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Hemispheric asymmetry in the perception of musical pitch structure

Matthew Adam Rosenthal
University of Nevada, Las Vegas, rosent17@gmail.com

HEMISPHERIC ASYMMETRY IN THE PERCEPTION OF MUSICAL PITCH STRUCTURE

By

Matthew Adam Rosenthal

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Indiana University
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Master of Arts -- Psychology
University of Nevada, Las Vegas
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Matthew Adam Rosenthal

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Mark Ashcraft, Ph.D., Committee Chair
Colleen Parks, Ph.D., Committee Member
David Copeland, Ph.D., Committee Member
Gregory Schraw, Ph.D., Graduate College Representative
Kathryn Hausbeck Korgan, Ph.D., Interim Dean of the Graduate College

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Abstract

Both the left and right hemispheres contribute to the perception of pitch structure in music. Music researchers have attempted to explain the observed asymmetries in the perception of musical pitch structure by characterizing the dominant processing style of each hemisphere.   However, no existing characterizations have been able to account for all of the empirical findings. To better explain existing empirical findings, this dissertation characterizes the left hemisphere as dominant in temporal pitch processing (i.e. with respect to the sequential ordering of pitches) and the right hemisphere as dominant in non-temporal pitch processing (i.e. without respect to the sequential ordering of pitches). Four listening experiments were performed utilizing the monaural listening paradigm to investigate hemispheric differences in the processing of temporal and non-temporal pitch structures. None of the experiments provided strong evidence of right hemisphere dominance for non-temporal pitch processing, but Experiments 2 and 4 found evidence in support of left hemisphere dominance for temporal pitch processing. The results of Experiment 2 suggest that the left hemisphere differentiates the stability of pitches in a set by forming temporal expectations for specific, in-set pitches. The results of Experiment 4 suggest that the left hemisphere is dominant for processing the sequential order of pitches. These studies indicate that the left hemisphere plays a more prominent role in temporal pitch processing than has been previously suggested.

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Chapter 1 -- Introduction

Hemispheric contributions to speech and music perception

It is common for auditory researchers to refer to speech and music as separate cognitive domains (Peretz & Coltheart, 2003). The term 'domain' here suggests that speech and music are fundamentally different classes of stimuli whose cognitive processing requires separate neural resources. Such neural separation has been supported by findings in brain lesion patients who demonstrate impairments in one domain while the other domain appears spared. Typically, impairments in musical pitch perception have been found to result from damage to the right hemisphere, particularly the temporal lobe, whereas impairments in word recognition have typically been found to result from damage to the left hemisphere (Ayotte, Peretz, Rousseau, Bard, & Bojanowski, 2000; Griffiths, Rees, Witton, Cross, Shakir, & Green, 1997; Liégeois-Chauvel, Peretz, Babaï, Laguitton, & Chauvel, 1998; Luria et al., 1965; Metz-Lutz & Dahl, 1984; Sidtis & Volpe, 1988; Takahashi, Kawamura, Shinotou, Hirayama, Kaga, & Shindo, 1992).

It is clear from other research, however, that this dichotomy is an oversimplification. Various methods converge to show the involvement of both hemispheres in the perception of speech and music. In speech, whereas the left hemisphere has been shown to be dominant for the perception of consonant-vowel combinations and syntax, neither hemisphere is dominant in the perception of isolated vowels (Blumstein, Tartter, Michel, Hirsch, & Leiter, 1977; Friederici & Mecklinger, 1996; Shankweiler & Studdert-Kennedy, 1967; Studdert-Kennedy & Shankweiler, 1970), and the right hemisphere is dominant for the perception of

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emotional prosody and some aspects of semantics (Beaucousin et al., 2007; Castro & Pearson, 2011; Grimshaw, Seguin, & Godfrey, 2009; Jung-Beeman, 2005; Ross, Edmondson, Seibert, & Homan, 1988; Ross & Monnot, 2008; Wildgruber et al., 2005). In music, the right hemisphere is dominant in fine pitch discrimination (Divenyi & Robinson, 1989; Hyde, Peretz, & Zatorre, 2008; Robin, Tranel, & Damasio, 1990) and has been suggested to be dominant for the perception of contour (the pattern of ups and downs of pitches over time) (Lee, Janata, Frost, Hanke, & Granger, 2011; Pertez, 1990), and the left hemisphere has been suggested to be dominant for the perception of specific intervallic relationships and some aspects of meter (Grahn & Brett, 2007; Peretz, 1990).

Some theoretical models have attempted to explain the differences between the two hemispheres in pitch processing. The local-global model (Balaban, Anderson, & Wisniewski, 1998; McKinnon & Schellenberg, 1997; Peretz, 1990) of hemispheric differences characterizes the right hemisphere as dominant for global pitch processing and the left hemisphere as dominant for local pitch processing. According to this conception, contour is a global pitch structure because it is independent of specific (i.e. local) interval relationships. The primary support for the local-global model has come from lesion studies. In these studies patients with unilateral lesions in either the right or left hemisphere heard two melodies and were asked to indicate whether they were the same or different. On trials in which the two melodies were different, one pitch would be altered in the second melody, resulting in a change in contour, interval, or in some studies, set membership. In Peretz (1990), based on the finding that right hemisphere lesions reduced

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participants' sensitivity to contour and interval and left hemisphere lesions reduced

participants' sensitivity only to interval, it was suggested that the right hemisphere

processes global pitch structure and the left hemisphere processes local pitch

structure.

The local-global model is useful for characterizing some aspects of the left

and right hemispheres' processing styles. However, the model appears to

inaccurately suggest that the perception of contour relies predominantly on the

right hemisphere. In studies comparing contour perception between individuals

with unilateral left or right hemisphere lesions (Ayotte et al., 2000; Liégeois-Chauvel

et al., 1998; Peretz, 1990; Zatorre, 1985), it was assumed that detecting changes to

contour required sensitivity *over time* to the succession of pitch directions.

However, a close inspection of the stimuli in these studies suggests that participants

could detect changes in "contour" without tracking the temporal order relationships

between pitches at all. In all of these studies, the manipulations of contour were

confounded with a change in how often pitches occurred (i.e. pitch frequency-of-

occurrence). For instance in Ayotte et al. (2000), the "contour-violated" melody

contained two occurrences of the note F, while the "initial" melody, to which the

contour-violated melody was compared, only contained one occurrence of F.

Similarly in Zatorre (1985), the "same scale different contour" melody contained

two occurrences of the note C, whereas the "original" melody only contained one

occurrence of the note C. In Liégeois-Chauvel et al. (1998), the "contour-violated"

melody contained two occurrences of the note F, while the "initial melody contained

one occurrence of F. In Peretz (1990), which is the only study that showed that

performance in the contour condition was significantly more disrupted than performance in the interval condition in individuals with right hemisphere lesions, the "contour violated" melody contained two occurrences of the note C, whereas the "contour preserved" and the "initial melody" only contained one occurrence of C. Instead of providing support for the right hemisphere's dominance in processing contour, these studies could suggest that the right hemisphere is dominant for processing non-temporal pitch information (i.e. information about pitch structure independent of sequential order), such as pitch frequency-of-occurrence.

Further evidence that the right hemisphere lesions primarily influence non-temporal processing comes from observing the performance in the set membership condition in Ayotte et al. (2000) and Zatorre (1985). In these studies, participants with right hemisphere lesions performed worse overall, but the relative performances in the contour and interval conditions were not significantly different between the two lesion groups. In the set-membership conditions, however, the right-lesion group considerably underperformed the left-lesion group. These findings suggest that the right hemisphere is especially dominant for the perception of set membership, whereas the findings do not support a particular role of the right hemisphere in contour perception. Because set membership can be described as a type of non-temporal pitch information (see next section), and because the perception of contour was confounded with non-temporal manipulations in all of these lesion studies (Ayotte et al., 2000; Liégeois-Chauvel et al., 1998; Peretz, 1990; Zatorre, 1985), it appears that the right hemisphere could be characterized as dominant for non-temporal pitch processing.

More recent studies have also claimed to provide support for the right hemisphere's dominance in contour processing (Balaban et al., 1998; Johnsrude, Penhune, & Zatorre, 2000; Lee et al., 2011; McKinnon & Schellenberg, 1997). However, the contour manipulations in these studies were also confounded with non-temporal manipulations. Balaban et al. (1998) used the monaural listening technique to show that infants were more sensitive to changes in contour presented to the left ear (hinting at right hemisphere dominance). In Experiment 1 of Balaban et al. (1998), although pitch frequency-of-occurrence was not confounded, the contour-altered sequence contained a note (B_2), that fell outside of the range of notes in the standard sequence (C_3 through G_3). The infants could have discriminated the melodies on the basis pitch range (i.e. distance in Hz. between the lowest and highest pitches in the melody) without tracking the order in which pitch direction changes occurred. In Experiment 2, the "contour altered" sequence contained three occurrences of the note C, while the "standard" sequence contained only two occurrences of the note C. The infants could have discriminated the melodies in this experiment on the basis of non-temporal pitch frequency-of-occurrence.

In the McKinnon and Schellenberg (1997) study, participants were asked to match the contour of a monaurally presented melody to one of several pictorial representations of the up-down contour pattern. Participants were more accurate when melodies were presented to the left ear, which was interpreted to support right hemisphere dominance for contour perception. However, because of the known dominance of the right hemisphere for visuospatial processing (Schotten et

al., 2011), the apparent right hemisphere dominance for contour processing in that study could be explained by the visuospatial component of the task.

In the Lee et al. (2011) study, fMRI measurements were obtained comparing brain responses to ascending melodies (i.e. melodies whose pitch directions go up) and descending melodies (pitch directions go down). Responses in the right superior temporal lobe differentiated the two different melody types and the authors concluded that the right superior temporal lobe was dominant for the perception of contour. However, this study contained a non-temporal confound that could explain the different responses to the ascending and descending melodies. For each ascending melody, the first note was C. For the descending melodies, the first note varied from trial to trial and was never C. The different responses to the ascending and descending melodies could therefore have reflected different starting notes rather than contour; melodies that started with C were classified as ascending and melodies that didn't start with C were classified as descending. Sensitivity to the pitch of the starting note would not require sensitivity to pitch structure over time.

In the Johnsrude et al. (2000) study, individuals with unilateral right or left temporal lobe lesions performed a pitch direction task. On each trial, two pitches were sounded and participants were asked to indicate whether the first pitch was higher or lower than the second pitch. One pitch was always 1000 Hz. and the other pitch would vary from 200 Hz. toward 1000 Hz. using a psychophysical 'staircase' procedure. Only individuals with right hemisphere lesions were impaired on the pitch direction task, while neither group was impaired on a simple same-different

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task. The authors suggested the dominance of the right superior temporal lobe for the perception of contour. However, the pitch direction task could have been performed without the participants actually being sensitive to pitch direction. Because one pitch on each trial was always C and because C was always the higher pitch, participants could have performed the task by holding C in working memory and answering "lower" whenever the first pitch of each trial was a note other than C and higher whenever the first pitch of the trial was C. Right hemisphere lesions might have reduced performance in this task by disrupting the ability to hold a note in working memory, not necessarily by disrupting the perception of pitch direction over time.

