, increasing variability among participants.

Another unexpected lack of finding is the absence of oscillatory activity in the high beta 20-30 Hz range, as observed in earlier studies (Iversen, Repp, & Patel, 2009). Beta band activity has been linked to movement, such as while tapping with a beat (Boonstra, Daffertshofer, Peper, & Beek, 2006; Thaut, 2003), even in the absence of overt movement (Schnitzler, Salenius, Salmelin, et al, 1997). However, unlike in the current study, the Iversen, Repp, & Patel, 2009 study tested participants that all had experience in musical performance. Thus, it is very likely that they were activating motor imagery in a way that the non-musician participants in the present study were not.

The next question assessed the role of metrical complexity in beat perception, and the extent to which prior experience with these meters modulated the response. The N1 amplitude showed contrasting effects of meter through the course of a trial. In the presence of physical accents, the N1 amplitude was larger for the simple meter trials than the complex meter trials. In contrast, with the subjective accents, the simple meter trials showed a smaller N1 response to the beat that the complex meter trials. The most likely explanation for this is that listeners are diverting greater attention to the beat location in the simple meter trials, yielding greater predictability (lower error) as the trial progresses. In contrast, there is diminished attention and anticipation at the beat location in the more difficult, complex meter trials. There were no between group differences observed.

Taken together, the study highlighted the role of physical accents and subjective accents, as listeners imagine the beat at different locations, perceiving an ambiguous rhythm in different ways. Early evoked potentials pointed to the effect of an initial induction phase, and of the effects of grouping, in perceiving rhythms. Oscillatory gamma responses, on the other hand, appeared to occur equally on all tones, and were not modulated by physical or subjective accents. Overall, this study points to the different factors that shape perception: ranging from exogenous factors such as grouping, durational contrasts, and intensity accents, to endogeous factors such as imagined accents and metrical interpretation.

CHAPTER 4

General Discussion

Every known culture around the world makes and listens to music. But our ability to parse the sequences of durations in music has been known to be affected by various factors. Western "simple" musical meters are dominated by an even, or isochronous, beat that can be subdivided or multiplied by simple integers such as 2:1. In contrast, non-isochronous, "complex", meters are composed of a non-isochronous pattern of alternating long and short durations, such as 3:2. One of the theories in music research is that these complex meters are more difficult to perceive (Clarke, 1987; Desain & Honing, 2003; Fraisse, 1982; Repp, London, & Keller, 2008) and produce (Collier & Wright, 1995; Povel, 1981; Repp, London, & Keller, 2005; Repp, London, & Keller, 2008; Repp, London, & Keller, 2010; Snyder, Hannon, Large, & Christiansen, 2006; Summers, Bell, & Burns, 1989; Summers, Hawkins, & Mayers, 1986). However, these complex meters are common in music throughout South Asia, Africa, the Middle East, and Eastern Europe (London, 1995; Rice, 1995; Singer, 1973), and listeners from the cultures are equally adept at processing both simple and complex meters (Hannon & Trehub, 2005a; 2005b; Kalendar, Trehub, & Schellenberg, 2013; Ullal-Gupta, Hannon, & Snyder, 2014). While this evidence suggests that the bias for simple meter processing is entirely experience driven, some evidence suggests that complex meters require greater cognitive resources (Lewis, Wing, Pope, Praamstra, & Miall, 2004; Sakai, et al., 1999) and even those who are familiar with complex meters display difficulty in processing meters that are highly complex (Hannon, Soley, & Ullal, 2012). Thus the important question remains: does experience with complex meters minimize the innate difficulty of processing these meters, or does lack of experience with these meters cause them to be difficult to process? In other words, to what extent are simple and complex meters processed differently, even by those to whom they are familiar?

To answer this question, this study tested the cognitive mechanisms (Experiment 1) and neural underpinnings (Experiment 2) of simple and complex meter processing. The first experiment explored the theory that the processing of rhythm might be driven by a domain general ability to process quantity. The results showed that an individual's ability to enumerate discrete quantities in the visual domain was correlated with their abilility to enumerate in the auditory domain. Specifically, the ability to count simultaneously presented visual items was correlated with the ability to count sequentially presented auditory items. More interestingly, the specific range of enumeration (subitizing versus counting) was important. Simple meter processing ability was correlated with enumeration ability across both ranges, but complex meter processing only correlated with performance on the counting range. Further, whereas performance on the complex meter task correlated significantly with working memory capacity, performance on the simple meter task did not.

These results offer novel evidence and strong support in favor of the theory that the difficulty with complex meters arises because of its greater cognitive requirements. Namely, simple meters are processed with hierarchical encoding of the entire rhythm (2:1, for instance). In contrast, complex meters, with irregular ratios between consecutive intervals, may require explicit processing for each time interval (Chapin, Zanto, Jantzen, Kelso, Steinberg & Large, 2010; Sakai, et al., 1999). In the domain of enumeration, subitizing has been described as being an automatic or implcit process, whereas counting has been described as being effortful, and requiring a larger working memory load (Shimomura & Kumada, 2011).

The second experiment explored the extent to which this distinction between simple and complex meter processing is innate, versus driven by experience. By using metrical ratios that varied in complexity, the results demonstrated that complex meters were processed differently, even by those to whom they were familiar. Specifically, while processing simple meter rhythms, listeners' brain activity initially showed greater N1 amplitudes in response to the expected beat in the simple meter versus in the complex meter condition. As the trial progressed, however, the pattern of activation reversed, with larger amplitudes in response to the imagined beat in the complex meter trials than in the simple meter trials. Together, these two sets of results were taken to suggest greater attention and better predictability in the simple meter condition, than in the complex meter condition. Further, the complex meter ratio used in this experiment (3:2:2) is typical of Balkan and Indian music, unlike the highly complex (7:4) ratios used in Hannon, Soley & Ullal (2012);. Thus, the distinction in performance between simple and complex meters in the Non-Western group should not have been due to unfamiliarity with these ratios. Instead, it suggests that experience with complex meters overrides the difficulty in performing a behaioral task. It is noteworthy that prior studies that used on-line sensitive measures of detecting differences in simple and complex meter processing in those familiar with both, found that these participants produced both meters with equal ease (Ullal-Gupta, Hannon, & Snyder, 2014).

Taken together, this study revealed that the constraints with complex meter processing arise out of greater, more effortful cognitive demands. Further, the results suggest that it is not the lack of experience with complex meters that causes this difficulty. Instead, with greater experience with these meters, we presumably develop cognitive strategies to overcome the constraits, yielding more accurate perception and production. In a future study, it would be extremely interesting to replicate the first experiment with those who are familiar with complex meters.

Appendix A

Correlation coefficient including all variables.

	MT	WMC	MA	Vsim% Sub	Vsim% Count	VsimR Sub	VsimR Count	Vseq% Sub	Vseq% Count	VseqR Sub	VseqR Count	Aseq% Sub	Aseq% Count	AseqR Sub	AseqR Count	WH	OK	OH	Tonal	Rtm
MT	1.00																			
WMC	.32*	1.00																		
MA	0.05	-0.10	1.00																	
Vsim%Sub	-0.28	0.07	-0.16	1.00																
Vsim%Count	-0.19	0.16	-0.15	0.05	1.00															
VsimRSub	-0.11	-0.08	0.13	-0.10	0.36*	1.00														
VsimRCount	-0.17	-0.12	0.15	0.07	0.66***	0.70***	1.00													
Vseq%Sub	0.01	-0.07	-0.04	-0.14	-0.11	-0.05	0.01	1.00												
Vseq%Count	0.30	0.00	-0.09	0.06	-0.14	-0.09	0.04	0.00	1.00											
VseqRSub	0.01	0.10	-0.03	0.33*	-0.12	-0.26	-0.10	0.07	-0.06	1.00										
VseqRCount	-0.12	0.02	0.13	0.21	0.09	0.08	0.16	-0.20	0.00	0.26	1.00									
Aseq%Sub	-0.03	0.02	-0.36*	0.48***	-0.13	-0.35*	-0.22	-0.11	0.12	0.33*	0.00	1.00								
Aseq%Count	0.21	0.32*	-0.19	-0.06	0.07	-0.04	-0.07	0.10	0.04	0.07	-0.07	0.11	1.00							
AseqRSub	-0.17	0.10	0.02	0.08	0.15	0.39**	0.20	-0.17	-0.13	-0.19	0.16	-0.28	-0.17	1.00						
AseqRCount	0.13	0.19	0.10	0.19	-0.17	0.29*	0.02	-0.13	0.03	-0.14	0.05	-0.21	0.01	0.37*	1.00					
WH	0.02	0.00	0.09	-0.06	0.24	-0.13	0.13	-0.06	-0.03	0.21	0.11	0.00	-0.08	-0.03	-0.16	1.00				
OK	-0.09	0.07	0.10	-0.14	0.29*	-0.18	0.05	0.01	-0.07	0.00	-0.01	-0.17	0.19	0.05	-0.13	0.58***	1.00			
OH	-0.08	-0.10	-0.02	0.01	0.22	-0.18	0.05	-0.30*	-0.06	0.06	0.08	0.00	0.05	-0.09	-0.20	0.58***	0.63***	1.00		
Tonal	.48***	0.13	-0.30	-0.23	0.05	-0.06	-0.09	0.20	0.00	0.17	-0.21	0.09	0.32*	-0.13	-0.14	-0.02	0.11	0.03	1.00	
Rtm	.49***	.38***	-0.32	-0.11	0.06	-0.21	-0.22	0.04	-0.14	0.14	-0.07	0.06	0.27	-0.10	0.00	0.11	0.22	0.25	0.72***	1.00
Mean:	1.91	5.46	22.40	.97	.83	715.81	1472.98	.73	.37	601.83	695.90	.94	.42	656.12	770.28	.75	.47	.45	25.00	26.70
SD:	3.60	1.01	5.95	.06	.20	144.71	389.09	.27	.12	95.46	104.50	.11	.18	89.91	97.97	1.11	.88	1.03	3.73	3.87

Note: N=48

* $p < .05$. ** $p < .01$. *** $p < .001$.

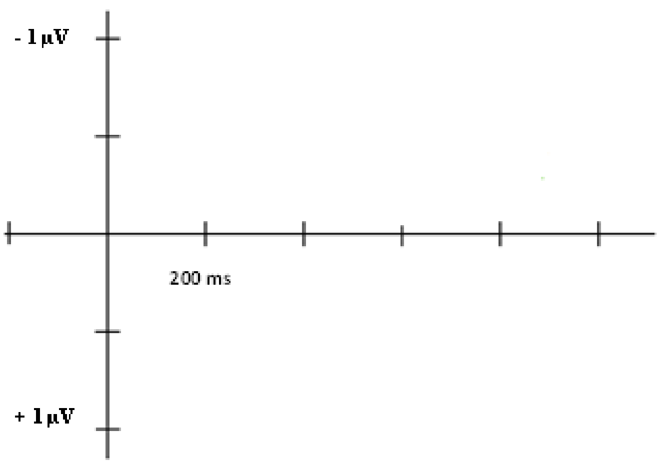
MT	Number of years of music training
WMC	Composite working memory score
MA	Math Anxiety score
VSim%Sub	Accuracy on Visual Simultaneous Enumeration – Subitizing Range
VSim%Count	Accuracy on Visual Simultaneous Enumeration – Counting Range
VSimRSub	Response Time on Visual Simultaneous Enumeration – Subitizing Range
VSimRCount	Response Time on Visual Simultaneous Enumeration – Counting Range
VSeq%Sub	Accuracy on Visual Sequential Enumeration – Subitizing Range
VSeq%Count	Accuracy on Visual Sequential Enumeration – Counting Range
VSeqRSub	Response Time on Visual Sequential Enumeration – Subitizing Range
VSeqRCount	Response Time on Visual Sequential Enumeration – Counting Range
ASeq%Sub	Accuracy on Auditory Sequential Enumeration – Subitizing Range
ASeq%Count	Accuracy on Auditory Sequential Enumeration – Counting Range
ASeqRSub	Response Time on Auditory Sequential Enumeration – Subitizing Range
ASeqRCount	Response Time on Auditory Sequential Enumeration – Counting Range
WH	Score on Within Harmony trials
OK	Score on Out of Key trials
OH	Score on Out of Harmony trials
Tonal	Score on Tonal Subtest of AMMA
Rtm	Score on Rhythm Subtest of AMMA

Appendix B

In the following mean amplitude figures, the electrodes are organized as follows:

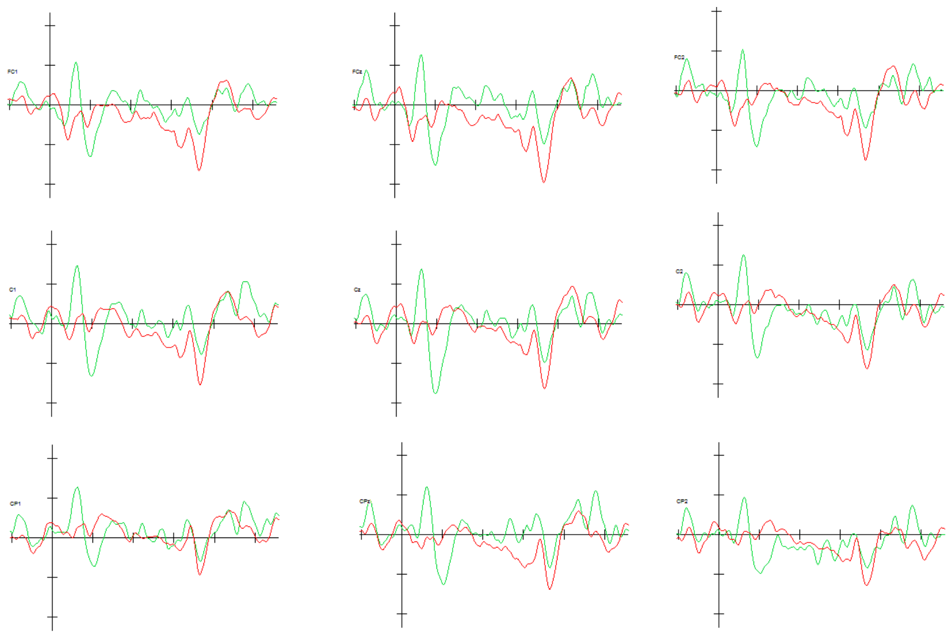
FC1	FCz	FC2
C1	Cz	C2
CP1	CPz	CP2

Scale:

