Real-Time Probing of Modulations in South Indian Classical (Carnātic) Music by Indian and Western Musicians

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We used Toiviainen and Krumhansl's (2003) concurrent probe-tone technique to track Indian and Western musicians' tonal-hierarchy profiles through modulations in Carnātic (South Indian classical) music. Changes of mode (rāgam) are particularly interesting in Carnātic music because of the large number of modes (more than 300) in its tonal system. We first had musicians generate profiles to establish a baseline for each of four rāgams in isolation. Then we obtained dynamic profiles of two modulating excerpts, each of which incorporated two of the four baseline rāgams. The two excerpts used the two techniques of modulation in Carnātic music: grahabēdham (analogous to a Western shift from C major to A minor), and rāgamālikā (analogous to a shift from C major to C minor). We assessed listeners' tracking of the modulations by plotting the correlations of their response profiles with the baseline profiles. In general, the correlation to the original rāgam declined and the correlation to the new rāgam increased with the modulation, and then followed the reverse pattern when the original rāgam returned. Westerners' responses matched those of the Indians on rāgams with structures similar to Western scales, but differed when rāgams were less familiar, and surprisingly, they registered the shifts more strongly than Indian musicians. These findings converged with previous research in identifying three types of cues: 1) culture-specific cues—schematic and veridical knowledge—employed by Indians, 2) tone-distribution cues—duration and frequency of note occurrence—employed by both Indians and Westerners, and 3) transference of schematic knowledge of Western music by Western participants.

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Tonal hierarchies, in which sets of pitch classes and their relationships to a tonic pitch are defined, are a universal feature in the musical cultures of the world. The tonal hierarchy can be expressed as a profile showing the relative importance of the various pitches. In cultures that use 12 semitones in the octave as their tonal material (Dowling, 1978), this profile shows the ratings given to the 12 pitches by listeners who judge how well those pitches fit a particular context that defines a tonality (such as, a scale or chord sequence). Extensive studies of this type using the "probe-tone method" have been carried out with Western music (Krumhansl, 1990; Vuvan, Prince, & Schmuckler, 2011). Krumhansl and Kessler (1982) studied Western musicians' internal representations of pitch relationships, and how those representations change over time as modulations occur in the music. These researchers obtained profiles for the major and minor keys generated in a variety of tonal contexts, and used multidimensional scaling to acquire a tonal map that is consistent with the pattern of key relationships described in Western music theory. This map is a spatial representation of musical keys, capturing the distances between keys on the basis of two sets of features: (a) the harmonic role of each chord in relation to each tonal center (e.g., the A minor chord in the key of C major), and (b) the tonal hierarchy expressing the relationship of each note of the chromatic scale to each key (e.g., the note A in the key of C major).

Krumhansl and Kessler (1982) also examined whether listeners automatically tracked changes of tonal center as shown by their shifting profiles of modulating chord sequences. These profiles were compared with the standard baseline major and minor profiles in order to ascertain how the sense of key changed over time when modulations occurred. They found that participants identified the initial tonal center, and then tended to change the center towards the modulating key. This change happened faster when the modulation was to a related key than to a distant key (e.g., C major to G major was faster than when C major modulated to B♭ major).

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Toiviainen and Krumhansl (2003) developed the probe-tone method further by recording listeners' ratings of fitness continuously via the concurrent probe-tone technique. In this approach, the single probe tone at the end of a melody or chord sequence was replaced with a continuous probe presented throughout the music. This technique is more effective in capturing dynamically changing profiles of scales, and is an ideal tool for tracking modulations in real time, as Toiviainen and Krumhansl demonstrated. The profiles obtained from this method can be correlated with the baseline profiles of the various modes thereby showing where the listeners perceived the music to be in terms of the tonal space.

The theory of the tonal hierarchy that Krumhansl and her colleagues developed to explain the results of the probe-tone studies is contingent on three propositions (Krumhansl & Cuddy, 2010): (a) It has a cognitive representation and hence, can be subjected to empirical research; (b) it strongly correlates with Western music theory; and (c) listeners, irrespective of the genre of music they are listening to, should be able to apply the principles of tonal hierarchy to it. This is dependent on listeners' ability to perceive statistical regularities in music, such as tone duration and frequency of its occurrence. A useful strategy to study the application of tonal hierarchies is to investigate how they are employed in non-Western cultures. This will provide answers as to whether such hierarchical representation of music can be generalized across different musical systems, such as music like that of India that does not conform to Western harmonic organization.

CROSS-CULTURAL STUDIES

Castellano, Bharucha, and Krumhansl (1984) demonstrated that the probe-tone method can be used to assess the tonal hierarchies of North Indian music, which shares with Western music the use of 12 semitones in the octave. This method can also be adapted to assess the tonal hierarchies in cultures that do not use the 12-tone chromatic scale for their tonal material, such as in Kessler, Hansen, and Shepard's (1984) study of Indonesian music. The structural regularities within the music of a culture help establish tonality and form the tonal hierarchy. Such regularities are found in, but are not limited to, pitch, tempo, rhythm, and contour. For instance, just the simple surface feature of how often a pitch is repeated can indicate its relative importance in the scale (Castellano et al., 1984; Oram & Cuddy, 1995).

Tonal hierarchies are all but universal in the musical cultures of the world. There are very few cultures that ethnomusicological reports suggest do not use fixed pitch levels and octave equivalence in their tonal systems (Dowling & Harwood, 1986), but all the other cultures divide the octave into fixed patterns of pitch classes, typically five to seven, that repeat from octave to octave. The ways in which this is done vary widely from culture to culture. However, all the cultures for which we have sufficiently detailed reports establish a hierarchy of stable and less stable pitches, defined by context, to be used in a given song or musical piece. When a tonal hierarchy is imposed on the pattern of pitches, the result is a "modal scale" (such as, C major or A minor in Western music). In Indian music, the tonic pitch is usually constant across melodies and modes, being constantly present in a drone instrument in the background. In that case, different modes are produced by selecting different sets of pitches in relation to the tonic.

South Indian classical (Carnātic) music is an ideal candidate for cross-cultural studies of the tonal hierarchy and of modulation because of the richness of its modal scale system. Carnātic music has approximately 350 rāgams (modes) currently in use, whereas Western music uses the major and minor modes extensively, with variations of the minor and some rarely used modes making up a grand total of about 13, including three forms of the minor mode, and four medieval church modes as well as five pentatonic modes. One advantage of studying a music system which has hundreds of modes is that it has an expansive set of alternative continuations of a musical context, thus imposing a substantial cognitive load on the acculturated listener (Bartlett & Dowling, 1988). The listener has to sort through and choose alternatives across several tonal maps to arrive at the correct mode. In Carnātic music, there are several rāgams that share all but one pitch (see Figure 1). Thus, schematic knowledge (Bharucha, 1987) of Carnātic music may take appreciably more time than Western schematic knowledge to apply in perceptual processing.

Carnātic music is also an ideal candidate for cross-cultural studies because it is easy to find acculturated participants in Chennai, a city in South India, who listen only to Carnātic music and popular music based on Carnātic rāgams. Since Carnātic music has limited popularity around the world, it is easy to find Western musicians in Dallas, Texas, who have never heard this music before. Finally, Carnātic music has two types of modulation that are similar to the two types in Western music (elaborated below). These modulations occur without harmonic progression as Carnātic music is entirely melody-based, unlike Western music, which involves functional harmony.

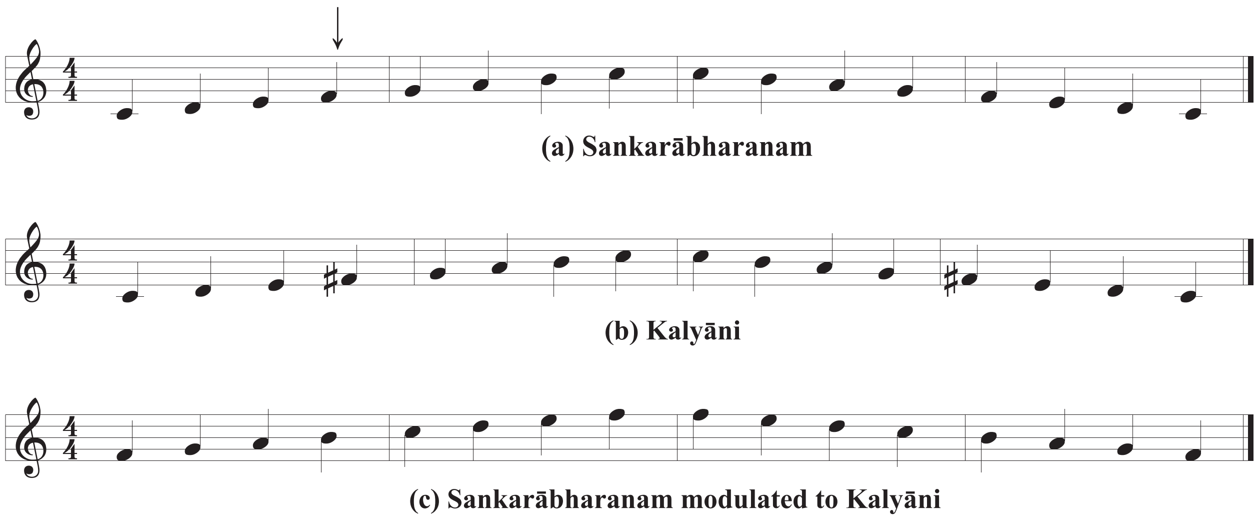

FIGURE 1. An example of two seven-note rāgams (a) Sankarābharanam and (b) Kalyāni. Note that the two rāgams start on the same tonic and share the same notes except for the raised fourth (F♯) in Kalyāni. It is also an example of a rāgamālikā, Sankarābharanam followed by Kalyāni. (c) An example of a grahabēdham. In rāgam Sankarābharanam, the tonal center is shifted to the fourth note of the scale (arrow in panel a) while the pitches of the original scale remain unchanged. The new scale is rāgam Kalyāni, which has the raised fourth (B in this case).

Carnātic music is one of the oldest theoretically based music systems still in existence. To our knowledge, research in the field of music perception and cognition has not used Carnātic music, although some research has been done with Hindustāni music (e.g., Balkwill & Thompson, 1999; Balkwill, Thompson, & Matsunaga, 2004; Castellano et al., 1984; Curtis & Bharucha, 2009). There are significant differences between Carnātic and Hindustāni music. Carnātic music is more complex than its northern counterpart, as it was the earliest form of Indian classical music, whereas Hindustāni music incorporated Arabic and Persian influences following the Moghul invasions of the sixteenth century. The 350 modes of Carnātic music contrast with the approximately 200 modes of Hindustāni music (Jairazbhoy, 1971), and Carnātic ornamentations are much more complex and detailed than Hindustāni ones. Finally, Hindustāni music is more generally popular in the West than Carnātic music due to the world-wide fame of performers such as sitar player Pandit Ravi Shankar (Jauhari, 2011).

GOALS AND HYPOTHESES

The overall objectives of this study were to study Indian and Western music teachers' implicit representations of musical pitches and scales in Carnātic music and to examine how these representations change with modulations. We expected listeners acculturated to Carnātic music would form coherent representations of the modes that were already familiar to them, and we wanted to see if Western listeners would be able to use tone-distribution cues and other surface cues in forming representations of the unfamiliar Carnātic music, in a way similar to what Castellano et al.'s (1984) listeners did in response to Hindustāni music. We also wanted to examine whether Westerners would also rely on the transfer of schematic knowledge from their own culture to the unfamiliar Carnātic music.