The confounds in the above studies suggest that the right hemisphere may not be dominant for contour perception. This claim is supported by the one known study that manipulated contour without a non-temporal confound. In a study by Stewart, Overath, Warren, and Foxton (2008), contour was manipulated by reversing the order of two pitches in a sequence rather than by substituting one note in the sequence with another note. This manipulation thus did not confound pitch frequency-of-occurrence, pitch range, or any other non-temporal property with the change in contour. Unlike the other studies of contour perception, Stewart et al. (2008) showed stronger responses in the *left* superior temporal lobe. Thus, when contour is manipulated without non-temporal confounds, the left hemisphere appears to be dominant, suggesting that the left hemisphere, not the right, is dominant in processing pitch relationships over time. It should be noted, however, that the left hemisphere response in Stewart et al. (2008) could reflect sensitivity to

interval, not contour. Either way, a close examination of the results on contour processing suggests that the right hemisphere could be dominant in processing non-temporal pitch relationships, and the left could be dominant in processing temporal pitch relationships.

The spectral-temporal model also has attempted to characterize hemispheric differences in the processing of pitch (Poeppel, 2003; Robin, Tranel, & Damasio, 1990; Tervaniemi & Hugdahl, 2003; Zatorre & Belin, 2001; Zatorre, Belin, & Penhune, 2002). According to this model, the primary difference between the hemispheres is the precision with which each hemisphere can perceive spectral and temporal variation. The right hemisphere is suggested to be dominant in spectral precision (i.e. discriminating small differences in pitch) whereas the left hemisphere is suggested to be dominant in temporal precision (i.e. discriminating small differences in duration). Much of the support for the spectral-temporal theory has come from lesion studies. These studies have presented participants with sounds that have to be discriminated by small differences in pitch or duration. Individuals with right hemisphere lesions have tended to show reduced sensitivity to differences in pitch whereas individuals with left hemisphere lesions have tended to show reduced sensitivity to differences in duration (Divenyi & Robinson, 1989; Robin et al., 1990). Neuroimaging studies have also supported the spectral-temporal dichotomy (Zatorre & Belin, 2001; Hyde et al., 2008).

Although the spectral-temporal model is able to explain some experimental findings, it cannot explain the left hemisphere's apparent dominance in interval perception (Pertez 1990; Stewart et al., 2008) and its dominance in processing

temporal order information of pitches in a sequence (Abla & Okanoya, 2008; Gelfand & Bookheimer, 2003). In particular, it is unclear how the left hemisphere's dominance in temporal precision would facilitate the processing of pitch intervals because pitch intervals in music do not usually occur at the rate (approximately 40 Hz.) associated with fast temporal processing in the left hemisphere. The spectral-temporal theory also cannot explain the right hemisphere's dominance for certain aspects of pitch perception as revealed in lesion studies (Ayotte et al., 2000; Liégeois-Chauvel et al., 1998; Peretz, 1990; Zatorre, 1985). Although it is ambiguous whether the findings from these lesion studies reflect contour or non-temporal pitch processing, neither type of processing necessarily relies on a high degree of pitch precision. Contour processing, in particular, has been assumed to rely on a coarse (i.e.. global) interpretation of pitch direction over time. It is thus unclear how the right hemisphere's dominance for precise pitch perception could explain the right hemisphere's supposed dominance for global contour perception.

Thus, neither the local-global model nor temporal-spectral model provides a complete explanation of existing empirical findings. Whereas the local-global model can explain the dominant role of the left hemisphere for interval perception, it cannot explain why contour perception would rely predominantly on the left hemisphere when potential non-temporal confounds are controlled (Stewart et al., 2008). Regarding the temporal-spectral model, whereas the left and right hemispheres do appear dominant in temporal and spectral precision, respectively, the model cannot explain the right hemisphere's dominance in "contour" (i.e. non-temporal pitch processing), nor can it explain the left hemisphere's involvement in

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some aspects of slow pitch processing (Abla & Okanoya, 2008; Gelfand & Bookheimer, 2003; Stewart et al., 2008).

The lingering effect of both models on the current literature is the implicit assumption that most aspects of musical pitch perception rely on the right hemisphere. In one review paper, Peretz and Zatorre (2005) suggested that the right hemisphere, particularly the right secondary auditory cortex, is dominant in "operations related to processing relationships between pitch elements as they change over time…" (p. 92). This assumption is still pervasive in some of the most recent research on musical pitch expectations. The goal of research on musical pitch expectations is to understand the neurocognitive mechanisms by which listeners interpret pitches in a musical sequence. Presumably, listeners form expectations for pitch events by taking into consideration the pitch structure of the preceding musical context. The fulfillment and violation of such expectations is thought to play a fundamental role in the listener's aesthetic and perceptual interpretation (Huron, 2006). In the literature on pitch expectations, the assumption of right hemisphere dominance is so strongly assumed that authors have tended to not discuss the potential role of the left hemisphere (Koelsch, Gunter, Friederici, & Schroger, 2000; Koelsch, Fritz, Schulze, Alsop, & Schlaug, 2005; Koelsch, Jentschke, Sammler, & Mietchen, 2007; Maess, Koelsch, Gunter, & Friederici, 2001; Tillman, Janata, & Bharucha, 2003), sometimes assuming right hemisphere dominance for pitch expectations due to a right hemisphere dominance for "tonal working memory" (c.f. Tillmann, Koelsch, et al., 2006; Zatorre, Evans, & Meyer, 1994). Even some of the most recent research on pitch expectations describes neural responses related to

pitch expectations generally as the ERAN (i.e. early *right* anterior negativity), even when certain types of pitch expectations in the same study were shown to evoke slightly stronger neural responses in the left hemisphere (Jentschke, Friederici, & Koelsch, 2014).

The distinction made in this section between temporal and non-temporal pitch processing is important to understanding the mechanisms that underlie the formation of musical pitch expectations. According to Collins, Tillmann, Barret, Delbé, and Janata (2014), Huron (2006), and Toiviainen and Krumhansl (2003), listeners could use both the "zeroth-order" pitch structures, which are independent of temporal order relationships between pitches, and "first-order" pitch structures, which are dependent on temporal order relationships between pitches, to form pitch expectations. The next section will further differentiate between those aspects of pitch expectations that can be described as temporal and non-temporal. The role of each hemisphere in the formation of temporal and non-temporal expectations will be considered.

Temporal and non-temporal pitch expectations in music

Pitch expectations in music emerge in part through acquired knowledge of musical pitch syntax (Corrigal & Trainor, 2010; Hannon & Johnson, 2005; Huron, 2006; Krumhansl, 1990; Krumhansl & Keil, 1982; Trainor & Trehub, 1992; Trainor & Trehub, 1994). Musical pitch syntax is a set of principles that govern the organization of pitches in a given musical system. In music, the syntactic relationships between pitches are determined by their membership and function within a set. A common set of co-occurring pitches in Western music is the major

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scale, which contains a subset of seven of the 12 Western pitch classes. Over the course of development, human listeners acquire knowledge of the structural characteristics of common pitch sets like the major scale and use this knowledge to form musical expectations and to perceive stability relationships (Huron, 2006; Krumhansl, 1990).

Two of the most common methods for studying knowledge of pitch syntax are the probe tone method and the harmonic priming task. In the probe tone method (Krumhansl & Kessler, 1982), participants are presented with a short context sequence of pitches drawn from the major scale and are asked to indicate how well a single pitch (i.e. a probe tone) fit with the context sequence on a scale of 1-7. Participants provide the lowest fit ratings for out-of-set pitches, higher ratings for in-set pitches, and the highest ratings for the tonic. In the harmonic priming task (Bigand, Poulin, Tillmann, Madurell, D'Adamo, 2003; Tillman, Janata, Birk, & Bharucha, 2003; Tillman, Janata, Birk, & Bharucha, 2008), participants are presented with a sequence of chords from a major scale that ends on the stable tonic, a less stable in-set chord (usually the subdominant), or an even less stable out-of-set chord. Participants are asked to make a speeded judgment on the final (target) chord of the sequence, such as indicating whether the target chord was consonant or dissonant or indicating which of two instruments played the target chord. The harmonic priming paradigm has shown that participants are faster to make judgments about the tonic chord compared to the less stable in-set and out-of-set chords, even though the judgments themselves do not pertain to the given chord's stability.

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The earliest emerging form of pitch knowledge allows listeners to discriminate pitches by their membership or lack of membership in a set (Corrigal & Trainor, 2010; Krumhansl & Keil, 1982; Trainor & Trehub, 1992; Trainor & Trehub, 1994). Because of knowledge of set membership, listeners perceive pitches that are not members of a set as jarring and unstable, and out-of-set pitches are said to occupy the lowest level of the stability hierarchy (Krumhansl, 1990; Krumhansl & Kessler, 1982). The ability to form expectations for which pitches are members of a set could be considered non-temporal in the sense that it would not require sensitivity to sequential order relationships.

A later form of pitch knowledge allows listeners to discriminate the stability of pitches within a set. Because of this knowledge, listeners perceive one particular in-set pitch, known as the tonic, as most stable and occupying the top level of the hierarchy (Huron, 2006; Krumhansl, 1990). Within-set expectations could be considered both temporal and non-temporal. According to a simulation by Leman (2000), listeners infer the stability of pitches within a set by comparing the frequency (in Hz.) of a given pitch with respect to echoic images of periodicity pitch in short-term memory. According to the Leman periodicity pitch model, pitches that are most closely related to the frequency (Hz.) of the greatest common frequency in the set are perceived as most stable. Pitches, such as the tonic and fifth scale degrees in the Western major scale may therefore be perceived as stable, at least in part, because they share simple integer relationships (i.e. perfect interval relationships) with multiple other pitches within the scale, whereas less stable pitches such as the subdominant and leading tone share perfect interval

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relationships with only one other pitch within the scale. The perception of periodicity pitch could be characterized as non-temporal processing in the sense that it requires sensitivity to pitch frequencies (Hz.) but not sensitivity to specific sequential relationships between pitches in the set.

According to Huron (2006), listeners could also infer the stability of pitches within a set by forming expectations for when certain pitches within that set will occur. For instance, pitches such as the tonic often occur at predictable moments in time, such as the ending of phrases, on strong metrical positions, and after certain other pitches within the set (e.g. the tonic following the leading tone or the tonic concluding an authentic cadence) (Huron, 2006; Järvinen, 1995; Krumhansl, 1990; Prince & Schmuckler, 2014; Prince, Thompson, & Schmuckler, 2009). According to Huron (2006), pitches that do not occur at expected moments in time are perceived as less stable. The ability to form expectations for when pitches occur could clearly be characterized as temporal in the sense that it would require sensitivity to the sequential orders in which pitches are likely to occur relative to other pitches in the set.

The formation of pitch expectations in music relies on the listener's acquired knowledge of non-temporal and temporal statistical regularities in pitch structure. One potential type of acquired statistical knowledge is pitch frequency-of-occurrence. The major key profile of probe tone ratings from Krumhansl and Kessler (1982) has been found to correlate with the frequency-of-occurrence values of pitches from a corpus of Western classical music (Knopoff & Hutchinson, 1983; Krumhansl, 1990; Youngblood, 1958), indicating that more stable pitches occur

more frequently in music. In the laboratory, participants are able to learn and retain (for longer than the duration of short-term memory) information about the frequency-of-occurrence structure of pitch sets (Loui, Wessel, & Hudson Kam, 2010). This learning of pitch frequency-of-occurrence appears to play a particularly important role in knowledge of set membership. In Experiment 1 of Rosenthal and Hannon (under review), adult listeners were familiarized with one of two 2-minute (whole-tone-scale) sequences that differed in how often certain pitches occurred (i.e. contained different pitch frequency-of-occurrence distributions). In a subsequent test phase, participants provided fit ratings for individual probe tones following short context sequences. Half of the participants heard familiarization and context sequences drawn from the same statistical distribution (congruent condition), while the other half heard a familiarization and context sequences drawn from different statistical distributions (incongruent condition). Participants rated non-occurring (i.e. out-of-set) pitches as fitting less well in the congruent condition than in the incongruent condition. This shows that when there is a correspondence in the pitch frequency-of-occurrence structure of previous experience (i.e. the familiarization) and the current context, participants have a stronger sense of which pitches are out-of-set. Pitch frequency-of-occurrence could therefore play an important role in acquiring knowledge of set membership.