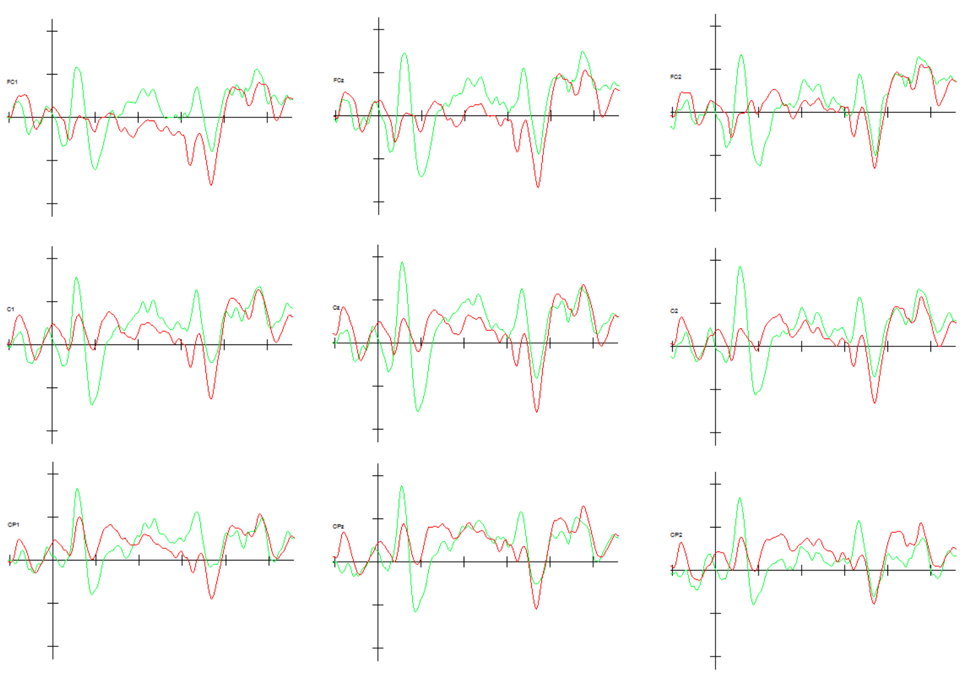


1. Simple meter: LSS (slow tempo): Accented versus Unaccented

Western Group

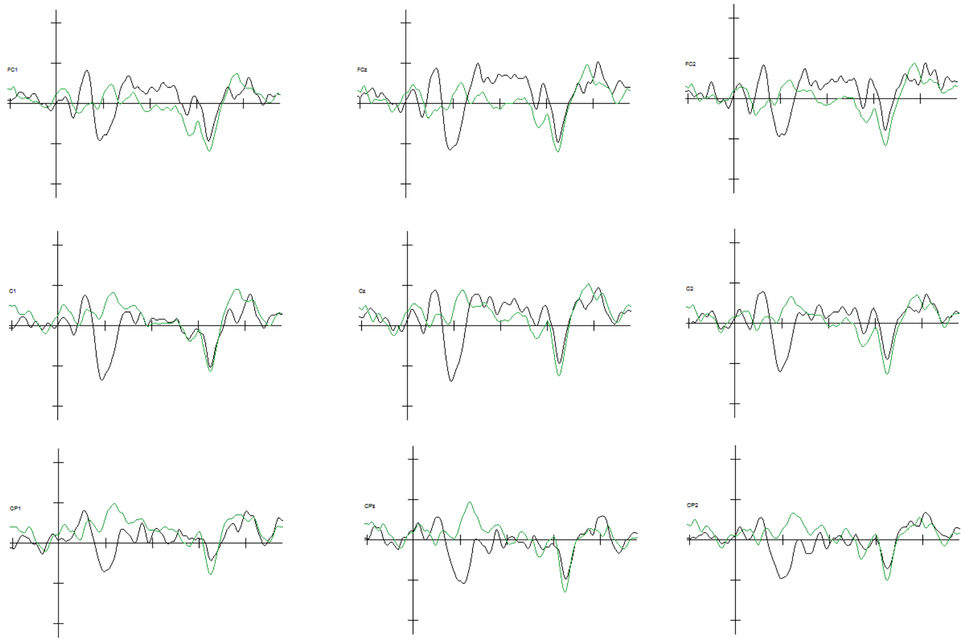


Non-Western Group

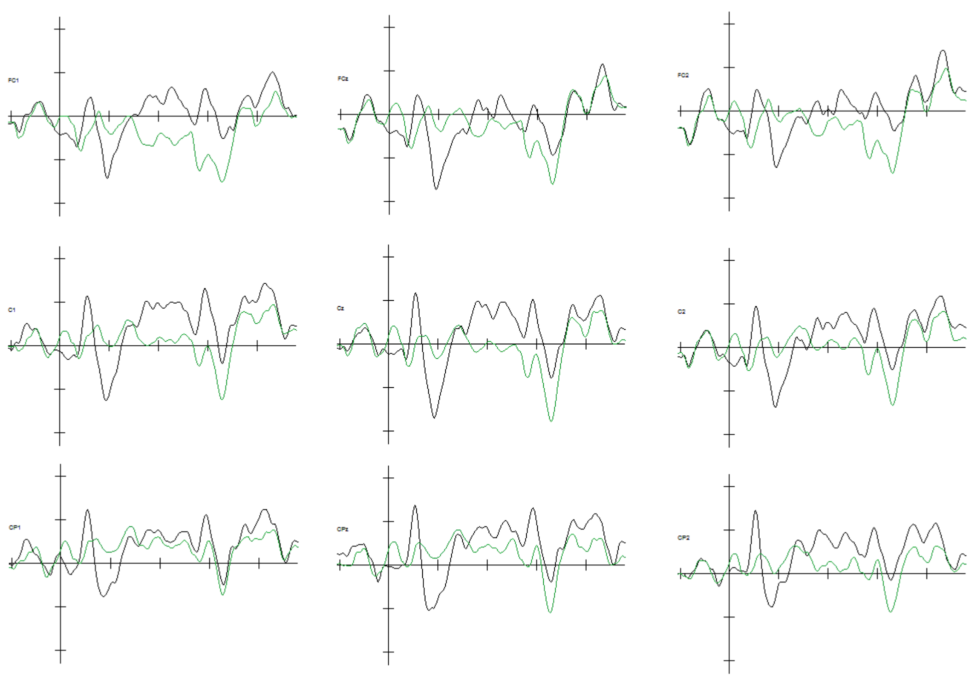


2. Simple meter: LSS (fast tempo): Accented versus Unaccented

Western Group

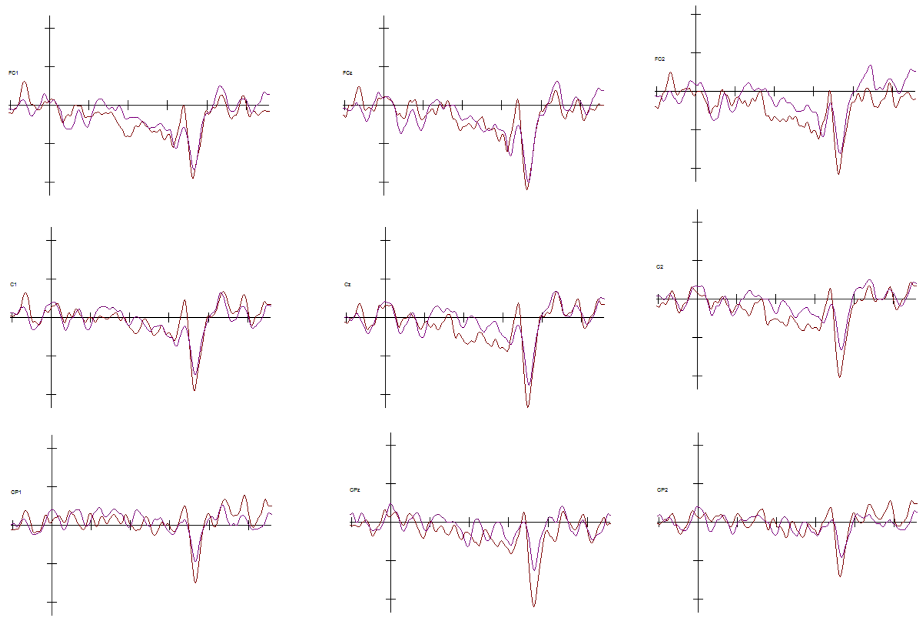


Non-Western Group

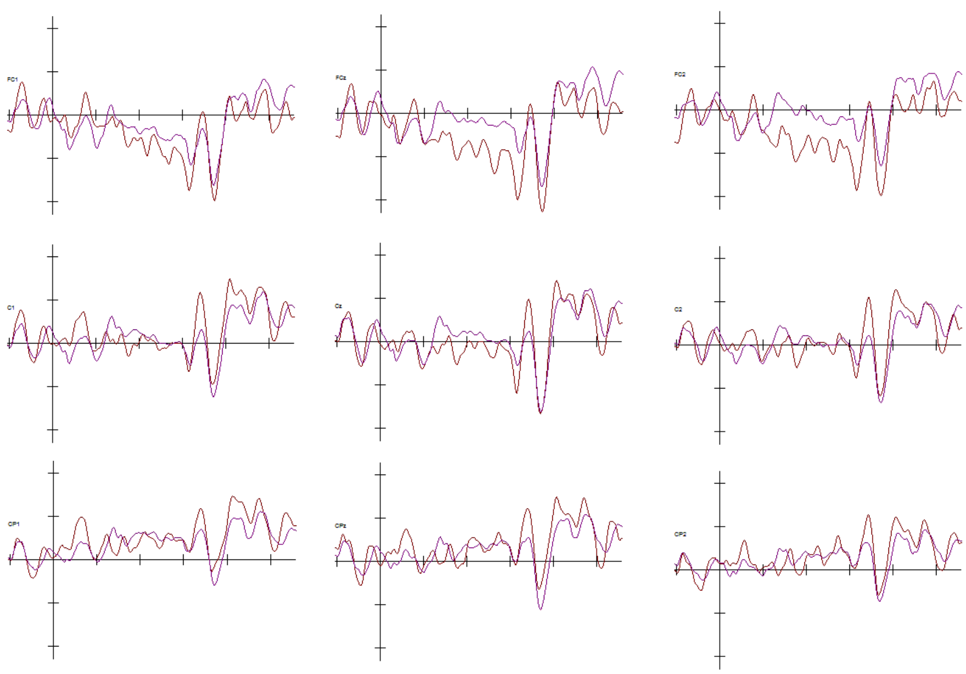


3. Simple meter: SSL (slow tempo): Accented versus Unaccented

Western Group

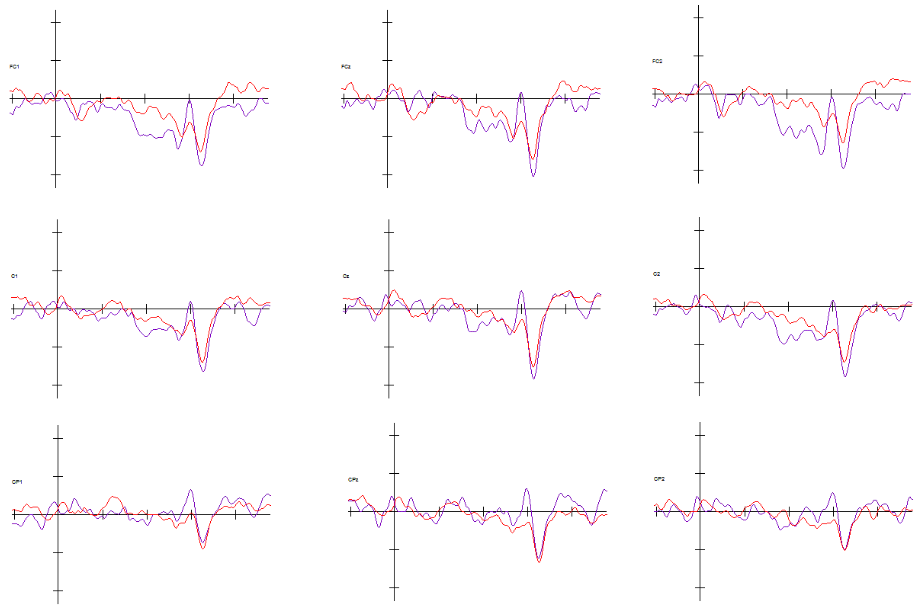


Non-Western Group

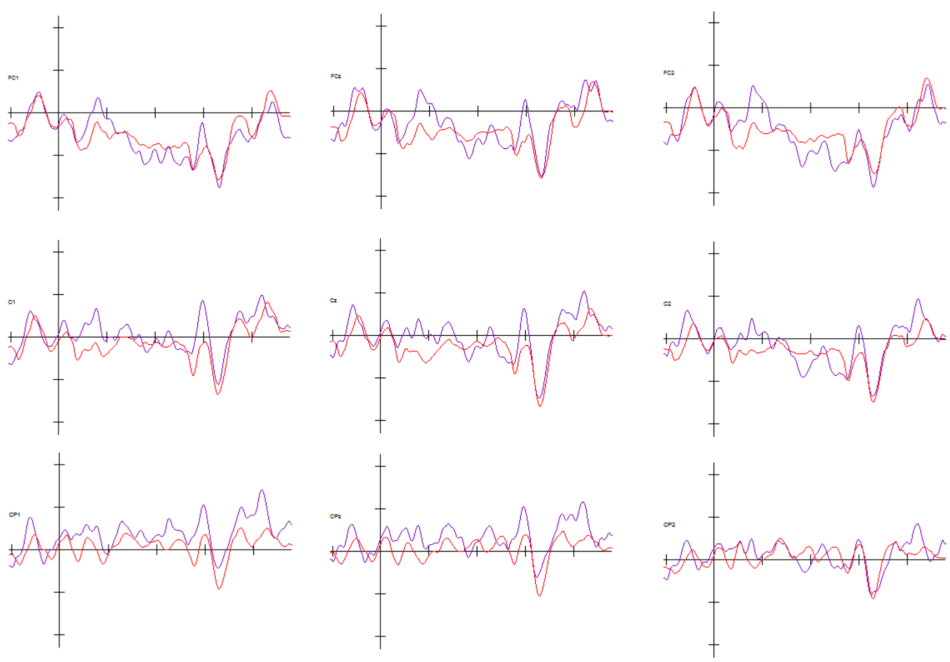


4. Simple meter: SSL (fast tempo): Accented versus Unaccented

Western Group

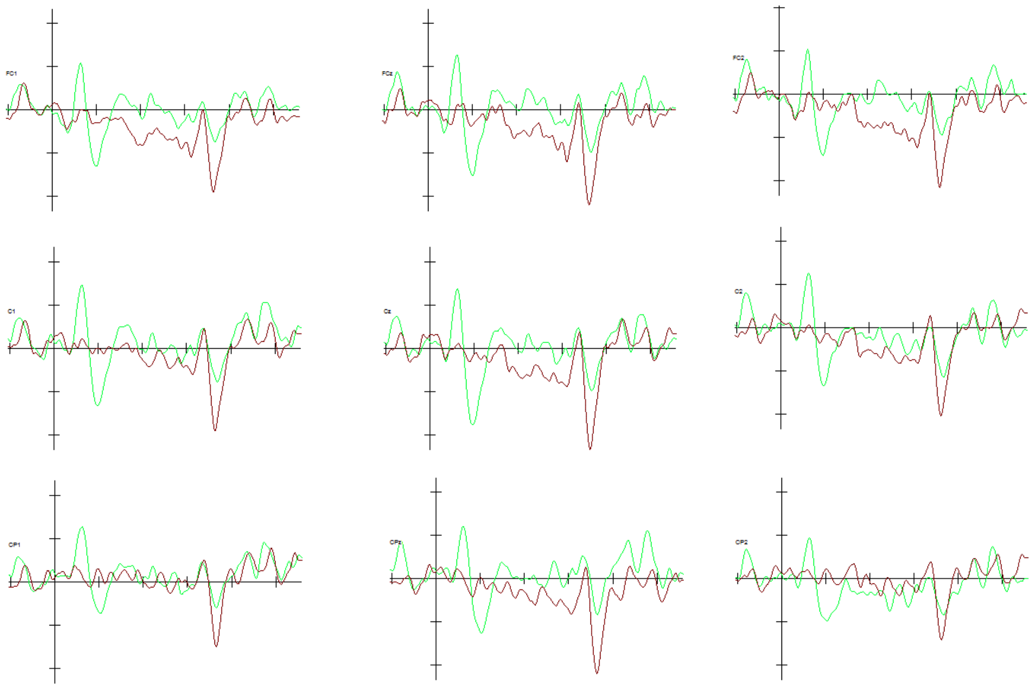


Non-Western Group

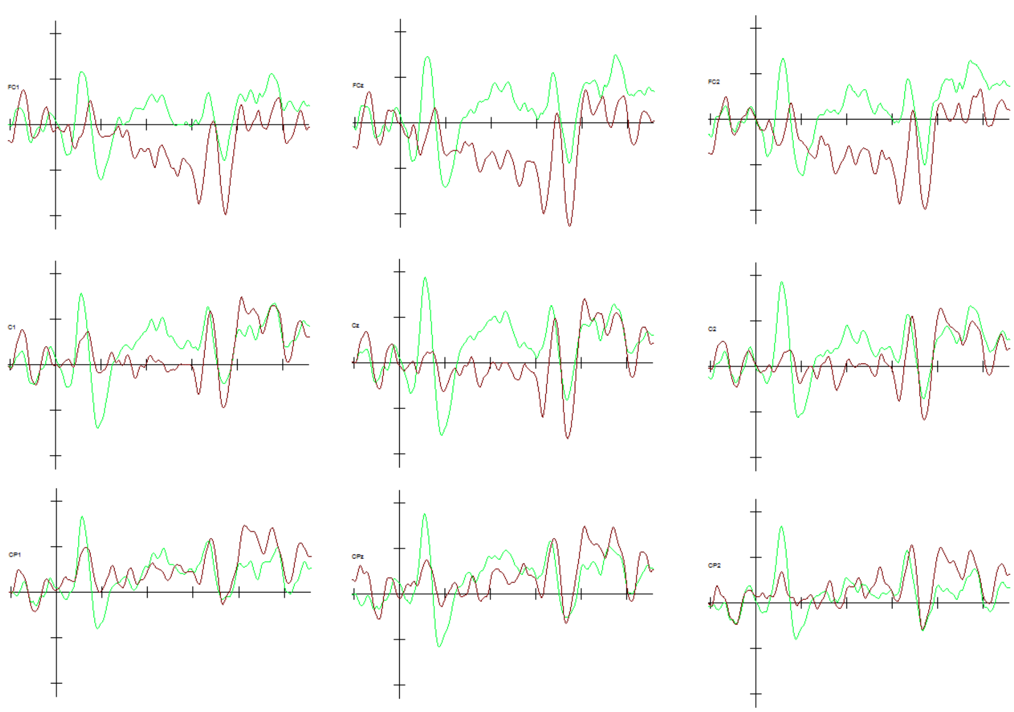


5. Simple meter: LSS (slow tempo) versus SSL (slow tempo): accented

Western Group

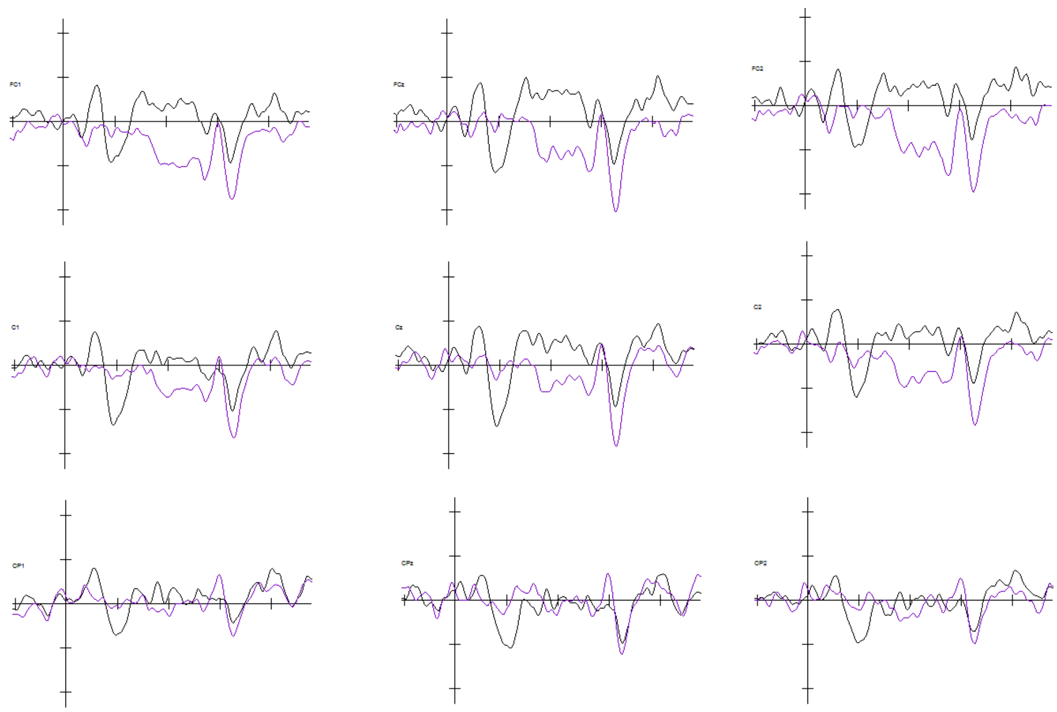


Non-Western Group

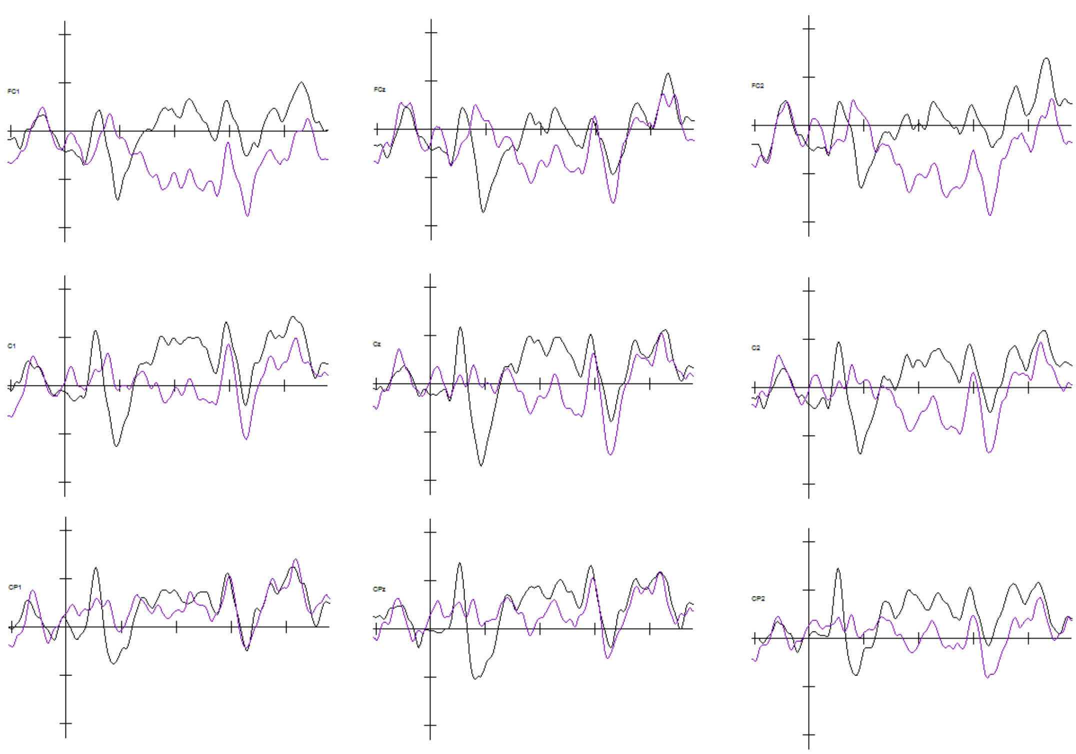


6. Simple meter: LSS (fast tempo) versus SSL (fast tempo): accented

Western Group

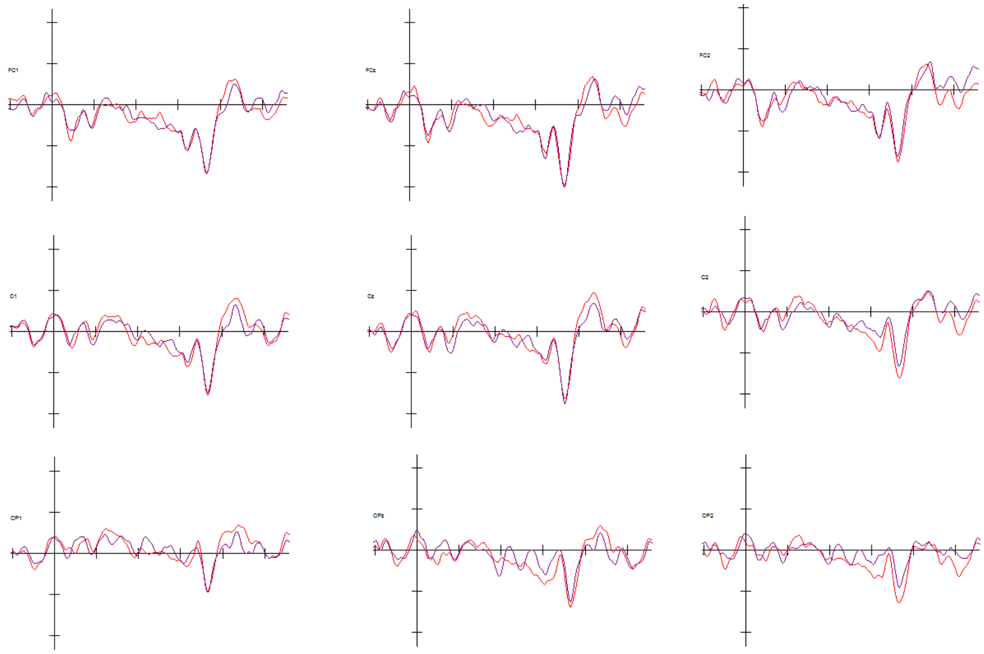


Non-Western Group

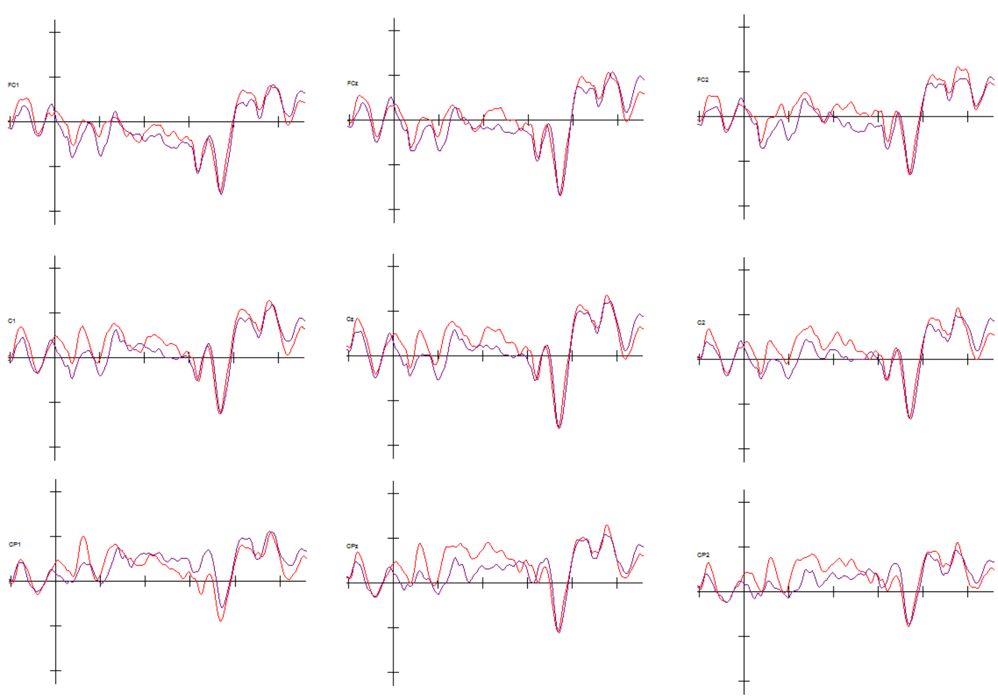


7. Simple meter: LSS (slow tempo) versus SSL (slow tempo): unaccented

Western Group

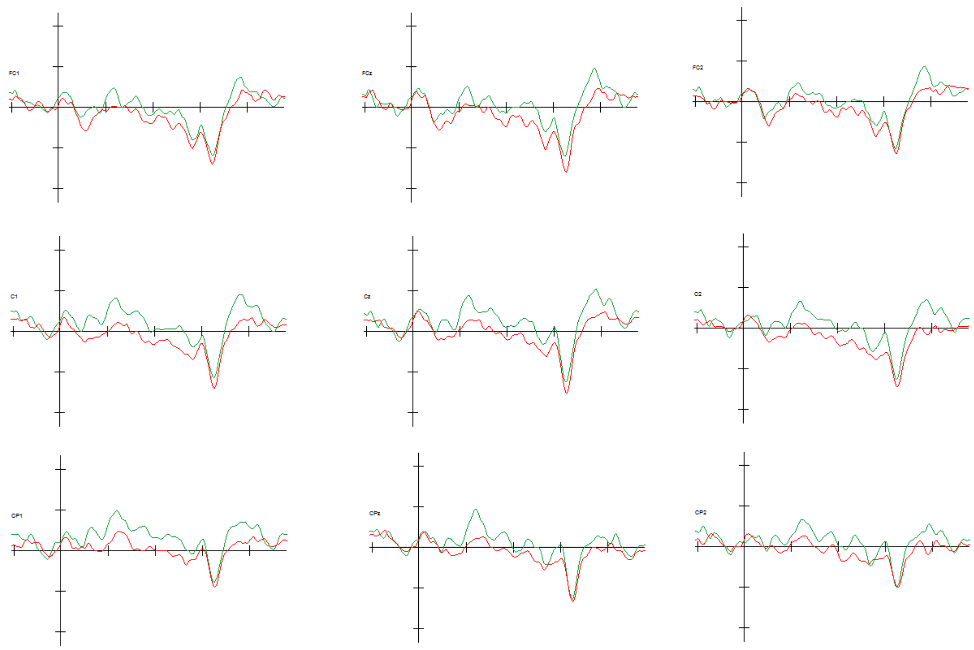


Non-Western Group

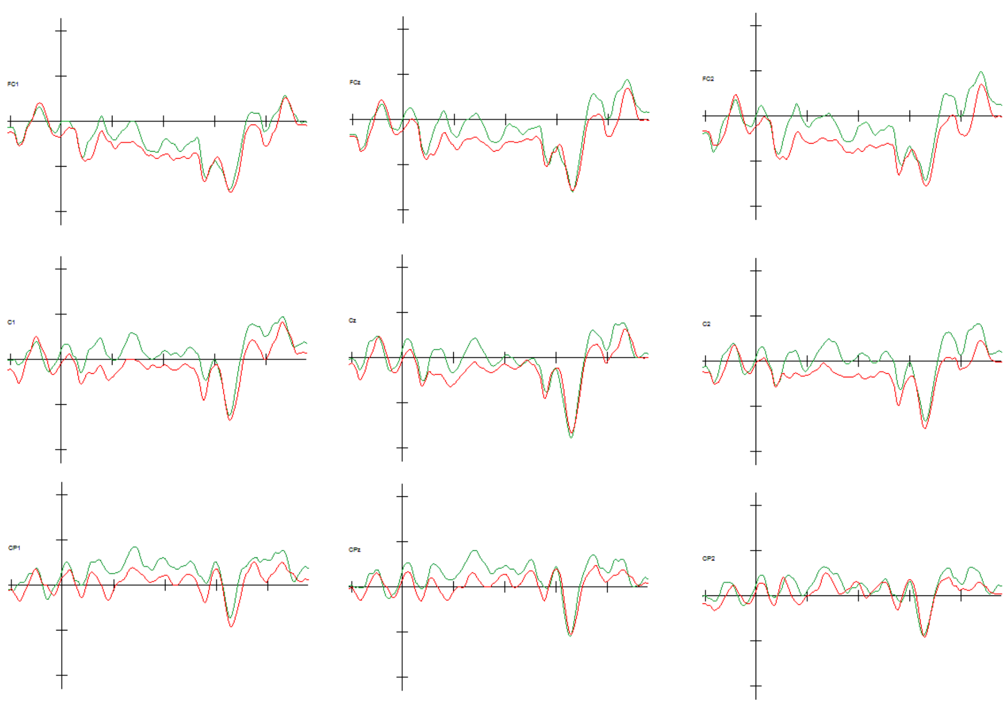


8. Simple meter: LSS (fast tempo) versus SSL (fast tempo): unaccented

Western Group

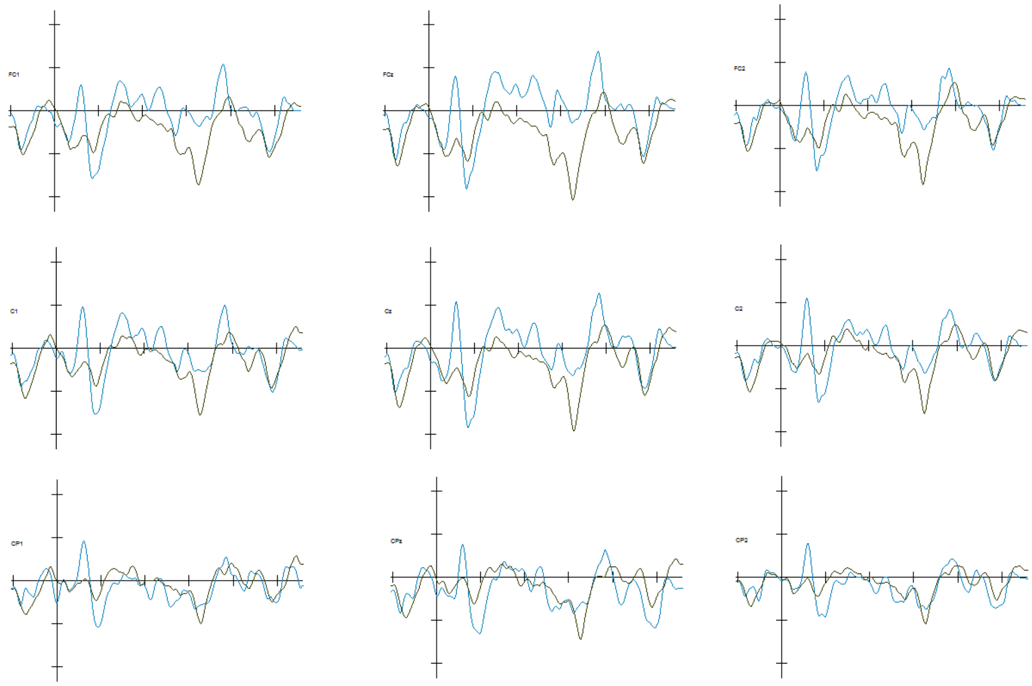


Non-Western Group

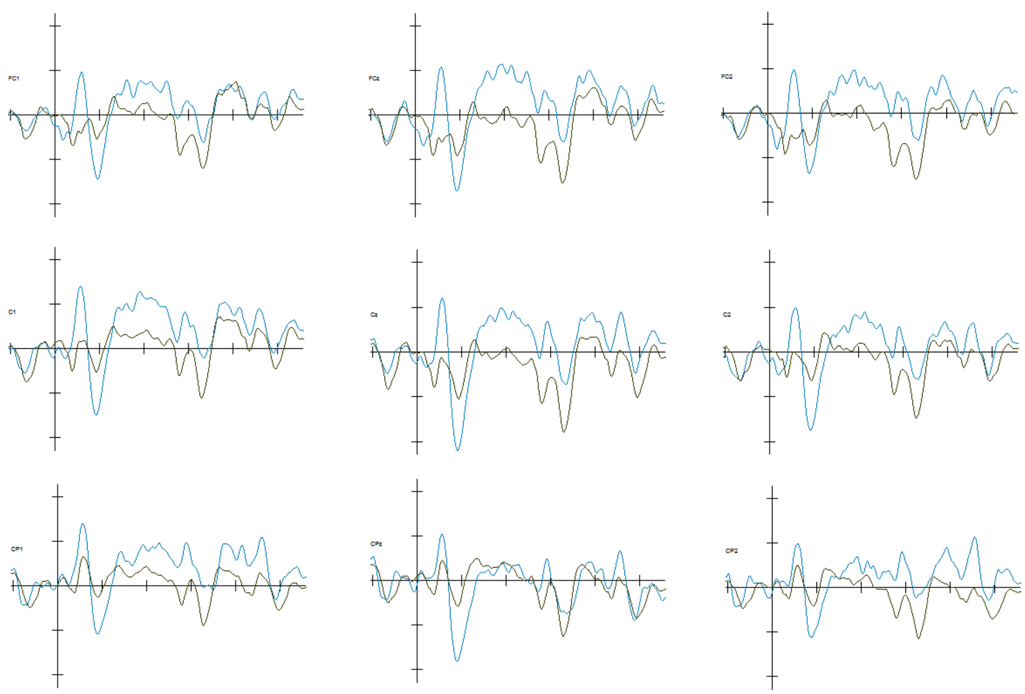


9. Complex meter: LSS (slow tempo): accented versus unaccented

Western Group

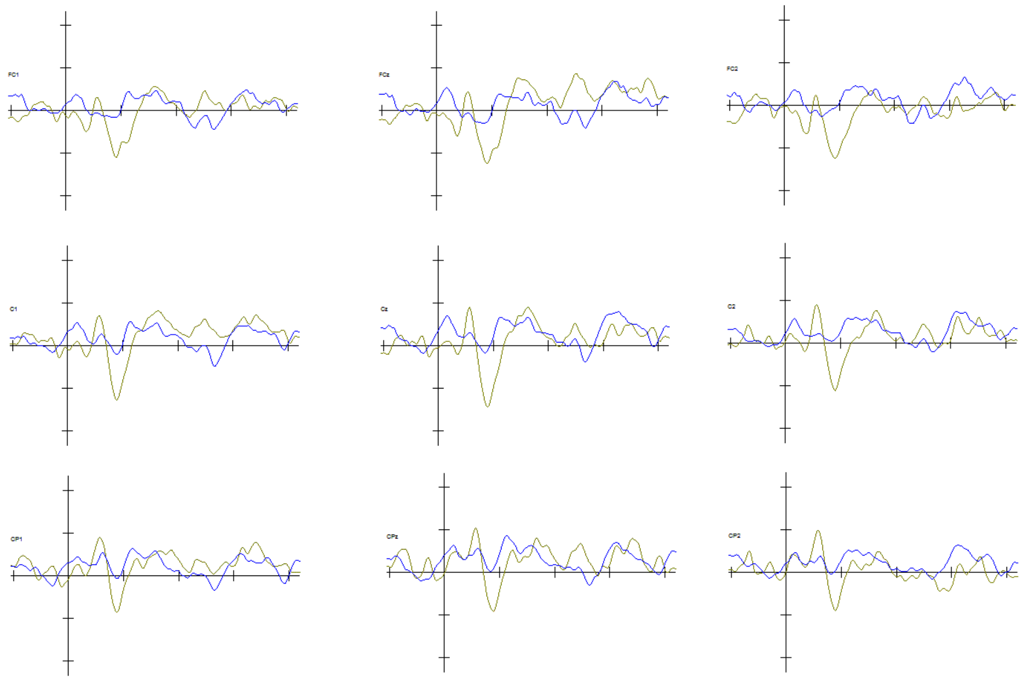


Non-Western Group



10. Complex meter: LSS (fast tempo): accented versus unaccented

Western Group



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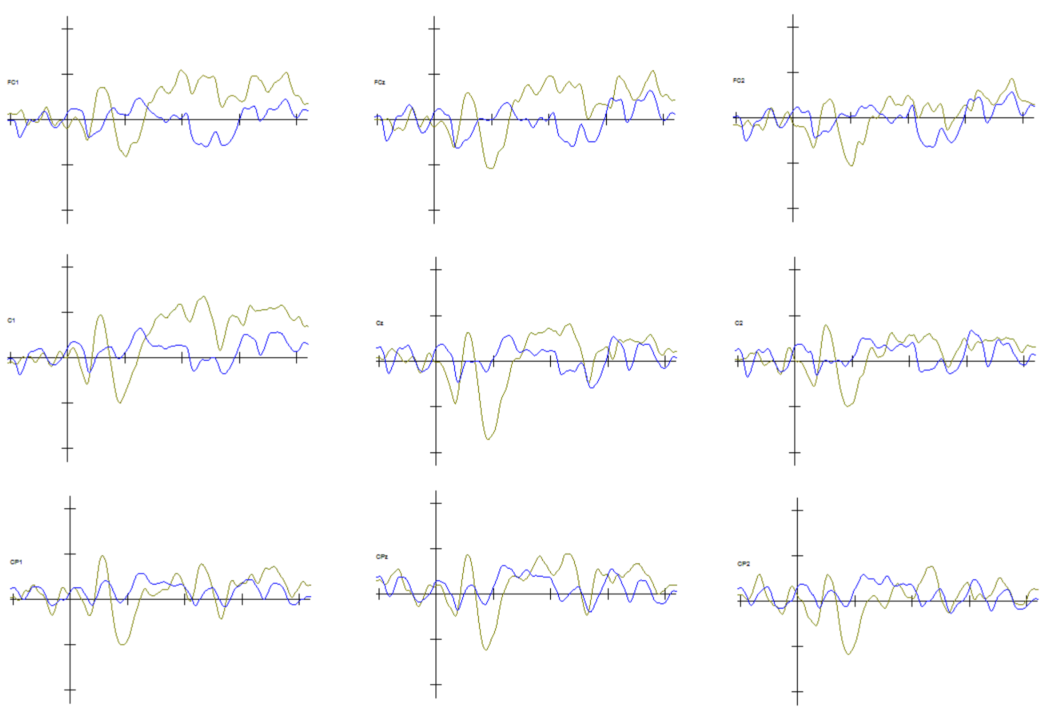
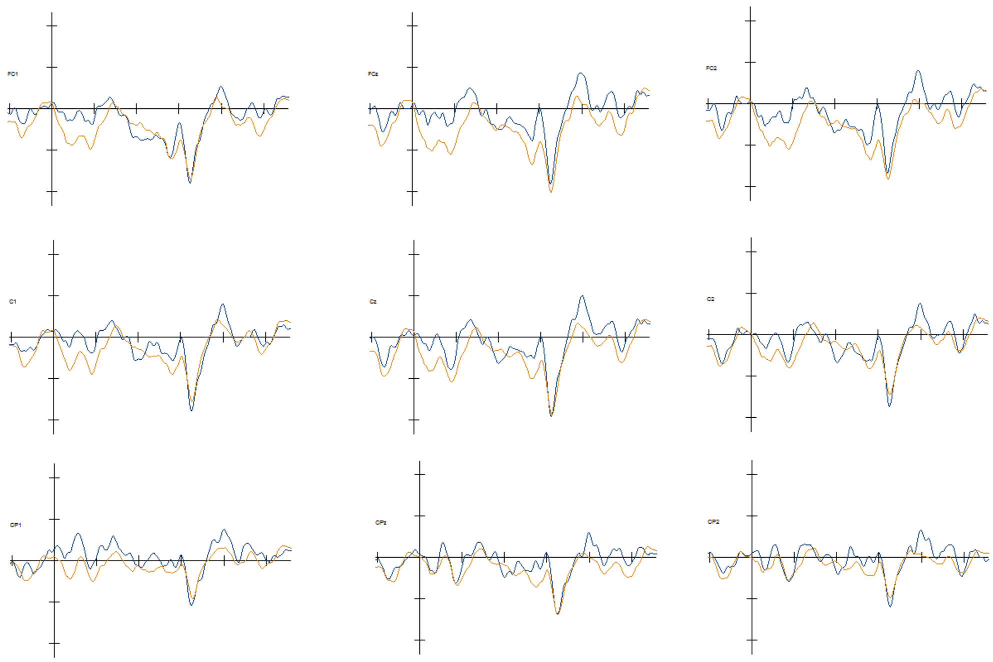


11. Complex meter: SSL (slow tempo): accented versus unaccented

Western Group



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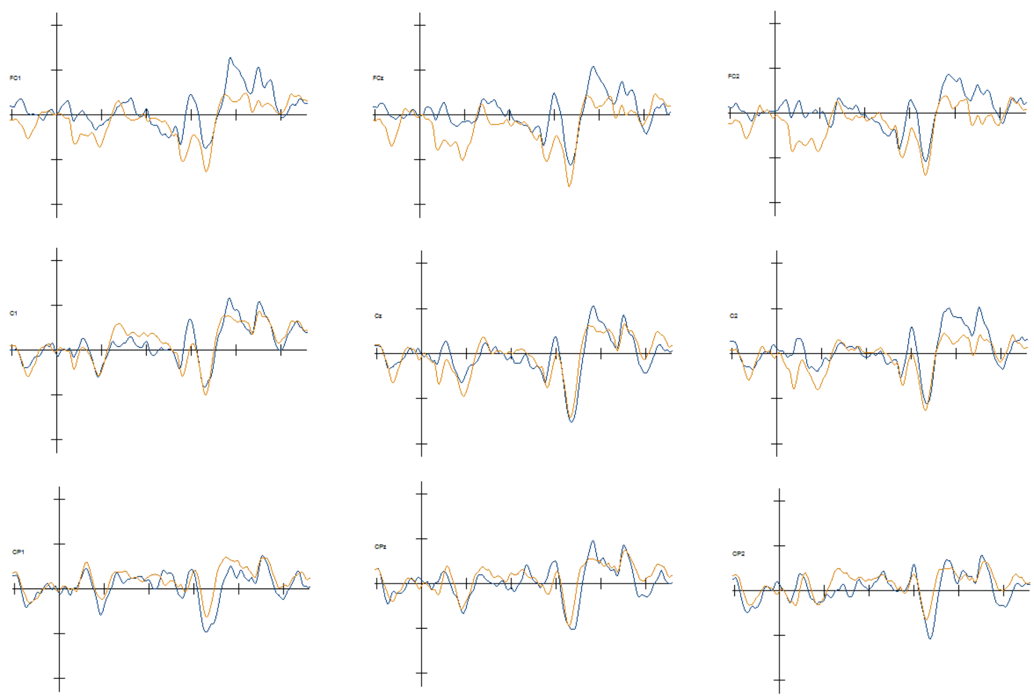
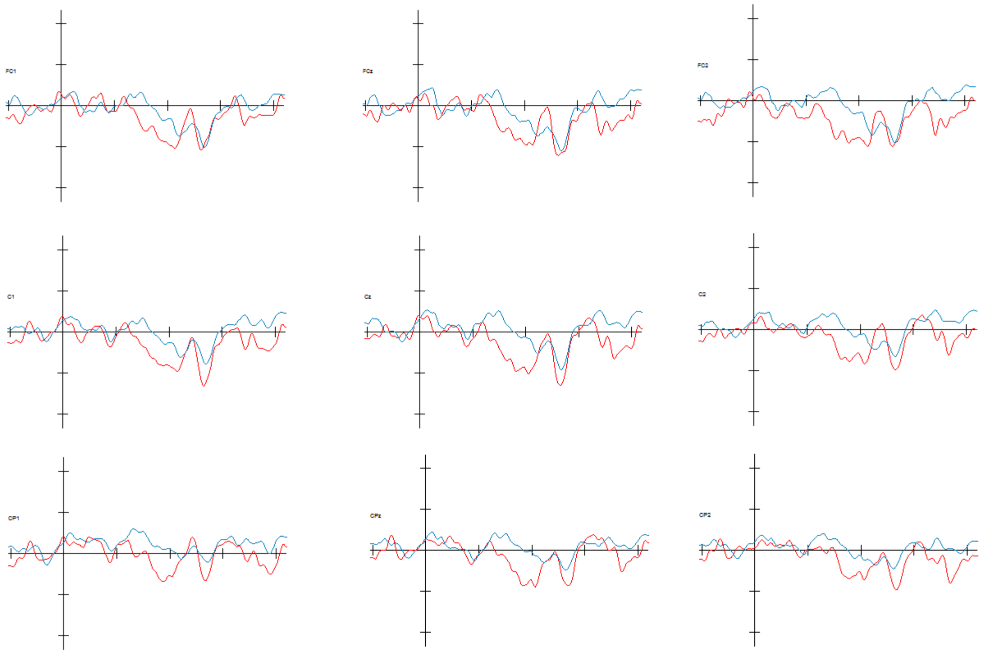


12. Complex meter: SSL (fast tempo): accented versus unaccented

Western Group



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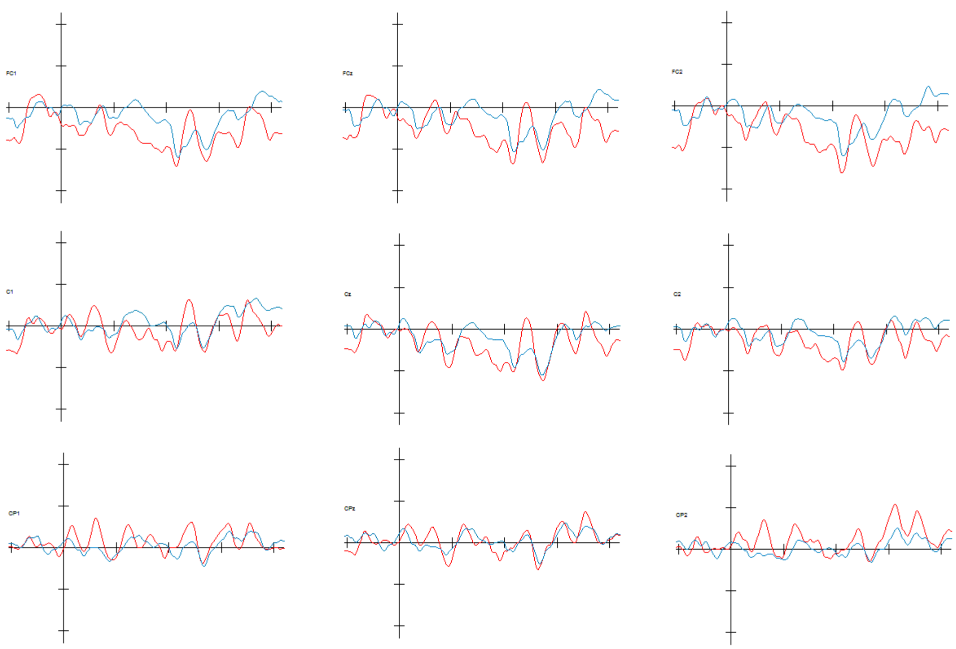
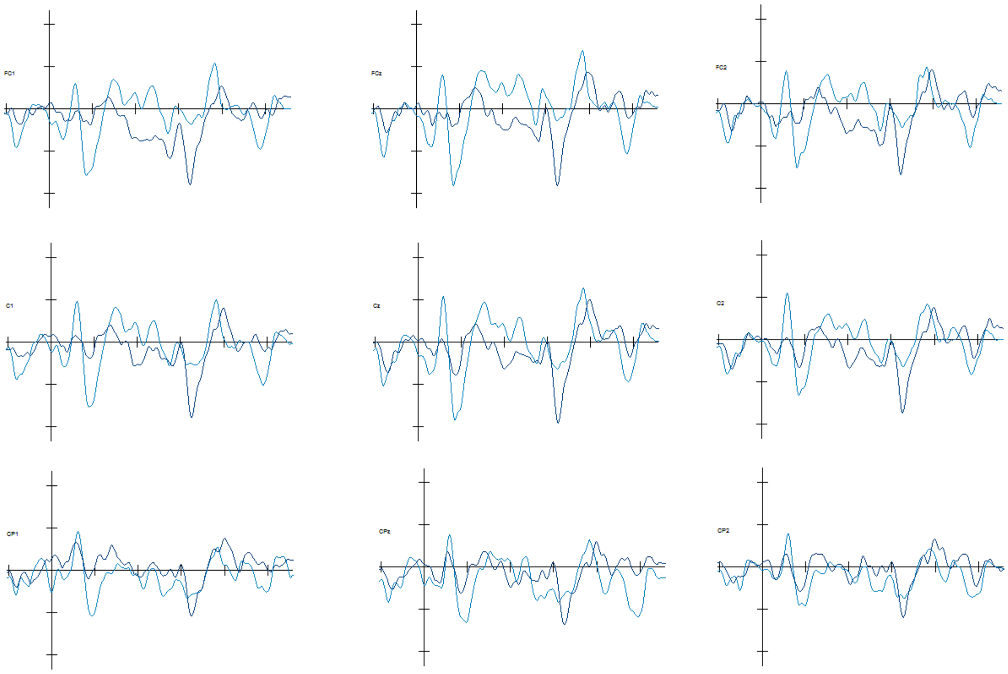