Our presentation of the stimuli was modeled on that of Toiviainen and Krumhansl (2003). Carnātic and Western music teachers listened to the excerpts in one ear while they heard a probe tone continuously in the other ear. Each excerpt was repeated 12 times with the 12 different probe tones (the notes of the chromatic scale). Participants made their judgments continuously while listening, using the mouse to control a slider on the computer monitor to indicate how well the probe tone fit with each rāgam at each moment in the excerpt.

We organized the study into two experiments. In Experiment 1 we used the concurrent probe-tone technique to produce baseline profiles of four selected rāgams in Carnātic music. In Experiment 2 we presented modulating excerpts that involved those four rāgams, and analyzed the responses to the modulations in terms of the baseline profiles collected in Experiment 1.

Carnātic music uses two types of modulation. In rāgamālikā, the tonic remains constant while the pitch patterns of the notes of the scale are changed. This is analogous to a change from C major to C minor in

Western music, which can be accomplished by lowering the pitches of the third, sixth, and seventh scale degrees by one semitone, keeping everything else constant. In grahabēdham, the tunings of the pitches in the scale are kept constant, while the tonic is shifted to a new pitch. This is analogous to a change from C major to A minor in Western music, which can be accomplished by moving the tonic from C to A while keeping all the tunings of the scale notes constant. Experiment 2 presented one example of each of these types of modulation, each of which used two of the rāgams whose baseline profiles were obtained in Experiment 1.

The goal of Experiment 2 was to use the concurrent probe-tone technique to produce dynamic profiles that we expected would change as the excerpts modulated to new rāgams, as they did for modulations in the Bach excerpt in Toiviainen and Krumhansl's (2003) study. To do this, we looked at changes in the correlations of the present profile with the baseline profiles at five different times: T1, when the initial rāgam was established; T2, when the modulation was first introduced; T3, when the rāgam to which the excerpt modulated was established; T4, when the modulation back to the initial rāgam was introduced; and T5, when the initial rāgam was re-established.

We wanted, first, to see whether Indian listeners would track the modulations as did the Westerners in Toiviainen and Krumhansl's (2003) study. Also, given that we expected the Westerners to produce coherent baseline profiles, we wanted to examine whether Westerners would track the modulations as well. In all of this, we wanted to differentiate the cues the two groups were using in generating their responses. In considering the two types of Carnātic modulation, we expected that Indian musicians' responses to rāgamālikā would be more clearly differentiated than for grahabēdham, because of their greater familiarity with the former. And we expected Westerners to produce more clearly differentiated responses to grahabēdham because of its similarity to the most common kinds of Western modulation, namely, the case in which the tonic shifts.

A fundamental purpose of this study was to test whether theories and principles of music cognition and perception derived from studies of Western music can be applied to other styles of music, in this case, Carnātic music. For instance, can certain aspects of music cognition developed on the basis of Western music—such as, the principles of an underlying tonal hierarchy, of the resultant maps of the tonal space, and of melodic expectancies—be applied to Carnātic music as well? That is, can Krumhansl and Cuddy's (2010) third proposition that involves the conceptual framework and theory of tonal hierarchies be generalized to Carnātic music? Also, will Toiviainen and Krumhansl's (2003) concurrent probe-tone technique be useful in the investigation of cross-cultural issues involved with the tonal hierarchy?

Though prior research has demonstrated the universality of the tonal hierarchy and melodic expectancies, such research primarily focused on obtaining data after the event had occurred; that is, at the end of the melodic phrase or chord sequence. As far as we know, only one study (Toiviainen & Krumhansl, 2003) has attempted to track participants' perception of music in terms of the tonal hierarchy and modulation in real time, and that with MIDI-generated materials. There are as yet no cross-cultural investigations tracking changes in tonality. Thus, the central objective of the current study was to extend previous studies by applying the concurrent probe-tone technique to ascertain cues to understand how listeners perceive modulation dynamically in recorded live performances of Carnātic music.

THE CUE-REDUNDANCY MODEL

In thinking about the possible cues that listeners were using in responding to the modulations, we found the cue-redundancy model of Balkwill and Thompson (1999; Thompson & Balkwill, 2010) very useful. Their model provides a conceptual framework for considering the various cues that participants—whether familiar or unfamiliar with a musical style—use in order to perceive intended musical aspects. Acculturated listeners use culture-specific cues as well as more superficial psychophysical and tone-distribution cues. Listeners unfamiliar with a particular musical culture or genre rely on the basic psychophysical and tone-distribution cues, and we suppose that they also import schematic knowledge (Bharucha, 1987) derived from their own culture. Balkwill and Thompson's psychophysical cues involve sound intensity, rate (tempo), melodic complexity, melodic contour, pitch range, rhythmic complexity, dynamics, and timbre. However, in addition to these psychophysical cues, other surface-level cues are involved in perceiving a melody. For instance, tone-distribution cues, such as frequency of note occurrence and note duration, are often used by listeners in perceiving both relatively familiar and novel musical sequences (Krumhansl & Cuddy, 2010). The efficacy of such distributional cues can be seen in the results of Oram and Cuddy (1995) and Lantz and Cuddy (1998) who studied the salience of distributional properties of notes in novel melodies. Oram and Cuddy found that listeners form tonal hierarchies in accordance with the frequency of occurrence of the notes; the more often a note was heard, the higher it was placed in the hierarchy. Lantz and Cuddy compared the relative importance of frequency of occurrence and note duration in novel melodies. Their results indicated that duration was a stronger predictor than frequency in the formation of tonal hierarchies. Krumhansl (1990) also reported that the results of Castellano et al. (1984) showed significant correlations between the responses of both Western and Indian musicians with note durations, as well as with the Western major scale. Certain Hindustāni scales (e.g., Kāfi) that are similar to the Western minor induce Western and Indian responses that correlate strongly with the minor.

The cue-redundancy model is particularly useful in differentiating among the different sources of information impinging on the listener's experience of the music and its structure. We assess the effects of tone-distribution cues by correlating the listener's probe-tone responses with profiles of note durations and frequencies of occurrence. And we assess the importance of Western listeners' use of their own schematic knowledge by correlating their responses to the rāgams with the Western major and minor profiles. To the extent that their responses are guided by their culturally determined profiles, and not what they are hearing, we would conclude that they were relying on their schematic knowledge of Western music. To make sure that this is the case, we correlated the profiles of the Indian listeners with the Western major and minor profiles to ensure that the Indian listeners are hearing the rāgams differently from the Western listeners.

THEORETICAL ASPECTS OF THE FOUR RĀGAMS

We now consider how the tonal hierarchy and modulation function in Carnātic music. We will provide a synopsis of the structural aspects of each of the four Carnātic rāgams used in this study, and their similarities and differences in relation to Western scales. The four rāgams are Ranjani, Sriranjani, Panthuvarāli, and Mōhanam (see Figures 2e to 2h). Like the Western modes, the rāgams have a hierarchical organization with the tonic (Sa)[1] as the most important note followed by the dominant (the fifth; Pa) and finally the scale notes. In some rāgams (such as, Ranjani and Sriranjani), the dominant may be omitted, in which case the natural fourth degree of the rāgam (Ma_1), if present, may assume the role of the dominant. Among the remaining scale notes, some are classified as vādi (the characteristic notes of the rāgam), and these notes are sounded more frequently and for longer durations. An example of such a note in Western music is the third degree of a major scale (e.g., E in the scale of C major). Also, each rāgam has characteristic phrases (prayōgam), and these together with the vādi notes provide a distinct emotional and tonal quality (rāgabhāvam) to the rāgam. Some Carnātic rāgams have a different pattern of notes in their ascending and descending forms, just as the Western melodic minor does (e.g., Ranjani; see Figure 2e).

Carnātic rāgams do not always contain seven pitch classes. The first two rāgams we used, Ranjani and Sriranjani (see Figures 2e and 2f), have only six and lack the dominant (Pa). In Ranjani, the natural seventh (Ni_2) is present only in the descending scale. Also, in the descending scale Ranjani has a characteristic phrase wherein the tonic is always preceded by the third note (Ga_1); that is, the phrase has to be Ga_1-Ri_2-Ga_1-Sa and cannot be Ga_1-Ri_2-Sa. Ranjani also has an unstable sharpened fourth note (Ma_2) but does not have a dominant to which it can resolve. More stable notes in Ranjani are the natural sixth (Da_2)—which is the vādi note of the rāgam—and second (Ri_2), because they are complementary to each other, being 7 semitones apart (i.e., a perfect fifth). The flattened third (Ga_1) does not have its complementary pitch class at an interval of 7 semitones, and thus it cannot establish stability.

In Sriranjani (see Figure 2f), according to Carnātic theory, the natural fourth (Ma_1) is considered the most stable after the tonic (Sa), and it assumes the role of the missing dominant (Pa), and is the vādi note of the rāgam. Again, as in Ranjani, the natural second (Ri_2) and sixth (Da_2) are more stable than the remaining notes because they are complementary to each other. The third and seventh notes (i.e., Ga_1 and Ni_1) are also 7 semitones apart and constitute a characteristic phrase.

Panthuvarāli (see Figure 2g), though heptatonic, is different from the Western scales. The unusual notes for the Western listener are the flattened second (Ri_1), the sharpened fourth (Ma_2), and the flattened sixth (Da_1). These notes are unstable, always requiring resolution to the tonic (Sa) or the dominant (Pa). The natural third (Ga_2) forms the major triad (i.e., Sa-Ga_2-Pa is equivalent to C-E-G in C major) and is more stable than the other notes of the rāgam. The natural seventh (Ni_2) is unstable and requires resolution to the tonic, as it does in the Western major scale. Ga_2-Ni_2, lying a fifth apart, forms an important pair and constitutes a characteristic phrase of the rāgam.

[1] Carnātic nomenclature is used to refer to the notes of the octave—Shadjam (Sa), Suddha Rishabham (Ri_1), Chathusruthi Rishabham (Ri_2), Sādhārana Gāndhāram (Ga_1), Anthara Gāndhāram (Ga_2), Suddha Madhyamam (Ma_1), Prathi Madhyamam (Ma_2), Panchamam (Pa), Suddha Dhaivatham (Da_1), Chathusruthi Dhaivatham (Da_2), Kaisiki Nishādham (Ni_1), and Kākali Nishādham (Ni_2); the tonic is Sa and the dominant is Pa.