Although it may be an important statistical cue, frequency-of-occurrence by definition neglects the rich temporal structure in which musical pitches are embedded. Perceptual studies have shown that both infants and adults are sensitive to the note-to-note probabilities (i.e. transitional probabilities) and pitch-meter

correlations in pitch sequences (Creel, Newport, & Aslin, 2004; Endress, 2010; Hannon & Johnson, 2005; Jonaitis, & Saffran, 2009; Krumhansl, 1979; Saffran, Johnson, Aslin, & Newport, 1999). Potentially, listeners could acquire knowledge of temporal relationships between pitches and use it to infer tonal stability (Huron, 2006).

Findings from Experiment 2 of Rosenthal and Hannon (under review) further support the role of temporal pitch structure in the acquisition of within-set pitch knowledge. In Experiment 2, adult listeners were familiarized with one of two pitch-meter distributions. Pitches that occurred primarily on strong metrical positions in one distribution occurred on weak metrical positions in the other and vice versa. Participants then provided fit ratings for individual probe tones following short context sequences in a subsequent test phase, with half of the participants hearing a familiarization and context sequence drawn from the same statistical distribution (congruent condition), and other half hearing a familiarization and context sequences drawn from different statistical distributions (incongruent condition). The pitch-meter distributions of the familiarization sequences influenced probe tone ratings for in-set pitches but not for out-of-set pitches. In particular, participants' ratings more readily discriminated between pitches within the set when the familiarization and context sequences were congruent. These findings show that pitch-meter structure exerts a longer-term influence on expectations within a pitch set, but pitch-meter structure does not appear to exert a longer-term influence on expectations of set membership.

In the preceding section, musical pitch expectations have been described in terms of a hierarchy of stability relationships, with out-of-set pitches forming the lowest level, followed by in-set pitches, and then the most stable tonic. Sensitivity to this hierarchy has been suggested to emerge as the listener acquires knowledge of the syntactical (i.e. statistical) structures in the relevant musical system, including knowledge of which pitches tend to co-occur to form sets, and which pitches within a set tend to occur frequently and at expected points in time. This section has also highlighted the distinction between non-temporal and temporal pitch expectations. This distinction is important because, as will be further described in the next section, the mechanisms that underlie non-temporal and temporal pitch expectations appear to dissociate between the left and right hemispheres.

The frontal-temporal system for syntactic integration

Syntactic expectations, whether in music or speech, involve functional connections between inferior frontal and posterior cortical regions, including the superior temporal lobe (Patel, 2003; Seger et al., 2013). According to Patel (2003), inferior frontal regions communicate with posterior temporal regions to integrate a chord (or a pitch) with respect to a syntactic expectation. When an unexpected chord is played, syntactic integration is more difficult and more resources are deployed to the superior temporal-inferior frontal system, which is indicated in neuroimaging studies by increased activation. Functional neuroimaging evidence supports the claim that the frontal and posterior temporal areas communicate for the formation and integration of chord expectations (Seger et al., 2013).

This neural system for musical syntax integration has been studied by presenting participants with a sequence of chords ending with an authentic cadence, to create a temporal expectation for the tonic, and measuring the neural responses to target chords that fulfill or violate the expectation. These studies have largely supported the involvement of the frontal and temporal lobes in the formation of pitch expectations. The early right anterior negativity (ERAN) is an ERP that is elicited by violations of pitch expectations and is thought to have strong sources in the inferior frontal lobe (Maess et al., 2001). As its name implies, the ERAN occurs in the right hemisphere, although it is accompanied by responses in the analogous region of the left hemisphere (i.e. Broca's area) (Maess et al., 2001). The amplitude of the ERAN is greater in response to unexpected chords (Koelsch, et al., 2000; Koelsch et al., 2005; Koelsch et al., 2007; Maess et al., 2001; Tillman et al., 2003), which suggests that it is sensitive to some of the nuances of the pitch stability hierarchy.

A close inspection of the neuroimaging literature on musical pitch expectations indicates subtle differences in hemispheric activations of the frontal-temporal syntax system depending on the properties of the unexpected chord. Chords with out-of-set pitches elicit a right-dominant brain response in the inferior frontal and superior temporal areas as measured with the ERAN and with similar fMRI paradigms (Koelsch et al., 2000; Tillman, et al., 2003; Koelsch et al. 2007; Koelsch et al., 2005), suggesting right hemisphere dominance for expectations of set membership. Results regarding expectations within a set are less clear. Tillman, Koelsch, et al. (2006) used fMRI to measure participants' brain activity in response

to the stable tonic and less stable subdominant chord following a major-key context. The authors reported a significant response to subdominant chords in the right inferior frontal area. A significant activation in the left inferior frontal area was also reported, although the authors chose to focus on the right hemisphere activation. No statistical test was performed to determine whether the right frontal activation was stronger than the left frontal activation, but a close examination suggests that the left and right inferior frontal responses were not significantly different. The authors reported that the left inferior frontal activation was significant at a threshold of $p<0.005$ and all other activations, including the right inferior frontal, were significant at $p<0.001$. However, the authors chose to use $p<0.001$ as the statistical threshold for significance, effectively wiping out the significant left hemisphere activation. As no direct statistical tests were reported comparing left and right inferior frontal activations, this study did not provide evidence that the frontal activation to the less expected within-set chords was actually right-dominant. This differs from the studies that were described earlier that examined neural responses to violations of set membership, which reported significant hemisphere-by-chord interactions (Koelsch et al., 2000; Tillman, et al., 2003; Koelsch, et al., 2005).

Thus, it does not appear that violations of pitch expectations within a set show the same right dominance as violations of set membership. In fact, some evidence suggests that violations of pitch expectations within a set show patterns of left hemisphere dominance. Table 1 in Tillman, Koelsch, et al. (2006) shows that in the temporal lobe, less expected subdominant chords elicited significant activations

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in several locations in the left temporal lobe, whereas no significant activations were reported in the right temporal lobe. Although the authors emphasize the role of the right hemisphere (particularly the right inferior frontal lobe) generally in pitch expectations, the data of this study actually appear to suggest left-dominant temporal lobe contributions to temporal expectations.

The dominance of the left hemisphere's syntax system for within-set expectations could be attributed to a domain-general specialization of the left hemisphere for temporal (i.e. sequential) processing. Even in non-auditory domains, such as motor planning, the left hemisphere shows stronger responses as a function of increasing sequencing demands (Crozier et al. 1999; Haaland, Elsinger, Mayer, Durgerian, & Rao, 2004). In a functional imaging study, activation in the left inferior frontal lobe predicted learning in a statistical word-learning task (Karuza, Newport, Aslin, Starling, Tivarus, & Bavelier, 2013). The authors suggested that the left inferior frontal lobe is a domain-general sequential processor that underlies the acquisition of sequential statistical knowledge. Consistent with this suggestion, Abla and Okanoya (2008) familiarized participants to a sequence of various 'tone words'. Each tone word corresponded to a specific three-pitch sequence that would recur throughout the familiarization sequence. Brain activation was measured with near infrared spectroscopy (NIRS) while participants listened to a continuous sequence of pitches that either contained the tone words presented in the same order (refereed to as the statistical sequence) or with the orders scrambled (random sequence). Compared to the baseline (NIRS measurements at rest), the statistical sequence elicited responses at frontal and temporal channels that were stronger in

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the left hemisphere.   These findings suggest that the left hemisphere frontal-temporal syntax system might be preferentially utilized in the acquisition of new temporal pitch structures.

Similarly, Stewart et al. (2008) used fMRI to record brain activation while participants were asked to decide whether two 4-pitch strings were the same or different. There were two conditions. In the so-called 'global' condition, different pitch strings contained the same four pitches as the standard but with the order of the two middle pitches reversed. The manipulation was called 'global' because switching the order of the two pitches also changed the contour of the string. It should be noted, however, that the contour task in Stewart et al. (2008) controlled for non-temporal confounds, while most of the other contour perception research has not. In the 'local' condition, different pitch strings contained a pitch that was not present in the standard but that preserved the contour. The only significant difference in activation between different and same pitch strings in the global condition was in the left superior temporal lobe. Activations to different melodies in the local condition showed a bilateral response. These findings indicate a role of the left superior temporal lobe in the encoding and comparison of temporal pitch information in short-term memory.

The regions that were implicated in temporal pitch processing in the above studies, the left inferior frontal and left superior temporal lobe, implicate the same regions as those suggested by Patel (2003) to form the frontal-temporal syntax system. Although the above studies did not directly address listeners' perception of pitch stability, the findings suggest a potential role of the left frontal-temporal

syntax system in processing temporal pitch patterns. As was mentioned earlier, the most stable tonic pitch may be perceived as more stable than other less stable in-set pitches because listeners possess acquired knowledge of its temporal and sequential predictability. Because of previous studies showing left hemisphere dominance in processing relatively slow temporal pitch structure (Abla & Okanoya, 2008; Stewart et al., 2008), and familiar metrical structures (Grahn & Brett, 2007), it is reasonable that the left hemisphere could underlie the acquisition of knowledge that is later used in the online formation of within-set pitch expectations.

A different learning mechanism might underlie acquired pitch knowledge and online pitch expectations in the right hemisphere. In the current review, pitch frequency-of-occurrence has been argued to play a particularly important role in the acquisition of set membership. Potentially, acquisition of pitch frequency-of-occurrence could be achieved without the listener taking temporal relationships between pitches into account. If the temporal learning mechanism of the left hemisphere underlies the acquisition of temporal pitch knowledge, then a non-temporal learning mechanism in the right hemisphere could underlie acquisition of pitch frequency-of-occurrence and set membership. Although no research has directly investigated hemispheric asymmetry in processing pitch frequency-of-occurrence, lesion evidence suggests a dominant role of the right hemisphere in sensitivity to frequency-of-occurrence of sounded words in a sequence (Jurado, Junqué, Pujol, Olivers, & Vendrell, 1997).

This section has described hemispheric asymmetries in the frontal-temporal syntax system with regard to expectations for musical pitch. Whereas within-set

expectations appear to emerge from knowledge of temporal relationships via the left hemisphere syntax system, expectations of set membership appear to emerge from knowledge of non-temporal relationships such as frequency-of-occurrence via the right hemisphere syntax system.