13. Complex meter: LSS (slow tempo) versus SSL (slow tempo): accented

Western Group



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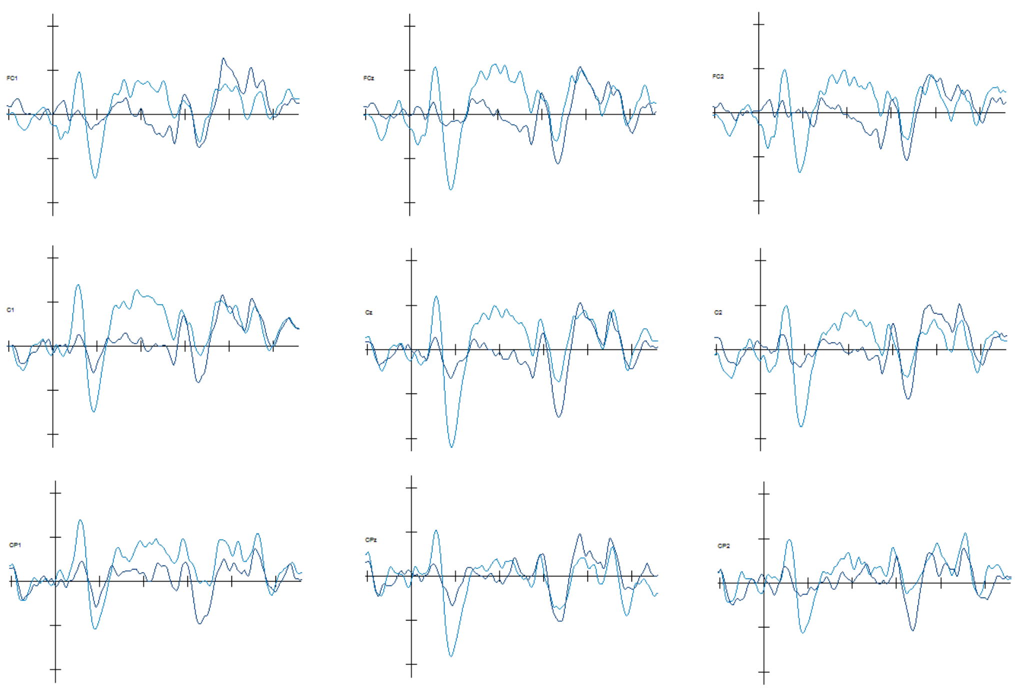
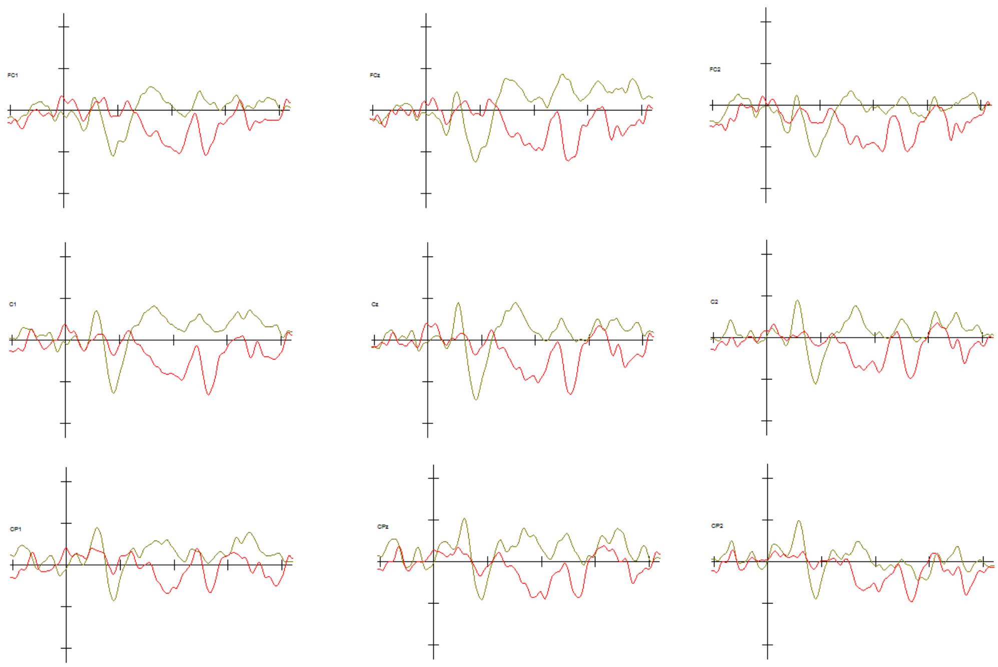


14. Complex meter: LSS (fast tempo) versus SSL (fast tempo): accented

Western Group



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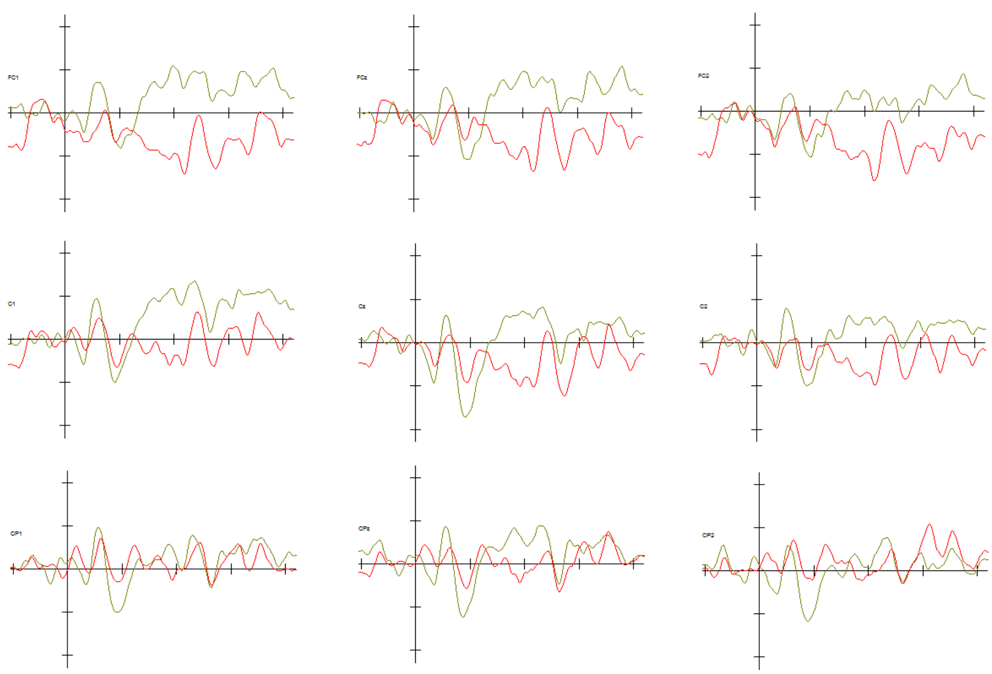
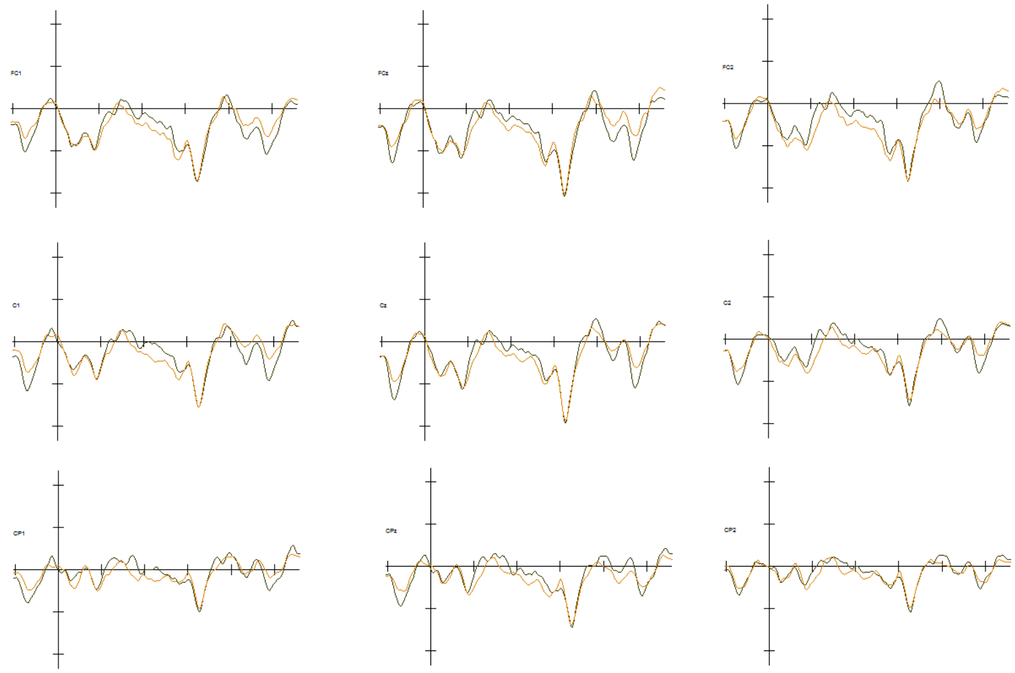
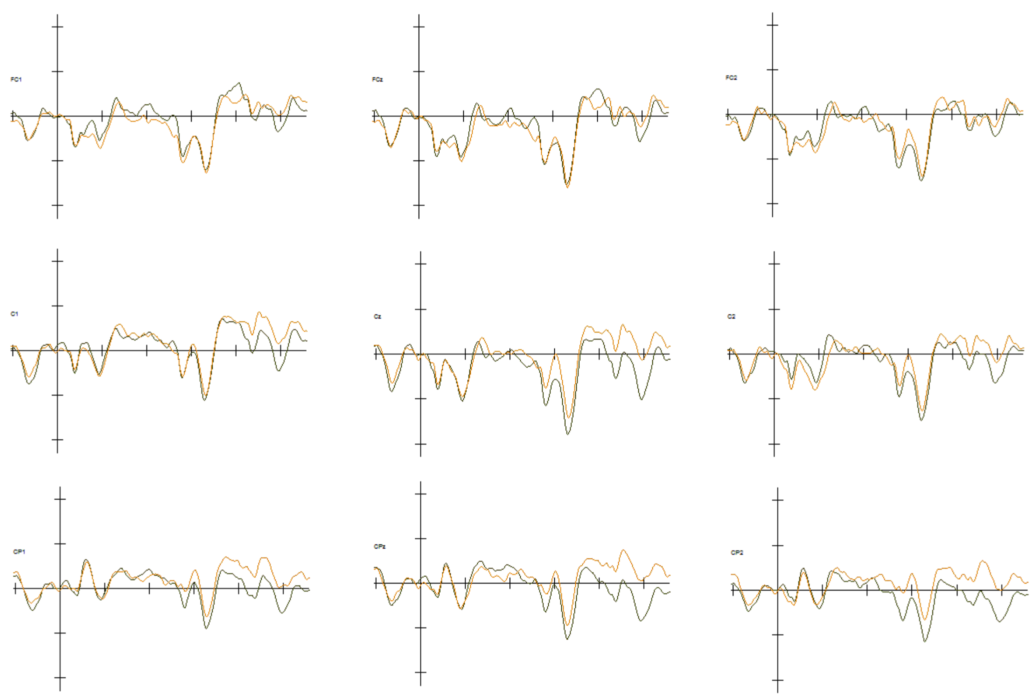


15. Complex meter: LSS (slow tempo) versus SSL (slow tempo): unaccented

Western Group

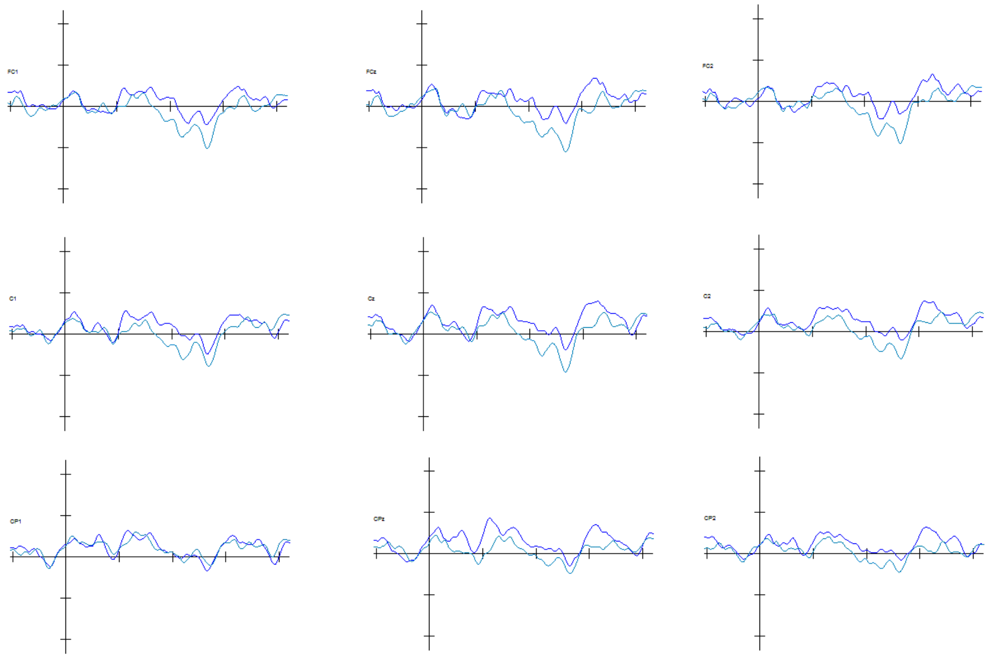


Non-Western Group

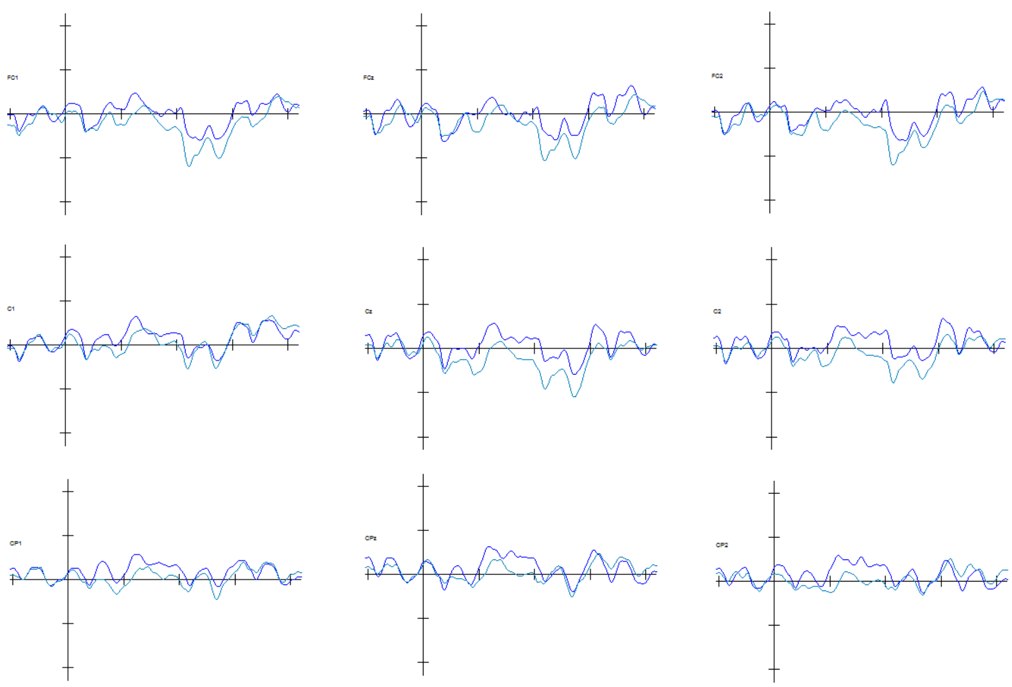


16. Complex meter: LSS (fast tempo) versus SSL (slow tempo): unaccented

Western Group



Non-Western Group

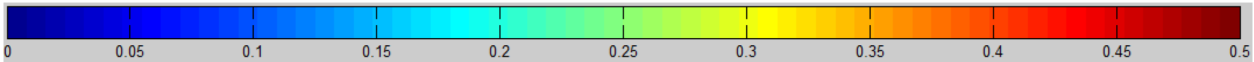


Appendix C

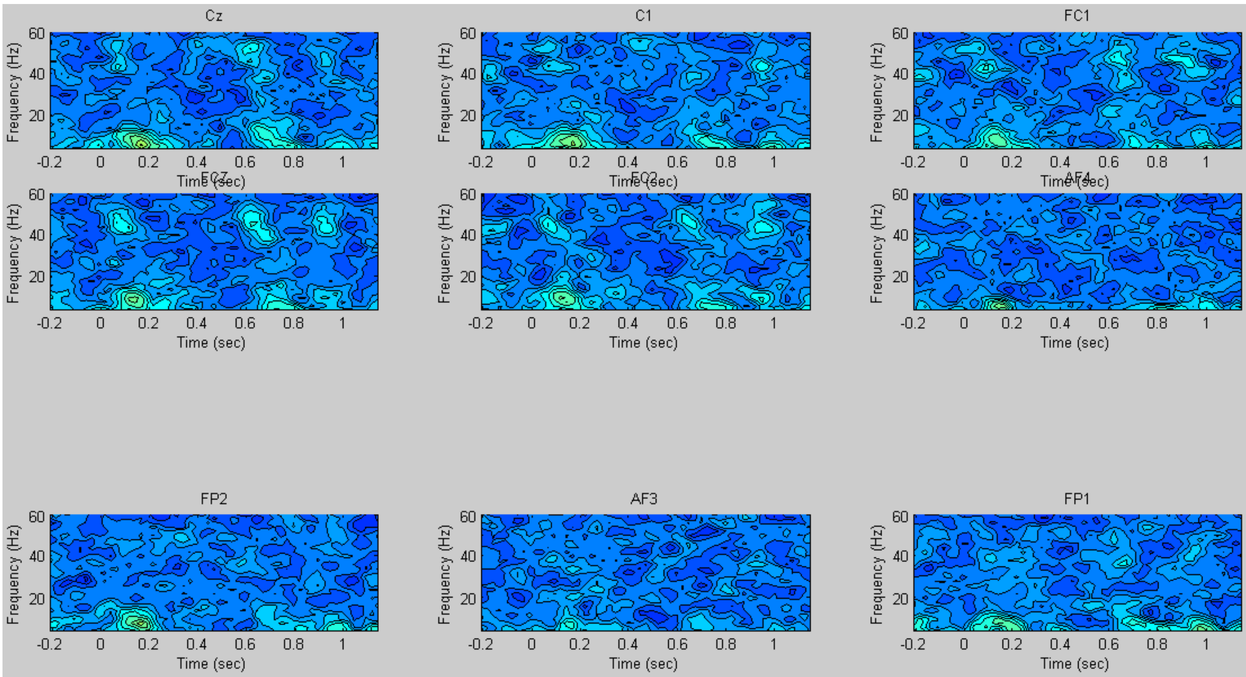
In the following evoked activity time frequency figures, the electrodes are organized as follows:

Cz	C1	FC1
FCz	FC2	AF4
FP2	AF3	FP1

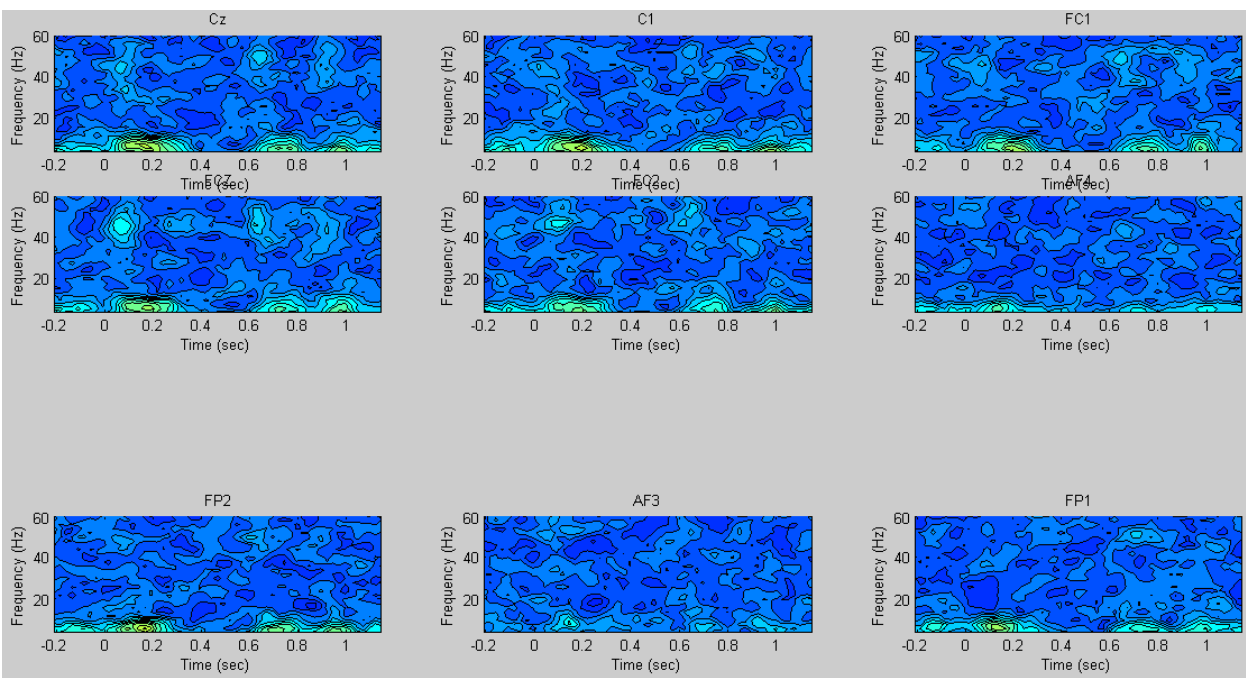
1. Simple meter: LSS (slow tempo): Accented



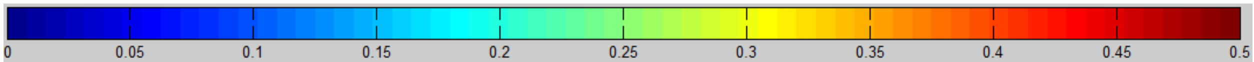
Western Group



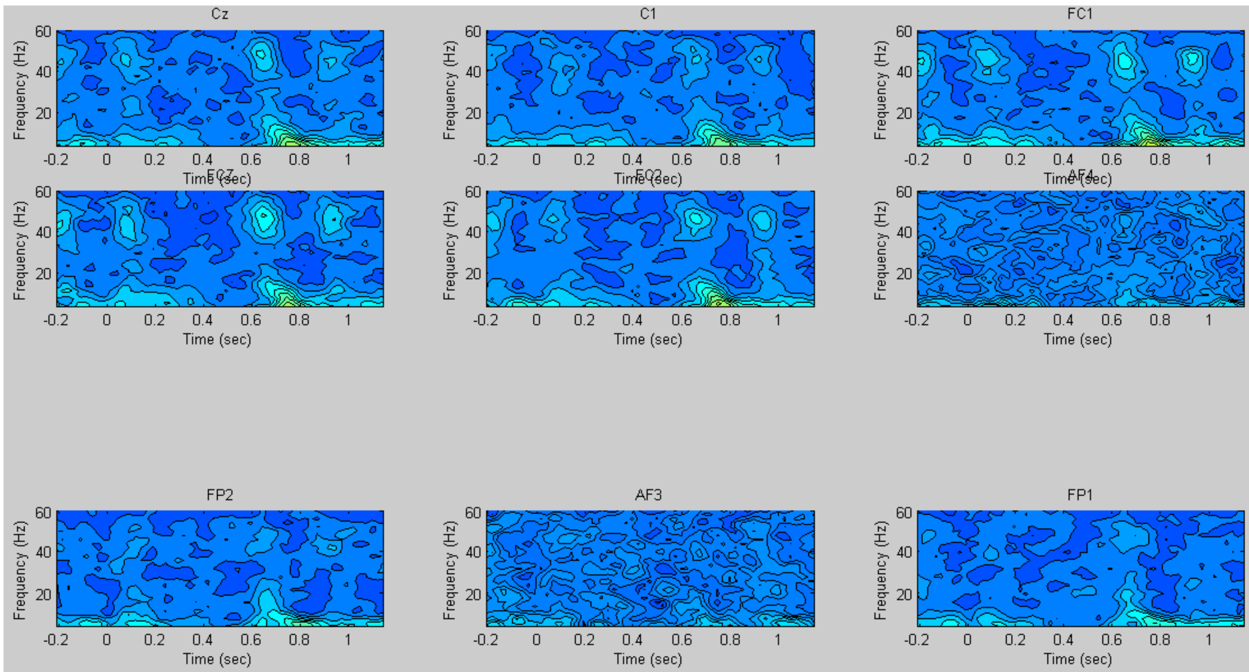
Non-Western Group



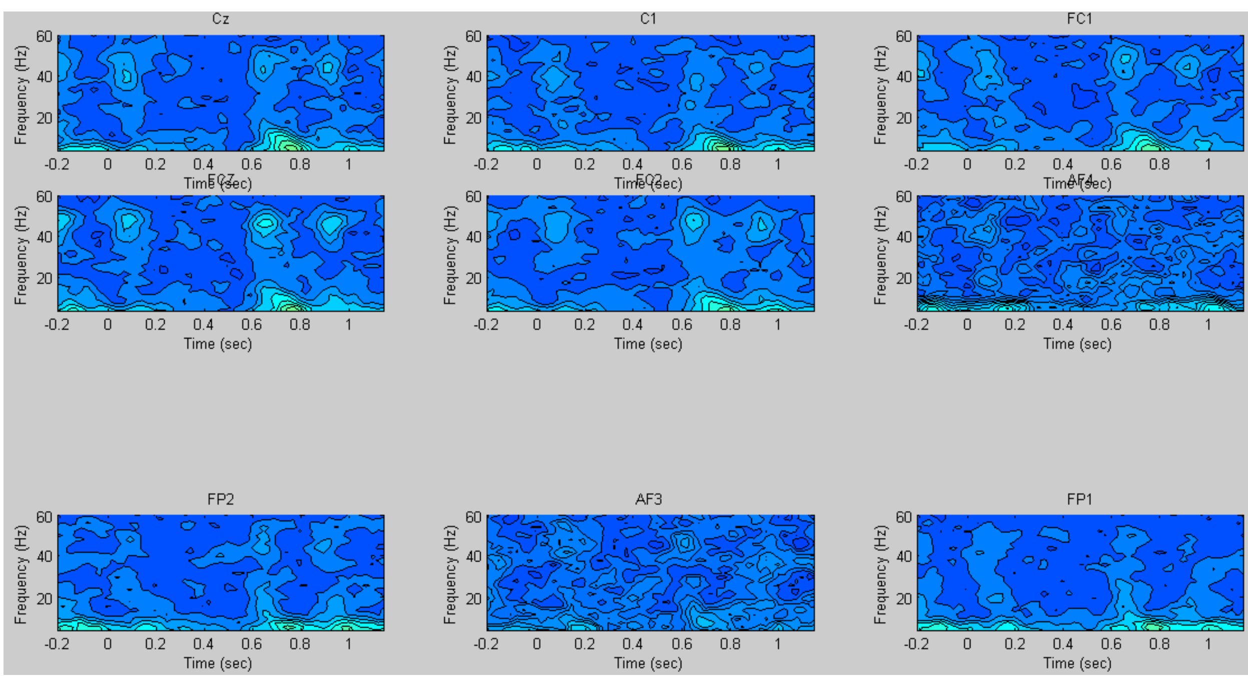
2. Simple meter: LSS (slow tempo): Unaccented



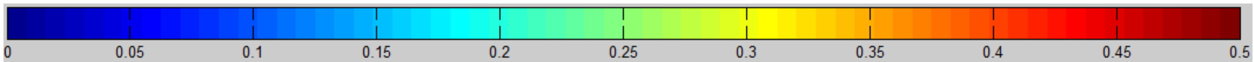
Western Group



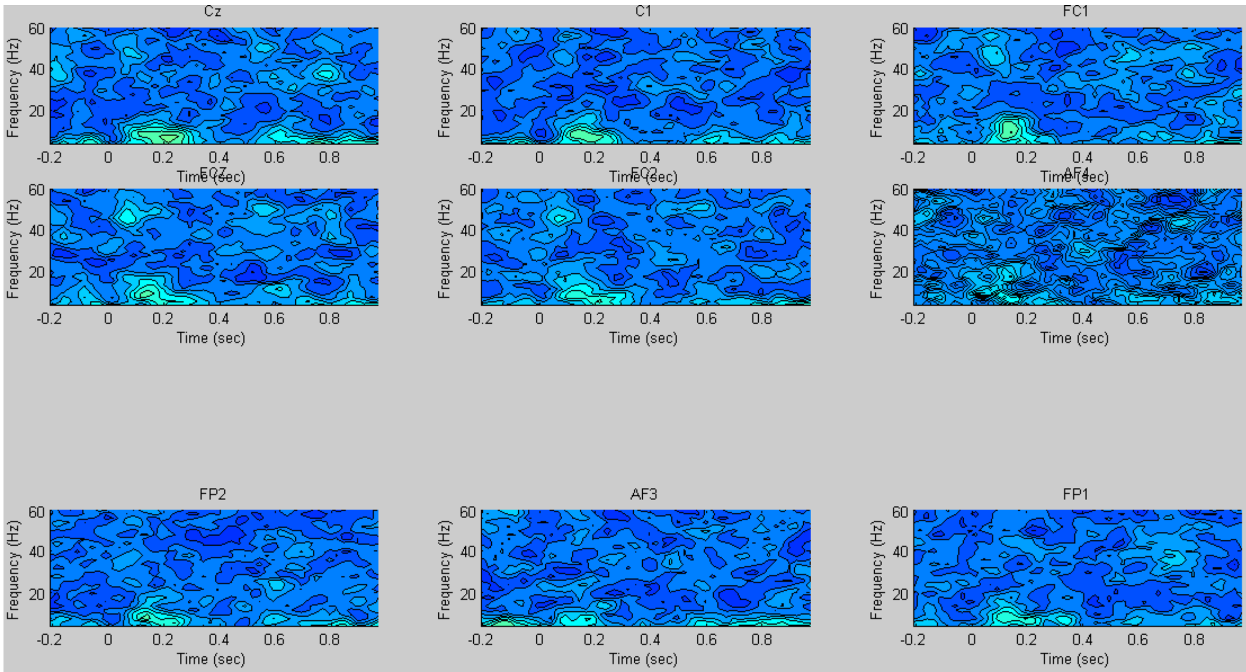
Non-Western Group



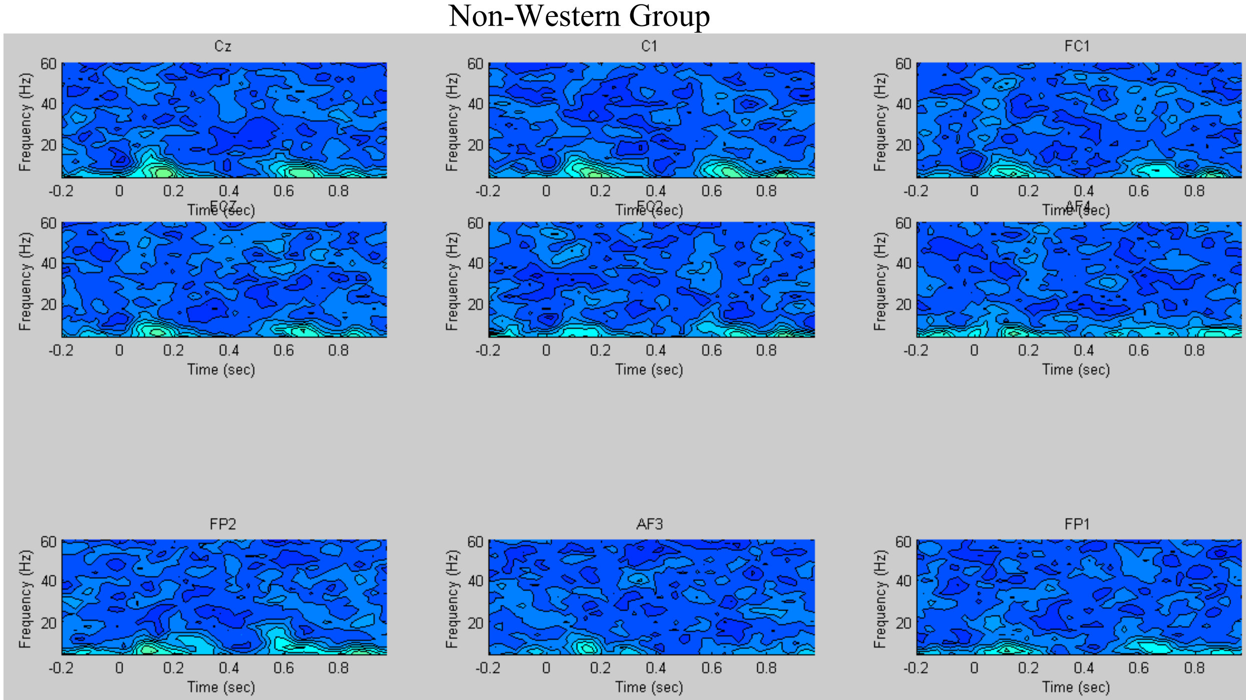
3. Simple meter: LSS (fast tempo): Accented