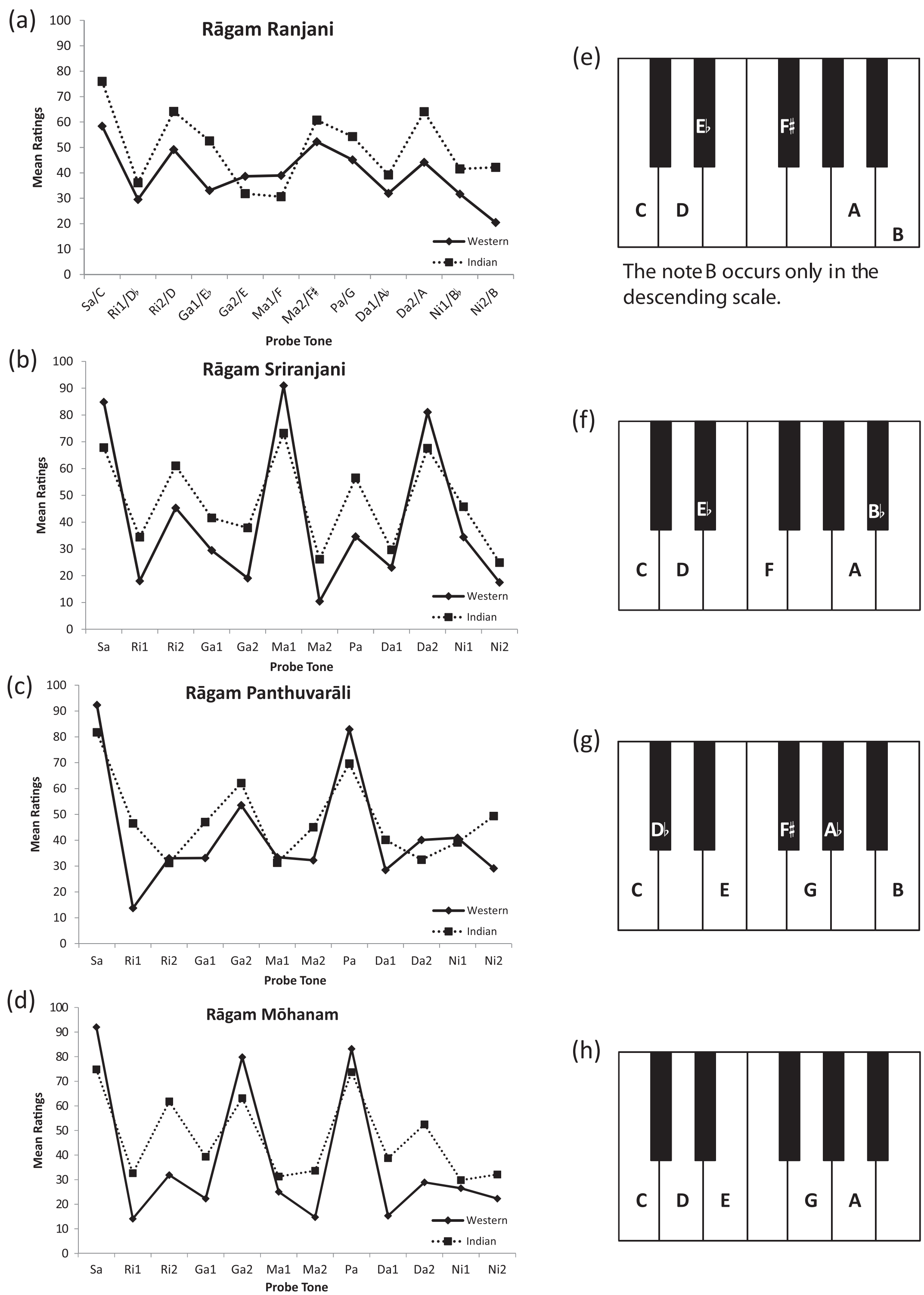

FIGURE 2. Left panel (a to d)—Baseline profiles of Indian (dotted lines) and Western (solid lines) participants for the four rāgams generated using the concurrent probe-tone technique. Responses were averaged across participants and probe tones. The profiles correspond to the tonal hierarchy for each rāgam. In Ranjani, apart from the tonic, Da_2 and Ri_2 are the strongest pitches, and the non-scale Ri_1, Ga_2, Ma_1, Da_1, and Ni_1 are the weakest. In Sriranjani, apart from the tonic, Ma_1 is the strongest pitch, and the non-scale Ri_1, Ga_2, Ma_2, Da_1, and Ni_2 are the weakest. In Panthuvarāli, apart from the tonic, Pa and Ga_2 are the strongest pitches, and the non-scale Ri_2, Ga_1, Ma_1, Da_2, and Ni_1 are the weakest. In Mōhanam, apart from the tonic, Pa and Ga_2 are the strongest pitches, and the non-scale Ri_1, Ga_1, Ma_1, Ma_2, Da_1, Ni_1, and Ni_2 are the weakest. Right panel (e to h)—Notes of each rāgam depicted on a piano keyboard with C as tonic.

Mōhanam (see Figure 2h) has the notes of the Western major pentatonic mode, with the tonic (Sa) and dominant (Pa) the most stable notes, followed by the natural third (Ga_2), which is the vādi note. Here again the tonic, third, and dominant (Sa-Ga_2-Pa) form a stable triad (i.e., C-E-G in C major). The tonic and dominant, as well as the second and sixth degrees (Ri_2 and Da_2) are complementary to each other, being 7 semitones apart.

MODULATION IN CARNĀTIC MUSIC

An aspect of music that directly involves the tonal hierarchy is modulation. One reason for studying perception of modulations rather than melodies with a single tonality is the perceptual dynamics engaged in such a process. The tonal continuity of the music is violated in the shift to a new tonality, and so one of the cues to the occurrence of modulation is the violation of expectancies based on the initial tonal hierarchy. As the tonality shifts and a new tonality is established, listeners modify their internal tonal maps to match the perceived key of the music they are hearing (Krumhansl & Kessler, 1982).

Modulation occurs in both Western and Carnātic music. In Western music, modulation typically involves a shift of the tonal center—the tonic pitch—as in moving from C major to G major. It can also involve a change of mode, as in moving from C major to C minor. And it can involve both of those changes, as in moving from C major to D minor. In Western music, modulations are usually accomplished by means of a progression of chords that leads smoothly from one key to the other, making use of pitches common to the two tonalities. In contrast, some composers such as Schubert sometimes simply move abruptly from one key to another, often hinging the move on a common tone between the two keys. After arriving in the new key, composers typically establish it by repeating some of its principal chords before elaborating it with more complex harmonies. Carnātic music, in contrast, is based entirely on melodies, with no harmony. Although Carnātic music does not involve functional harmony, the music is performed with a constant drone consisting of the tonic, fifth, and octave pitches produced by the "sruthi" (drone) box. One of the functions of the drone is to establish the tonic, much like the function of principal chords in Western harmony, which imply a tonal center. Modulation in Carnātic music involves cues provided by changes in the pitches of the melody and their relationships to one another in terms of emphasis and characteristic turns of phrase. Modulations are also often cued by a pause in the song, filled with a characteristic drum pattern.

Carnātic modulation always involves a change of mode (rāgam), and as noted above, this can be accomplished in one of two ways. In grahabēdham, the tonal center (the "tonic") is shifted to a "new tonic," a shift analogous to a Western shift from C major to A minor. All the individual pitches remain the same, but now the musician is playing or singing a new rāgam based on the new tonal center. For example, Figure 1 shows two heptatonic rāgams, Sankarābharanam (a) and Kalyāni (b), first alone with C as the tonic, and then with Kalyāni shifted so as to take F as its tonic (c), using the pitches of the Sankarābharanam rāgam. This shift occurs while the sruthi box drone continues to emit the tonic-fifth-octave notes of the original tonal center, thus introducing a contrast between the old and new tonal centers. When the melody shifts to a new rāgam, the musician takes care to establish the new key by dwelling at some length on the new tonic, and by introducing characteristic turns of phrase and ornaments before moving on. Only a very few eminent musicians perform grahabēdham, as it requires tremendous training and thorough knowledge of the rāgams.

In rāgamālikā, in contrast, the tonic remains the same, and the tuning of the pitches of the scale notes shifts to those of the new rāgam, analogous to a Western shift from C major to C minor. For example, in Figure 1, Sankarābharanam (a) shifts to Kalyāni (b) by raising the fourth note of the scale by one semitone (F to F♯). The rāgams in a rāgamālikā can have different numbers of pitches in their scales, such as five or six, as well as the seven shown in Figure 1. The rāgams to which the song modulates are usually chosen by the composer in such a way that each rāgam contrasts in character with the one preceding or succeeding it. Note that the range of possible rāgams to modulate to is much larger in rāgamālikā than in grahabēdham, since for the latter the possibilities are limited by the pitches available in the original rāgam. Two cues for detecting shifts in rāgamālikā are the occurrence of new pitches that were not present in the preceding rāgam, and shifts of emphasis on the various scale degrees (i.e., changes in the details of the tonal hierarchy).

Experiment 1: Creating Baseline Profiles

METHOD

Participants. The study was conducted both in Chennai, India, and in Dallas, Texas. Ten Carnātic music teachers of Indian origin living in Chennai and 10 Western music teachers of non-Indian origin in Dallas participated in the study. We chose music teachers for two reasons: (1) Most of the studies that have used the probe-tone method have had just musicians as their participants (exceptions include Halpern, Kwak, Bartlett, & Dowling, 1996; Krumhansl & Shepard, 1979; Lantz & Cuddy, 1998, 2006). In those exceptions, musicians showed more robust response patterns than nonmusicians (except in Lantz & Cuddy, 1998). (2) Music teachers are experts with explicit knowledge of music theory. Since to our knowledge this is the first cross-cultural study using the concurrent probe-tone technique, we wanted to analyze the response patterns of an expert group.

We recruited Indian and Western participants based on their avid interest in their respective music, which was indicated by the number of concerts they attended in a year (a minimum of 25 concerts), how often they listened to tapes/CDs (a minimum of 3 times per week), as well as the fact that they taught music lessons daily. The two groups were homogeneous, in that they were matched in age, Indian $M = 71.5$ years, Western $M = 69.6$ years, $t(18) = 0.65$[2]; music training, Indian $M = 27.4$ years, Western $M = 27.7$ years, $t(18) = 0.03$; years of music teaching, Indian $M = 24.3$ years, Western $M = 25.1$ years, $t(18) = 0.12$; and performance, Indian $M = 29.3$ years, Western $M = 35.8$ years, $t(18) = 0.81$. Indian teachers reported that they did not listen to Western music at all, and only listened to Carnātic music and rāgam-based popular songs. Similarly, Western teachers reported that they had never heard Carnātic music. All participants reported having normal hearing and a regular school education of at least 12 years. We obtained informed consent from each participant before the start of the experiment, and all participants completed a brief questionnaire on their musical experience.

Stimuli. Stimuli consisted of four excerpts taken from four popular Carnātic songs. Each excerpt was in a different rāgam, and the rāgams chosen for Experiment 1 were the same as in Experiment 2: Ranjani, Sriranjani, Panthuvarāli, and Mōhanam (see Figures 2e to 2h). The excerpts were dubbed from CD recordings of mandolin, saxophone, and veena (an ancient Carnātic instrument; see Appendix A for a list of songs and their tempi). Each excerpt lasted for 15 to 17s. The rhythmic patterns of the excerpts were the traditional rhythmic patterns of these songs of which various versions are available on YouTube (see Appendix A for web links to the songs). We edited the excerpts in order to balance sound quality and to ensure that they ended naturally, for example, at the end of a musical phrase. We chose the excerpts carefully so that they did not modulate to another rāgam and thus had only a single tonal framework. Each excerpt formed a block in which there were 13 trials. The first trial in every block familiarized the participants with the excerpt they would hear throughout the block. In this trial, participants heard the excerpt in both ears. The order of the subsequent 12 trials of each block was randomized. In these 12 trials, the excerpt played in one ear only, and in the other ear the probe tone was heard. This probe tone was one of the 12 semitones in the octave (i.e., the chromatic scale: C, C♯, D, D♯, etc.); thus, the excerpt paired with one of the 12 probe tones constituted the 12 trials. Note that Carnātic music is always sung or played with a drone that consists of the tonic, fifth, and octave (see Introduction). Therefore, we used a distinctive timbre for the probe tone so that it would not blend in with the music. Each probe tone was a combination of three sine waves at octave intervals in the range B♭3 to D6, spanning the range of the melodies. The instruments were tuned approximately to equal temperament, and we adjusted our probe tones to the reference pitch for each particular instrument's tuning. For instance, C was the tonic in the Ranjani song and C4 was tuned to 261.63 Hz, B♭ was the tonic in the Sriranjani and Panthuvarāli songs and B♭3 was tuned to 233.08 Hz, and E♭ was the tonic in the Mōhanam song and E♭4 was tuned to 311.13 Hz. The probe tones themselves were tuned to equal temperament based on the reference pitches. The excerpts were familiar to Carnātic musicians but were unfamiliar to the Western group. The total duration of the whole task was approximately 25 min. All the excerpts were played sequentially in a pseudo-random order using MATLAB software version 7.14.0.739 (R2012a).