Measuring hemispheric asymmetries with the monaural listening paradigm

This dissertation will attempt to clarify the roles of the left and right hemispheres in the acquisition of pitch knowledge and in the online formation of pitch expectancies using the monaural listening paradigm. The monaural listening paradigm measures hemispheric asymmetries behaviorally by having participants respond to target sounds that are presented in one ear. That is, advantages or disadvantages in processing stimuli delivered to one ear are interpreted to indicate processing primarily in the contralateral hemisphere; that is, if consistent advantages are found for a certain condition when stimuli are presented to the left ear, the conventional interpretation is that the right hemisphere is dominant for the relevant processing, and that there is a hemispheric asymmetry. Considerable evidence supports this inferential logic. For example, functional imaging evidence supports the idea that each ear projects more strongly to the contralateral superior temporal gyrus (Jancke, Wustenberg, Schulze, & Heinze, 2002; Scheffler, Bilecen, Schmid, Tscopp, & Seelig, 1998; Schonwiesner, Krumbholz, Rubsamen, Fink, & von Cramon, 2007; Stefanatos, Joe, Aguirre, Detre, & Wetmore, 2008). Similarly, using an individual differences approach, Van der Haegen, Westerhausen, Hugdahl, and Brysbaert (2013) divided participants into two groups depending on hemispheric dominance for speech. Brain responses were measured with fMRI while

participants mentally generated words. Those participants with stronger responses in the right inferior frontal area were assigned to the right hemisphere dominant speech group and those with stronger responses in the left inferior frontal area were assigned to the left hemisphere dominant speech group. In a subsequent task, participants were asked to report the speech sound they heard best out of two dichotically presented (one sound in each ear) speech sounds. Participants who showed right hemisphere speech dominance according to fMRI showed a significant left ear advantage in the dichotic listening task. Participants who showed left hemisphere speech dominance according to fMRI showed a significant right ear advantage. Thus, stronger performance in one ear appears to reflect hemispheric dominance of the contralateral hemisphere. The stronger response in the inferior frontal lobe in this study could reflect the role of this region in the acquisition of sequential word knowledge. Lesion evidence also strongly supports the role of each hemisphere in perceiving sounds in the contralateral ear. Individuals with unilateral lesions, especially to the superior temporal lobe, show reduced perceptual sensitivity in the contralateral ear (Brizzolara, Pecini, Brovedani, Ferretti, Cipriani, & Cioni, 2002; Chilosi et al., 2005; Harris, 1994; Hugdahl, Bodner, Weiss, & Benke, 2003; Moore & Papanicolaou, 1988; Schulhoff & Goodglass, 1969; Sidtis & Volpe, 1988; Shankweiler, 1966; Wester, Irvine, & Hugdahl, 2001; Woods, 1984). Thus, in keeping with this logic, a significant effect of ear (ear to which stimuli are presented) may lead to an inference about the contralateral hemisphere's dominance in processing.

Experiments 1 and 4 of this dissertation investigated the roles of each of the hemispheres in the processing of novel temporal and non-temporal pitch structures. To minimize the influence of previously acquired pitch knowledge, Experiments 1 and 4 employed an unfamiliar (whole-tone) scale (Creel & Newport, 2002; Loui et al. 2010). Experiments 2 and 3 investigated the role of each hemisphere in the online formation of temporal and non-temporal pitch expectations. Both Experiments 2 and 3 employed the major scale so as to measure temporal and non-temporal pitch expectations that are presumably influenced by previously acquired pitch knowledge.

Experiment 1 investigated possible hemispheric asymmetries in the acquisition of three different statistical structures, pitch frequency-of-occurrence (Task 1), pitch-meter correlation (Task 2), and transitional probability (Task 3), using the statistical learning paradigm. Participants were presented with a familiarization sequence whose pitches were structured according to a statistical distribution. After the familiarization, participants choose which of two test sequences, both played in either the left or right ear, sounded most similar to the familiarization. Because of the left hemisphere's greater sensitivity to temporal structures, such as transitional probability (Abla & Okanoya, 2008; Karuza et al., 2013), and simple meters (Ayotte et al., 2000; Grahn & Brett, 2007), and the right hemisphere's greater sensitivity to non-temporal structures, such as frequency-of-occurrence (Jurado et al., 1997), participants were expected to show greater accuracy in the left ear for acquiring pitch frequency-of-occurrence (Task 1) and greater accuracy in the right ear for acquiring transitional probability (Task 2) and

pitch-meter correlation (Task 3). Significant ear effects could be interpreted to indicate the dominance of the contralateral hemisphere for the acquisition of the given pitch structure (i.e. of the non-temporal or temporal pitch structure).

Experiment 2 investigated hemispheric asymmetry in the formation of pitch expectations using the probe tone task (Krumhansl & Kessler, 1982). Participants were presented with short context sequences using pitches from the major scale and a probe tone on each trial, both played to the same ear. One context was an ascending major scale ending on the leading tone to create a temporal expectation for the tonic. The other contexts were pitches from the major scale in a random order. Participants provided fit ratings for the tonic pitch, a less stable in-set pitch (the supertonic), and an out-of-set pitch. It was hypothesized, based on previous neuroimaging (Koelsch et al., 2000; Tillman, et al., 2003; Koelsch et al. 2007; Koelsch et al., 2005), that the out-of-set pitch would receive lower ratings in the left ear than the right, and that the difference in probe tone ratings between the tonic and out-of-set pitch would be greater in the left ear. It was also hypothesized, based on neuroimaging (Tillmann et al., 2006), that only for the ascending context, the supertonic would receive lower ratings in the right ear than the left, and the difference in probe tone ratings between the tonic and supertonic would be greater in the right ear. Significant ear effects could be interpreted to indicate hemispheric dominance of the contralateral hemisphere for the formation of temporal or non-temporal pitch expectations.

Experiment 3 investigated hemispheric asymmetry in the formation of pitch expectations using the harmonic priming task (Bigand et al. 2003; Hoch & Tillmann

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2010). Participants were presented with short context sequences using chords from the major scale ending with a target chord, either the tonic, a less stable in-set chord (the subdominant), or an out-of-set chord. The final two chords before the target chord formed a cadence (ii chord followed by V chord) to create a temporal expectation for the tonic. Both the context and the target chord were played in either the left or right ear. Participants were asked to determine quickly and accurately the name of the instrument playing the target chord. Because violations of set membership more strongly activate the right hemisphere frontal-temporal syntax system (Koelsch et al., 2000; Tillman, et al., 2003; Koelsch et al. 2007; Koelsch et al., 2005), the out-of-set chord was expected to be processed more slowly in the left ear and the difference in reaction time between the tonic and out-of-set chord was expected to be greater in the left ear. Because violations of temporal expectations within a set more strongly activate the left hemisphere temporal lobe (Tillmann et al, 2006), the less stable subdominant chord was expected to be processed more slowly in the right ear and the difference in reaction times between the tonic and the subdominant was expected to be greater in the right ear. Significant ear effects could be interpreted to indicate hemispheric dominance of the contralateral hemisphere for the formation of temporal or non-temporal pitch expectations.

Experiment 4 investigated hemispheric asymmetry in the ability to encode and detect differences in the temporal and non-temporal pitch properties of six-pitch strings. Participants rated two melodies (i.e. pitch strings), both played in the left or right ear, on how similar they sound. Pitch strings differed by either a change

of sequential order of two pitches within-the set (i.e. within the whole tone scale), or by the substitution of one pitch with a pitch from outside the set. For Experiment 4, it was assumed that the greater responses in the left superior temporal lobe to unexpected temporal pitch structures in Stewart et al. (2008) reflected participants' increased sensitivity to the difference in temporal structures between the preceding standard and the current context. Based on the findings of Stewart et al. (2008), participants were expected to provide lower similarity ratings for sequential violations in the right ear (i.e. sequential violations should be more salient in the right ear). Based on evidence that violations of set membership more strongly activate the right hemisphere (Koelsch et al., 2000; Tillman, et al., 2003; Koelsch, et al., 2005), participants were expected to provide lower similarity ratings for set membership violations in the left ear. However, it was also acknowledged that set membership violations could show equal ratings in both ears as a similar condition in Stewart et al. (2008) showed bilateral responses. Significant ear effects could be interpreted to indicate hemispheric dominance of the contralateral hemisphere for processing temporal or non-temporal pitch structures.

Chapter 2 -- Method

Participants and general procedure

All four experiments recruited participants from the UNLV subject pool.

Participants were required to be right-handed, to speak English, and to have no

known auditory or visual impairments. Data were collected from 118 right-handed

(75 female; M_{age} = 20.5, age range: 18-40) university students with normal hearing

who received course credit for participating in the experiment. Formal music

training ranged from 0-13 years (M = 3.0; SD = 3.0). One participant's data was

excluded from Experiment 2 and two participants were excluded from Experiment 4

for failing to follow directions. Experiment 1 contained three different statistical

learning tasks (Tasks 1, 2, and 3, performed between subjects). The number of

participants in Tasks 1, 2, and 3, were 56, 31, and 31, respectively. Originally,

approximately 30 participants were planned to participate in each task. More

participants were run in Task 1 than expected because only this task appeared to

show weak statistical power after analyzing the data at 31 participants.

Participants sat at a Macintosh computer and directions appeared on the

screen at the beginning of each task. The total length of all four experiments was

about 45 minutes. The experiments were presented and controlled using PsyScope

software (Cohen, MacWhinney, Flatt, & Provost, 1993) over Sony MDRZX100

headphones. Participants first participated in Experiment 1, then Experiment 2,

then Experiment 3, and finally Experiment 4. The reason for running participants in

this order was the following: Experiment 1 was a difficult learning task using the

whole tone scale, and Experiment 1 was chosen to be first so that participants would

be fresh. I decided that the next two experiments should use the major scale so that participants had a break from experiments using the whole tone scale. Experiments 2 and 3 were chosen to be second and third, respectively because they used the major scale. Experiment 4 was chosen to be last because it used the whole tone scale.

Stimuli and Procedure

Experiment 1 (statistical learning tasks). Stimuli consisted of familiarization sequences ranging from about 90-120 s in duration and shorter test sequences that either did or did not correspond to the statistical distribution of the familiarization. In each of three tasks, Task 1, Task 2, and Task 3, participants heard a familiarization presented in both ears during a learning phase. During the test phase, on each trial, participants were asked to choose which of two monaurally presented test sequences (both presented in the same ear) sounded most similar to the familiarization.

Task 1 (pitch frequency-of-occurrence). The familiarization sequence consisted of a string of pitches (150 ms duration, 250 ms inter-onset interval, 480 total pitches) organized according to a frequency-of-occurrence distribution. The pitches were from a 6-pitch, whole-tone scale with lowest note middle C. Pitches were pseudo randomly selected to occur either 36%, 18%, or 9% of the time during the familiarization. The order of the pitches was random. The familiarization was presented in both ears simultaneously. Each test trial presented two 11-pitch sequences separated by a 1 s silent interval. One pitch sequence corresponded precisely to the frequency-of-occurrence distribution of the familiarization and the

other corresponded to a somewhat opposite distribution; pitches that occurred 36%

of the time in one distribution occurred 18% or 9% of the time in the opposite

distribution, and pitches that occurred with 9% probability in one distribution

occurred with 18% or 36% in the opposite. There were four test sequences that

corresponded to the frequency-of-occurrence distribution of the familiarization and

four non-corresponding test sequences. Each corresponding test sequence was

paired with one non-corresponding test sequence and each pair was be played four

times, twice in the left ear and twice in the right ear, half the time with the

corresponding sequence as the first sequence and half the time with the non-

corresponding sequence as the first sequence (16 total trials).

Task 2 (transitional probability). The familiarization sequence consisted of a

string of pitches (150 ms duration, 250 ms inter-onset interval, 384 total pitches)

organized into 3-pitch tone words using pitches from a 6-pitch, whole-tone scale

with lowest note middle C. The four tone words were DAbE, CBbF#, BbDE, and

F#CAb. Each of the six pitches in the scale occurred in two tone words and all

pitches occurred with equal frequency-of-occurrence in the familiarization. Tone

words were played one after the other in a pseudorandom order to make 4 blocks of

16 tone words, with the constraint that no tone word was played twice in a row. In

each block, each tone word was played 4 times. Each block was played twice during

the familiarization. Within-word pitch transitional probabilities were 0.5 and

between word transitional probabilities were 0.2 (transitional probability of x

equals the frequency-of-occurrence of the sequential pairing , x and y, divided by the

total frequency-of-occurrence of x). The familiarization was presented in both ears

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simultaneously. Each test trial presented the participant two tone words separated by 1 s of silence. One tone word occurred in the familiarization and the other tone did not. The non-occurring tone word was composed of the same pitches as the occurring tone word, but with the order of pitches changed.   Each occurring tone word was paired with the same non-occurring tone word, and each pair was played four times, twice in each ear, half the time with the occurring tone word as the first sequence and half the time with the non-occurring tone word as the first sequence (16 total trials).