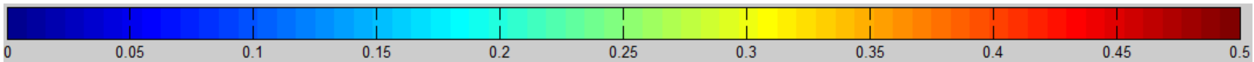
Western Group



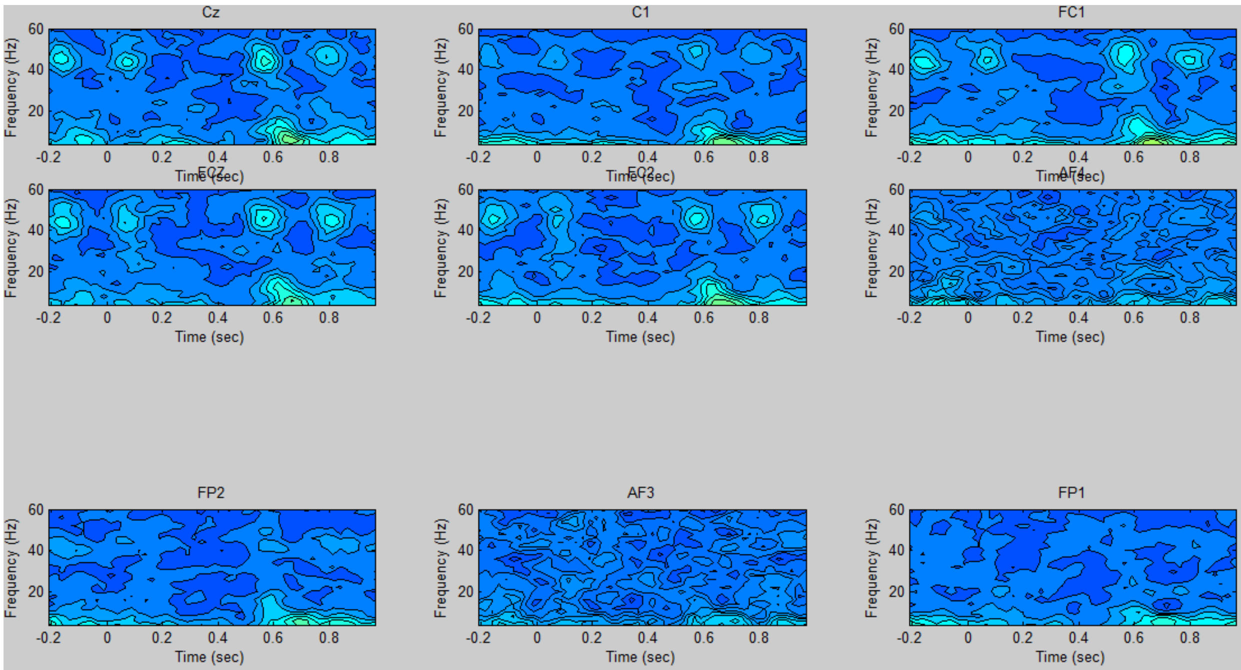
Non-Western Group



4. Simple meter: LSS (fast tempo): Unaccented



Western Group



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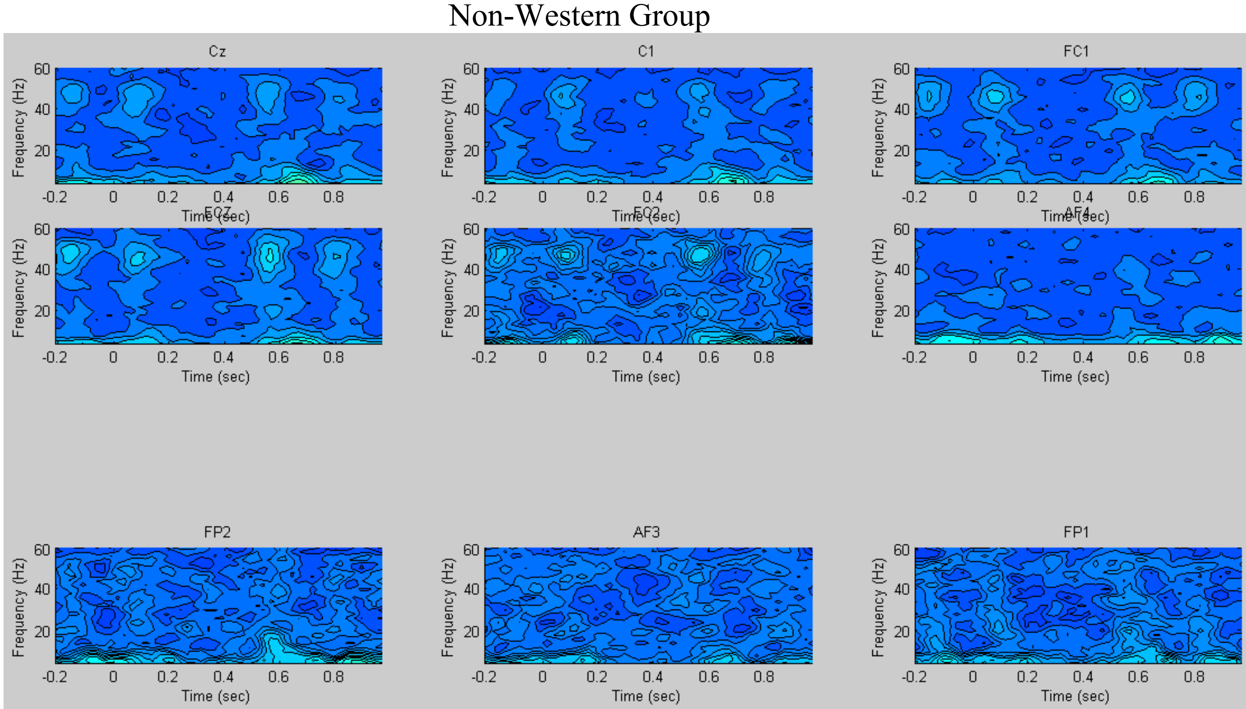
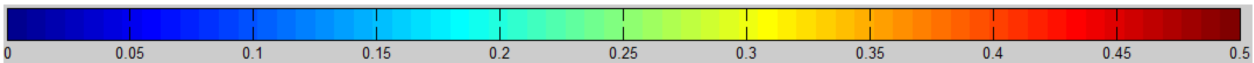
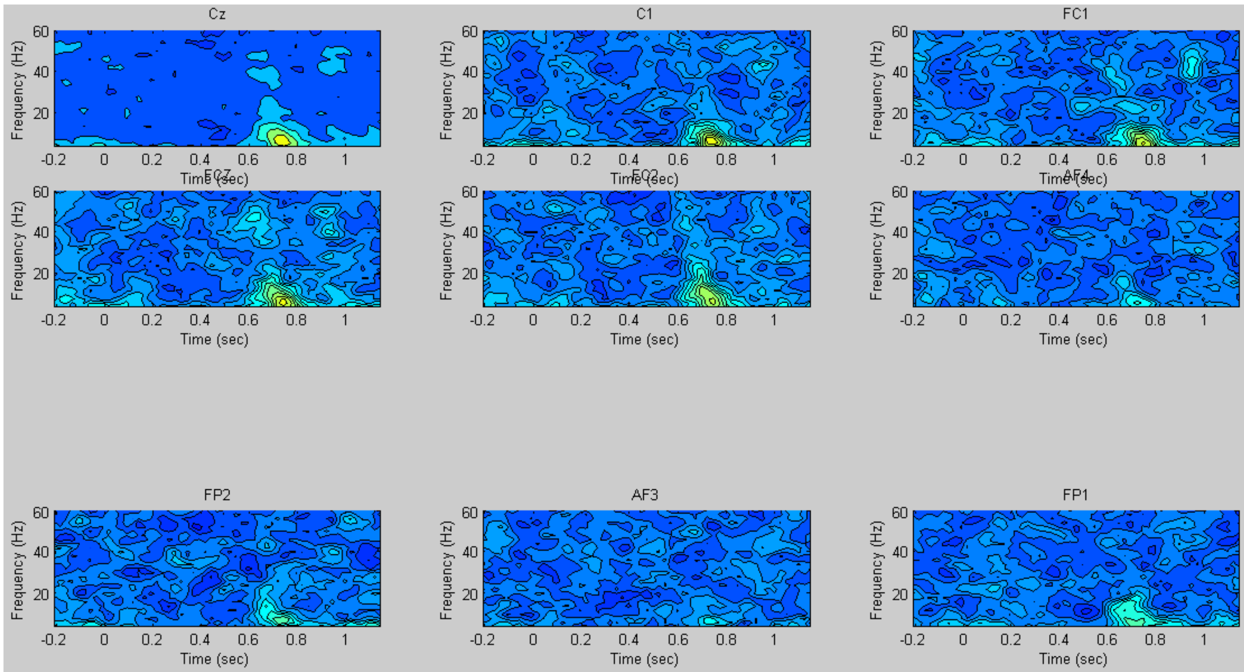


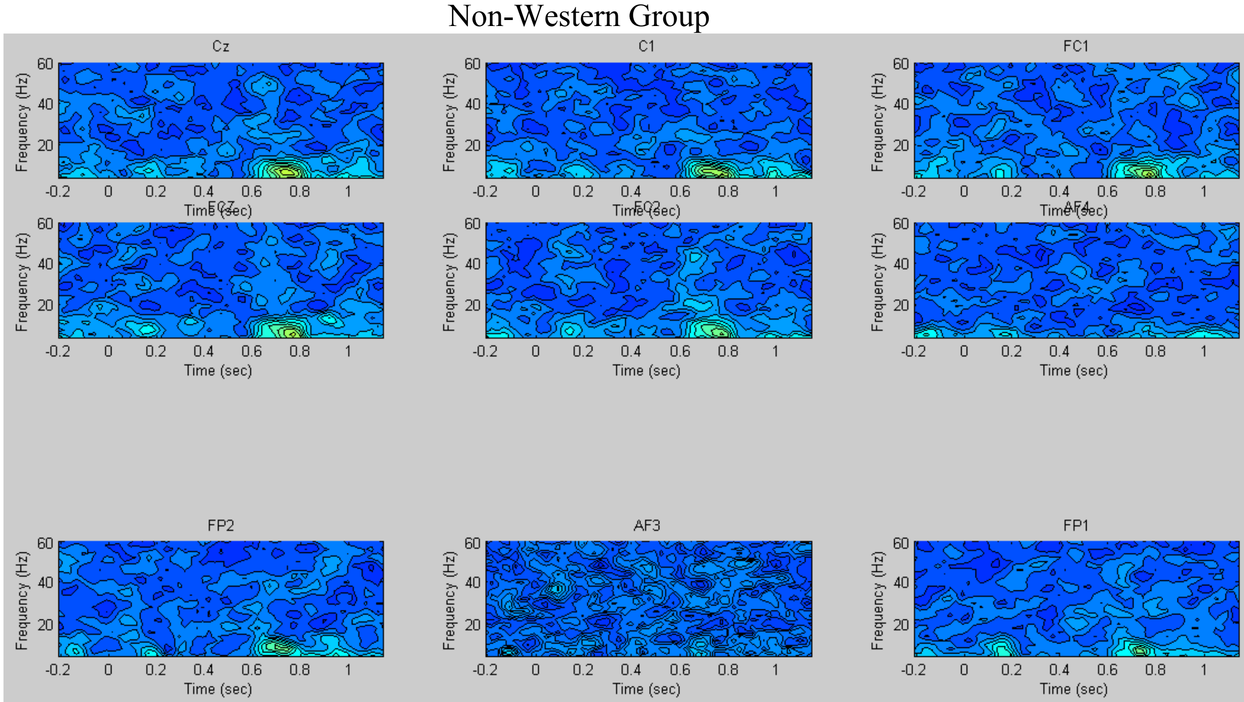
5. Simple meter: SSL (slow tempo): Accented



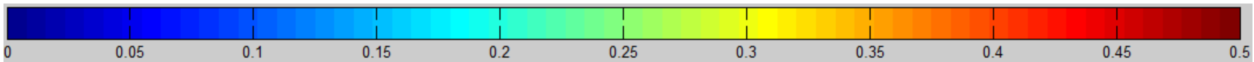
Western Group



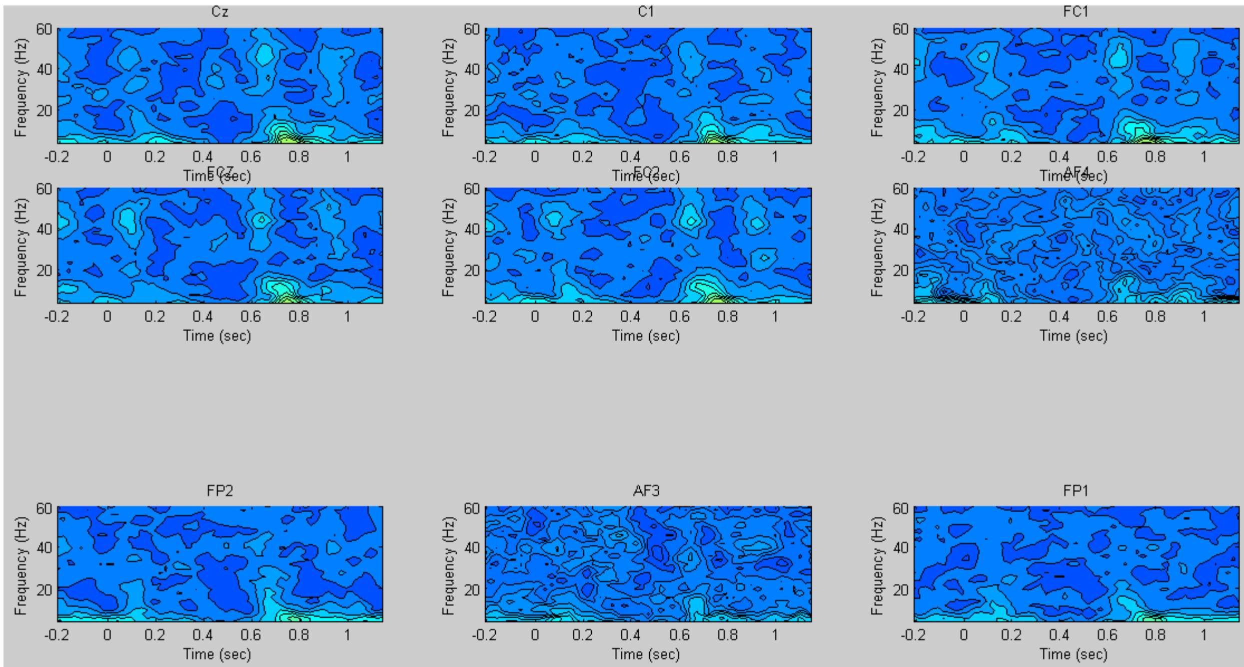
Non-Western Group



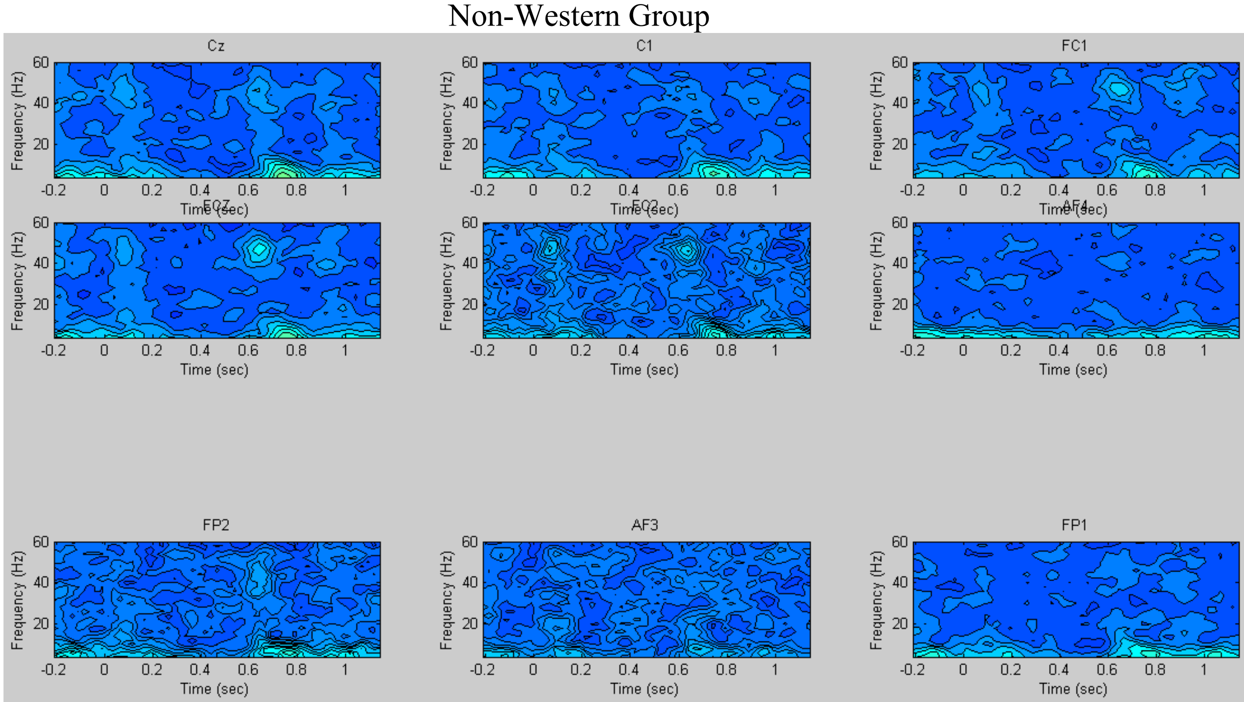
6. Simple meter: SSL (slow tempo): Unaccented



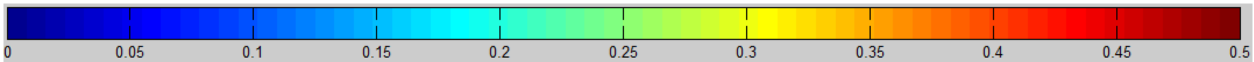
Western Group



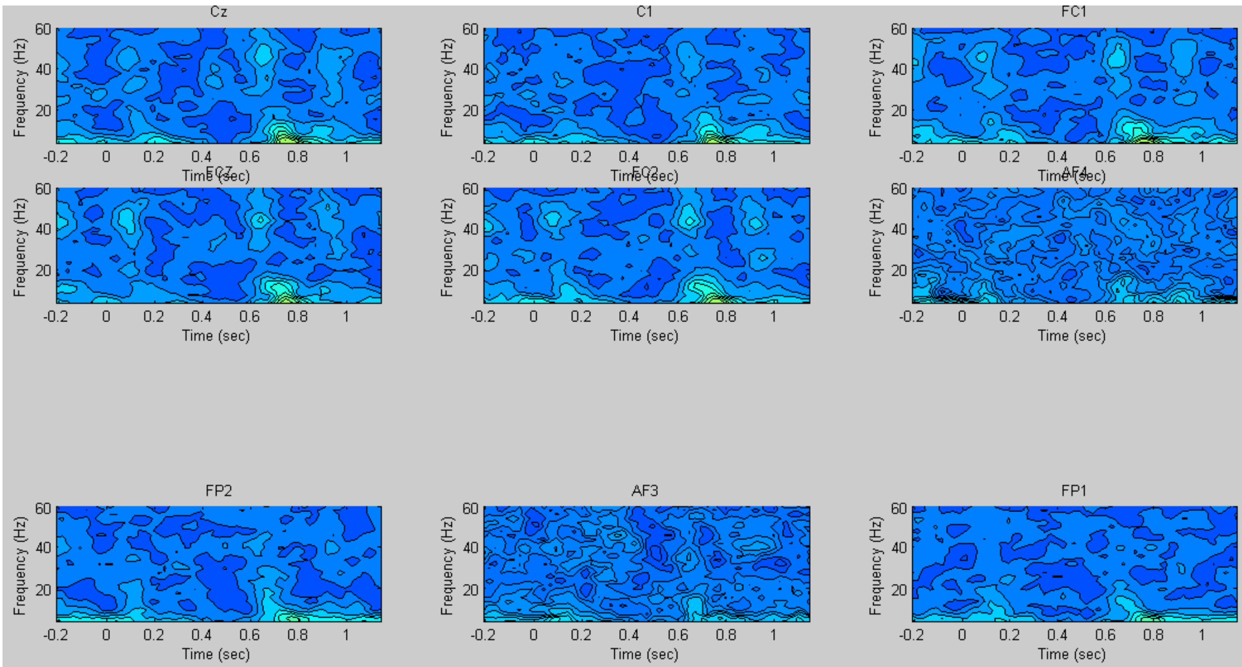
Non-Western Group



7. Simple meter: SSL (fast tempo): Accented



Western Group



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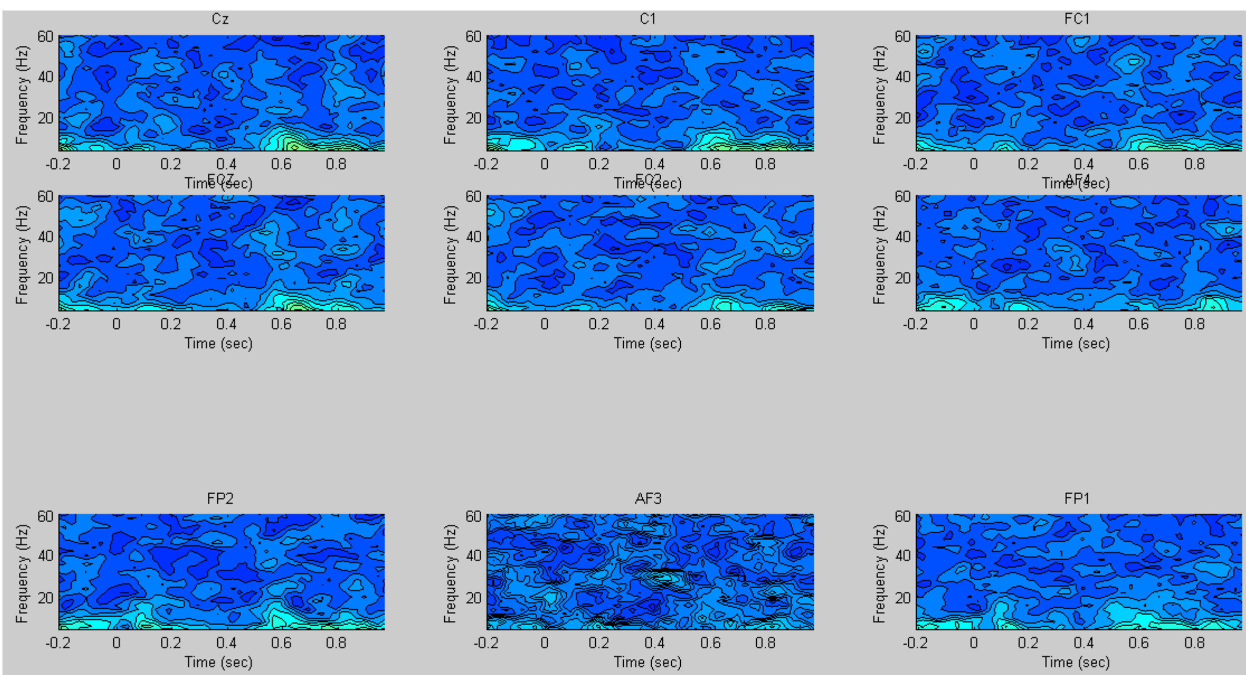
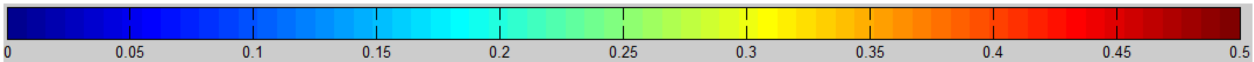
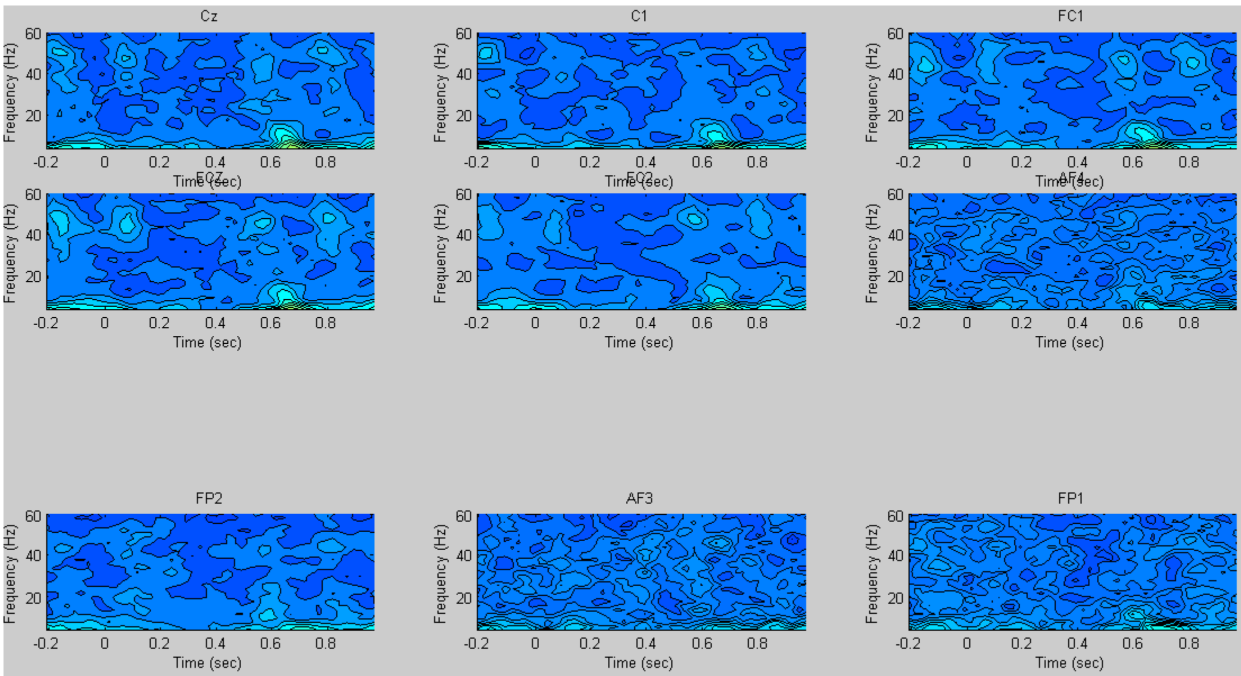


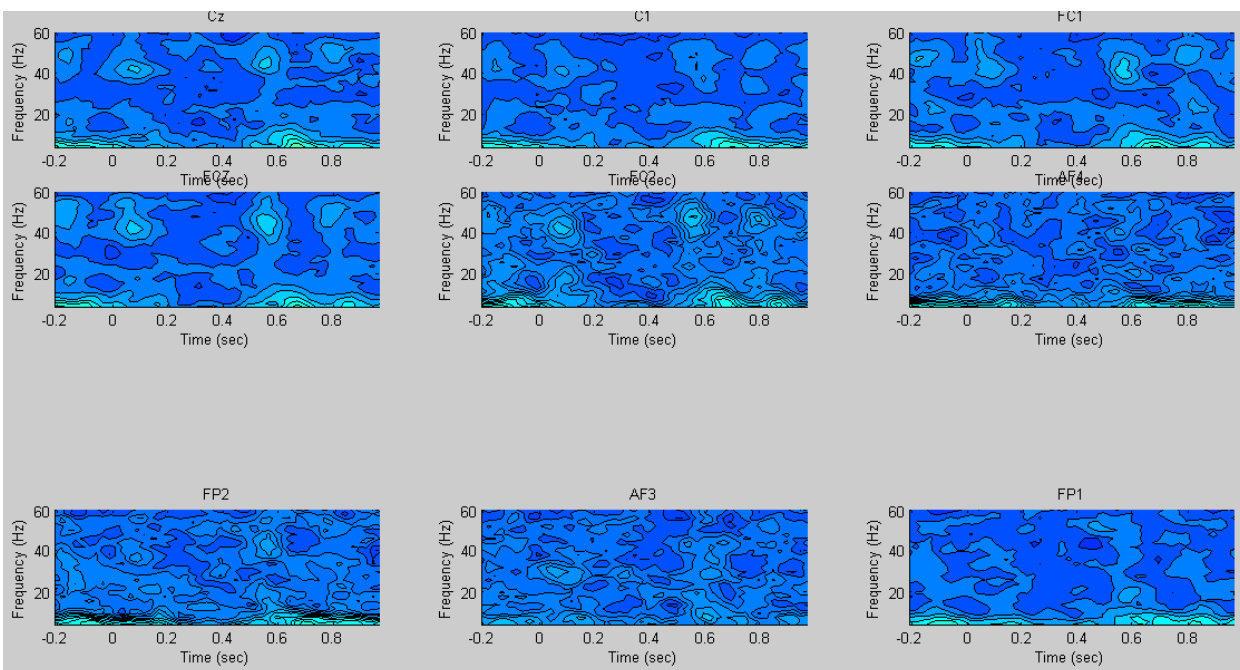
8.   Simple meter: SSL (fast tempo): Unaccented



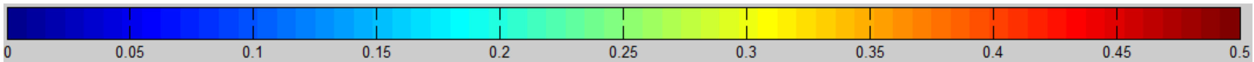
Western Group



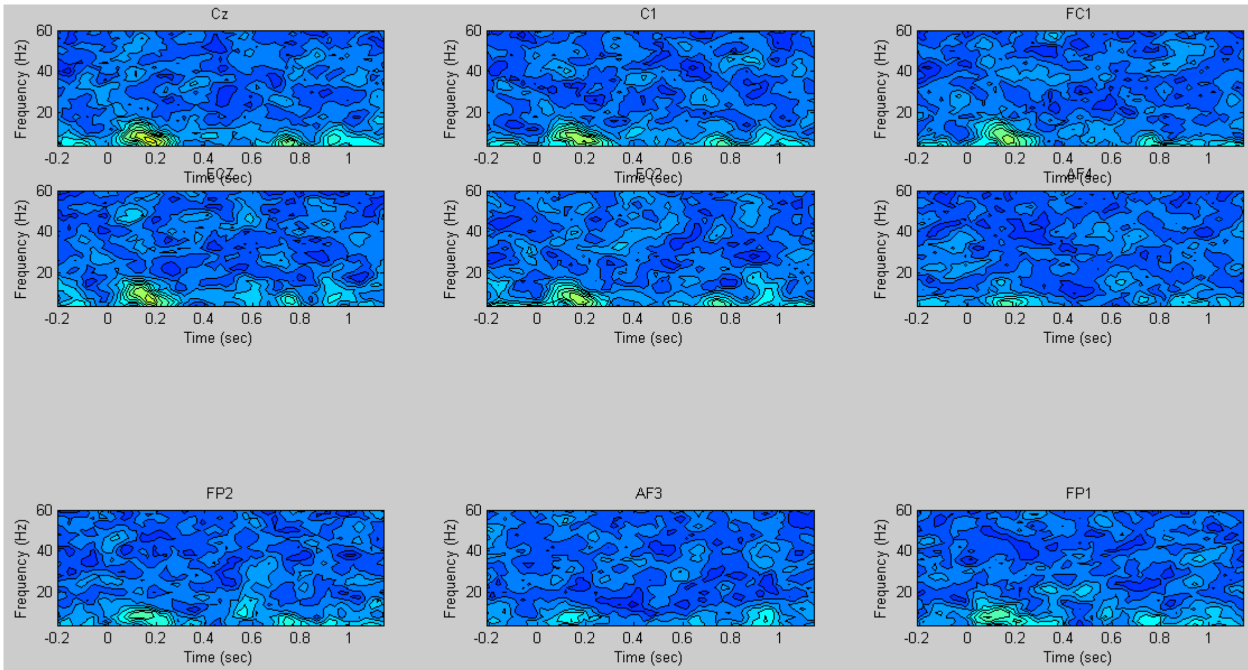
Non-Western Group



9. Complex meter: LSS (slow tempo): Accented



Western Group



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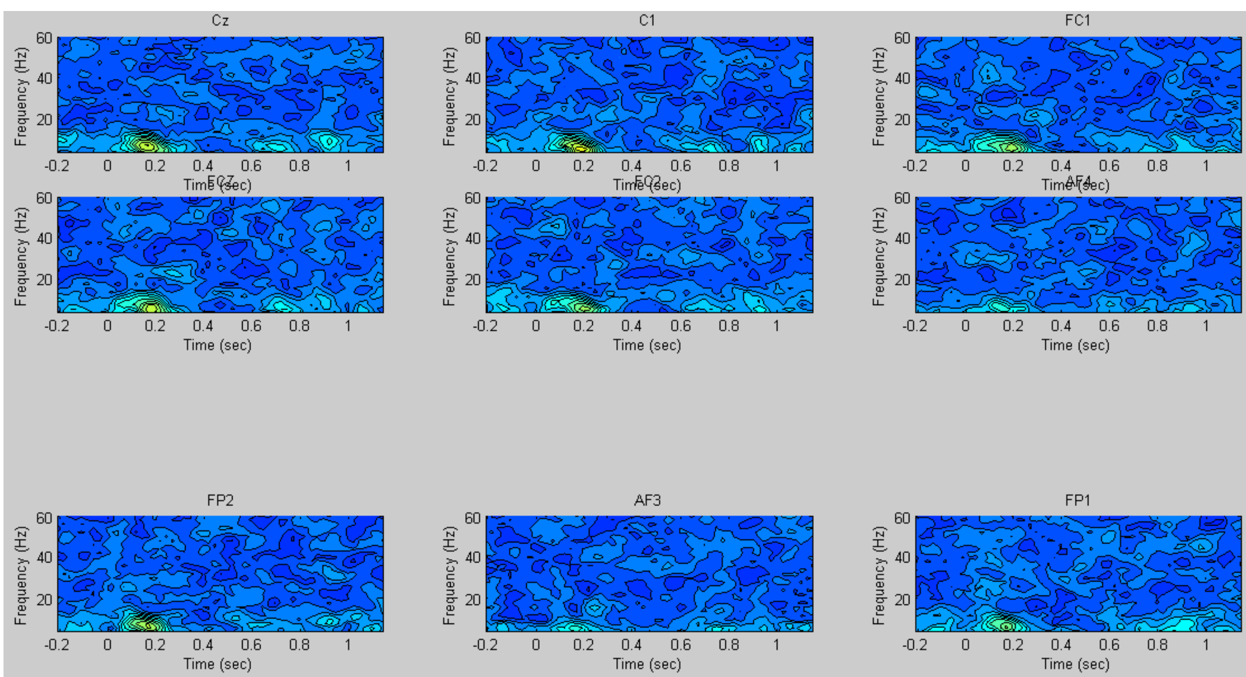
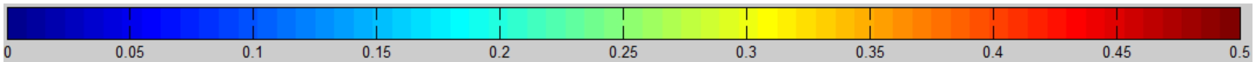
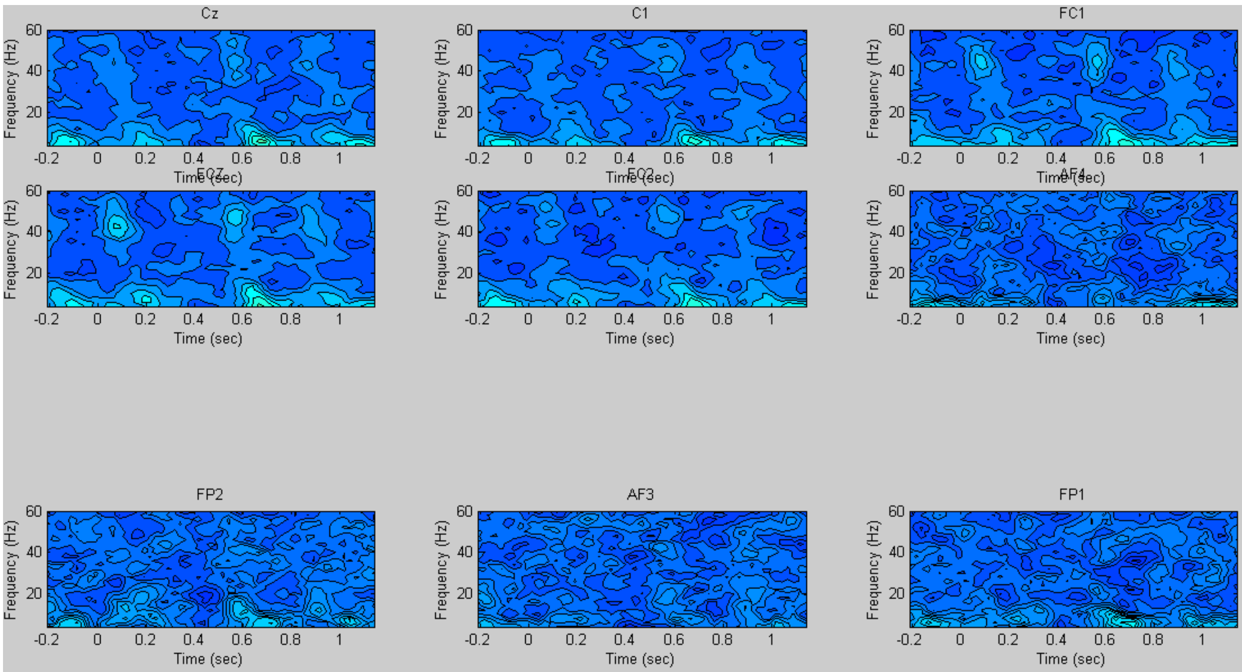