Procedure. Participants heard the four blocks of excerpts in a random order over good quality headphones. We counterbalanced the ear in which they heard the probe tone so that for the first two blocks, the probe tone sounded in one ear, whereas for the remaining two blocks, it sounded in the other ear. We provided substantially the same instructions to Indian and Western participants. Western teachers did not receive additional theoretical information about Carnātic music. We instructed participants to listen to short excerpts in one ear while they heard a probe tone in the other ear that either belonged (in-scale) or did not belong (non-scale) to the rāgam of the excerpt. The task was to rate continuously how well the probe tone fitted with the rāgam throughout the length of the excerpt. Participants recorded rating responses using a mouse connected to

[2] One-tailed t-tests for independent samples, Steiger's z-tests for dependent samples, and Fisher's z-tests for independent samples were used for comparisons between means as our predictions for the results had a definite direction for the difference of the means.

a slider on the computer monitor. The slider was calibrated in terms of a rating scale from 0 to 100 with "0" indicating least fit and "100" indicating best fit. All data were recorded by the MATLAB program. Participants first completed a practice block of six trials. Once they had finished practicing and understood the task, the actual experiment began.

Scoring. The position of the slider at every 200 ms of the excerpt constituted the raw data. Each trial had about 78 to 83 recorded slider positions (approximately 16000 ms/200 ms) for each participant. We averaged across these 78 to 83 rating responses for each trial for each participant individually, producing a mean rating for that probe. For each block, each participant had 12 averaged values corresponding to the 12 probe tones. We then averaged all 10 participants' data (separately for each nationality) across each probe tone so that the final baseline profile consisted of the 12 mean values. In this manner, we obtained four baseline profiles for Indian and four for Western participants for the four rāgams. These profiles were similar to Krumhansl and Kessler's (1982) profiles and served as the baseline profiles for Experiment 2. Finally, we correlated each participant's profile for each rāgam with the corresponding group baseline profile for that rāgam in order to check that each group was homogeneous in their responses. Here, we wanted to use the same basis for each participant's contribution to the group average, and hence, we used the same baseline profile for all these comparisons.

The variability of both the Indian and Western profiles over time was generally in the same range in all conditions. In order to check on the stability of ratings over time, we correlated the average of the second half of the rating responses with the whole baseline profiles. This indicated no difference, with all $r(10) > .99$, $p < .001$.

RESULTS

The results of Experiment 1 consist of the eight group baseline profiles: four for Indian participants and four for Western participants. The Carnātic music notations used in Figure 2 are parallel to Western solfège with a moveable do (Jairazbhoy, 1971). The tonic is Sa, which is equivalent to the Western do. The 12 chromatic notes of an octave are named as Sa, Ri_1, Ri_2, Ga_1, Ga_2, Ma_1, Ma_2, Pa, Da_1, Da_2, Ni_1, and Ni_2 (see Figure 2a for equivalent Western nomenclature).

Indian participants. Figure 2 (left panel—dotted lines) shows the four baseline profiles obtained from Indian teachers. Figure 2 (right panel) shows the notes of the corresponding rāgam written in Western notation. With Ranjani (Figure 2a), Carnātic teachers gave the highest ratings of fitness to the tonic (Sa), followed by the second (Ri_2) and sixth (Da_2), then the sharpened fourth (Ma_2), and finally the third (Ga_1). They rated the non-scale flattened and in-scale natural seventh notes (Ni_1 and Ni_2 respectively) similarly. Surprisingly they rated the dominant (fifth note, Pa), which is not in the rāgam, higher than the third and the seventh notes. Though the dominant is not part of the rāgam, it is constantly presented in the drone that accompanies any Carnātic melody. The teachers gave lower ratings to the remaining non-scale notes.

For Sriranjani (Figure 2b), Indian participants rated the fourth note (Ma_1) as the most stable, closely followed by the tonic (Sa) and the sixth (Da_2) notes. This was followed by the second (Ri_2), the seventh (Ni_1), and finally the third (Ga_1) notes. Once again, Indian teachers rated the dominant (Pa), which is not in the rāgam, higher than the seventh and third notes. And the teachers gave lower ratings to all the other non-scale notes.

With rāgam Panthuvarāli (Figure 2c), the tonic (Sa) received the highest ratings of stability followed by the dominant (Pa), then the third (Ga_2), and finally the remaining scale notes in the following order: seventh (Ni_2), second (Ri_1), fourth (Ma_2), and sixth (Da_1). The unusual rating here was for the non-scale flattened third (Ga_1), which received ratings slightly higher than the second, fourth, and sixth. The remaining non-scale notes received lower fitness ratings.

With rāgam Mōhanam (Figure 2d), the tonic (Sa) received the highest ratings of fitness closely followed by the dominant (Pa), then the third (Ga_2), second (Ri_2), and the sixth (Da_2) notes. All non-scale notes of the rāgam received lower ratings.

Western participants. Figure 2 (left panel—solid lines) depicts the four baseline profiles of rāgams obtained from Western teachers. With Ranjani (Figure 2a), Western teachers provided the highest ratings of fitness to the tonic (Sa), followed by the unstable fourth note (Ma_2), then the second (Ri_2), the sixth (Da_2), and the third (Ga_1) notes. The additional seventh note of Ranjani in the descending scale, which is not in the ascending scale, was not noticeable to the Western participants. They gave the least ratings out of the in-scale and non-scale notes to the seventh note (Ni_2), implying that they considered it as the most unstable note. The non-scale dominant (Pa) received the fourth highest ratings following the second note, once again indicating that Western participants, like the Indian participants, were registering the presence of the dominant sounded in the drone. Western teachers also rated the non-scale natural

TABLE 1. *Percentage of Occurrence of Notes (Freq.) and Percentage of Total Duration (Dur.) in the Four Baseline Rāgams*

Note Names[1]	Ranjani		Sriranjani		Panthuvarāli		Mōhanam	
	Freq.	Dur.	Freq.	Dur.	Freq.	Dur.	Freq.	Dur.
Sa (C)	30.97	40.57	10.41	11.65	19.05	24.00	25.93	25.29
Ri_1 (D♭)					12.70	10.00		
Ri_2 (D)	6.19	5.94	13.02	8.96			18.52	11.49
Ga_1 (E♭)	10.33	8.91	10.41	7.17				
Ga_2 (E)					12.70	9.00	22.22	27.59
Ma_1 (F)			20.82	29.57				
Ma_2 (F♯)	18.59	17.81			14.29	10.00		
Pa (G)[2]	5.00	5.00	5.00	5.00	15.87	22.00	11.11	18.39
Da_1 (A♭)					14.29	13.00		
Da_2 (A)	22.71	18.80	23.43	25.99			22.22	17.24
Ni_1 (B♭)			16.92	11.65				
Ni_2 (B)	6.19	2.97			11.11	12.00		
r-value[3]	.97		.94		.94		.94	

[1]Note names are given in Carnātic terminology with its Western equivalent in parentheses assuming C as the tonic. [2]Since the note Pa (G) is a non-scale note to rāgams Ranjani and Sriranjani, a value of 5% is assigned to it. Hence, the remaining notes in the two rāgams are computed on the basis of 95% of the cases. [3]Correlations (Pearson's r) between the percentage values of Frequency and Duration for each rāgam.

fourth (Ma_1) and third (Ga_2) higher than the in-scale flattened third. Note that these two notes are part of the Western major scale (i.e., F and E in C major).

The pitches of Sriranjani are the same as those of the Western Dorian mode, but without the dominant. For Sriranjani (Figure 2b), the Western participants rated the fourth note (Ma_1) as the most stable, followed closely by the tonic (Sa), then the sixth (Da_2). Beyond this, they were able to distinguish the in-scale from the non-scale notes by giving higher fitness ratings for the second (Ri_2), seventh (Ni_1), and third (Ga_1) notes. The non-scale dominant (Pa) also received ratings similar to the seventh. All other non-scale notes received lower ratings.

With rāgam Panthuvarāli (Figure 2c), the Western teachers rated the tonic (Sa) and dominant (Pa) as the most stable, followed by the third (Ga_2), but the remaining four unstable in-scale notes were not differentiated from the non-scale notes, and in fact received lower ratings. The non-scale notes in Panthuvarāli, which are part of the Western C major scale (Da_2, Ma_1, and Ri_2 = A, F, and D), were rated higher than the remaining four in-scale notes. Participants considered the seventh note (Ni_2) as more unstable than the non-scale Ni_1. Also, they considered the in-scale second note (Ri_1) as the most unstable of all.

Rāgam Mōhanam (Figure 2d) is similar to the Western major pentatonic mode and the most stable notes are the tonic (Sa), followed by the dominant (Pa). Western teachers rated the third note (Ga_2) high and were able to differentiate the other in-scale notes from the non-scale notes by giving higher fitness ratings for the second (Ri_2) and sixth (Da_2) notes. They rated all the non-scale notes lower than the in-scale notes.

Tone-distribution cues. Based on earlier work by Castellano et al. (1984), Curtis and Bharucha (2009), Krumhansl, Louhivuori, Toiviainen, Järvinen, and Eerola (1999), and Krumhansl, Toivanen, Eerola, Toiviainen, Järvinen, and Louhivuori (2000), tone-distribution cues, such as frequency of note occurrence and note duration, may be important and used in order to get a fundamental understanding of the music. In order to verify if Indian and Western participants used tone-distribution cues, we did the following check: For frequency of note occurrence, we counted the number of times a note occurred in every rāgam. For note duration, we calculated the total number of eighth-notes values (♪) for each note (see Table 1). Finally, we computed the sum of all the note frequencies and durations in each rāgam separately in order to obtain each note's percentage of occurrence and duration in relation to the other notes in the rāgam (out of 95% in rāgams Ranjani and Sriranjani, as a value of 5% was assigned to the non-scale fifth note Pa as it was present in the drone[3]). We correlated the frequency and duration profiles for each rāgam, which yielded strong positive correlations between $r(10) = .94$ and $.97$, $p < .001$ (see Appendix D). We then correlated the baseline profiles of Indian and Western participants with the values of frequency of note

[3] A value of 5% was chosen as it represents a value above 0 and is small enough to not significantly contribute to the data (also see Table 1).