Task 3 (pitch-meter correlation). The familiarization consisted of a string of events (i.e. pitches and silences)(150 ms duration pitches, 250 ms inter-event interval, 481 total events) organized according to a pitch-meter distribution. The distribution distinguished between strong pitches, which tended to occur at accented moments of the metrical cycle, and weak pitches, which tended to occur at less accented moments. Triple-meter rhythms were created by placing accents every three events (i.e. every 750 ms). Accents were defined based on the following rules (adapted from Povel and Essens, 1985):

1. No silence occurred on strong metrical positions.

2. Pitch events on strong metrical positions were never both preceded and followed by other pitch events.

3. Pitch events on weak metrical positions were never followed by silence.

Each event that contained a pitch was assigned a pitch from a six-pitch, whole-tone scale with middle C as the lowest pitch. Three of the pitches were designated as "strong," meaning they were more likely to occur at strong metrical

positions, and three were designated as "weak," meaning were be more likely to occur at weak metrical positions. Strong and weak pitches occurred approximately 90% of the time on their designated metrical position and approximately 10% of the time at the other position. The familiarization was presented in both ears simultaneously.

Each test trial presented two 15-event sequences separated by a 1 s silent interval. One pitch sequence corresponded to the pitch-meter distribution of the familiarization and the other corresponded to a somewhat opposite distribution. Pitches that occurred primarily on strong metrical positions in one distribution occurred primarily on weak metrical positions in the opposite and vice versa. Each corresponding test sequence was paired with one non-corresponding test sequence, and each pair was played four times, twice in each ear, half the time with the corresponding sequence as the first sequence and half the time with the non-corresponding sequence as the first sequence (16 total trials). Frequency-of-occurrence of each pitch was the same for each test sequence of a given pair.

Experiment 2 (probe tone task). Stimuli consisted of three context sequences and three probe tones. Each context contained seven different pitches (250 ms duration, 500 ms inter-onset interval) from C major. One context sequence was structured to preserve the temporal order of pitches in the major scale (i.e. an ascending major scale starting on C4 and ending on B4). The other two contexts were created by randomly ordering the pitches in the major scale (A4 G4 B4 F4 C5 D4 E4; B4 G4 E4 C4 F4 D4 A4). Probe tones consisted of the tonic (highly stable), C4, the supertonic (less stable), D4, and one out-of-set pitch (least stable)(C#4). On

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each trial, both the context and the probe tone were played in either the left or right ear. The probe tone was played 1 s after the context. Each context was paired with each probe tone twice, once in each ear, for a total of 18 trials.

On each trial, participants heard a short major-key context sequence and indicated how well a probe tone fit with the previously heard context sequence on a scale of 1-7, with 1 meaning not fitting well and 7 meaning fitting well. Participants were instructed to use the full range of the scale.

Experiment 3 (harmonic priming task). Stimuli consisted of a context sequence composed of seven sounded chords, and target chords. The context sequence was based on the "no-target-in-context" condition of Bigand et al. (2003). The chords in the context sequence were A min, E min, D min, G maj, A min, D min, G maj. The context sequence contained a mixture of chords in root position and inversion, although the final G maj chord of the context and the target chord were in root position. On each trial, the final chord of the context was followed by one of three target chords, the tonic (highly stable), the subdominant (less stable), or an out-of-set Db major chord (least stable). The Db chord contained two out-of-set pitches, Db and Ab. This out-of-set chord is very similar to a chord used to elicit right-dominant responses to tonal expectations in previous work, the Neapolitan sixth chord (Koelsch, et al., 2005), except that Db major contains Db instead of F in the base so that the chord is in root position instead of inverted. The first seven chords of each context were played in a piano timbre and the eighth chord (i.e. the target chord) was played in either a guitar or organ timbre. Half the trials ended on the guitar timbre and half on the organ timbre. The inter-onset interval between

chords was 500ms. The duration of the target chord was 1 s. There were 24 trials, half in the left ear, half in the right. On each trial, reaction time was measured for participants to identify the timbre of the target chord in each context sequence.

Experiment 4 (Stewart pitch string task). Stimuli were based approximately on the stimuli used in Stewart et al. (2008). Stimuli consisted of 6-pitch strings. Six-pitch strings were chosen over the four-pitch strings of Stewart et al. (2008) to make the task harder. The duration of pitches was 150 ms, with 250 ms inter-onset interval. In each string, pitches were from the same six-pitch whole-tone scale with lowest note middle C. The whole-tone scale was chosen to minimize participants' familiarity with the scale. A set of 4 standard pitch strings was created by randomly ordering the six pitches from the whole-tone scale with each pitch occurring once. Another set of violation strings was created by altering the standard strings. Four violation strings altered the sequential order of two of the pitches from the corresponding standards (sequential violation strings). Another set of four violation strings replaced one pitch in the corresponding standard with an out-of-set note that was one half step away from the corresponding pitch in the standard (set membership violation strings). On each trial, participants heard a standard string and then a test string that was either a repetition of the standard, a sequential violation string, or a set membership violation string. In half of the trials, both strings were played in the left ear, and in the other half of the trials, both strings were played in the right ear. There were 24 total trials.

On each trial, participants heard a standard string and a test string. Participants rated how similar the two strings sounded on a scale of 1 to 7, with 1

meaning NOT similar and 7 meaning similar. Participants were instructed to use the

full range of the response scale.

Chapter 3 -- Results and Discussions

Results for Experiment 1.

For each of the three tasks, one-sample t-tests were performed to determine whether participants were significantly above chance at choosing the correct test sequences. For Task 1 (Frequency-of-occurrence), participants chose the correct test sequence on 57.6% of the trials. This was significantly above chance $t(55) = 3.647$, $p < .0025$, $d = 0.49$. For Task 2 (Transitional probability), participants chose the correct test sequence on 58.9% of the trials. This was significantly above chance $t(29) = 3.364$, $p < 0.0025$, $d = 0.60$. For Task 3 (Pitch-meter correlation), participants chose the correct test sequence on 61.3% of the trials. This was significantly above chance $t(29) = 3.906$, $p < 0.0025$, $d = 0.70$.

Task 1. In Task 1 (frequency-of-occurrence), participants chose the correct test sequence in the left ear on 59.6% of the trials and in the right ear on 55.6% of the trials. A paired samples t-test did not reveal a significant difference between the left and right ear accuracy scores $t(55) = 1.336$, $p = 0.187$, $d = 0.18$.

Task 2. In Task 2 (transitional probability), participants chose the correct test sequence in the left ear on 59.3% of the trials and in the right ear on 58.5% of the trials. A paired samples t-test did not reveal a significant difference between the left and right ear accuracy scores $t(30) = 0.232$, $p = 0.82$, $d = 0.04$.

Task 3. In Task 3 (pitch-meter correlation), participants chose the correct test sequence in the left ear on 60.8% of the trials and in the right ear on 61.7% of the trials. A paired samples t-test did not reveal a significant difference between the left and right ear accuracy scores $t(30) = 0.204$, $p = 0.84$, $d = 0.04$.

Discussion for Experiment 1.

For all three tasks of Experiment 1, participants performed above chance. However, the ear effects were weaker than expected and did not reach statistical significance. Thus, definitive claims about hemispheric asymmetries in statistical learning of pitch structure cannot be made.

For Task 1, the failure to find a significant asymmetry suggests that sensitivity to frequency-of-occurrence is not dominant in the right hemisphere. This finding appears inconsistent with Jurado et al. (1997), which found that individuals with right frontal lesions were less sensitive to word frequency-of-occurrence than individuals with left frontal lesions. However, the failure to find an ear difference for Task 1 could also stem from the repetition of test sequences across subsequent test trials. Potentially the first time participants heard a given test sequence, it could only have been evaluated based on its non-temporal structure. However, when the same test sequence was repeated across trials, participants could have recognized each test sequence based on its unique sequence of pitches. Because such a strategy would rely on temporal pitch processing, the contribution of the right hemisphere might have been reduced, resulting in no significant left-ear advantage. This problem could have been avoided by creating more test sequences and by not repeating test sequences on different trials. The reason that Task 1 was not designed this way is that the study on which Task 1 was based, Rosenthal and Hannon (under review), used only a small set of test sequences that repeated on different trials. Future studies should consider creating many more test sequences to minimize the repetition of test sequences across trials.

The failure to find a significant ear asymmetry in Tasks 2 and 3 does not support previous findings of left hemisphere dominance of the frontal and temporal lobes for learning transitional probability of pitches (Abla & Okanoya, 2008) and left hemisphere dominance of the inferior frontal lobe for processing simple metrical structures (Grahn & Brett, 2007). Task 2 may have failed to find left hemisphere dominance because of subtle, but important differences between the learning procedures used in the tasks of Experiment 1 and Abla and Okanoya (2008). In Abla and Okanoya (2008), although participants did listen to a familiarization sequence that was similar to the familiarization sequences used in Task 2, participants also heard the "tone words" in isolation and were explicitly asked to remember what they heard. This explicit training phase was not included for any of the tasks in Experiment 1 of this dissertation. The explicit training phase in Abla and Okanoya (2008) could have enhanced learning and resulted in a stronger reliance on the left hemisphere. Although participants were clearly sensitive to the temporal structures in both Tasks 2 and 3, it may require more than 4 minutes of passive listening for the left hemisphere's dominance for temporal processing to override the right hemisphere's dominance for tonal working memory (Zatorre et al. 1994). In particular, left hemisphere dominance for acquisition of temporal pitch structures may require either explicit encoding processes, as in Alba and Okanoya (2008), or left hemisphere dominance may require a longer duration between learning and testing to allow time for memory consolidation. Consistent with this memory consolidation explanation, a learning study found that the left inferior frontal area became increasingly activated in response to violations of sequential structure of

visual letter strings on subsequent days of repeating the same task (Forkstam, Hagoort, Fernandez, Ingvar, & Petersson, 2006).

For Task 3, it may be the case that the perception of metrical structure is not as dominant in the left hemisphere as the results of Grahn and Brett (2007) suggest. Although Grahn and Brett (2007) did show stronger activation in the left inferior frontal area in response to simple metrical structures, lesion studies have shown quite mixed evidence regarding hemispheric dominance in processing meter. In Ayotte et al. (2000), individuals with lesions to the left hemisphere temporal lobe significantly underperformed individuals with right hemisphere lesions in processing metrical structures and rhythm, whereas in Liégeois-Chauvel et al. (1998) individuals with right hemisphere temporal lobe lesions underperformed individuals with left hemisphere lesions using the same tasks. These lesion studies appear to show that rhythm and meter perception rely on both temporal lobes. Nevertheless, the findings of Grahn and Brett (2007) indicate left hemisphere dominance in the left inferior frontal area for the processing of simple metrical structures. Future studies may find a right ear advantage for processing acquired knowledge of pitch-meter correlation by including an explicit training phase, as in Abla and Okanoya (2008), or by allowing time for memory consolidation between learning and testing (Forkstam et al., 2006).