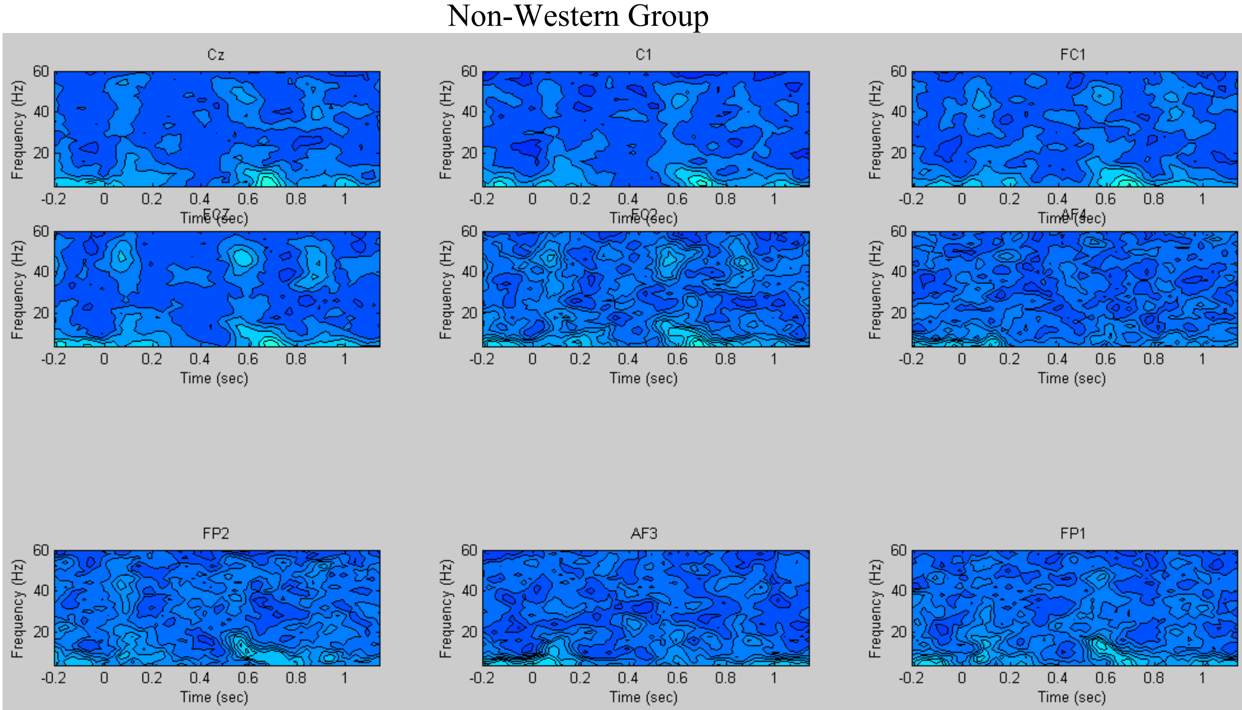
10. Complex meter: LSS (slow tempo): Unaccented



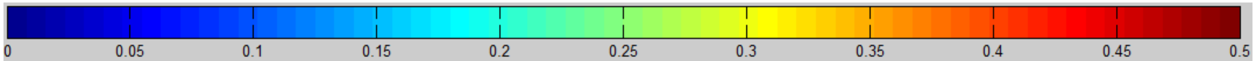
Western Group



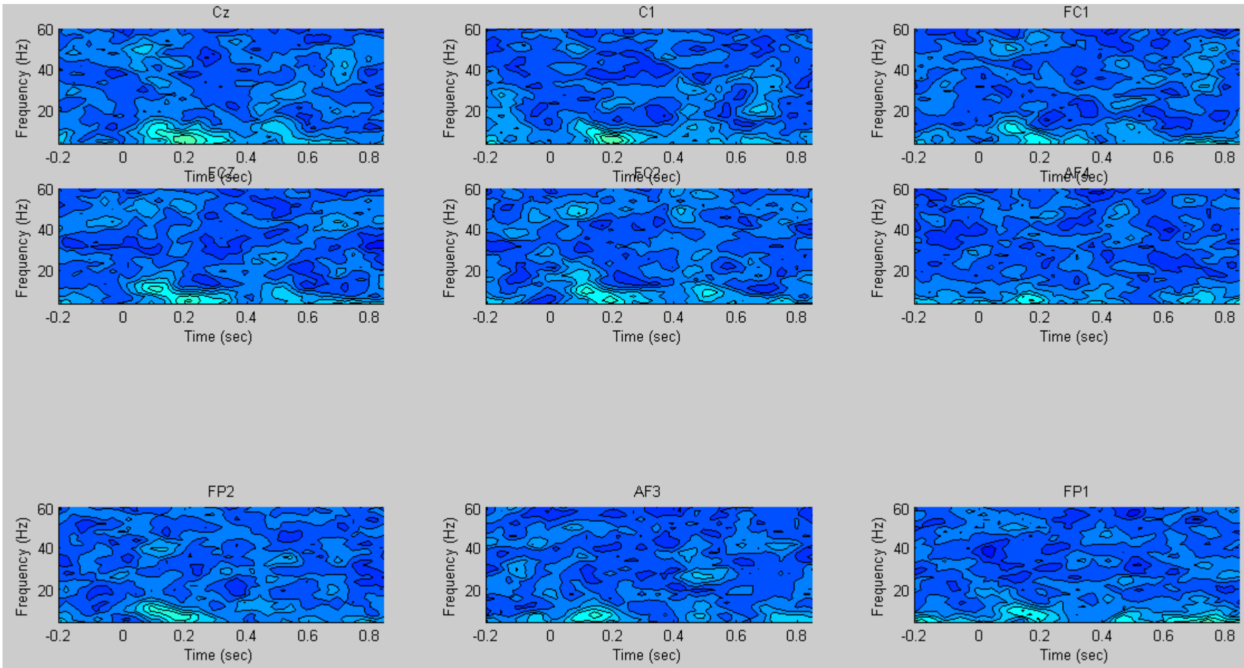
Non-Western Group



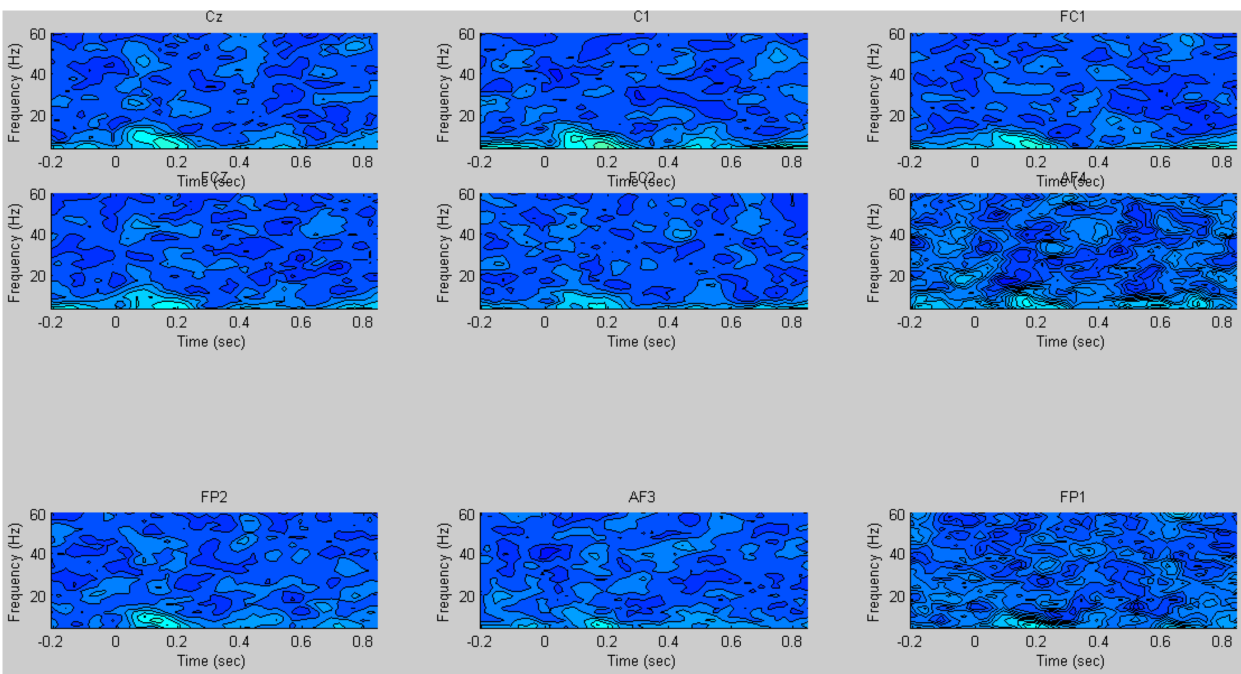
11. Complex meter: LSS (fast tempo): Accented



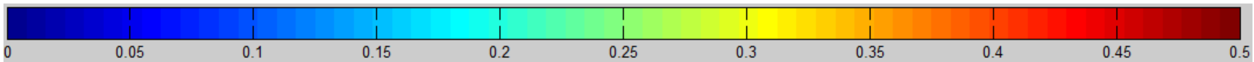
Western Group



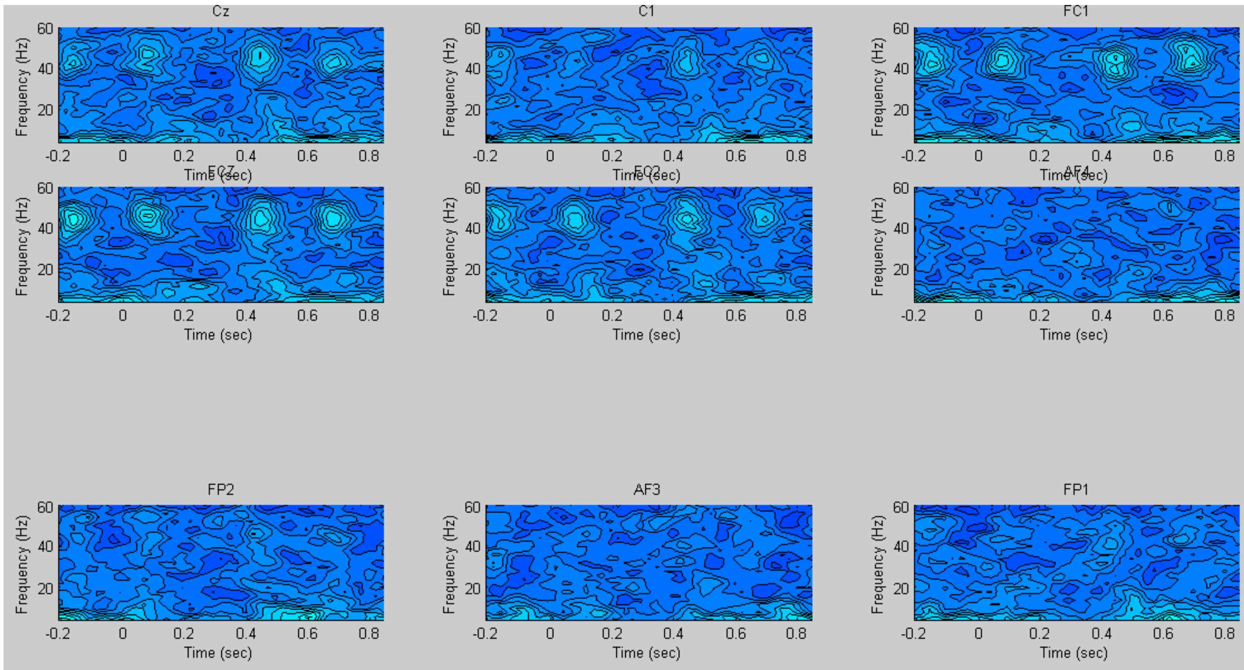
Non-Western Group



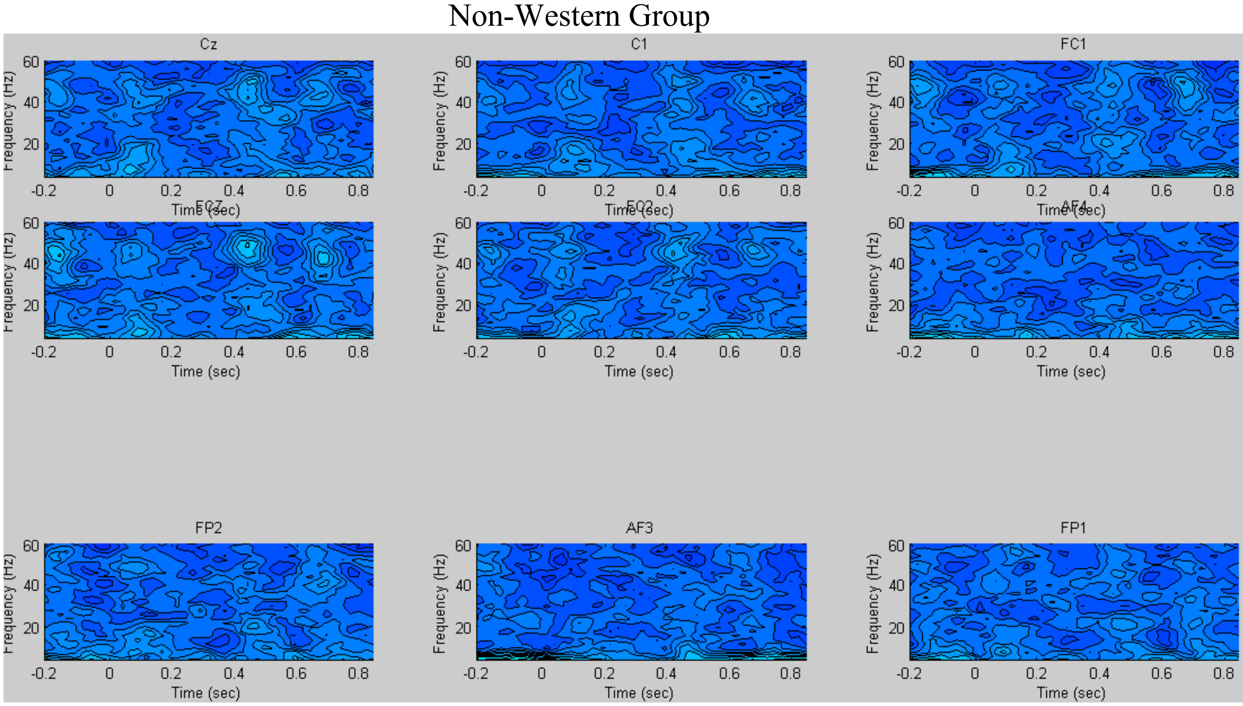
12. Complex meter: LSS (fast tempo): Unaccented



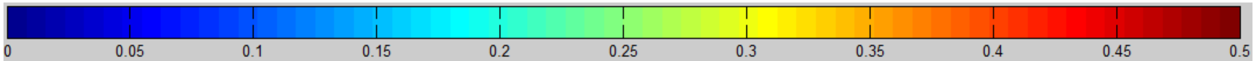
Western Group



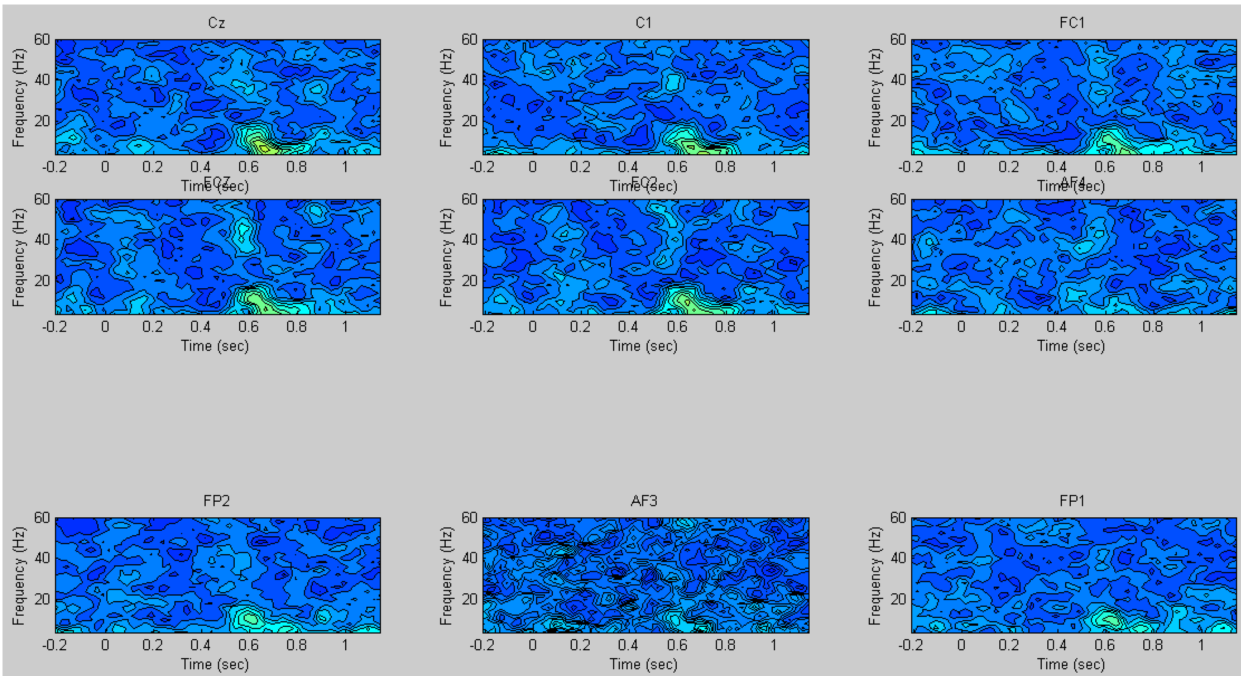
Non-Western Group



13. Complex meter: SSL (slow tempo): Accented



Western Group



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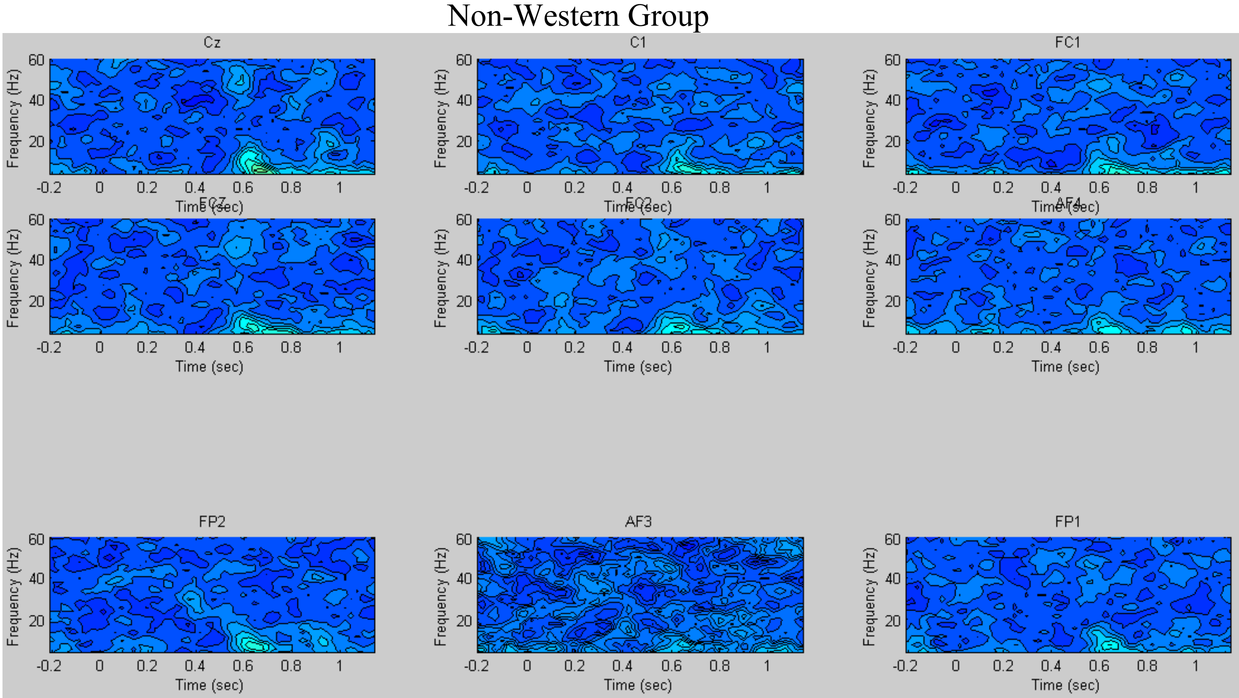
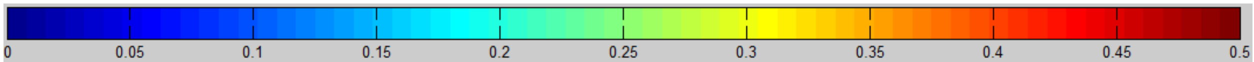
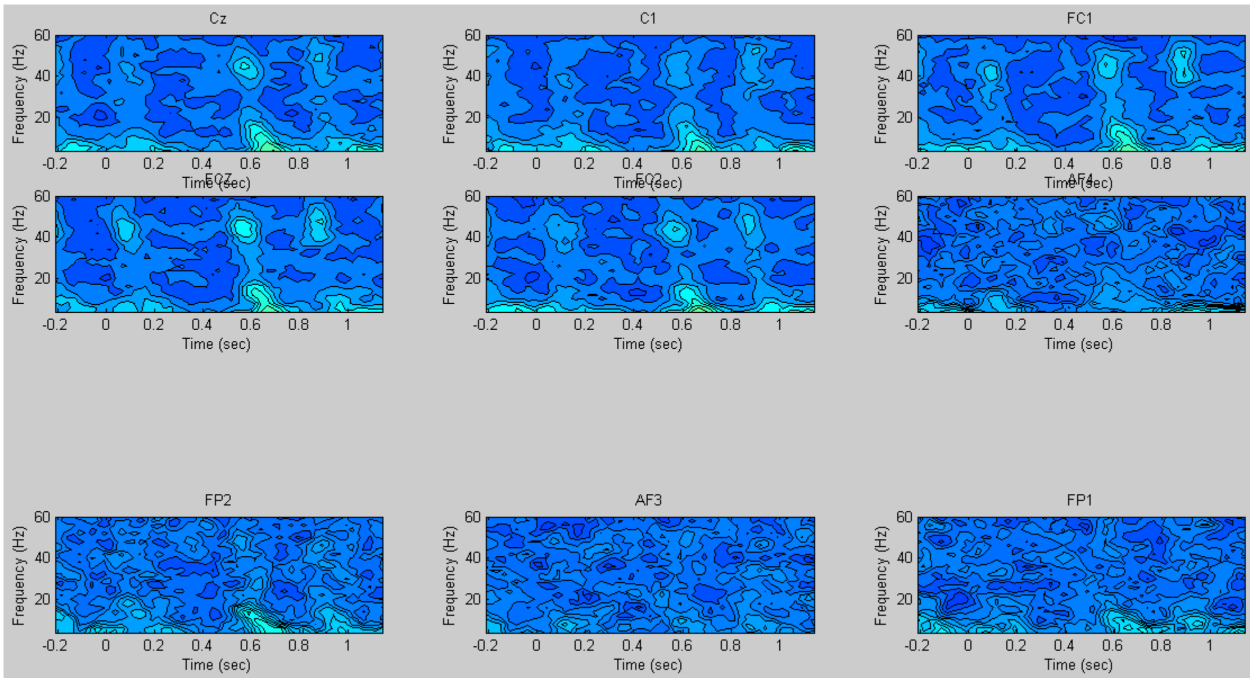


14. Complex meter: SSL (slow tempo): Unaccented



Western Group



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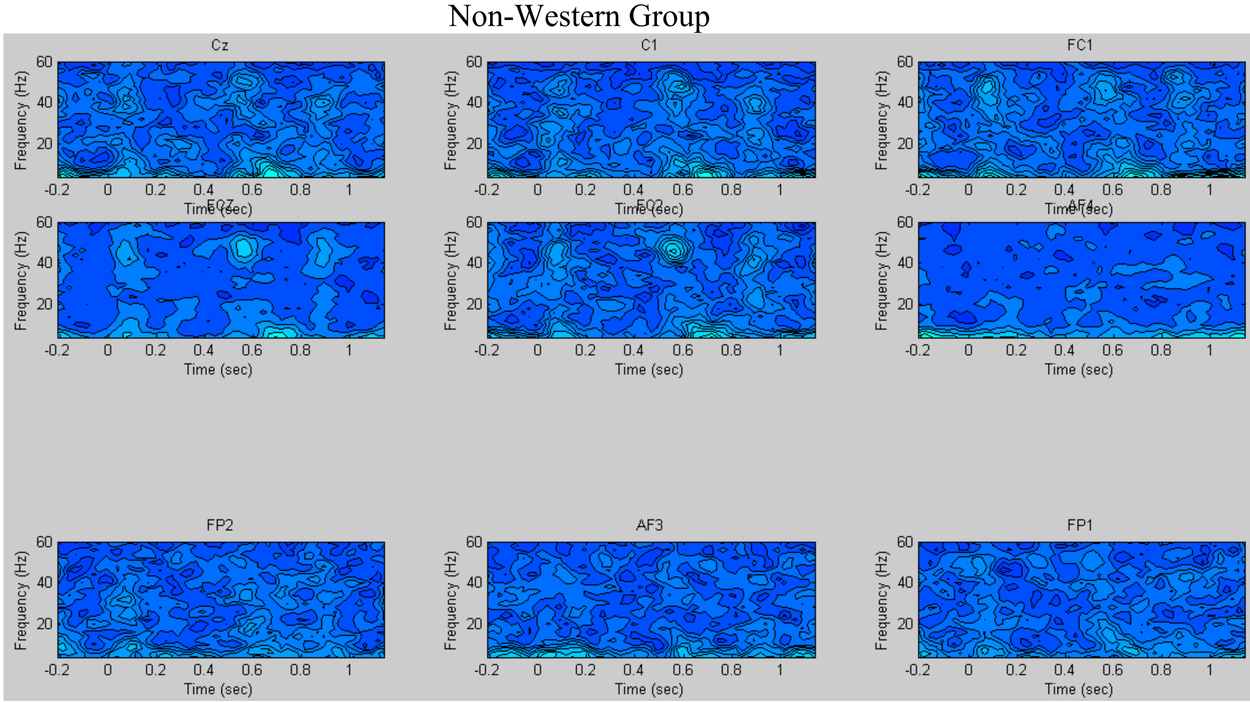
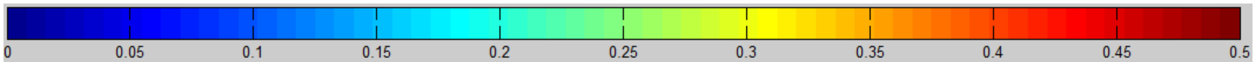
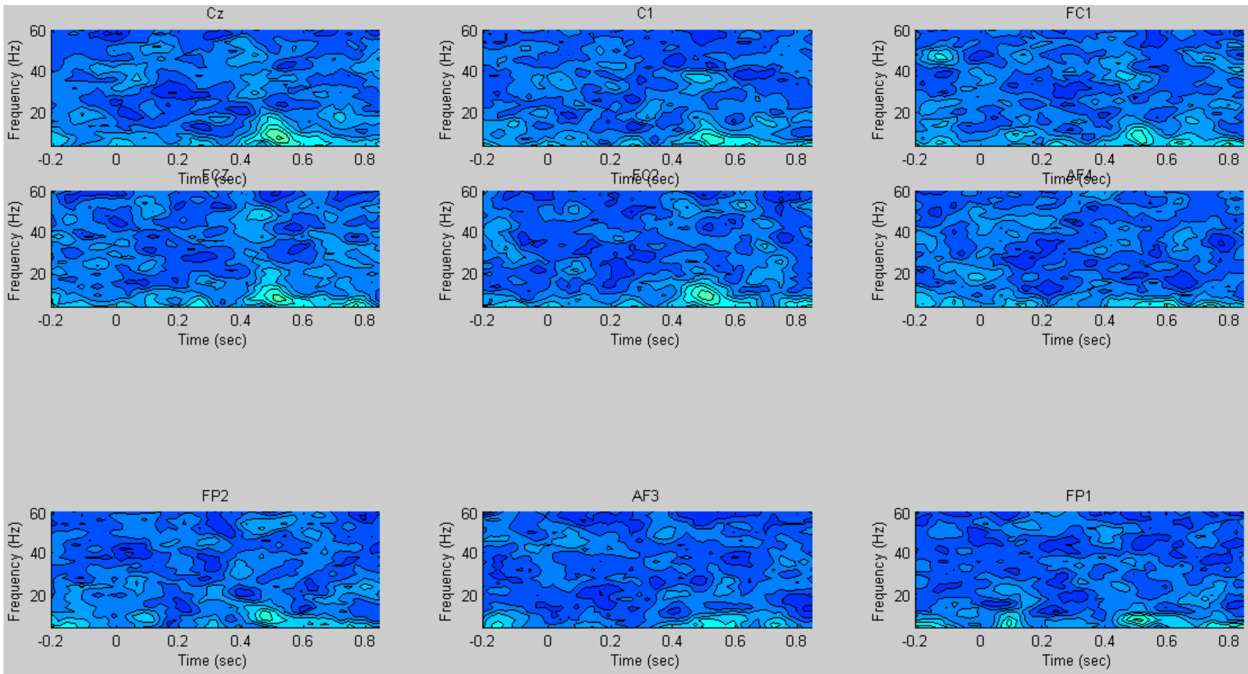