TABLE 2. *Correlations (Pearson's r and 95% Confidence Intervals) between the Western Baseline Profiles of the Four Rāgams and the Percentage Values of Frequency of Note Occurrence and Note Duration from Table 1, and Krumhansl and Kessler's (1982) Western Major and Vuvan et al.'s (2011) Three Minor Profiles*

Rāgam	Frequency	Duration	Major	Natural Minor	Harmonic Minor	Melodic Minor
Ranjani	.67*	.73**	.64*	.10	.02	−.02
	[.16, .90]	[.27, .92]	[.10, .89]	[−.50, .64]	[−.56, .59]	[−.59, .56]
Sriranjani	.81**	.90**	.59*	.28	−.01	.29
	[.44, .94]	[.67, .97]	[.02, .87]	[−.35, .74]	[−.58, .57]	[−.34, .74]
Panthuvarāli	.44	.65*	.89**	.69*	.46	.55$^+$
	[−.18, .81]	[.12, .89]	[.65, .97]	[.19, .91]	[−.15, .82]	[−.03, .85]
Mōhanam	.73**	.89**	.90**	.50$^+$	.28	.32
	[.27, .92]	[.65, .97]	[.67, .97]	[−.10, .83]	[−.35, .74]	[−.31, .76]

$^*p < .05$ $^{**}p < .01$ $^+.05 < p < .10$

TABLE 3. *Correlations (Pearson's r and 95% Confidence Intervals) between the Indian Baseline Profiles of the Four Rāgams and the Percentage Values of Frequency of Note Occurrence and Note Duration from Table 1, and Krumhansl and Kessler's (1982) Western Major and Vuvan et al.'s (2011) Three Minor Profiles*

Rāgam	Frequency	Duration	Major	Natural Minor	Harmonic Minor	Melodic Minor
Ranjani	.87**	.85**	.41	.24	.27	.33
	[.59, .96]	[.54, .96]	[−.21, .80]	[−.39, .72]	[−.36, .73]	[−.30, .76]
Sriranjani	.82**	.85**	.65*	.34	−.08	.26
	[.46, .95]	[.54, .96]	[.12, .89]	[−.29, .76]	[−.63, .52]	[−.37, .73]
Panthuvarāli	.76**	.85**	.69*	.43	.38	.34
	[.33, .93]	[.54, .96]	[.19, .91]	[−.19, .81]	[−.25, .78]	[−.29, .76]
Mōhanam	.86**	.91**	.84**	.39	.26	.25
	[.56, .96]	[.70, .97]	[.51, .95]	[−.24, .79]	[−.37, .73]	[−.38, .72]

$^*p < .05$ $^{**}p < .01$

occurrence and note duration from Table 1 (see Tables 2 and 3).

Tables 2 and 3 show that Indian and Western participants have employed tone-distribution cues of note frequency and note duration for all the four rāgams. Note that Steiger's z-values[4] for dependent groups indicate that when compared to Indian teachers, Western participants appear to have relied less on note frequency cues to understand the scale structure of rāgams Ranjani and Mōhanam, and with Panthuvarāli, they seem to have relied less on both note frequency and duration cues (see Table 6).

Schematic cues: Western baseline profiles versus Western major and minor profiles. In order to examine whether Western teachers applied schematic knowledge acquired through long-term exposure to music of their own culture to the Carnātic rāgams, we correlated their baseline profiles with Krumhansl and Kessler's (1982) Western major profile and Vuvan et al.'s (2011) natural, harmonic, and melodic minor profiles (see Table 2). Further, we used Steiger's z-test (see Table 4) for dependent groups to see whether there were any significant differences among the Western baseline correlation coefficients for the four rāgams compared with Western major and minor profiles. Steiger's z-values address the issue of whether the two rāgams in a pair are similar or different in their relation to the Western modes. We expected the Western profile for Mōhanam to correlate strongly with the Western major scale, since Mōhanam is equivalent to the Western major pentatonic mode and shares all five of its notes with the Western major scale. Strong correlations of the Western profiles for Ranjani, Sriranjani, and Panthuvarāli with the major or minor scales would indicate participants' use of Western schematic cues.

We also correlated Indian baseline profiles with the Western major and minor profiles (see Tables 3 and 6) in order to further verify whether the correlation values in Table 2 truly indicated transfer of schematic knowledge for Western participants, or if it merely represented their use of tone-distribution cues in terms of

[4] Steiger's z-test for dependent samples and Fisher's z-test for independent samples are used to test the statistical significance of the difference between two correlation coefficients.

TABLE 4. *Steiger's z-values for Dependent Samples comparing Western Correlation Coefficients for the Western Major and Minor Modes between Pairs of Rāgams from Table 2 (see Appendix C for the Third Correlation Value[a]; Negative z-values indicate that the Second Rāgam of the Pair has a Higher Correlation Coefficient)*

Rāgam	Major	Natural Minor	Harmonic Minor	Melodic Minor
Ranjani vs. Sriranjani	0.20	−0.53	0.03	−0.79
Ranjani vs. Panthuvarāli	−1.68*	−2.26*	−1.53⁺	−1.88*
Ranjani vs. Mōhanam	−1.72*	−1.29⁺	−0.80	−0.93
Sriranjani vs. Panthuvarāli	−1.71*	−1.37⁺	−1.27	−0.80
Sriranjani vs. Mōhanam	−1.81*	−0.61	−0.68	−0.08
Panthuvarāli vs. Mōhanam	−0.19	1.93*	1.56⁺	2.06*

[a]Steiger's z-test for dependent samples requires a third correlation value, as it involves a triangular relationship between the correlation coefficients.
*$p < .05$ $^{+}.05 < p < .10$

TABLE 5. *Steiger's z-values for Dependent Samples comparing Indian Correlation Coefficients for the Western Major and Minor Modes between Pairs of Rāgams from Table 3 (see Appendix C for the Third Correlation Value[a]; Negative z-values indicate that the Second Rāgam of the Pair has a Higher Correlation Coefficient)*

Rāgam	Major	Natural Minor	Harmonic Minor	Melodic Minor
Ranjani vs. Sriranjani	−0.82	−0.28	0.52	0.20
Ranjani vs. Panthuvarāli	−0.93	−0.52	−0.30	−0.03
Ranjani vs. Mōhanam	−2.05*	−0.51	0.03	0.27
Sriranjani vs. Panthuvarāli	−0.15	−0.22	−0.67	−0.18
Sriranjani vs. Mōhanam	−1.06	−0.16	−0.54	0.03
Panthuvarāli vs. Mōhanam	−0.98	0.16	0.45	0.34

[a]Steiger's z-test for dependent samples requires a third correlation value, as it involves a triangular relationship between the correlation coefficients.
*$p < .05$

frequency of note occurrence and note duration. The logic underlying this computation is that if the Indian baseline profiles for Ranjani, Sriranjani, and Panthuvarāli showed as strong a positive correlation with the Western major profile as did the Western baseline profiles for the three rāgams, then it would indicate that the correlations were due to the perceived features shared between the rāgams and the Western major scale for both groups of participants, rather than transfer of schematic knowledge by Western participants. On the other hand, we expected a strong positive correlation between the Indian baseline profile for rāgam Mōhanam and the Western major scale, due to their shared notes. Hence, a strong correlation of the Indian baseline profile for Mōhanam would not bear on the issue of Western reliance on schematic knowledge, since that schematic knowledge is presumably very similar for both groups of listeners.

As expected, Tables 2 and 3 show a strong positive correlation of both Western and Indian profiles for Mōhanam with the Western major scale. Table 2 shows that Western participants appear to have applied the Western major scale in order to assimilate the structure of the unfamiliar rāgams. This can be seen in Westerners' tendency to produce profiles for certain rāgams that correlate more strongly with the Western major mode profile than do the profiles produced by Indian listeners. For example, Steiger's z-test for dependent groups to compare the correlation coefficients of Western and Indian baseline profiles with the Western major and minor scales (see Table 6) shows that rāgams Panthuvarāli and Ranjani have higher z-values (> 1), indicating that there is a greater difference between the two groups for these two rāgams. Also, comparison of Tables 2 and 3 shows that Western teachers have higher correlation coefficients than Indian teachers for rāgam Panthuvarāli for both the major and minor modes. With Ranjani, on the other hand, Western teachers have a higher correlation coefficient than Indian teachers only for the major mode, and in fact their correlations for the minor mode were close to zero. Indian teachers perceived Mōhanam to resemble the Western major more than they did Ranjani (see Table 5). This provides further support that the Indian teachers did not perceive a strong resemblance between the scale structures of rāgams Ranjani, Sriranjani, and Panthuvarāli, and the Western major and minor scales. This provides evidence of schematic transfer, in that Western teachers used the Western major scale to comprehend rāgams Ranjani and

TABLE 6. *Steiger's z-values for Dependent Samples between Correlation Coefficients from Tables 2 and 3 of Western and Indian Baseline Profiles of the Four Rāgams and Frequency of Note Occurrence, Note Duration, Western Major and Minor Profiles (see Appendix B for the Third Correlation Value[a]; Negative z-values indicate that the Indian Baseline Profiles have a Higher Correlation Coefficient)*

Rāgam	Frequency	Duration	Major	Natural Minor	Harmonic Minor	Melodic Minor
Ranjani	-1.55^{+}	-0.95	1.19	-0.60	-1.07	-1.34^{+}
Sriranjani	-0.14	0.84	-0.58	-0.47	-0.53	0.23
Panthuvarāli	-2.06^{*}	-1.64^{+}	1.85^{*}	1.58^{+}	0.43	1.16
Mōhanam	-1.42^{+}	-0.33	0.84	0.76	0.13	0.45

[a]Steiger's z-test for dependent samples requires a third correlation value, as it involves a triangular relationship between the correlation coefficients.
$^{*}p < .05$ $^{+}.05 < p < .10$

Panthuvarāli, and to some extent the minor scales to comprehend Panthuvarāli.

Contributions of tone-distribution cues and Western schematic cues. We used Steiger's z-test (see Tables 7 and 8) for dependent groups to compare the correlation coefficients of the four baseline profiles with tone-distribution profiles and the Western major and minor profiles. Steiger's z-values indicate the relative contributions of the various cues that listeners used. There is a consensus that this method is preferable in this regard to the use of stepwise multiple regression because when stepwise regression is used for post hoc analyses, it can lead to an excessive number of false positives (Cohen & Cohen, 1983).

Table 7 indicates that for the Indian teachers, in general, tone-distribution cues contributed more than the Western major and minor modes for all four rāgams, indicated by positive z-values. Table 8 shows that for the Western teachers, tone-distribution cues contributed more than the Western major and minor modes for Ranjani and Sriranjani, and more than the minor modes for Mōhanam. On the other hand, the major mode contributed more than the tone-distribution cues to Western teachers' profile for Panthuvarāli, indicating assimilation in terms of Western schematic cues. Among the tone-distribution cues, note duration contributed more than frequency of note occurrence for all rāgams except Ranjani for the Indian teachers, and for all rāgams for the Western teachers, indicated by negative z-values. This is in general in agreement with the results of Lantz and Cuddy (1998; also 2006), who found duration to be the more important cue in determining ratings in profiles with novel melodies. For Western teachers, the major mode contributed the most toward assimilation of Ranjani, Panthuvarāli, and Mōhanam in comparison to the three minor modes. For Indian teachers, the Western major was clearly more related to the scale structure of Mōhanam than were the three minor modes (see Table 7).

Indian versus Western baseline profiles. We correlated the four Indian baseline profiles with the corresponding Western baseline profiles, obtaining strong positive correlations, $r(10) = .75$ to $.92$, $p < .01$ (see Appendix B). Hence, we used the Indian baseline profiles for further comparisons with the Indian and Western profiles obtained in Experiment 2, since it is the Indian profile that represents the best understanding of the structure of the rāgam.