Results for Experiment 2

Probe tone ratings (see Figures 1 and 2) were submitted to a $3 \times 2 \times 2$ (Pitch [tonic, supertonic, out-of-set] $\times$ Context [ascending, random] $\times$ Ear [left, right]) analysis of variance (ANOVA). The ANOVA revealed a significant effect of Pitch $F(2,115) =$

182.19, $p = {}< 0.001$, $\eta^2 = 0.611$, with the out-of-set pitch receiving the lowest and the tonic receiving the highest probe tone ratings. There was also a significant Pitch $\times$ Ear interaction $F(2, 115) = 4.56$, $p < 0.025$, $\eta^2 = 0.038$, a significant Pitch $\times$ Context interaction $F(2, 115) = 18.01$, $p < 0.001$, $\eta^2 = 0.134$, and a significant Pitch $\times$ Context $\times$ Ear interaction $F(2, 115) = 3.81$, $p < 0.05$, $\eta^2 = 0.027$.

The Pitch $\times$ Ear interaction was driven primarily by the supertonic, which received significantly lower ratings in the right ear than the left $F(1, 116) = 10.10$, $p < 0.0025$, $\eta^2 = 0.087$, whereas the difference between the left and right ears did not reach significance for the tonic, $F(1, 116) = 1.73$, $p = 0.191$, $\eta^2 = 0.015$, or the out-of-set pitch, $F(1, 116) = 0.95$, $p = 0.333$, $\eta^2 = 0.008$. The difference in ratings between the tonic and supertonic was significantly greater in the right ear, $F(1, 116) = 7.45$, $p < 0.01$, $\eta^2 = 0.060$, whereas the difference in ratings between the tonic and out-of-set pitch was not significantly influenced by ear of presentation, $F(1, 116) = 3.34$, $p = 0.07$, $\eta^2 = 0.028$.

The Pitch $\times$ Context interaction was driven primarily by the tonic and supertonic, both of which received higher ratings for the random contexts than for the ascending context, $F(1, 116) = 13.39$, $p < 0.001$, $\eta^2 = 0.103$ (for the tonic), and $F(1, 116) = 69.04$, $p < 0.001$, $\eta^2 = 0.373$ (for the supertonic). The ratings for the out-of-set pitch were not differentially influenced by the contexts, $F(1, 116) = 1.01$, $p = 0.317$, $\eta^2 = 0.009$.

To understand the Pitch $\times$ Context $\times$ Ear interaction, separate 3×2 ANOVAs were run for each of the context melodies. The Pitch $\times$ Ear interaction was significant for the ascending context, (Melody 1) $F(2,115) = 4.83$, $p < 0.025$, $\eta^2 = 0.040$, but not for either of the random contexts, $F(2,115) = 0.97$, $p = 0.397$, $\eta^2 = 0.008$ (Melody 2), $F(2,115) = 1.42$, p $= 0.244$, $\eta^2 = 0.012$ (Melody 3). For the ascending context, the

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difference in ratings between the tonic and supertonic was greater in the right ear, $F(1,116) = 9.91$, $p < 0.0025$, $\eta^2 = 0.079$, whereas the difference in ratings between the tonic and out-of-set pitch was not influenced by ear of presentation, $F(1,116) = 0.35$, $p = 0.554$, $\eta^2 = 0.003$.

Discussion for Experiment 2

In the probe tone paradigm, pitches that are highly expected receive higher ratings. Consistent with prior research, Experiment 2 showed lowest ratings for the out-of-set pitch and the highest ratings for the tonic. However, participants' probe tone ratings were modulated by ear of presentation. The finding that participants' probe tone ratings discriminated between the tonic and the supertonic more strongly in the right ear suggests that some pitch expectations are lateralized to the left hemisphere. Due to the right-ear advantage being significant only for the ascending context, it appears that the right-ear advantage resulted from a temporal expectation. The lower ratings for the supertonic in the right ear suggest that the left hemisphere interprets within-set pitches that are not temporally expected as less stable. This role of the left hemisphere in temporal expectation is consistent with the previously observed role of the left hemisphere for processing temporal relationships between pitches (Abla & Okanoya, 2008; Gelfand and Bookheimer, 2003; Stewart et al., 2008).

The results of Experiment 2 did not support a dominant role of the right hemisphere for expectations of set membership. Right hemisphere dominance for set membership would predict lower ratings for out-of-set pitches in the left ear. The failure to demonstrate the predicted ear differences for the out-of-set pitch in

Experiment 2 may be explained by a specific characteristic of the probe tone task.

The probe tone task requires the participant to evaluate the specific aspect of the

pitch structure that is the focus of the investigation. Some research outside of the

music domain has suggested that many of the right hemisphere's contributions to

perception occur in tasks in which participants do not evaluate the specific aspect of

pitch structure under investigation. Some of the most compelling evidence comes

from individuals with severe dyslexia (i.e. alexia) caused by extensive damage to the

left hemisphere (Larsen, Baynes, & Swick, 2004; Shallice & Saffran, 1986; Saffran &

Coslett, 1998). Although the individuals in these studies could not explicitly identify

a given word to which they were looking or could not explicitly report a given

word's meaning, they performed well above chance in lexical decision and semantic

categorization tasks. In the lexical decision and semantic categorization tasks,

rather than having to produce a correct response, participants were asked to choose

the correct response out of two options. The results of these studies suggest that

the right hemisphere could contribute to perception when the participant does not

have to directly evaluate an aspect of the relevant structure. Potentially, the

stronger responses in the right hemisphere for violations of set membership in

neuroimaging studies (Koelsch et al., 2000; Tillman, et al., 2003; Koelsch, et al.,

2005) could reflect processes that would not be detectable using the probe tone

task, but which would be detectable using forced-choice tasks, such as same-

different tasks (Ayotte et al., 2000; Liégeois-Chauvel et al., 1998; Peretz, 1990;

Zatorre, 1985) or the harmonic priming task (Bigand et al. 2003; Hoch & Tillmann

2010). Future research should attempt to determine whether expectations of set membership would show a left-ear advantage using the harmonic priming task.

In conclusion, Experiment 2 suggests that the formation of temporal expectations among pitches within a set relies more strongly on the left hemisphere. This is the first behavioral study to link the perception of pitch stability to the left hemisphere. Future research should be performed to fully understand the role of the right hemisphere in expectations of set membership.

Results for Experiment 3

Individual trials were excluded if participants responded before the target chord was sounded or if participants responded incorrectly. Additionally, the first trial was excluded as a practice trial. Three participants who had 50% or more of their trials excluded for the above reasons were excluded in their entirety. Reaction times (see Figure 3) were calculated for the tonic, subdominant, and out-of-set target chords. Reaction times were submitted to a 3 × 2 (Chord [tonic, subdominant, out-of-set) × Ear [left, right] repeated-measures ANOVA. There was no significant effect of Ear $F(2,113) = 0.01$, $p = 0.927$, $\eta^2 = 0.000$, or Chord $F(2,113) = 0.62$, $p = 0.615$, $\eta^2 = 0.005$, or Ear × Chord interaction $F(2,113) = 1.30$, $p = 0.275$, $\eta^2 = 0.011$.

Discussion for Experiment 3

There results of Experiment 3 are surprising because of the failure to show the fastest reaction times for the tonic, followed by the subdominant, followed by the out-of-set chord (i.e. a failure to show a priming effect). There are several subtle differences between Experiment 3 and previous work using the same paradigm that could potentially explain this failure to replicate.

For one, almost all previous studies using the harmonic priming paradigm have varied the key of the context sequence from trial to trial. In the current study, all chord sequences were from the same key of C major. Previous authors have not explained why they have used various keys, but one possible explanation for not finding the effect in the current study is that the repetition of hearing the same context sequence from the same key on each trial makes it easier for the participant to ignore the context sequence and to perform the timbre identification task without forming pitch expectations. Another potential explanation for the failure to replicate the priming effect is that the current study used fewer trials than previous studies. Previous studies have tended to have participants perform around 100 trials, whereas the current study had participants perform only 24 trials. It is possible that the number of trials in the current study was not sufficient to average out noise in the reaction time data. Although additional participants were added to increase power, power was not sufficiently increased enough to detect significant effects.

Overall, Experiment 3 provided little information about the roles of the left and right hemispheres in the formation of pitch expectations. The failure to replicate the priming effect suggests that the contexts did not sufficiently drive participants to form pitch expectations. Future studies should implement changes so as to replicate the priming effect and to produce more statistical power to detect ear asymmetries. This could be accomplished by increasing the number of trials and by having the context sequences vary from key to key on each trial.

Results for Experiment 4

The data from five participants were excluded for answering with the extreme ends of the response scale (1 and 7) on over 80% of the trials. Similarity ratings (see Figure 4) were submitted to a 2 × 2 (Type of Violation [sequential, set membership] × Ear [left, right] repeated measures ANOVA. There was a significant effect of Ear $F(1,112) = 5.01$, $p < 0.03$, $\eta^2 = 0.043$, with participants providing lower ratings to violations occurring in the right ear. There was also significant effect of Pitch $F(1,112) = 26.32$, $p < 0.001$, $\eta^2 = 0.190$, with participants providing lower similarity ratings to sequential violations. The Pitch × Ear interaction was not significant $F(1,112) = 0.20$, $p = 0.653$, $\eta^2 = 0.002$. The difference in ratings between the left and right ears did not approach significance for test trials in which the test string and the standard string were the same $t(112) = 0.55$, $p = 0.585$, $d = 0.05$

Discussion for Experiment 4

It was expected that participants would better detect (i.e. provide lower similarity ratings for) sequential violations in the right ear and that participants would provide lower similarity ratings for set membership violations in the left ear. Surprisingly, there was a main effect of Ear, with the right ear showing lower similarity ratings for violations than the left, but no Pitch × Ear interaction. For both sequential and set membership violations, similarity ratings were lower in the right ear.

The results of Experiment 4 are fairly consistent with the neuroimaging data of Stewart et al. (2008). Stewart et al. (2008) found stronger responses in the left superior temporal lobe on "global trials" (corresponding to sequential violation

trials in the current study) and bilateral responses on "local trials" (corresponding to the set membership violation trials in the current study). Overall, Stewart et al. (2008) found stronger responses in the left temporal lobe compared to the right, which is consistent with the right ear advantage (left hemisphere advantage) found in Experiment 4.

Even though the expected interaction was not found, the fact that participants provided lower similarity ratings in the right ear is consistent with a role of the left hemisphere in encoding the sequential order of pitch strings. The failure to find a left-ear advantage for set-membership violations may be due to participants not establishing a strong sense of set membership. Participants' greater similarity rating for out-of-set violations suggests that out-of-set violations were less salient than sequential violations. Potentially, out-of-set violations were not very salient because of the use of the whole-tone scale. Previous research has shown that, although participants can detect pitch alterations to melodies composed using the whole-tone scale, participants are considerably better able to detect changes to melodies composed using scales that contain uneven steps (e.g. the major scale) (Trehub, Schellenberg, & Kamenetsky, 1999). If participants did not establish a strong sense of set membership, then it is reasonable that their performance on set-membership trials would not be strongly influenced by the right hemisphere.

As the stimuli in Experiment 4 did not use familiar scales or familiar pitch sequences, these results suggest that the left hemisphere could be used for acquiring knowledge about the sequential order of pitches in music. Presumably, then, the left

hemisphere could contain a temporal learning mechanism that underlies the acquisition of the prototypical temporal structures of the Western musical system. It is not clear based on the results of Experiment 4, however, whether the right hemisphere contains a non-temporal learning mechanism.

Chapter 4 -- General Discussion

Contributions of the left and right hemispheres to pitch perception

Neither Experiments 1 nor 3 showed the expected ear asymmetries. As is described in the individual discussion sections for each of these experiments, these failures could potentially be attributed to methodological nuances. Despite the failures of Experiments 1 and 3, both Experiments 2 and 4 of this dissertation showed evidence of left hemisphere dominance for temporal pitch processing. None of the experiments provided evidence of right hemisphere dominance for non-temporal pitch processing.