15. Complex meter: SSL (fast tempo): Accented



Western Group



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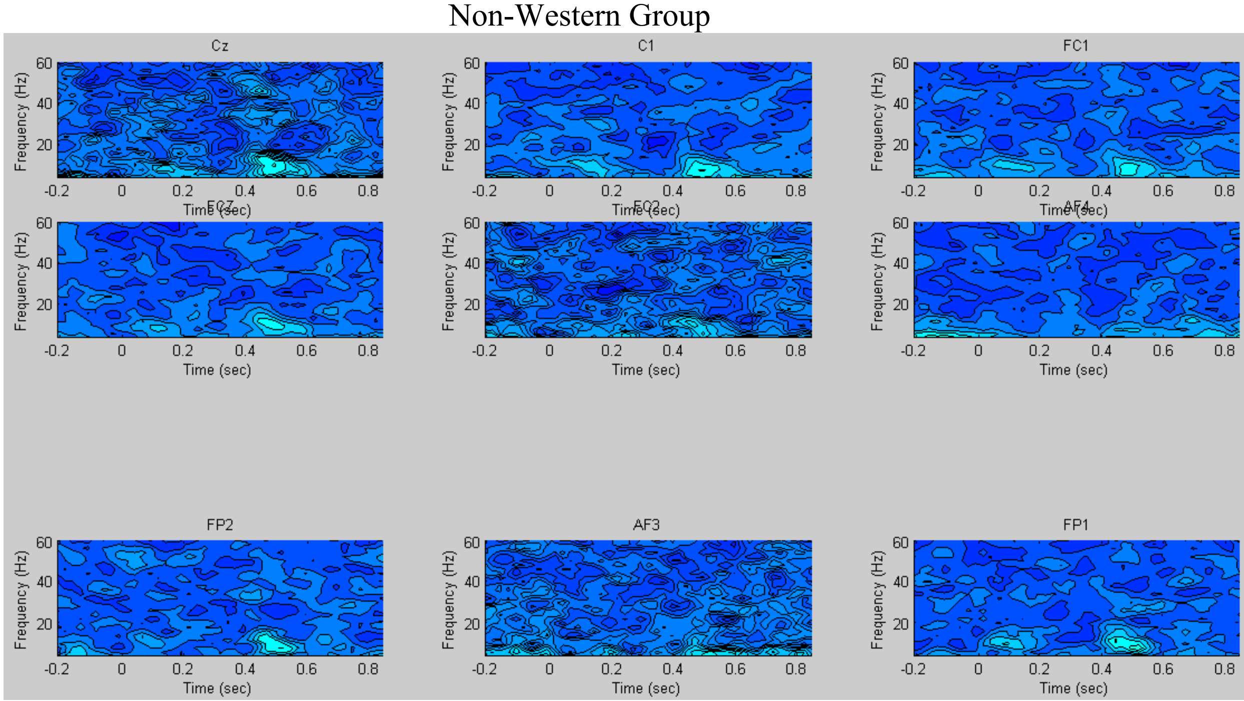
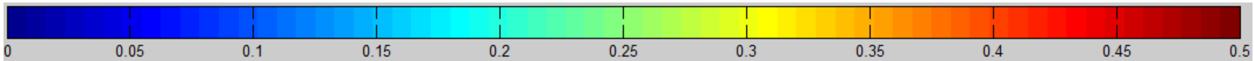
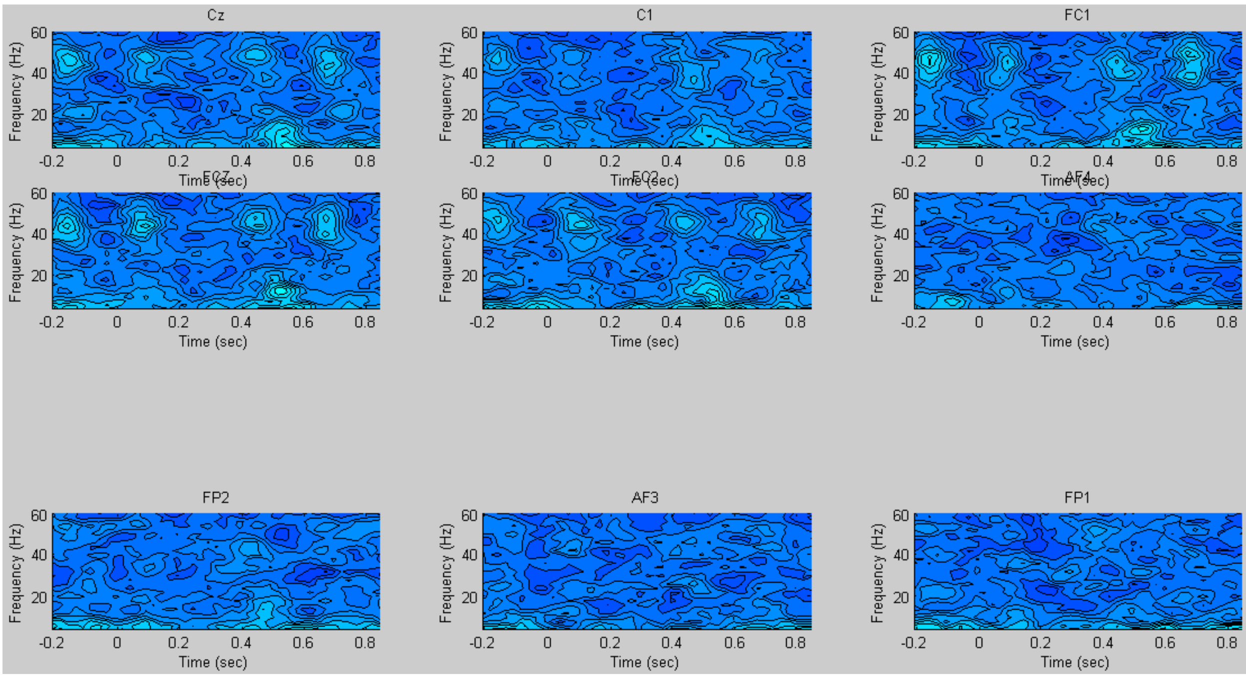


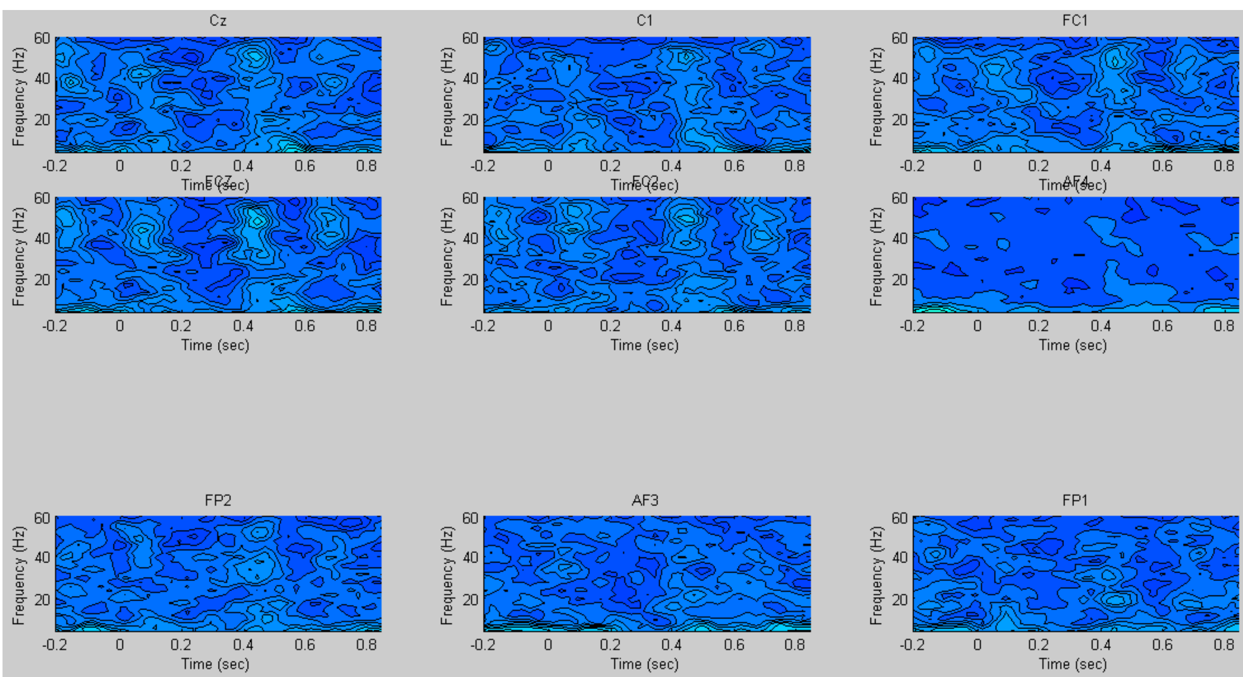
16. Complex meter: SSL (fast tempo): Unaccented



Western Group



Non-Western Group

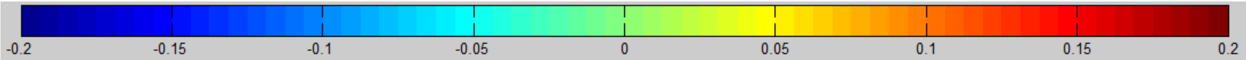


Appendix D

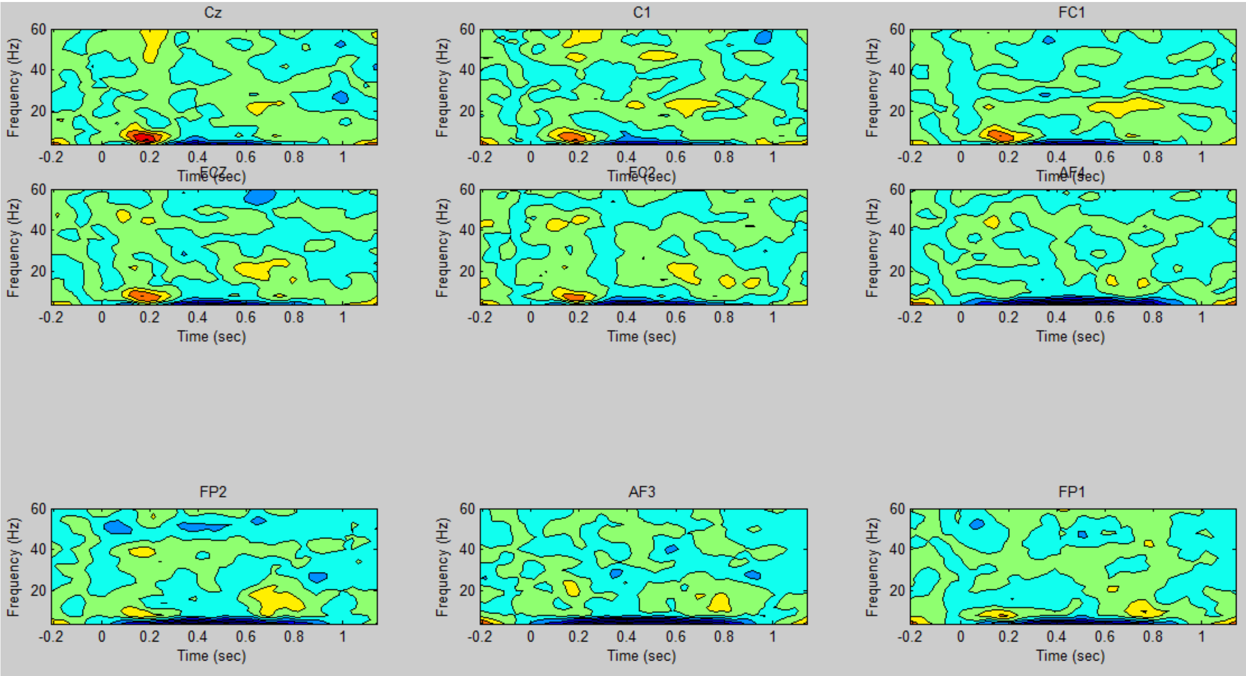
In the following induced activity time frequency figures, the electrodes are organized as follows:

Cz	C1	FC1
FCz	FC2	AF4
FP2	AF3	FP1

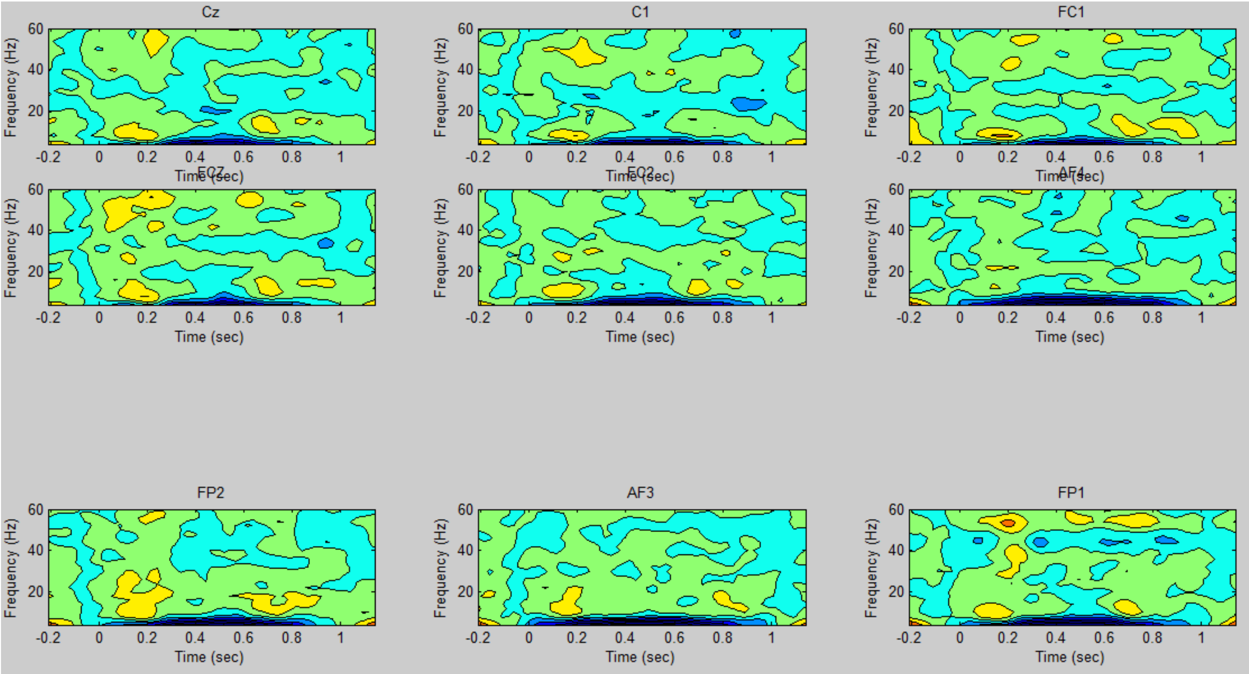
1. Simple meter: LSS (slow tempo): Accented



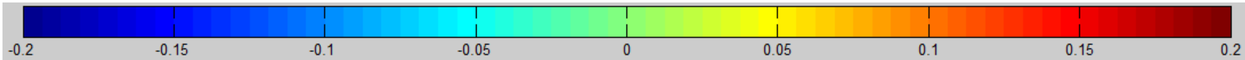
Western Group



Non-Western Group



2. Simple meter: LSS (slow tempo): Unaccented



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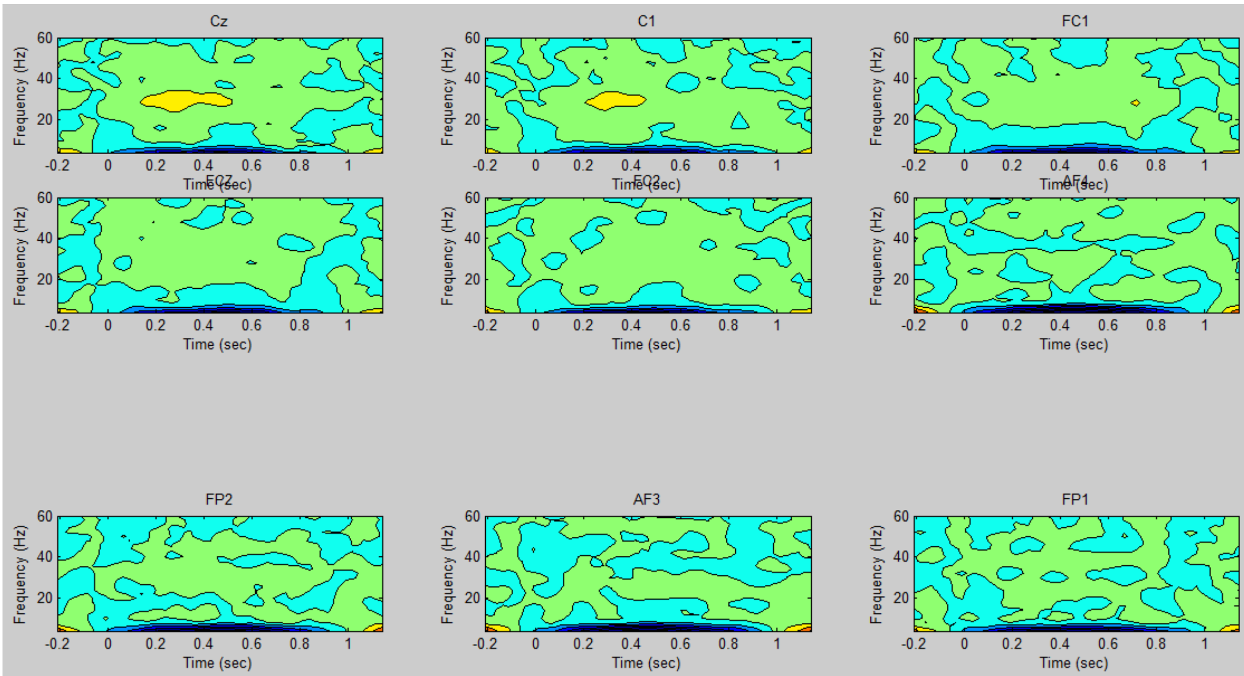

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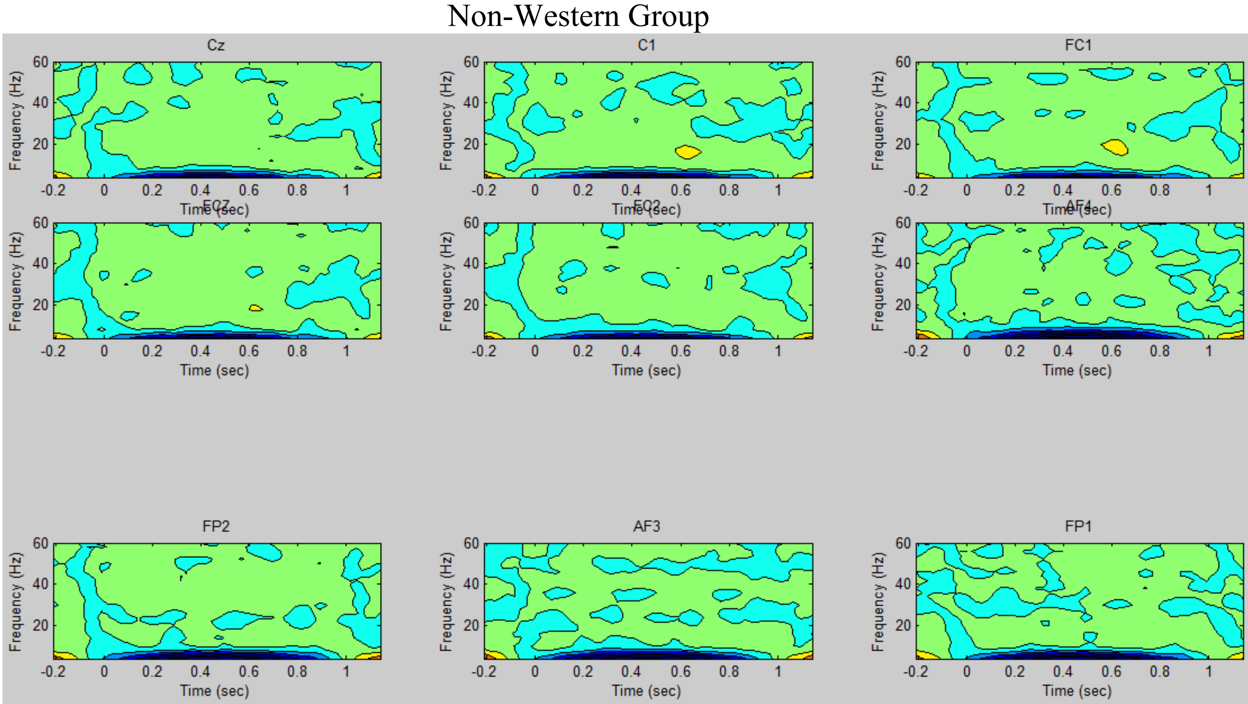
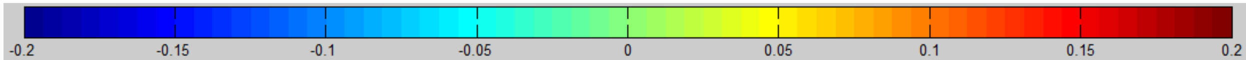


3. Simple meter: LSS (fast tempo): Accented



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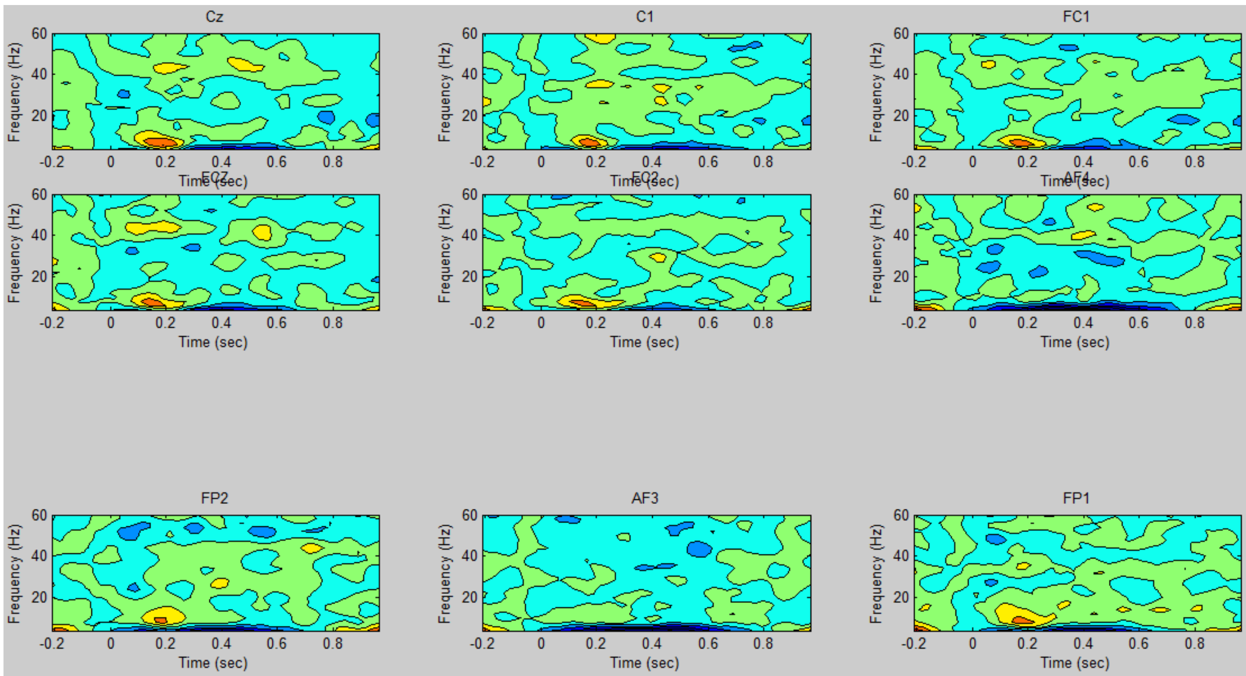

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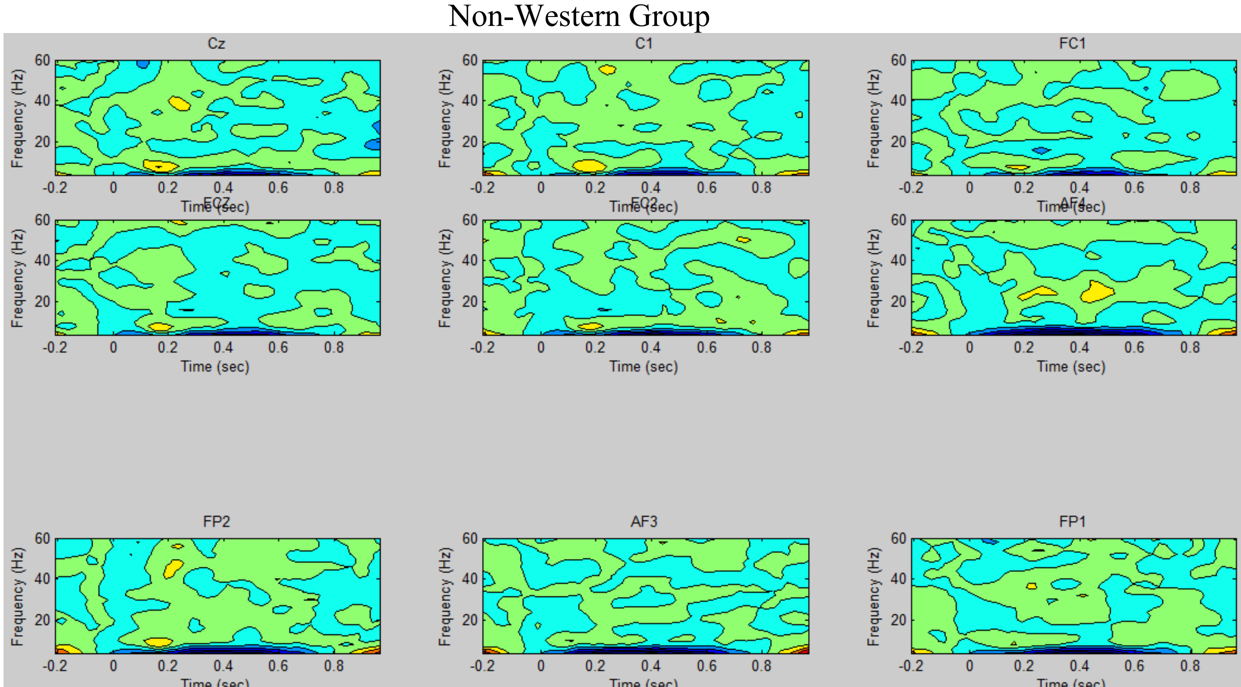
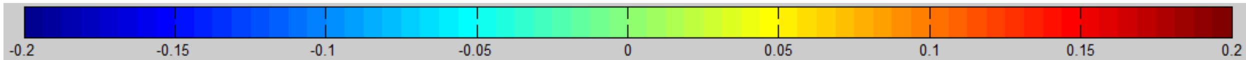


4. Simple meter: LSS (fast tempo): Unaccented



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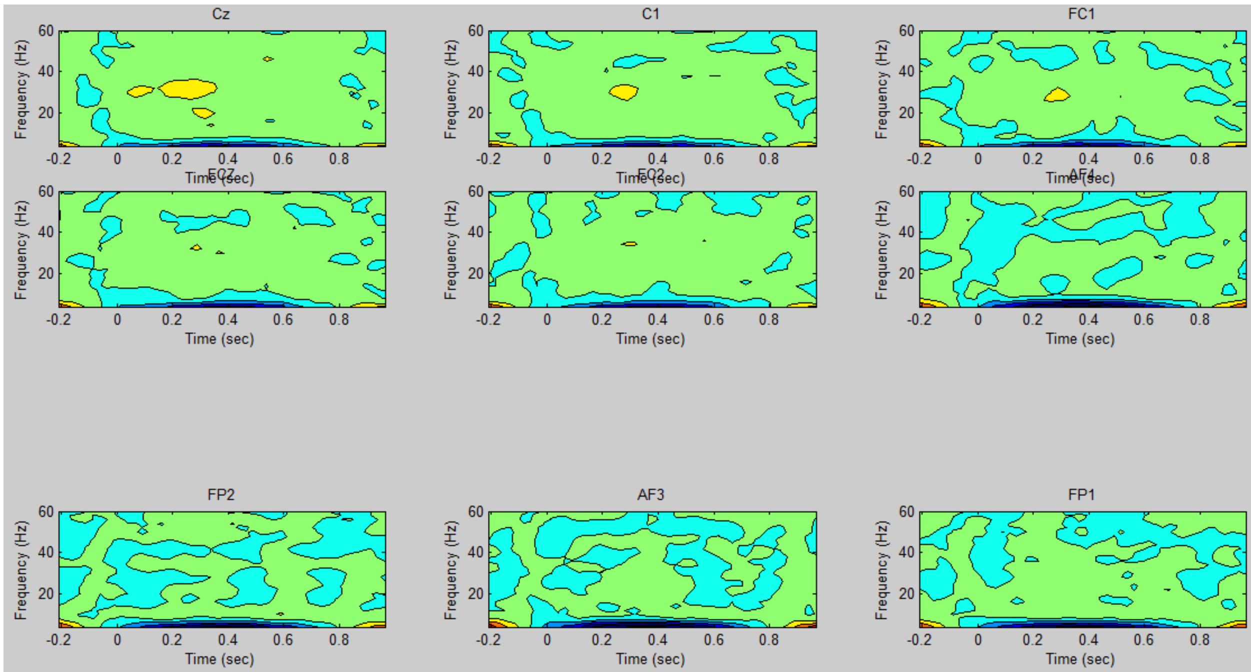

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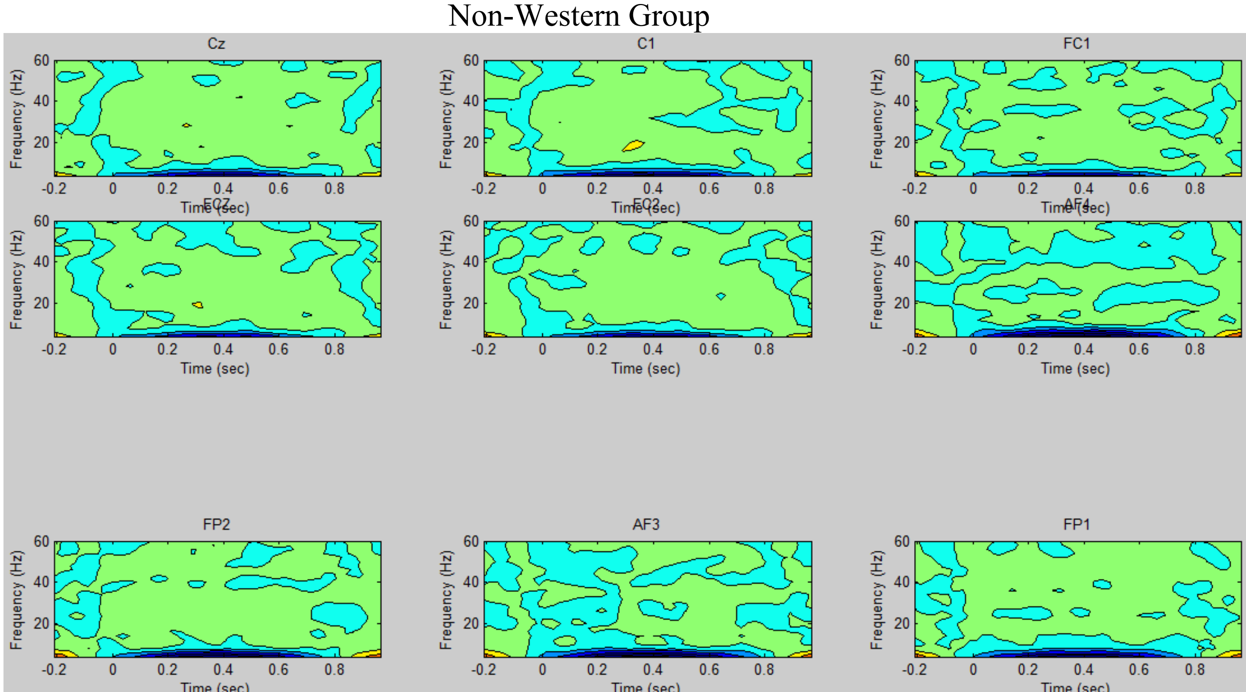
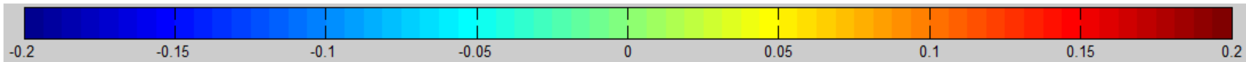


5. Simple meter: SSL (slow tempo): Accented



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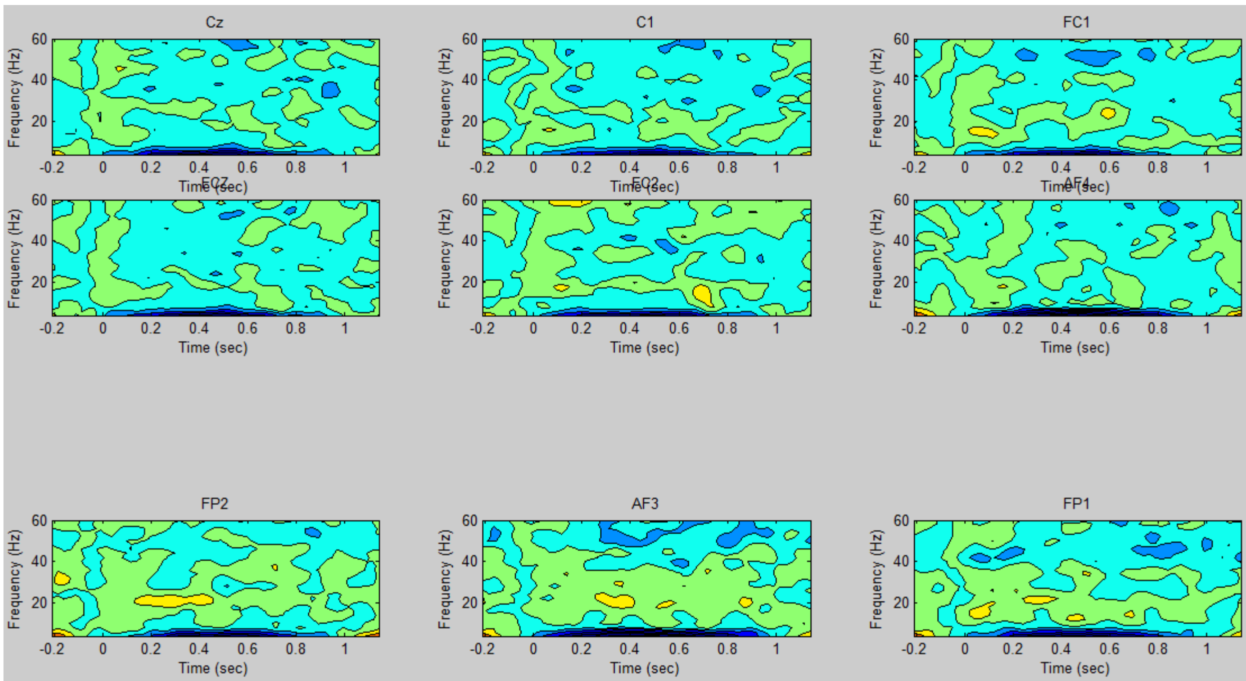