We also correlated each group's baseline profiles for the pairs of rāgams that appeared in the rāgamālikā and grahabēdham modulations in Experiment 2: Ranjani versus Sriranjani, and Panthuvarāli versus Mōhanam (see Table 9). We wanted to ascertain the degree of relatedness within the pairs of rāgams, because if the rāgams of a pair are closely related, it would be difficult to detect the effects of modulation between them. Table 9 also shows Fisher's z-values for independent samples for the differences between the Indian and Western correlation coefficients. The rāgams Panthuvarāli and Mōhanam in the grahabēdham were clearly more closely related than were Ranjani and Sriranjani in the rāgamālikā. But note that Panthuvarāli and Mōhanam are strongly correlated only when the tonic is the same, as with the baseline profiles, but not when the tonic is different, as it is in the shift brought about in grahabēdham.

Experiment 2: Tracking Modulations

The profiles for the four rāgams obtained in Experiment 1 with Indian teachers were used as the baselines to compare with the profiles of modulating excerpts in Experiment 2.

METHOD

Participants. The same participants in Experiment 1 also participated in Experiment 2, which followed Experiment 1 in the same session.

TABLE 7. *Steiger's z-values for Dependent Samples comparing Indian Correlation Coefficients for Frequency of Note Occurrence (F), Note Duration (D), Western Major (M), Natural (N), Harmonic (H), and Melodic (MM) Minor Modes for the Four Rāgams from Table 3 (see Appendix D for the Third Correlation Value[a]; Negative z-values indicate that the Second Profile of the Pair has a Higher Correlation Coefficient)*

	Frequency vs.					Duration vs.				Major vs.			N vs.		H vs.
Rāgam	D	M	N	H	MM	M	N	H	MM	N	H	MM	H	MM	MM
Ranjani	0.49	2.15*	2.26*	2.30*	2.21*	2.15*	2.17*	2.12*	2.03*	0.51	0.39	0.24	−0.10	−0.45	−0.31
Sriranjani	−0.49	0.85	1.78*	2.30*	1.97*	1.09	1.91*	2.47**	2.13*	1.07	1.65*	1.25	0.87	0.40	−0.89
Panthuvarāli	−1.37^{+}	0.34	1.10	1.38^{+}	1.30^{+}	1.02	1.80*	2.17*	2.05*	0.96	1.03	1.19	0.18	0.47	0.21
Mōhanam	−1.00	0.19	1.87*	2.07*	2.12*	0.88	2.45**	2.63**	2.66**	1.94*	2.16*	2.26*	0.45	0.71	0.05

[a]Steiger's z-test for dependent samples requires a third correlation value, as it involves a triangular relationship between the correlation coefficients.
$^{*}p < .05$ $^{**}p < .01$ $^{+}.05 < p < .10$

TABLE 8. *Steiger's z-values for Dependent Samples comparing Western Correlation Coefficients for Frequency of Note Occurrence (F), Note Duration (D), Western Major (M), Natural (N), Harmonic (H), and Melodic (MM) Minor Modes for the Four Rāgams from Table 2 (see Appendix D for the Third Correlation Value[a]; Negative z-values indicate that the Second Profile of the Pair has a Higher Correlation Coefficient)*

	Frequency vs.					Duration vs.				Major vs.			N vs.		H vs.
Rāgam	D	M	N	H	MM	M	N	H	MM	N	H	MM	H	MM	MM
Ranjani	−1.04	0.13	1.51^{+}	1.80*	1.86*	0.44	1.82*	2.02*	2.10*	1.71*	1.76*	1.84*	0.26	0.38	0.00
Sriranjani	−1.61^{+}	0.97	1.87*	2.39**	1.82*	1.81*	2.51**	3.07**	2.53**	1.01	1.61^{+}	0.94	0.88	−0.05	−1.38^{+}
Panthuvarāli	−2.20*	−2.17*	−0.77	−0.06	−0.30	−1.60^{+}	−0.17	0.74	0.36	1.38^{+}	2.06*	1.84*	0.98	0.88	−0.52
Mōhanam	−2.56**	−1.51^{+}	0.80	1.28^{+}	1.22	−0.14	1.93*	2.36**	2.28*	2.16*	2.65**	2.62**	0.79	0.95	−0.21

[a]Steiger's z-test for dependent samples requires a third correlation value, as it involves a triangular relationship between the correlation coefficients.
$^{*}p < .05$ $^{**}p < .01$ $^{+}.05 < p < .10$

TABLE 9. *Correlations (Pearson's r and 95% Confidence Intervals) between the Baseline Profiles of Pairs of Rāgams in Experiment 2 and Fisher's z-values for Independent Samples between Indian and Western Correlation Coefficients (Negative z-values indicate that the Western Baseline Profiles have a Higher Correlation Coefficient)*

Rāgam	Indian	Western	z-value
Ranjani vs. Sriranjani	.37	.46	−0.23
	[−.26, .78]	[−.15, .82]	
Panthuvarāli vs. Mōhanam	.64*	.93**	−1.91*
	[.10, .89]	[.76, .98]	
Panthuvarāli vs. Mōhanam[a]	.30	.51^{+}	−0.54
	[−.33, .75]	[−.09, .84]	

[a]Correlation between the baseline profiles of Panthuvarāli and Mōhanam, wherein the tonic of Mōhanam is shifted.
$^{*}p < .05$ $^{**}p < .01$ $^{+}.05 < p < .10$

Stimuli. Experiment 2 applied the method of Experiment 1 to modulations in Carnātic music. The construction of stimuli for Experiment 2 was similar to that of Experiment 1 except for the following differences: There were only two excerpts constituting two blocks of 13 trials each (see Appendix A for a list of songs and tempi). Each excerpt lasted for 70 to 77s. Each excerpt contained one of the two types of modulation used in Carnātic music: rāgamālikā (e.g., C major to C minor shift) and grahabēdham (e.g., C major to A minor shift). The rāgamālikā excerpt employed the first two rāgams from Experiment 1: Ranjani and Sriranjani (see Figures 2e and 2f). The grahabēdham excerpt employed the remaining two rāgams from Experiment 1: Panthuvarāli and Mōhanam (see Figures 2g and 2h). Note that, unlike the figure, the tonal center changed in this excerpt. For example, if Panthuvarāli, a seven-note scale, has C as its tonic, then Mōhanam, can be obtained by starting on the third degree of Panthuvarāli and omitting the tonic and dominant (see Figure 3). Omission of the tonic and/or the dominant of the original key in order to obtain a pentatonic or hexatonic (six-note) scale on a new tonic is permitted in grahabēdham. The probe tones were tuned to equal temperament based on the reference pitches. In the rāgamālikā, A was the tonic and A3 was tuned to 220 Hz, and in the grahabēdham, E♭ was the tonic and E♭3 was tuned to 155.56 Hz.

Each excerpt had two shifts of tonality: from rāgam A to rāgam B, and back to rāgam A. Each excerpt dwelled on each rāgam for approximately 18 to 31s, providing ample time to establish a tonal center. The total duration of the whole task was about 30 min. All the excerpts were played sequentially in a pseudo-random order using MATLAB software version R2012a.

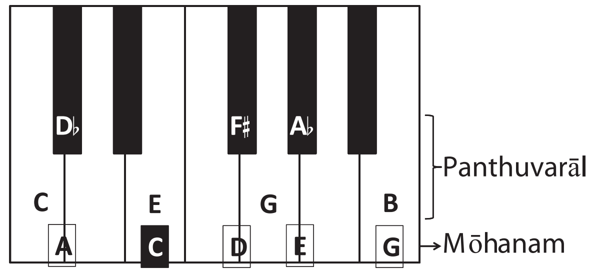

FIGURE 3. Western notation of the two rāgams Panthuvarāli and Mōhanam used in the grahabēdham excerpt. The seven notes in the upper portion of the keyboard belong to Panthuvarāli. The five notes represented in a box belong to Mōhanam. The note C, enclosed in a black box, represents where the new tonic has shifted.

We chose the particular modulating excerpts because in a previous study of modulation detection by Indian and Western listeners (Raman & Dowling, 2014) those particular songs led to the highest hit rates for both groups. However, one result of that choice was that, in addition to being familiar with the four rāgams, the Indian music teachers were also familiar with the particular song we used in the rāgamālikā.

Procedure. The procedure was same as in Experiment 1 except for the following differences: The number of trials varied from Experiment 1. Also, we told participants that the excerpts involved modulations and that they would hear the rāgam change in the middle of the song.

Scoring. As in Experiment 1, the raw data was the position of the slider at every 200 ms of each excerpt. In Experiment 2, each trial had about 375 recorded slider positions (approximately 75000 ms/200 ms). These data were then smoothed by averaging across slider positions every 800 ms in order to minimize noise in the data due to motor limitations and other artifacts (Toiviainen & Krumhansl, 2003). This gave a total of about 93 slider positions (75000 ms/800 ms) per trial. This allowed us to capture participants' perceptions of tonality at a little more than once per second, giving approximately 93 tonal profiles for each participant across the 12 trials in a block.

We then selected five time periods in each excerpt to examine more closely: T1, when the initial rāgam was fully established, consisting of the last 10s before the first modulation; T2, the 10s following the introduction of the second rāgam; T3, when the second rāgam was established, consisting of the 10s just before the shift back; T4, the 10s following the shift back to the initial rāgam; and T5, the last 10s of the excerpt, when

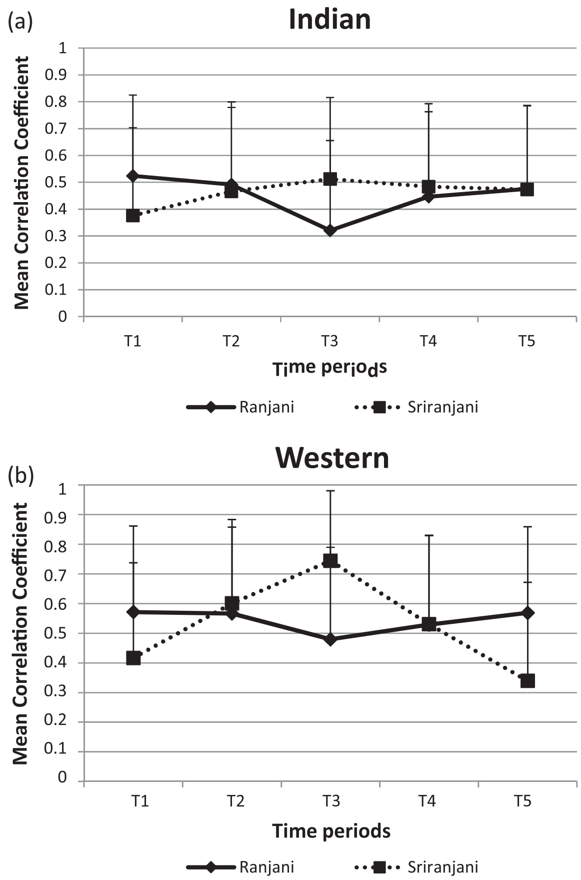

FIGURE 4. Comparison of profiles of (a) Indian and (b) Western participants for the rāgamālikā excerpt (i.e., modulation retaining tonal center) generated using the concurrent probe-tone technique. Responses were averaged within five time periods and smoothed across a jumping window of time. Finally each profile generated was correlated with Indian baseline profiles of the corresponding rāgams obtained in Experiment 1. The shift from Ranjani to Sriranjani occurs between time periods T1 and T2, and the return to Ranjani lies between time periods T3 and T4. Error bars indicate standard error of the mean.