The results of Experiment 2 are consistent with a role of the left hemisphere in using acquired knowledge to form expectations among the pitches in a set. In Experiment 2, the difference in probe tone ratings between the tonic and supertonic was bigger in the right ear for the ascending context only. Presumably, the ability to differentiate the stability of the tonic and supertonic is acquired with experience throughout development (Corrigal & Trainor, 2010; Krumhansl & Keil, 1982; Trainor & Trehub, 1992; Trainor & Trehub, 1994). Thus, the finding of Experiment 2 could reflect a left hemisphere mechanism for acquiring knowledge of statistical regularities of temporal order (Abla & Okanoya, 2008; Karuza et al., 2013). However, future research will be required to determine whether the right ear advantage in Experiment 2 was the result of experience, or whether the effect can be explained solely by bottom-up factors.

No research has directly addressed the role of experience in hemispheric asymmetry of pitch processing, but developmental research has shown that the

right hemifield advantage for reading words is positively correlated with age and reading ability (Miller & Turner, 1973), suggesting that the right-ear advantage for some tasks could be acquired. One way of addressing the role of experience in the right-ear advantage of Experiment 2 would be to compare adults and children's probe tone ratings for the ascending context using a monaural presentation. If experience with the temporal structure of music drives the right ear advantage in Experiment 2, then there should be an increased ability to discriminate the tonic from other in-set pitches with increasing age, and this increased ability should correspond to a stronger right ear advantage. Similarly, a cross-cultural design investigating ear asymmetries in probe tone ratings for the ascending context could provide insight into the causal role of experience for the right ear advantage shown in Experiment 2. Specifically, although cultures with minimal exposure to Western tonal music might be able to discriminate the tonic from other in-set pitches on the basis of bottom-up factors, such as periodicity pitch, cultures with minimal exposure to Western tonal structure should have more difficulty discriminating the tonic from other in-set pitches on the basis of temporal structure, and should show a weaker right ear advantage or no right ear advantage at all.

The findings from Experiment 2 are consistent with the suggestion that the left hemisphere is dominant in the perception of local interval structure (Peretz, 1990). Presumably, to form a temporal pitch expectation for the tonic, participants had to be sensitive to the specific pattern of intervals in the ascending context. When a different interval pattern was used, as was the case in the random contexts, there was no evidence of ear asymmetry. Although the findings are consistent with

the local-interval characterization of the left hemisphere, it might be more appropriate to characterize the left hemisphere more generally as dominant in temporal pitch processing instead. Part of the reason that Peretz (1990) characterized the left hemisphere as dominant in local-interval processing was the assumption that the right hemisphere was dominant in global-contour processing. Although it is not inaccurate to characterize the right hemisphere as dominant in some aspects of global processing (e.g. set membership), it appears that the right hemisphere is not dominant in the perception of contour when non-temporal confounds are controlled (Stewart et al., 2008). If the right hemisphere does not process the 'coarse' pitch relationships that supposedly underlie perception of contour, then it appears that the right hemisphere may actually process specific interval relationships. In support of this possibility, Zatorre (1988) and Paquette, Bourassa, and Peretz (1996) both support the dominance of the right hemisphere in processing periodicity pitch. As periodicity pitch perception requires sensitivity to harmonic overtone structure and the ability to perceive a specific pitch as the fundamental frequency, it appears inaccurate to suggest that the right hemisphere does not process local interval relationships. The main difference between the left and right hemispheres in pitch processing is that only the left hemisphere appears to process interval relationships with respect to temporal order.

The results of Experiment 2 clearly cannot be explained by the spectral-temporal model. The spectral-temporal model would predict right hemisphere dominance for all pitch expectations due to a right hemisphere dominance for tonal working memory and pitch precision (Zatorre et al., 1994, Zatorre et al., 2002).

Thus, the spectral-temporal predicts that all pitch expectations should be dominant in the right hemisphere. The findings of left hemisphere dominance for the formation of temporal expectations in Experiment 2 also cannot be explained by the spectral-temporal model's suggestion of left hemisphere dominance for temporal precision, as the stimuli in Experiment 2 occurred at a relatively slow tempo.

The findings of Experiment 4 suggest that the perception of contour is not dominant in the right hemisphere when non-temporal confounds are controlled (Stewart et al., 2008). The results of Experiment 4 are inconsistent with the widespread suggestion that the right hemisphere is dominant in processing pitch relationships over time (Peretz and Zatorre, 2005), including contour (Peretz, 1990). However, the results of Experiment 4 are consistent with the local-global model's suggestion of a role of the left hemisphere in processing interval relationships. The results of Experiment 4 thus only partially support the local-global model.

The spectral-temporal model cannot explain the results of Experiment 4. The spectral-temporal model would predict greater accuracy (i.e. lower similarity ratings for all violation trials in the left ear (right hemisphere). The findings in Experiment 4 were in the opposite direction to what the spectral-temporal model would predict. Although the spectral-model can explain some asymmetries in low level perception, it appears not to be able to account for the asymmetries in higher-level perception of temporal and non-temporal pitch structures shown in the current study and elsewhere (Abla & Okanoya, 2008; Stewart et al., 2008). A better explanation of asymmetries for higher-level pitch processing is that those pitch

structures that can be processed independently of the temporal order of the pitches,

such as set membership (Ayotte et al., 2000; Koelsch et al., 2000; Tillman, et al.,

2003; Koelsch, et al., 2005; Zatorre, 1985), pitch frequency-of-occurrence, and pitch

range (Ayotte et al., 2000; Balaban et al., 1998; Jurado et al. 1997; Liégeois-Chauvel

et al., 1998; Peretz, 1990; Zatorre, 1985), dominantly involve the right hemisphere,

whereas those pitch structures that can be processed with respect to the temporal

order of pitches, including interval and contour (Abla & Okanoya, 2008; Stewart et

al., 2008; Tillmann et al., 2006), dominantly involve the left hemisphere.

Future Directions and Conclusion

Overall, the findings of this dissertation emphasize the role of the left

hemisphere in the processing of temporal pitch structure. The conception of the left

hemisphere as dominant in temporal processing is relevant to impairments in

speech perception, such as in dyslexia, autism and schizophrenia. In addition to

speech impairments, these clinical disorders are often associated with abnormal

brain responses and anatomy in the left hemisphere (Alary et al., 2013; Bleich-

Cohen, 2012; Dehaene et al., 2010; Dollfus et al., 2005; Eyler, Pierce, & Courchesne,

2012; Illingworth & Bishop, 2009; Kasai, et al., 2003; McCarley, et al., 1999; Paulesu

et al., 2001; Prior & Bradshaw, 1979; Simos et al., 2011) and impairments in the

temporal processing of relatively slow, musical stimuli (Depape, Hall, Tillmann, &

Trainor, 2012; Huss, Verney, Fosker, Mead, & Goswami, 2011; Ramage, Weintraub,

Allen, & Snyder, 2012; Thomson & Goswami, 2008; Weintraub et al., 2012; Ziegler,

Pech-Georgel, George, & Foxton, 2012). As of yet, there have been few attempts to

understand the connection between speech and slow temporal processing in clinical

populations or typically developing individuals, but most authors have tended to focus their efforts on the right hemisphere because of its apparent dominance in processing relatively slow musical structures (Abrams, Nicol, Zecker, & Kraus, 2008; Goswami, 2011). The findings here should encourage researchers to reassess their understanding of the left hemisphere's role in speech and temporal processing. It appears that the left hemisphere may serve as a common locus for speech and temporal processing because of the left hemisphere's dominant role in processing and recognizing familiar temporal structures, whether the structures occur on a slow or fast timescale.

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perception in children with developmental dyslexia. *Brain & Language, 120,*

265-270.

Appendix 1 -- Figures

Figure 1
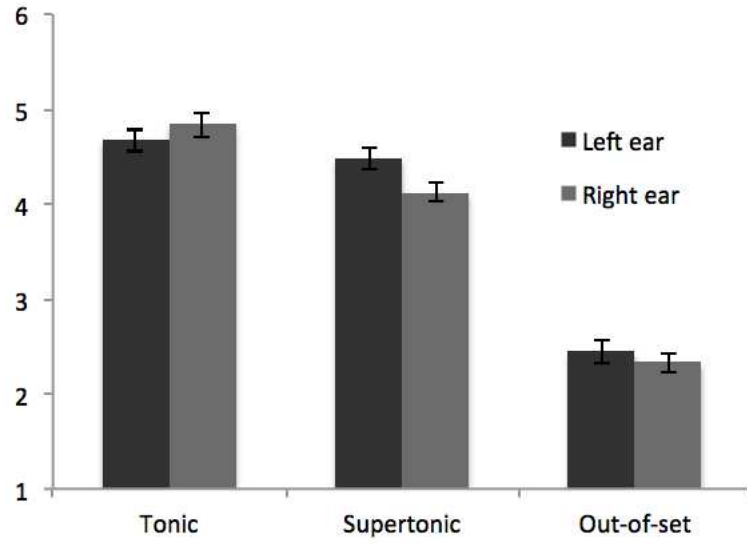Probe tone ratings collapsed across ascending and random contexts.

Figure 2
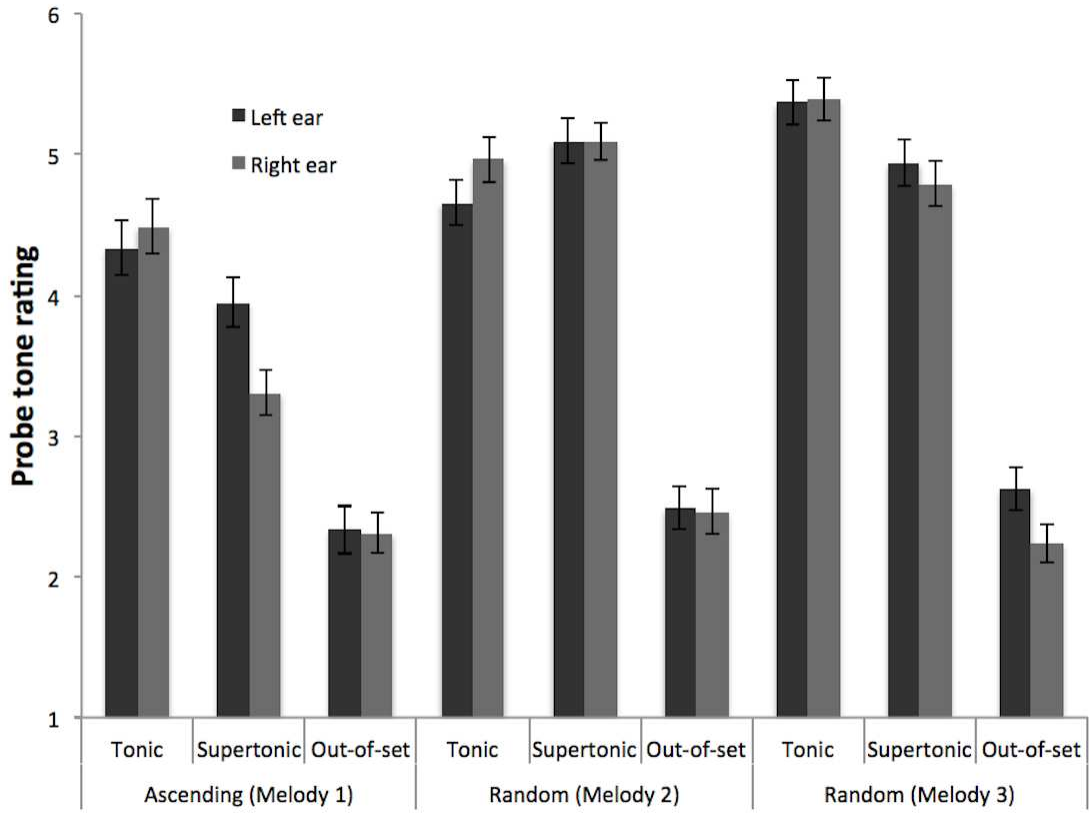Probe tone ratings for each of the three context sequences of Experiment 2.