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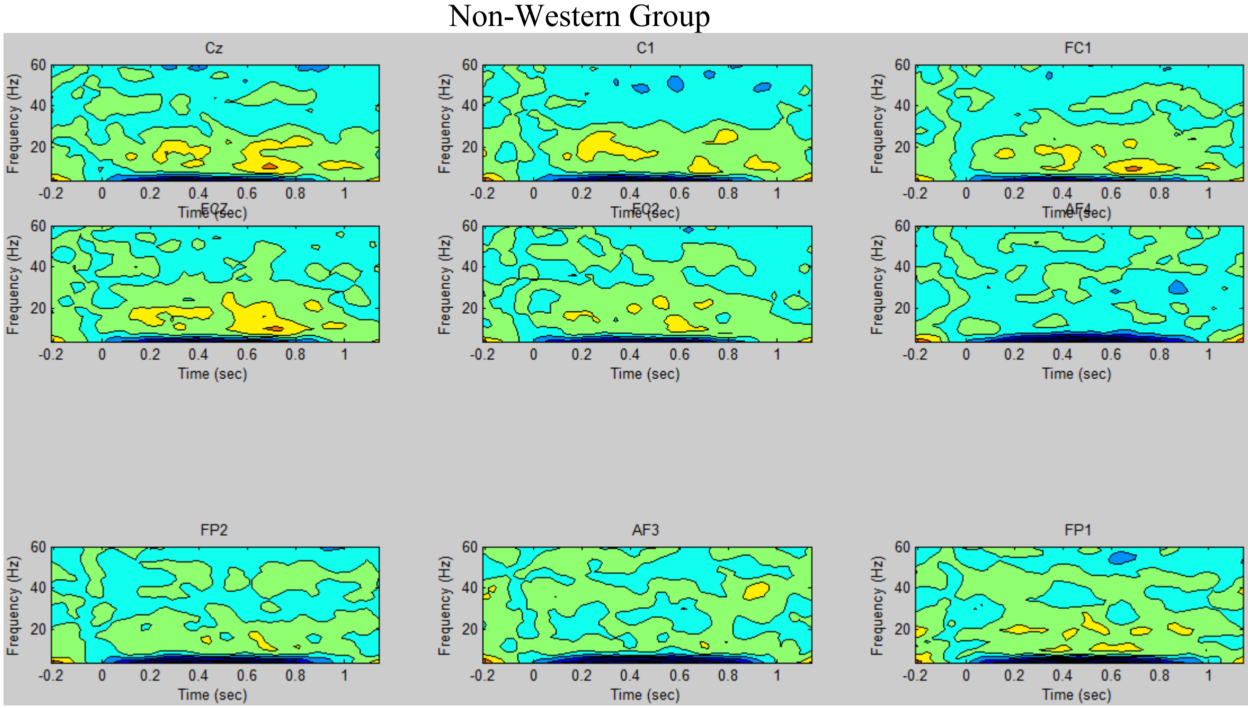
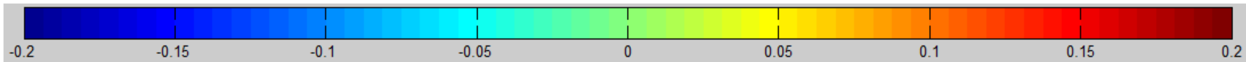


6. Simple meter: SSL (slow tempo): Unaccented



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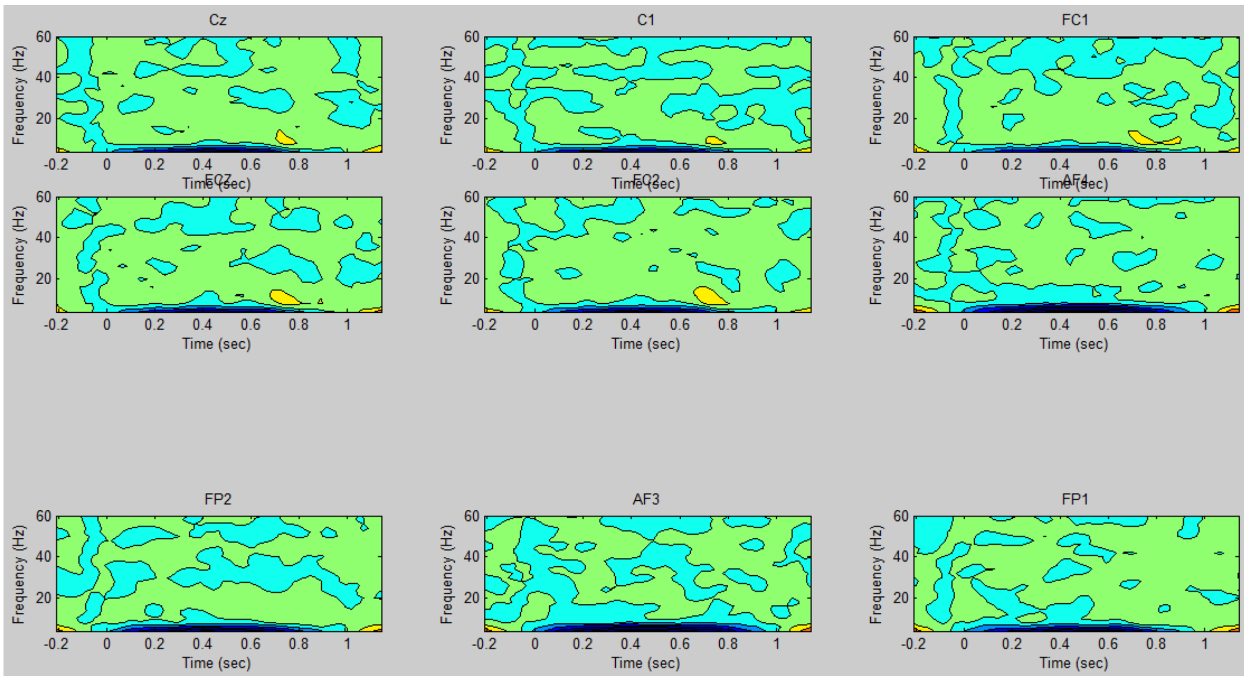

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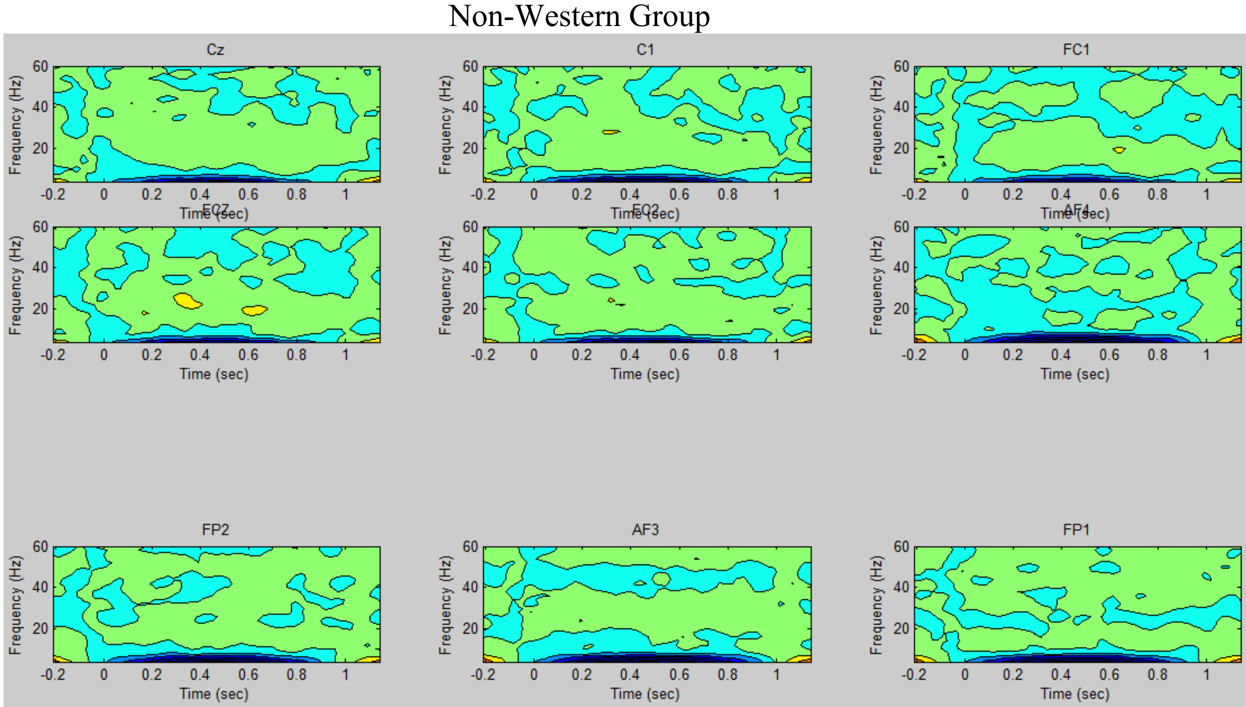
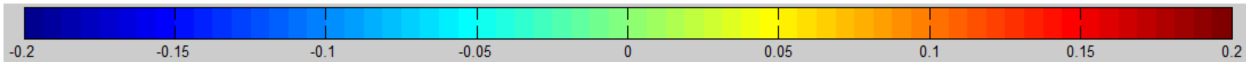


7. Simple meter: SSL (fast tempo): Accented



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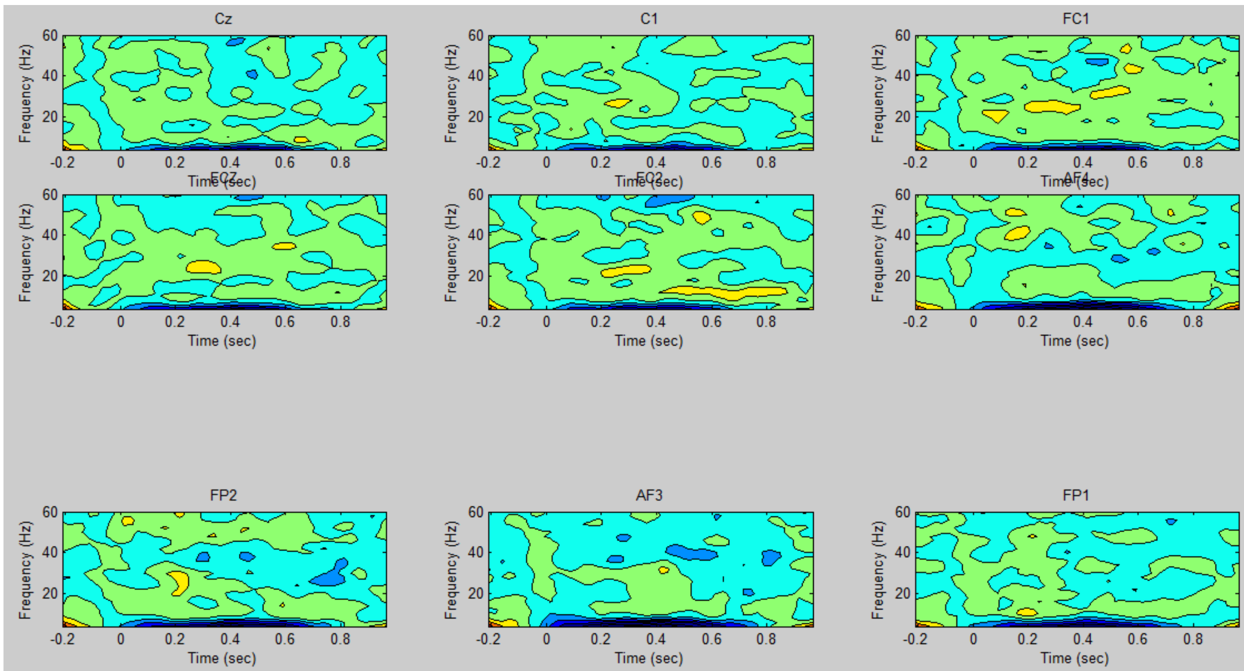

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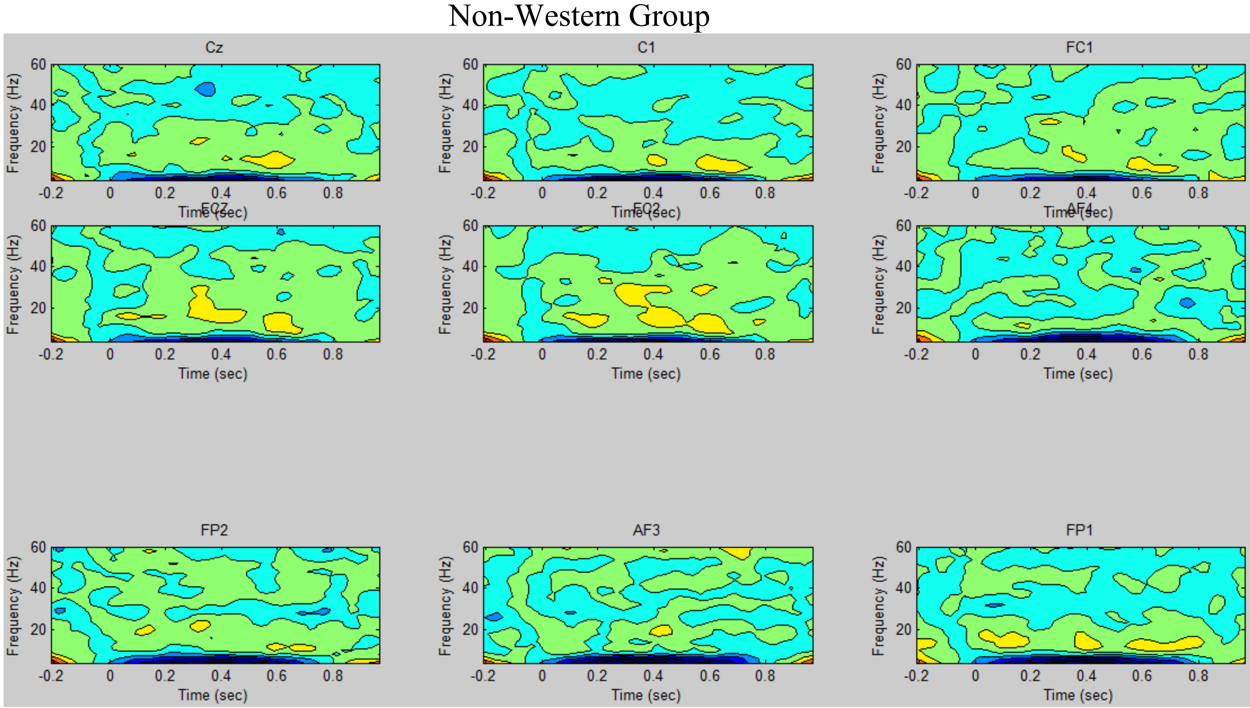
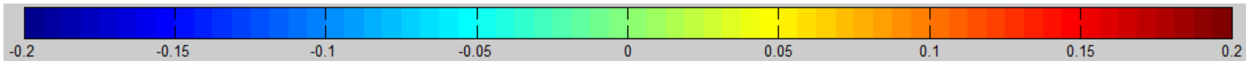


8. Simple meter: SSL (fast tempo): Unaccented



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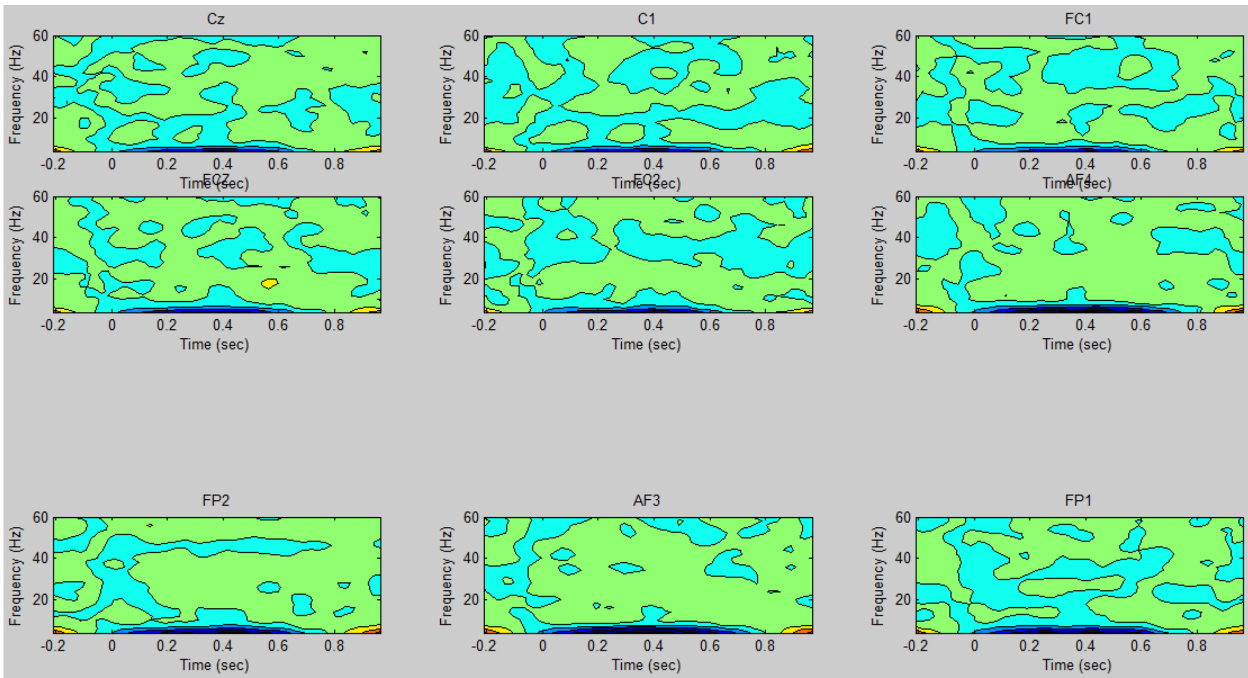

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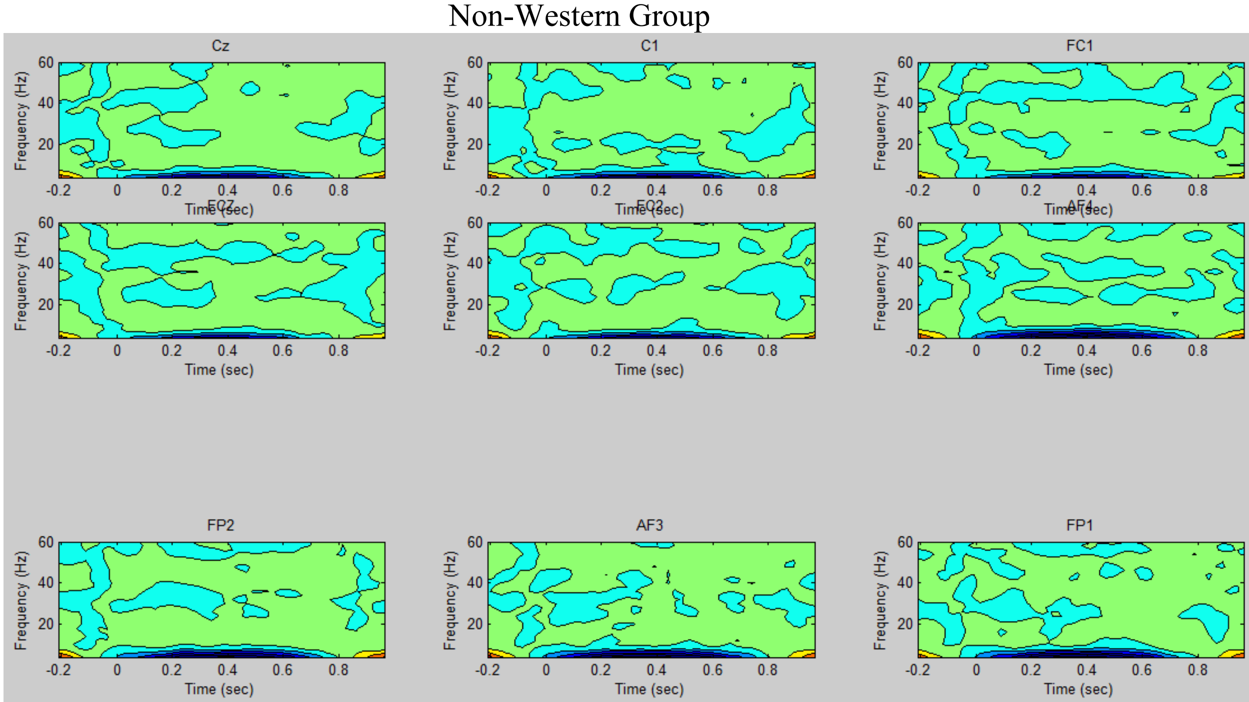
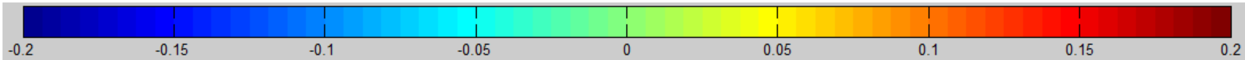


9. Complex meter: LSS (slow tempo): Accented



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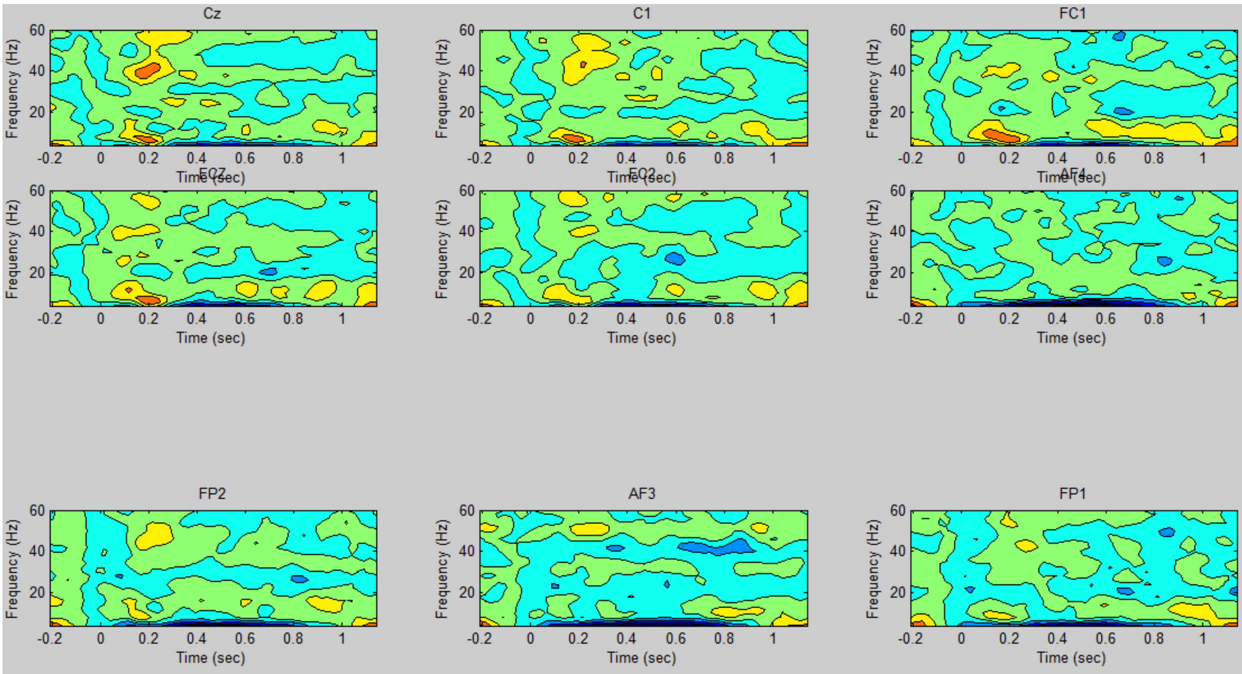

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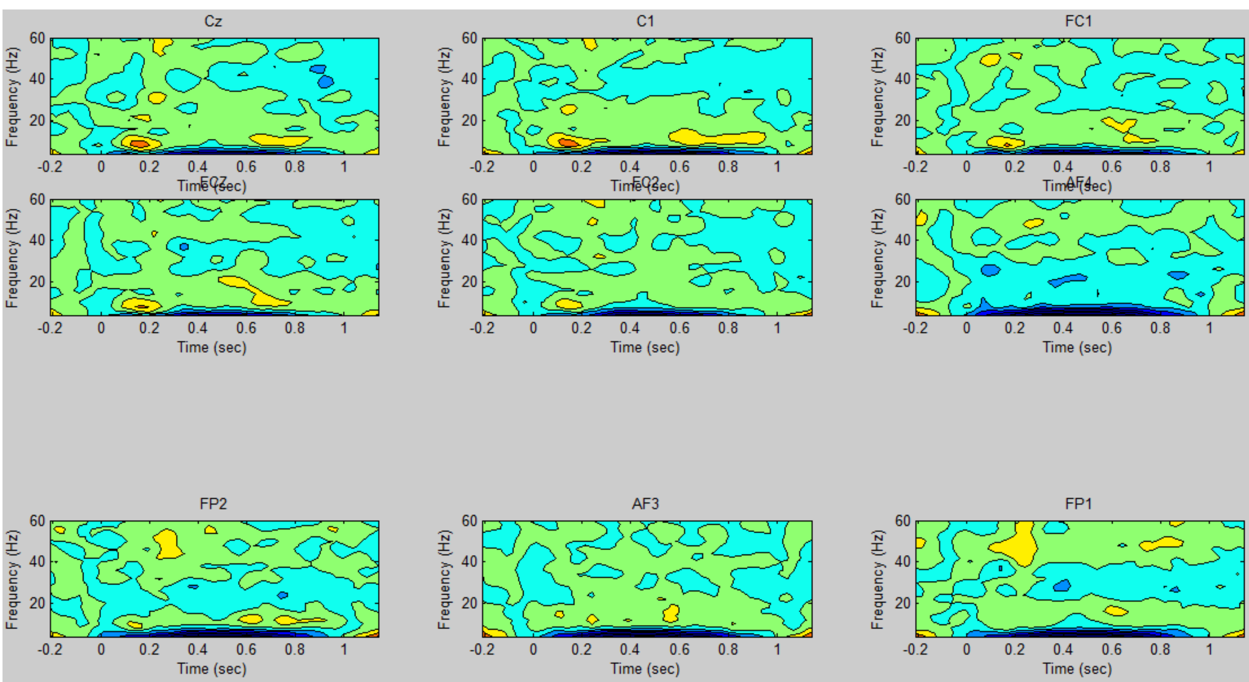
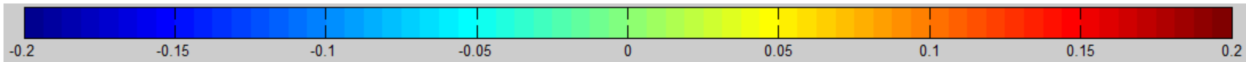


10. Complex meter: LSS (slow tempo): Unaccented



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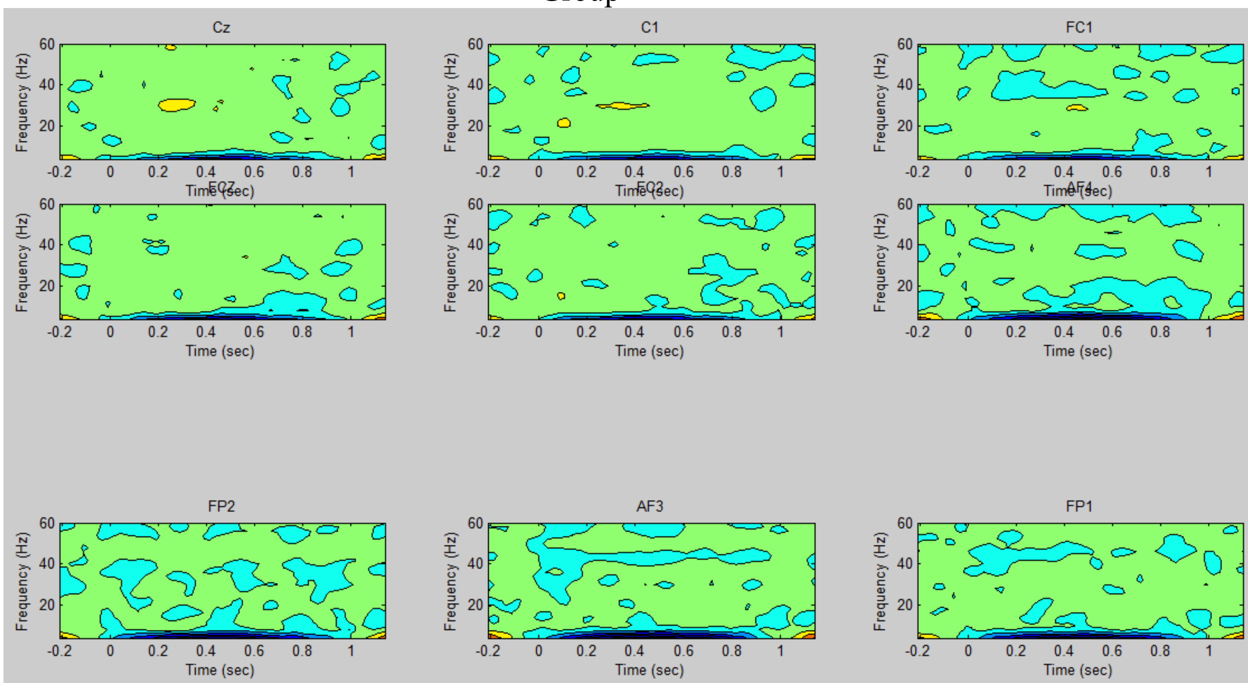

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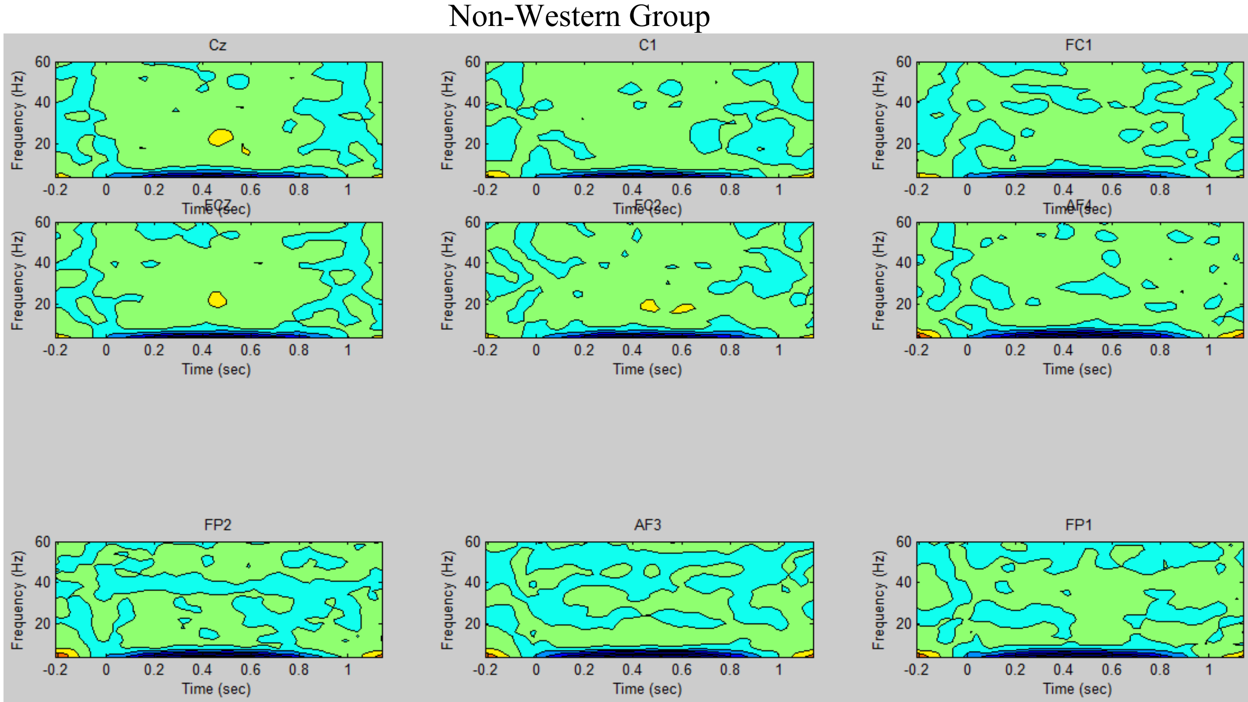
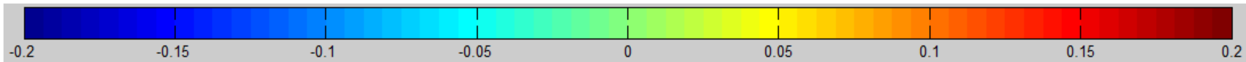