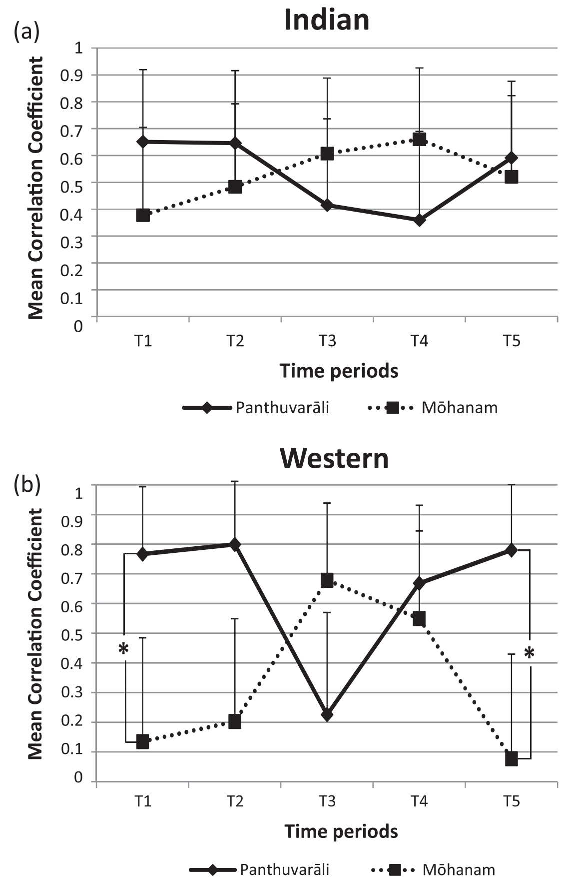

FIGURE 5. Comparison of profiles of (a) Indian and (b) Western participants for the grahabēdham excerpt (i.e., tonal center changes) generated using the concurrent probe-tone technique. Responses were averaged within five time periods and smoothed across a jumping window of time. Finally each profile generated was correlated with Indian baseline profiles of the corresponding rāgams obtained in Experiment 1. The shift from Panthuvarāli to Mōhanam occurs between time periods T1 and T2, and the return to Panthuvarāli lies between time periods T3 and T4. Error bars indicate standard error of the mean. $^*p < .01$

the initial rāgam was re-established. We then computed correlations between each of these five profiles and the baseline profiles of the two rāgams involved. This yielded 10 correlation coefficients (Pearson's r): one for each time period for each rāgam. We converted these r-values into z-values using Fisher's r-to-z transformation in order to average across the r-values for each participant within each group for each of the five time periods. We then converted the averaged z-values back to r-values, obtaining 10 averaged r-values, in order to obtain a time-by-correlation graph of participants' tracking of the modulations (see Figures 4 and 5). The comparison of the modulating profiles with the baseline profiles obtained in Experiment 1 indicated the participants' responses to the modulations. Since we expected the Indian baseline profiles to match theoretical predictions of Carnātic music more closely than the Western baseline profiles, we used only the Indian baseline profiles to compare with the Indian and Western profiles in Experiment 2. Given some of the qualitative differences between Indian and Western baseline profiles in rāgams Ranjani and Panthuvarāli (see Figures 2a and 2c), we also compared Western participants' profiles from Experiment 2 with Western baseline profiles. This comparison found no qualitative differences from the correlations using only the Indian baseline profiles.

RESULTS

We performed two mixed design 2-way multivariate analyses of variance (MANOVA)[5] with 2 Nationalities x 5 Time Periods separately for the rāgamālikā and grahabēdham excerpts on the correlation coefficients obtained from each participant (see Figures 4 and 5), where nationality involved a between-groups comparison, and time period involved a within-groups comparison. We performed post hoc univariate analyses using mixed design 3-way analyses of variance (ANOVA) with 2 Nationalities x 2 Rāgams x 5 Time Periods separately for the rāgamālikā and grahabēdham excerpts, where only nationality involved a between-groups comparison. Finally, we performed a set of planned one-tailed Steiger's z-tests for dependent samples in order to provide a more fine-grained analysis.

Figures 4 and 5 show the correlations obtained for Indian and Western participants for the rāgamālikā and grahabēdham excerpts. Here the x-axis represents the five 10-s time periods within the excerpt: We compared time periods T1 and T3, and T3 and T5, for each rāgam, and T1, T3, and T5 across the two pairs of rāgams. Any differences among these comparisons would indicate participants' perception of modulation.

The MANOVA showed a significant main effect of time period with both the rāgamālikā, $F(8, 11) = 5.25$, $p = .007$, Wilks' lambda $= .62$, and the grahabēdham excerpts, $F(8, 11) = 8.57$, $p < .001$, Wilks' lambda $= .34$, but that does not indicate any qualitative changes in the participants' performance differentiating the rāgams. The aspects of the data that concern us involve the effects of time period and its interaction with nationality for each rāgam.

With rāgamālikā, Time Period x Nationality approached significance overall, $F(8, 11) = 2.60$, $p = .07$, Wilks' lambda $= .76$. This interaction was not significant for Ranjani, $F(4, 15) = 0.46$, $MSE = 0.01$, $\eta_p^2 = .02$, $p = .69$, but was significant for Sriranjani, $F(4, 15) = 4.60$, $MSE = 0.02$, $\eta_p^2 = .20$, $p = .007$, indicating that Western teachers were differentiating the profile for Sriranjani across time periods more sharply than the Indian teachers (see Figure 4). Sriranjani in particular may have been especially easy for Westerners to track because of its similarity to the Dorian mode. Univariate analyses of the two rāgams in the rāgamālikā, with the Bonferroni correction (critical value: $p = .025$) showed significant interactions of Time Period x Rāgam, $F(4, 72) = 8.94$, $MSE = 0.02$, $\eta^2 = .05$, $p < .001$, and Time Period x Nationality, $F(4, 72) = 4.98$, $MSE = 0.01$, $\eta^2 = .02$, $p = .0097$.

With grahabēdham, Time Period x Nationality interaction was not significant overall, $F(8, 11) = 1.83$, $p = .17$, Wilks' lambda $= .58$, but it was significant for the individual rāgams Panthuvarāli, $F(4, 15) = 5.22$, $MSE = 0.03$, $\eta_p^2 = .22$, $p = .005$, and Mōhanam, $F(4, 15) = 6.47$, $MSE = 0.03$, $\eta_p^2 = .26$, $p = .003$. Univariate analyses of the two rāgams in the grahabēdham, with the Bonferroni correction (critical value: $p = .025$) showed significant interactions of Time Period x Rāgam x Nationality, $F(4, 72) = 8.77$, $MSE = 0.03$, $\eta^2 = .06$, $p < .001$, of Time Period x Rāgam (this interaction is meaningful only when interpreted as part of the 3-way interaction that includes nationality), $F(4, 72) = 30.82$, $MSE = 0.03$, $\eta^2 = .20$, $p < .001$, and approached significance with Time Period x Nationality, $F(4, 72) = 2.77$, $MSE = 0.03$, $\eta^2 = .02$, $p = .05$, all indicating that Western teachers were differentiating the profiles for the two rāgams across time periods more sharply than the Indian teachers (see Figure 5). With grahabēdham, rāgam Mōhanam in particular may have been especially easy for Westerners to track because of its shared structural property with the Western major pentatonic mode. These contrasts between types of modulation and Indian and Western teachers will be tested and explained in what follows.

Indian participants. Figure 4a shows Indian participants' responses for the rāgamālikā excerpt. We performed planned one-tailed Steiger's z-tests for dependent samples[6] with the Bonferroni correction (critical value: $p = .025$)[7] for multiple comparisons between time periods T1 and T3, and T3 and T5 for rāgams Ranjani and Sriranjani in the rāgamālikā excerpt. Indian participants' responses did not show any significant differences. Similarly, comparing time periods T1, T3, and T5 between the two rāgams (Bonferroni critical value: $p = .017$)[8] also showed no significant differences. Though Indian participants' responses did not show significant differences in their perception of

[5] Greenhouse-Geisser corrections for sphericity were applied to the MANOVA and the ANOVA results.

[6] Steiger's z-test for dependent samples requires a third correlation value, as it involves a triangular relationship between the correlation coefficients. Here the third value was obtained by correlating Indian (and Western) profiles at time periods T1 and T3, and at T3 and T5 for each rāgam, and between pairs of rāgams at T1, T3, and T5.

[7] Bonferroni correction applied to the z-tests for $p < .10$ is $p = .05$. All p-values between .025 and .05 were considered as approaching significance. All p-values less than .025 were considered as significant.

[8] Bonferroni correction applied to the z-tests for $p < .10$ is $p = .033$. All p-values between .017 and .033 were considered as approaching significance. All p-values less than .017 were considered as significant.

modulations, the trends in their data were in the predicted direction.

Figure 5a shows that Indian teachers in grahabēdham tracked the shift away from Panthuvarāli, whereas for Mōhanam the reverse trend was much less pronounced, though this difference was not statistically significant. Planned one-tailed Steiger's z-tests with the Bonferroni correction (critical value: $p = .025$) showed that Indian participants' responses to rāgams Panthuvarāli and Mōhanam were not significantly different between time periods T1 and T3, nor between T3 and T5. Comparing time periods T1, T3, and T5 between the two rāgams (Bonferroni critical value: $p = .017$), Indian participants' responses showed no significant differences. As with rāgamālikā, participants' perception of the two shifts can be observed qualitatively at time periods T1, T3, and T5.

Western participants. Figure 4b shows Western participants' responses for the rāgamālikā excerpt. Planned one-tailed Steiger's z-tests for dependent samples with the Bonferroni correction (critical value: $p = .025$) indicated that in rāgamālikā, with rāgam Ranjani, Western participants' responses showed no differences between T1 and T3, nor between T3 and T5. With rāgam Sriranjani, Western participants' responses were close to a significant difference between T3 and T5, $z = 1.65$, $p = .05$, but were not significantly different between T1 and T3. Comparing time periods T1, T3, and T5 between the two rāgams (Bonferroni critical value: $p = .017$), Western participants' responses showed no significant differences. As with the Indian participants, Western participants' perception of the two shifts can be observed qualitatively at time periods T1, T3, and T5.

Figure 5b shows the pattern of Western responses to the grahabēdham excerpt. Planned one-tailed Steiger's z-tests with the Bonferroni correction (critical value: $p = .025$) showed that Western participants' responses were close to a significant difference with rāgam Panthuvarāli between T1 and T3, $z = 1.85$, $p = .03$, and between T3 and T5, $z = -1.73$, $p = .04$. Similarly with rāgam Mōhanam, Western participants' responses were close to a significant difference between T1 and T3, $z = -1.69$, $p = .05$, and between T3 and T5, $z = 1.63$, $p = .05$. Comparing time periods T1, T3, and T5 between the two rāgams Panthuvarāli and Mōhanam (Bonferroni critical value: $p = .017$), Westerners' responses showed significant differences at time periods T1, $z = 2.38$, $p = .009$, and at T5, $z = 2.58$, $p = .005$, but did not show a significant difference at T3.