Figure 3
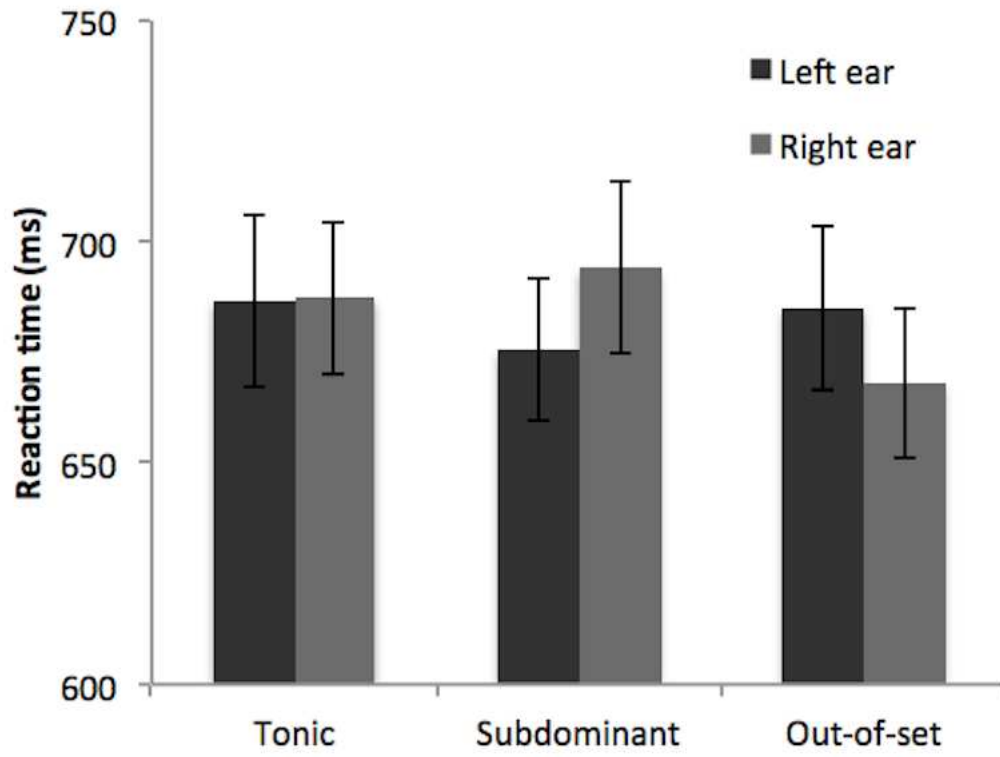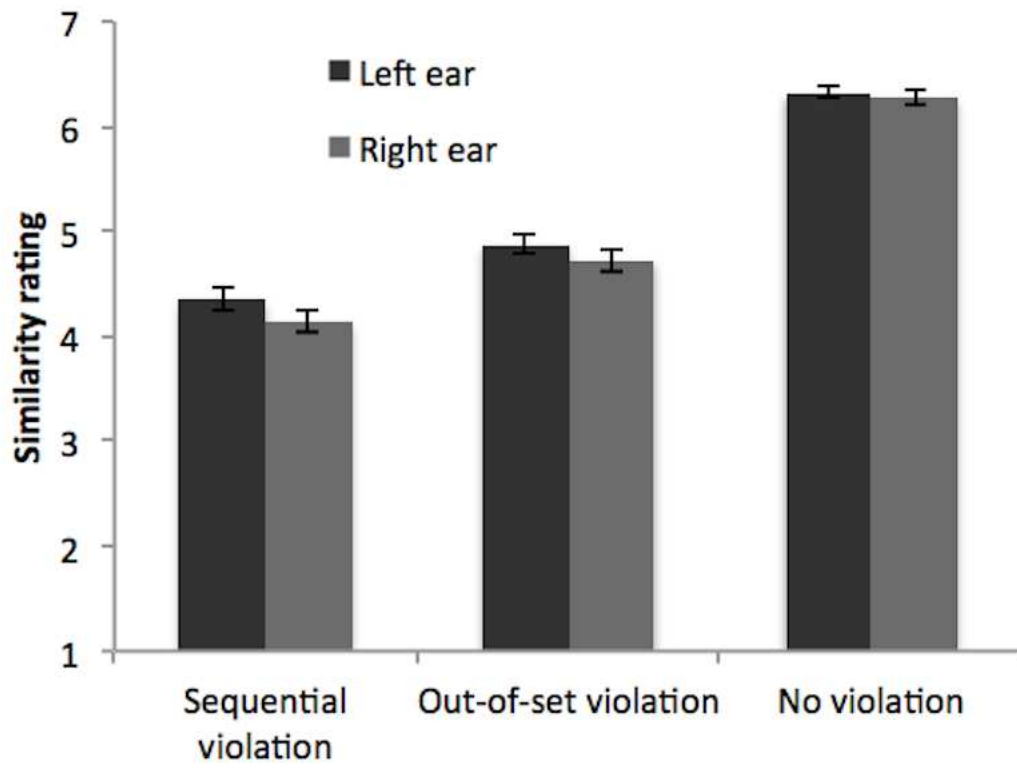Reaction times for Experiment 3.

Figure 4
Similarity ratings for Experiment 4.

Social/Behavioral IRB – Expedited Review Approval Notice

NOTICE TO ALL RESEARCHERS:

Please be aware that a protocol violation (e.g., failure to submit a modification for any change) of an IRB approved protocol may result in mandatory remedial education, additional audits, re-consenting subjects, researcher probation, suspension of any research protocol at issue, suspension of additional existing research protocols, invalidation of all research conducted under the research protocol at issue, and further appropriate consequences as determined by the IRB and the Institutional Officer.

DATE: December 18, 2013 **TO: Dr. Mark Ashcraft**, Psychology **FROM:** Office of Research Integrity - Human Subjects

RE: Notification of IRB Action Protocol Title: **Musical Pitch Perception**

Protocol #: 1311-4643 Expiration Date: December 17, 2014

This memorandum is notification that the project referenced above has been reviewed and approved by the UNLV Social/Behavioral Institutional Review Board (IRB) as indicated in Federal regulatory statutes 45 CFR 46 and UNLV Human Research Policies and Procedures.

The protocol is approved for a period of one year and expires December 17, 2014. If the above-referenced project has not been completed by this date you must request renewal by submitting a Continuing Review Request form 30 days before the expiration date.

PLEASE NOTE:

Upon approval, the research team is responsible for conducting the research as stated in the protocol most recently reviewed and approved by the IRB, which shall include using the most recently submitted Informed Consent/Assent forms and

recruitment materials. The official versions of these forms are indicated by footer which contains approval and expiration dates.

Should there be *any* change to the protocol, it will be necessary to submit a **Modification Form** through ORI - Human Subjects. No changes may be made to the existing protocol until modifications have been approved by the IRB. Modified versions of protocol materials must be used upon review and approval. Unanticipated problems, deviations to protocols, and adverse events must be reported to the ORI – HS within 10 days of occurrence.

If you have questions or require any assistance, please contact the Office of Research Integrity - Human Subjects at IRB@unlv.edu or call 895-2794.

Curriculum Vita
Matthew Adam Rosenthal
7303 South Woodward Avenue Apt. 208
Woodridge IL, 60517
Email: rosent17@unlv.nevada.edu; rosent17@gmail.com
Phone: 317-445-5371

Education

University of Nevada, Las Vegas, Las Vegas, NV
　　　Ph.D, Psychology (December 2014)
　　　Emphasis in Cognitive Psychology
　　　Advisor: Dr. Mark Ashcraft

Doctoral Advisory Committee:
　　　Dr. Mark Ashcraft
　　　Dr. David Copeland
　　　Dr. Colleen Parks
　　　Dr. Gregory Schraw

University of Nevada, Las Vegas, Las Vegas, NV
　　　M.A., Psychology (Spring 2011)
　　　Adviser: Dr. Erin Hannon

Indiana University, Bloomington IN
　　　B.S., Psychology (Spring 2008)
　　　Concentration in Mathematics

Teaching Experience

Department of Psychology**,** University of Nevada, Las Vegas
Instructor
• Lectured, created and graded course materials
　° Introductory Psychology (PSY 101), Fall 2010, Spring 2010, Fall 2011,
　　Spring 2011, Fall 2012, Spring 2012, Fall 2013, Spring 2013, Fall 2014,
　　Spring 2014

Teaching assistant
• Graded homework assignments, papers, and tests
　° Research Methods (PSY 240), Statistics for Psychology (PSY 708, 709)
　　Developmental Psychology (PSY 330)

Awards

- HHMI Capstone Grant (Indiana University, 2005)- $1000.
- Dynamic Field Theory workshop travel grant (Fall 2008)- $500
- Society for Music Perception and Cognition travel grant (Summer 2011)- $250
- UNLV GPSA travel award (Summer 2013)- $400

Publications

Rosenthal, M.A. (2014). Hemispheric asymmetry in the formation of musical pitch expectations: a monaural listening and probe tone study. *Neuropsychologia, 65,* 37-40.

Manuscripts in prep

Rosenthal, M.A., & Hannon, E.E. (Under revision). Listeners use pitch frequency-of-occurrence and pitch-meter correlation to learn about musical tonality. *Music Perception.*

Presentations

Rosenthal, M.A. & Hannon, E.E. (2009). *Stimulus-driven expectancies and the perceptual enhancement of visual stimuli*. Society for Music Perception and Cognition, Indiana University-Purdue University, Indianapolis, Indiana.

Anaya, E. M., & Rosenthal, M. A. (2010). *Behavioral correlates of speech in noise perception*. DeVault Laboratory, Indianapolis Indiana.

Rosenthal, M.A., Quam, R., & Hannon, E.E. (2010). *Learning mechanisms for acquiring knowledge of tonality in music*. Auditory Perception, Cognition, and Action meeting, St. Louis, Missouri.

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Rosenthal, M.A. & Hannon, E.E. (2012). *Longer-term tonal learning*. Auditory Cognition and Neuroscience Society. Tucson, Arizona.

Rosenthal, M.A. & Hannon, E.E. (2013). *The role of temporal structure in tonal learning*. Society for Music Perception and Cognition. Toronto, Ontario.

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Ad Hoc reviewer

- Frontiers in Psychology (2013). *Holistic processing for other-race faces in Chinese participants occurs for upright but not inverted faces.* doi:10.3389/fpsyg.2013.00029.

Undergraduate student mentoring

- Caleb Picker
    Fall 2009-Fall 2010
    -I mentored Caleb while he was an undergraduate at UNLV. He is now a PhD student at UNLV.
- Rikka Quam
    Fall 2010-Fall 2012
    -I mentored Rikka while she was an undergraduate at UNLV. She won the psychology department's research poster competition for a project we worked on together.   She is now a graduate student at the University of Texas, Austin.
- Vanessa Lamorte
    Fall 2012-Spring 2013
    -I mentored Vanessa while she was an undergraduate at UNLV. She placed 2nd at the psychology department's research poster competition for a project we worked on together.