11. Complex meter: LSS (fast tempo): Accented



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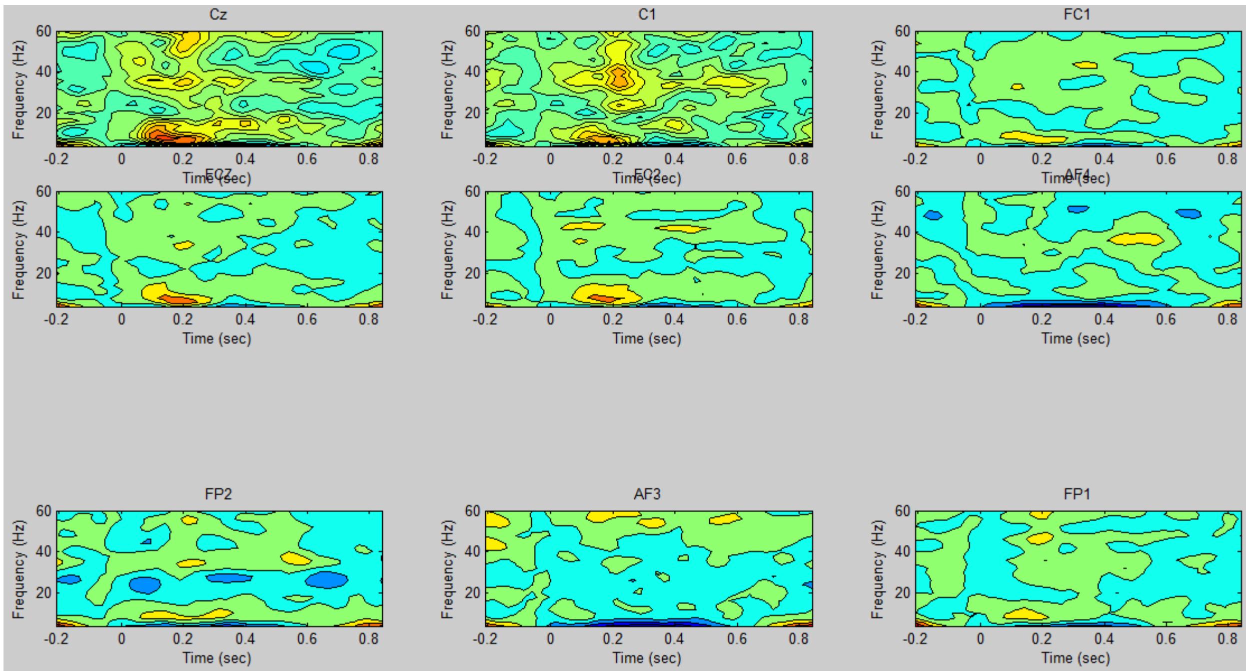

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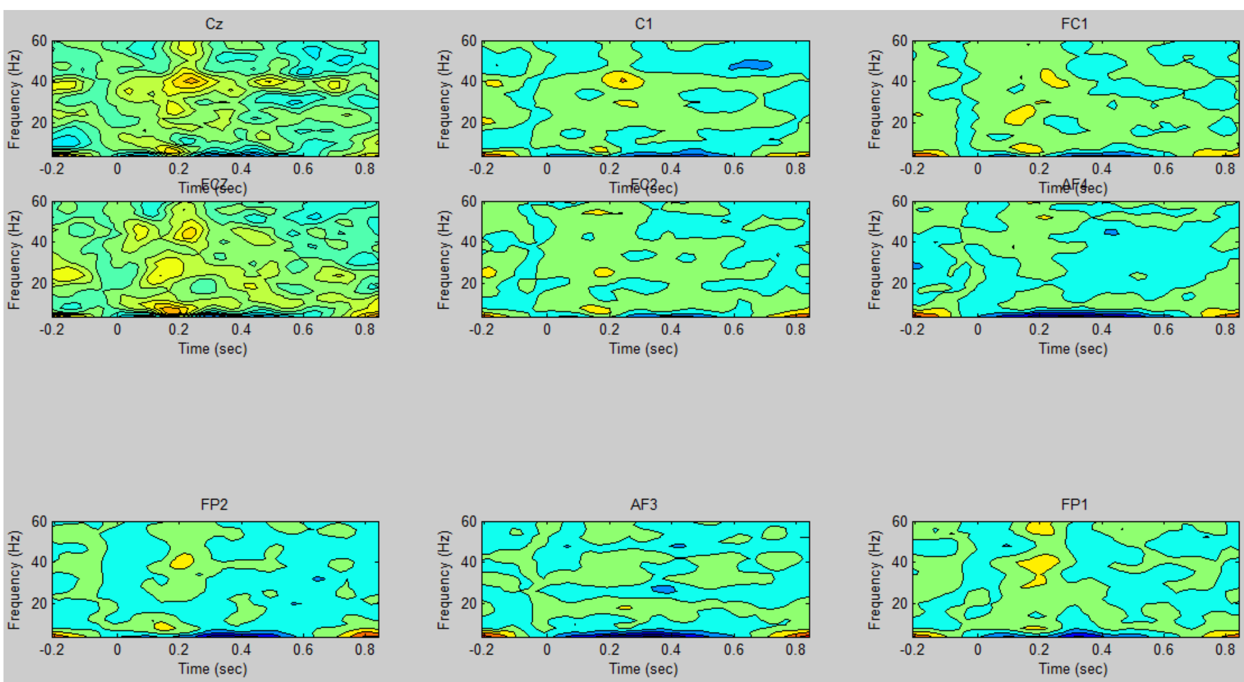
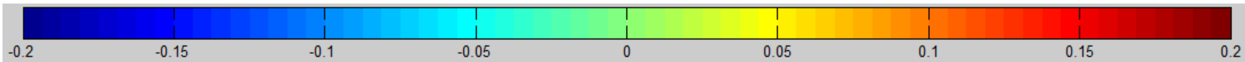


12. Complex meter: LSS (fast tempo): Unaccented



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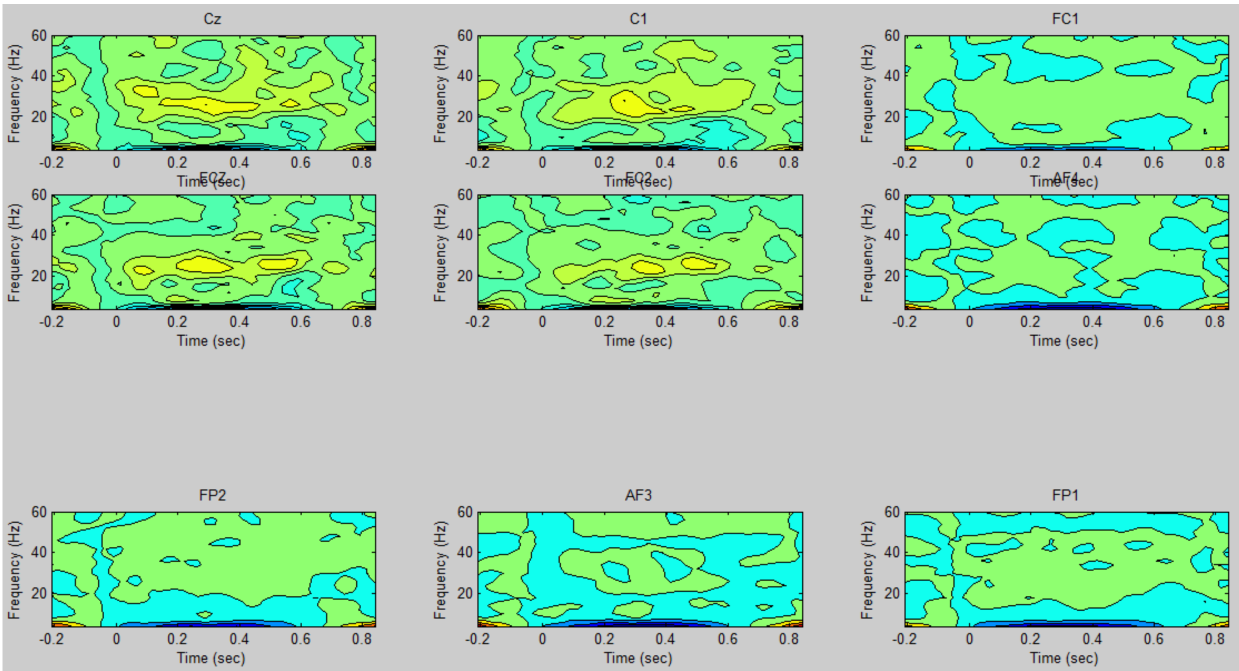

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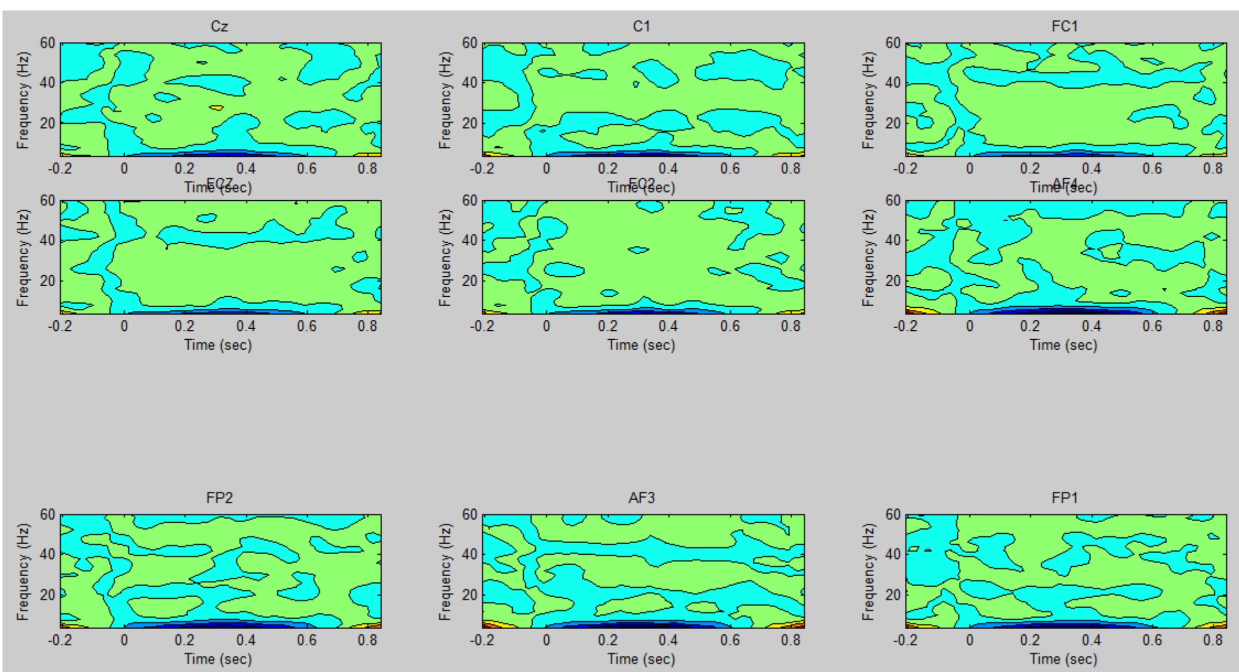
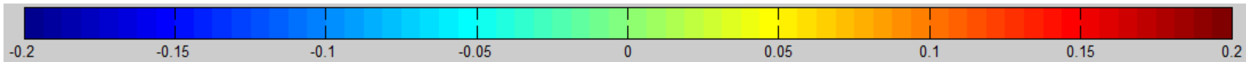


13. Complex meter: SSL (slow tempo): Accented



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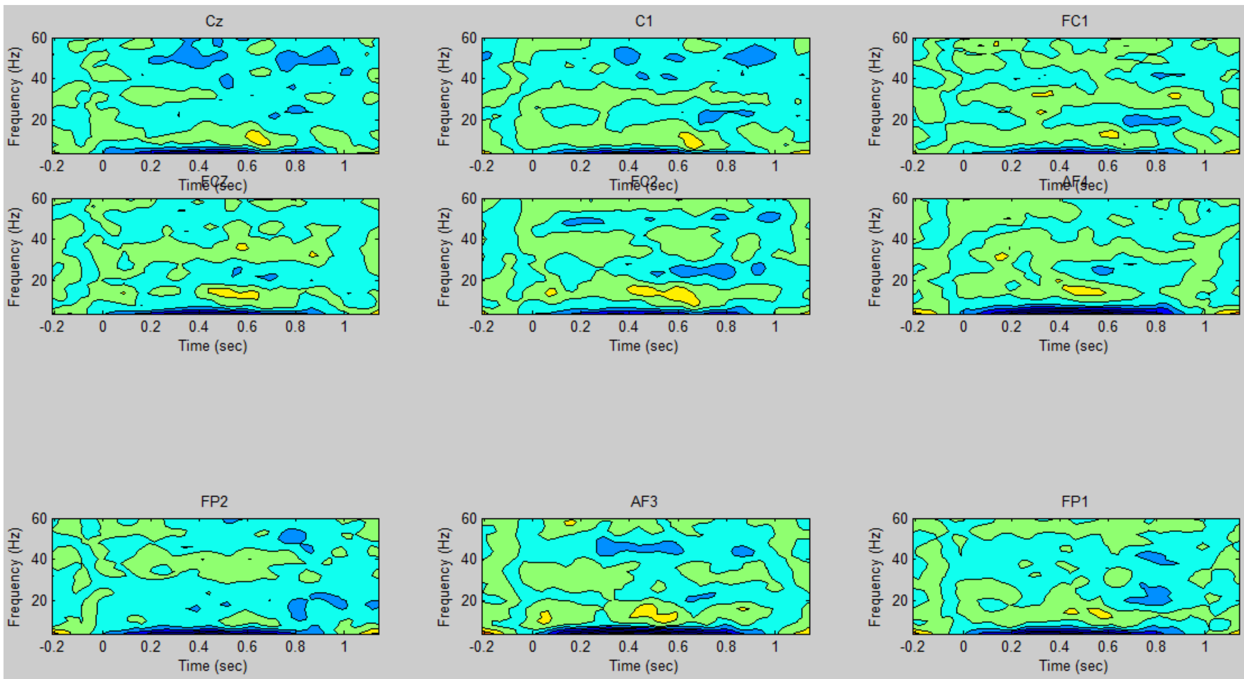

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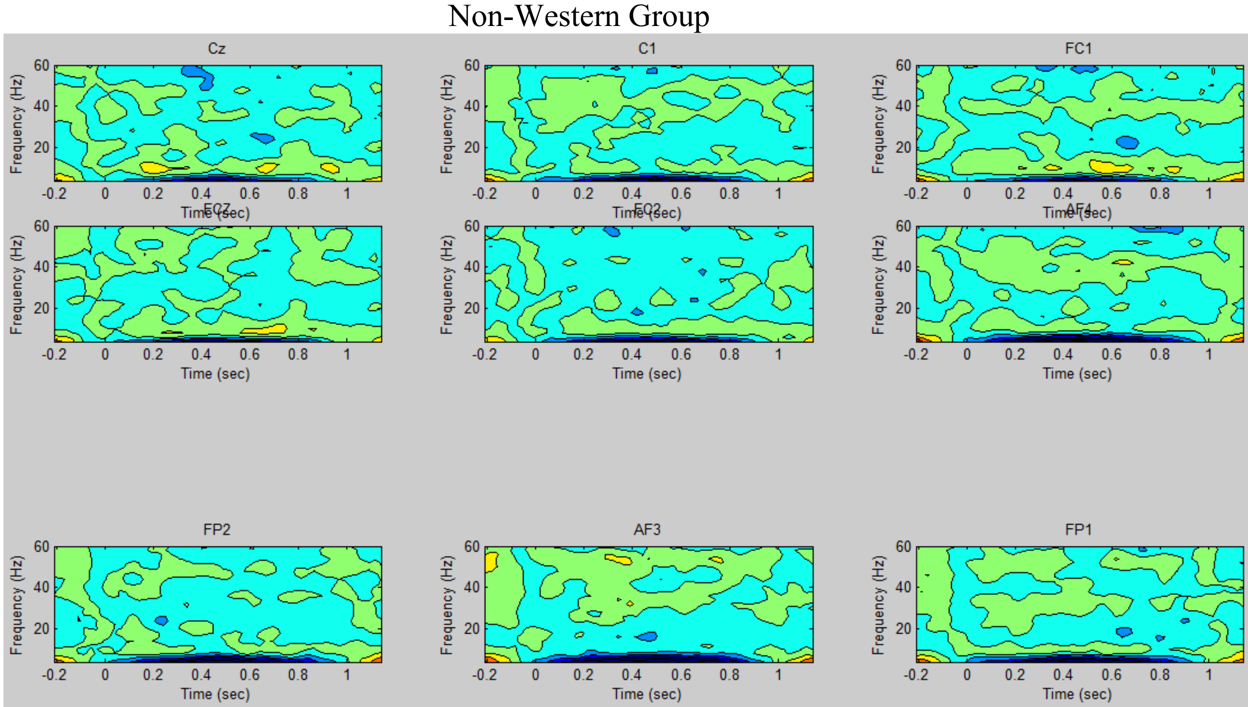
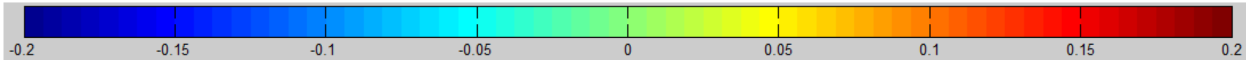


14. Complex meter: SSL (slow tempo): Unaccented



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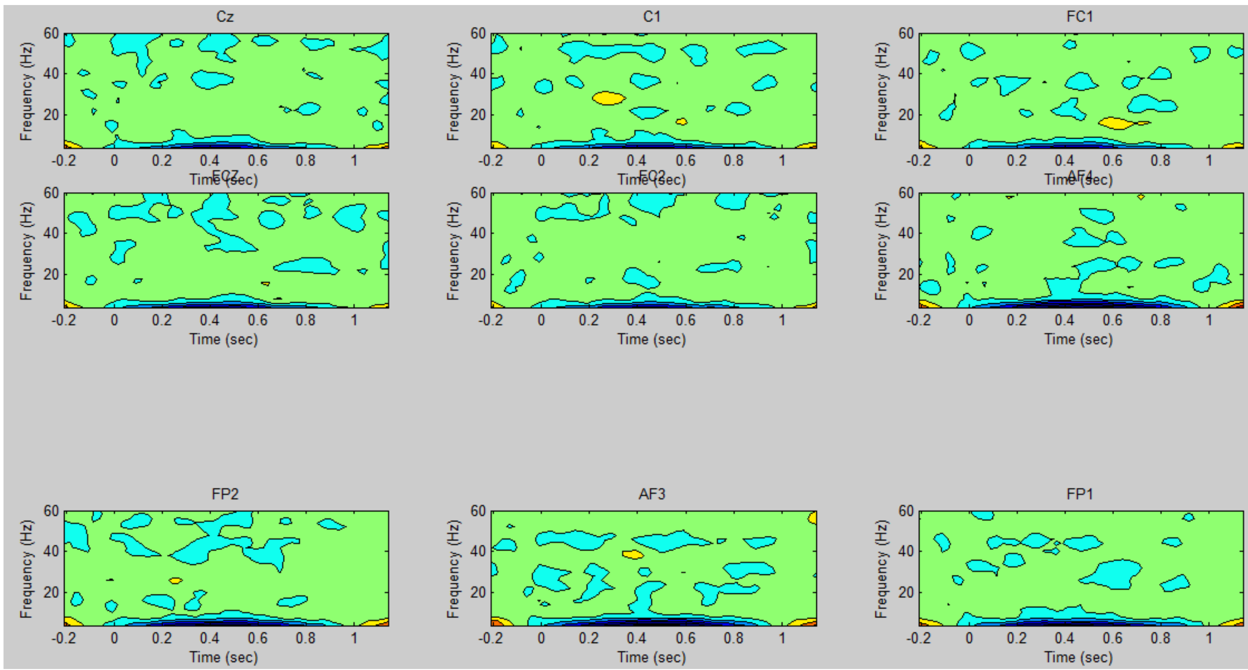

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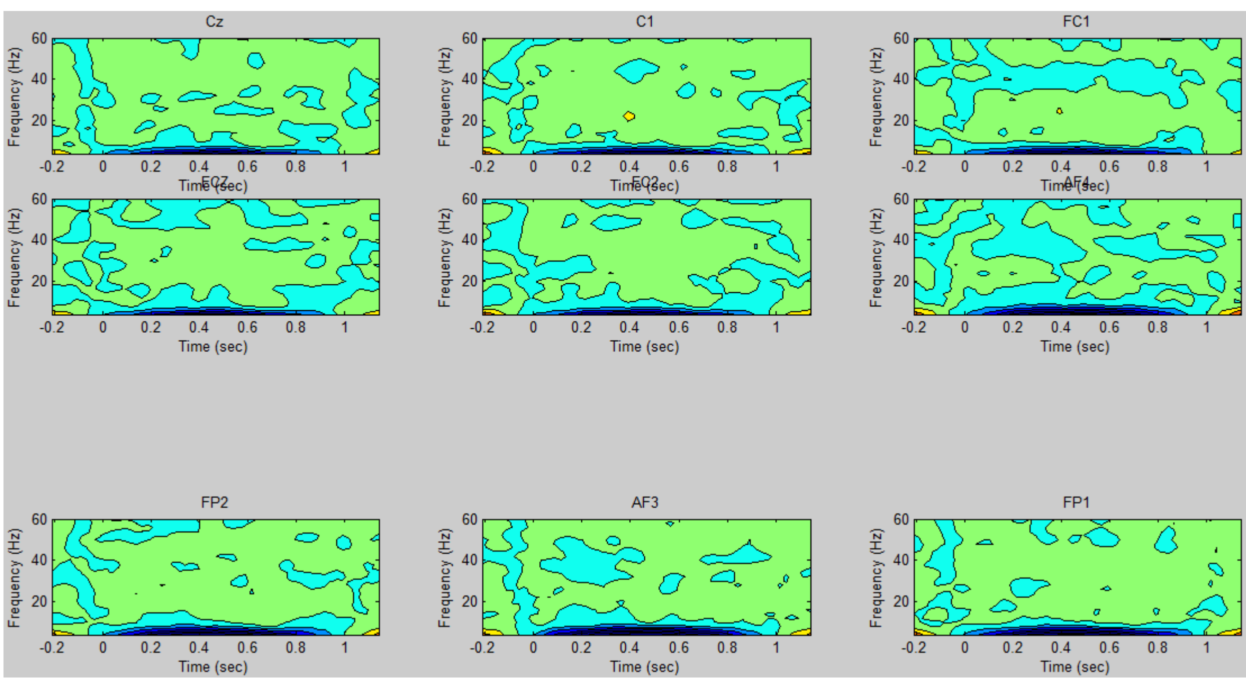
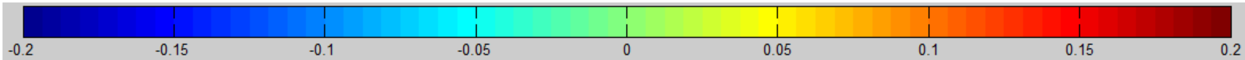
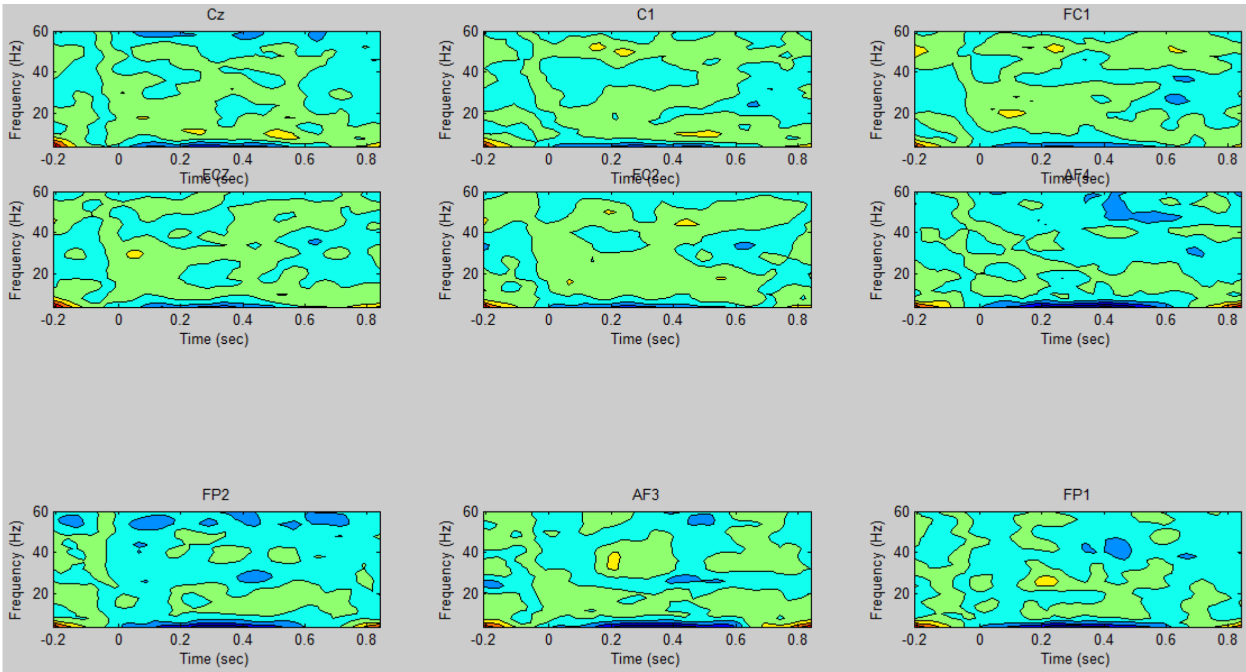


15. Complex meter: SSL (fast tempo): Accented



Western Group



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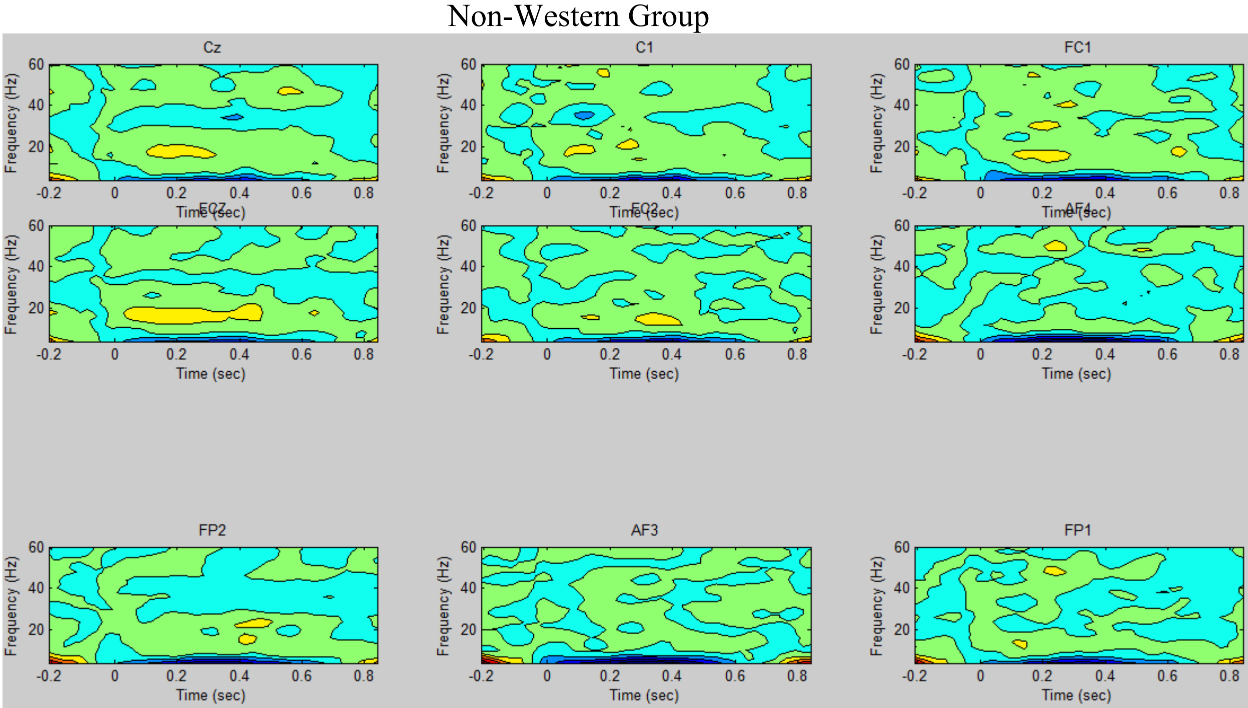
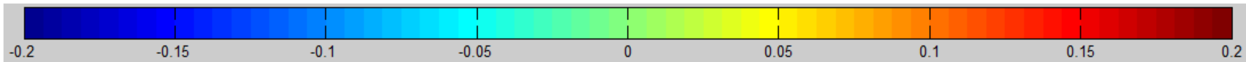
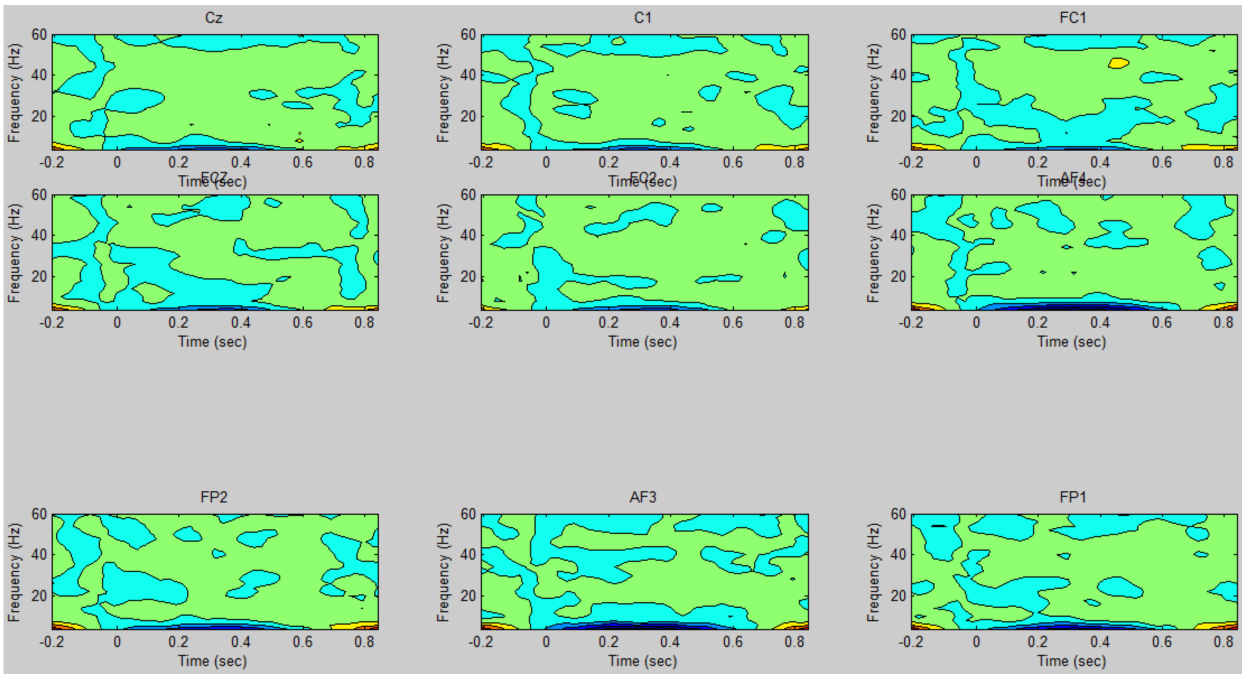


16. Complex meter: SSL (fast tempo): Unaccented



Western Group



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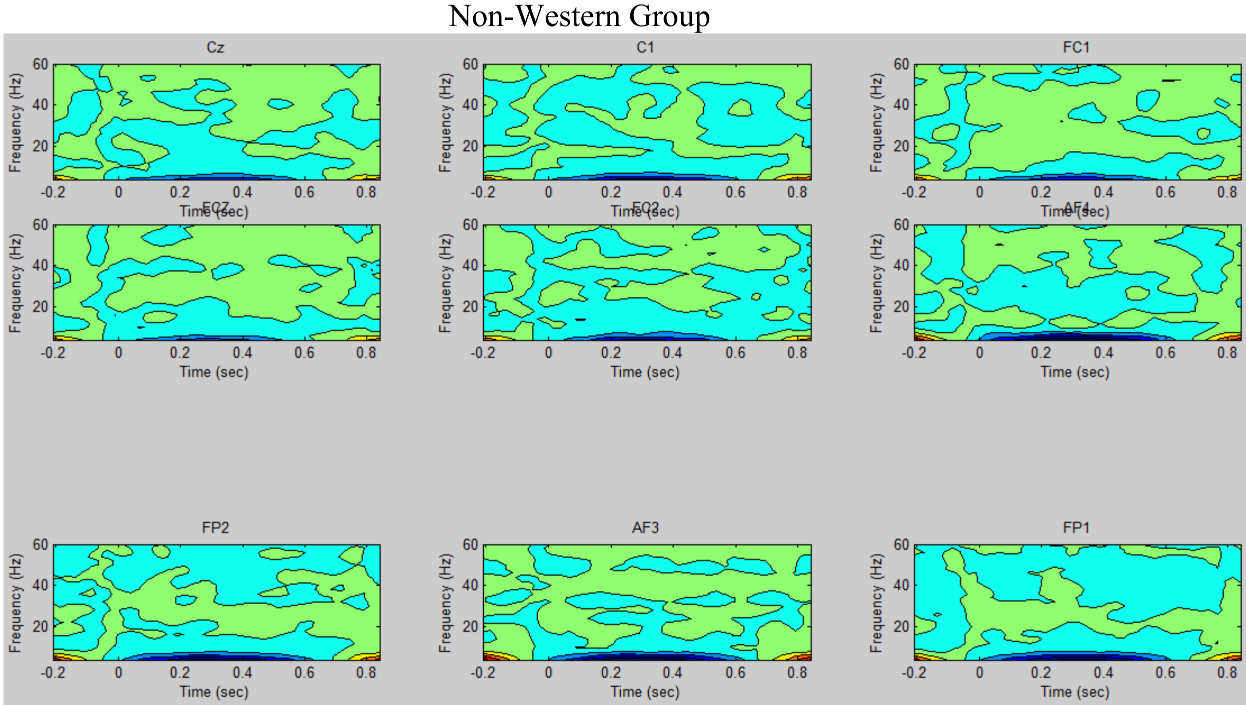

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