Indian versus Western participants. We performed planned one-tailed Fisher's z-tests for independent samples to analyze differences between Indian and Western responses to modulations. Although most of the results discussed below were not statistically significant, the differences can nevertheless be observed qualitatively. Figures 4a and 4b show the Indian and Western responses for the rāgamālikā excerpt. Western participants showed a stronger positive correlation at T3 with the baseline profile of Sriranjani when compared to Indian participants, $r(10) = .74$ versus .51. At T5, Western participants, were better able to differentiate between Ranjani and Sriranjani, $r(10) = .57$ versus .34, than their Indian cohort, $r(10) = .48$ versus .47. Similarly, Figures 5a and 5b show the Indian and Western responses for the grahabēdham excerpt. Qualitatively, Indian and Western teachers performed similarly on this task but Indian teachers' responses overall were not as marked. This difference is evident especially at time periods T1, T3, and T5, where the two rāgams are well-established. Note that for Westerners the difference between the two rāgams (Figure 5b) is more obvious than for Indian participants (Figure 5a): for Mōhanam at T3, $r(10) = .68$ versus .61. Also at T1, differentiation of Panthuvarāli and Mōhanam was stronger for Western participants, $r(10) = .77$ versus .13, than for the Indian cohort, $r(10) = .65$ versus .38. Similarly at T5, Western participants' responses showed stronger differentiation, $r(10) = .78$ versus .08, when compared to the Indian participants, $r(10) = .59$ versus .52, $z = 1.85$, $p = .03$. Western teachers responded faster than Indian teachers in recognizing the shift back to the first rāgam at T4, as shown by the difference between the correlation coefficients of the two rāgams at T4, Western $r(10) = .19$ versus Indian $r(10) = -.39$.

In order to compare differences between the two groups in the perception of the two types of modulation used in Experiment 2, we counted the number of participants whose individual profiles showed responses in the direction (significant or not) of the theoretically dominant rāgam in time periods T1, T3, and T5. This is shown in Table 10. The majority of Indian and Western participants gave higher ratings to the theoretically dominant rāgam Ranjani at T1 and Sriranjani at T3. All 10 Western participants rated Srianjani as the dominant rāgam at T3, which is reflected in the steeper curve of Western participants at T3 in Figure 4b. At T5 Indian participants were divided equally regarding the two rāgams. With grahabēdham, all 10 Western teachers rated Panthuvarāli as more dominant at T1 and T5, and at T3 the majority of them rated Mōhanam as more dominant. On the other hand, while the majority of the Indian teachers correctly rated Panthuvarāli as more

TABLE 10. *Number of Cases where Indian (I) and Western (W) Participants showed Responses in the Direction (significant or not) of the Theoretically Dominant Rāgam (highlighted in bold) in Time Periods T1, T3, and T5. (n = 10)*

		T1		T3		T5	
Type of Modulation	Rāgam	I	W	I	W	I	W
Rāgamālikā	Ranjani	**6**	**7**	2	0	**5**	**8**
	Sriranjani	4	2	**7**	**10**	5	2
Grahabēdham	Panthuvarāli	**9**	**10**	4	2	**5**	**10**
	Mōhanam	1	0	**5**	**8**	4	0

dominant at T1, the group's responses were inconclusive at T3 and T5.

General Discussion

Krumhansl and Kessler (1982) applied the probe-tone technique to determine mental representations of tonal hierarchies and their development over time in modulations involving chord sequences. Toiviainen and Krumhansl (2003) extended this line of research in introducing the concurrent probe-tone technique to track changes in listeners' tonal space in real time. The primary goal of our study was to apply Toiviainen and Krumhansl's technique to determine what kinds of cues Indian and Western listeners use in their perception of modulations in Carnātic music. We conducted two experiments: In Experiment 1 we obtained baseline profiles of four rāgams (modes) that we used in two modulating excerpts in Experiment 2. The modulating excerpts used the two types of modulation that occur in Carnātic music: rāgamālikā and grahabēdham. These are analogous to a Western shift from C major to C minor, and from C major to A minor, respectively. We wanted to track changes in the tonal hierarchy profiles of what listeners were hearing at each moment as the modulation occurred, and to identify the cues that the listeners were using that led them to those changes. We wanted to see what cues listeners used to track the tonal hierarchy patterns of music from an unfamiliar culture. We identified three types of cues: surface cues, such as tone-distribution cues, involving the frequency of occurrence of notes and note durations; culture-specific cues; and cues imported from the music of the listener's own culture, that is, the transference of schematic knowledge already acquired.

The results from our earlier study (Raman & Dowling, 2014), in which the task was simply to indicate when a modulation occurred, showed that Indian and Western listeners used relevant cues in order to detect modulations of the two types. Those and the present results provide support for Balkwill and Thompson's (1999) cue-redundancy model, in that listeners were clearly using both culture-specific and psychophysical, in this case, tone-distribution, cues.

INDIAN PARTICIPANTS

Two types of culture-specific cues were evident in the Indian listeners' responses: (1) cues based on Carnātic theory involving knowledge of Carnātic tonal hierarchies, and (2) veridical cues (Bharucha, 1987) based on familiarity and exposure to the particular melodies. The baseline profiles from Experiment 1 show that Indian teachers' responses closely matched each rāgam's theoretical structure (see Figures 2a to 2d), and indicated that they were familiar with the four rāgams in this study. In Experiment 2, the Indian listeners did not register the individual rāgams as clearly as they did in Experiment 1, nor as clearly as the Westerners did in Experiment 2 (see Figures 4 and 5), which was the opposite of our prediction. Musicians generally show sharper response patterns with unambiguous melodies when compared to nonmusicians (e.g., Halpern et al., 1996) and non-native listeners (e.g., Castellano et al., 1984), but it is possible that musicians may engage in slightly different perceptual processes to take account of the ambiguity in melodies with a shifting tonal center. One plausible reason for the less marked Indian response patterns could be that the rāgamālikā we used is well known, unlike the grahabēdham excerpt; hence, Indian participants had prior veridical knowledge of the melody, its rāgams, and their characteristic notes and phrases. Such veridical knowledge could have influenced their responses by leading them to expect precisely the modulations that they heard. Thus their familiarity with the song could have reduced the sharpness of the contrast between the two rāgams, which they viewed as simply features of the same song.

Familiarity may have led the Indian teachers to hear the rāgamālikā song more holistically, rather than as simply a collection of individual features. For instance, the individual features of musical notes, rhythm, timbre, and so forth are perceived together as a melody, and that melody is perceived as a coherent whole even though it changes mode in midstream. Research involving holistic processing in various domains has shown that experts tend to process information more holistically than novices. Young, Hellawell, and Hay (1987) found that composite faces made from combining the top half of one face with the bottom half of another are more confusing when the two halves are aligned to form a coherent whole pattern, suggesting that people (who are generally experts at face processing) are using holistic processing with the coherent faces; that is, they were unable to just focus on one half and ignore the other half. Similarly, Boggan, Bartlett, and Krawczyk (2012) found that chess masters had difficulty ignoring the irrelevant half of a chess board constructed in an analogous way to Young et al.'s faces. Chess masters were relying on features depending on the relative positions of pieces in different regions of the board, indicating holistic processing. Concerning music perception, Kim and Levitin (2002) studied whether participants with at least 10 years of music training could identify familiar melodies when the pitches were made indistinct by acoustic filtering. The results showed that the musicians were able to identify the melodies though they were not able to identify the individual pitches. Kim and Levitin suggested that the listeners in their study were relying on holistic processing of the familiar melodies, in the absence of unambiguous information concerning particular features. These studies suggest that the perceptual learning that experts in an area have been through lead them to process elaborate stimuli in that domain in a holistic way, suggesting in turn the possibility that Indian teachers' expertise and familiarity with the rāgamālikā song may in effect have led them to hear it more holistically.

One characteristic of the Indian teachers' more holistic processing of the familiar rāgams in the rāgamālikā excerpt is the possibility that they were hearing the two rāgams as components of the same melody, even though the two rāgams never occurred simultaneously. This is somewhat like the phenomenon of bitonality, utilized in twentieth-century Western music, in which two tonalities are simultaneously present in the piece. Thompson and Mor (1992) employed the probe-tone method to investigate listeners' perception of bitonality in Dubois's *Circus* and Milhaud's *Sonata No. 1 for Piano*. Their results indicated that listeners were sensitive to both keys but preferred one key over the other, determined by their perception of the key's importance in the melody. In our study, there is some support that Indian teachers might have been holding on to a tonal map of the earlier rāgam even when the song had shifted to the second rāgam, indicated by the more differentiated response pattern for the first rāgam, Ranjani (see Figure 4a). Hence, they may not have shifted their perspective entirely to that of the new rāgam.

Another possibility involving bitonality arises with grahabēdham, in which the two rāgams involved share most of their notes. When the rāgam changes, there are no new pitches introduced. Thus, Indian teachers might have considered the second rāgam as an extension of the first, similar to the results of Dowling, Raman, and Tillmann (2014), who, using the concurrent probe-tone technique to track perfunctory modulations to the dominant in classical minuets, found that listeners tended to perceive the dominant as simply an extension of the tonic key (see also Cuddy & Thompson, 1992).

A third possibility for explaining the attenuation of the Indian profiles as compared with the Western could be related to the complexity of their music system, which has more than 350 rāgams. This increases the difficulty of applying their schematic knowledge of Carnātic music. Each rāgam invokes an extensive set of alternative rāgams to choose from. For instance, Sriranjani differs from Karaharapriyā only by the inclusion of the dominant, and from Ābōgi only by the exclusion of the seventh (see Figure 2f). The proliferation of such options could impose a considerable cognitive load on the listeners (Bartlett & Dowling, 1988), thereby weakening their responses.

One more instance of the influence of the acculturation of the Indian listeners is evident in their relative delay in responding to shifts in the grahabēdham excerpt. This delay was also evident in Indians' responses in Raman and Dowling's (2014) detection study. Further analysis of the two time periods T2 and T4, corresponding to the first 10s from the point of the shift, showed that the teachers recognized the shifts approximately 10s after their occurrence. This was evident when we averaged the responses in the 10- to 15-s window after the shifts: Panthuvarāli at T2, $r(10) = .51$, and at T4, $r(10) = .53$, intersected with Mōhanam at T2, $r(10) = .48$, and at T4, $r(10) = .59$. Many teachers reported that they waited for the change in emotional and tonal quality (rāgabhāvam), and the characteristic notes (vādi) and phrases (prayōgam) of each rāgam to be elaborated upon, before acknowledging the shift and changing their ratings for each probe tone accordingly. The rāgabhāvam, vādi notes, and prayōgam associated with a rāgam are learned only through practice and exposure to songs in that rāgam. It could be argued that one possible effect of Indian teachers' greater expertise is that they take longer to integrate individual events into a coherent structure. The greater difficulty of applying schematic knowledge of Carnātic music, referred to above, could delay identification of the new rāgam. However, if this were true then it should be the case for both rāgamālikā and grahabēdham. With rāgamālikā, Indian teachers recognized the shifts relatively quickly compared with grahabēdham. With grahabēdham, lack of novel pitches to signal a shift in rāgam and its unfamiliarity to the Indian teachers probably contributed to this delay and hence, their need to rely more on culture-specific cues, such as rāgabhāvam.

Table 3 shows that Carnātic teachers used both types of tone-distribution cues (i.e., both frequency of note occurrence and note duration) in comprehending the structure of the four rāgams. In fact, they relied much more heavily on tone-distribution cues than on the relation of the rāgams to the Western modes, which makes sense for listeners not acculturated in the Western system (see Table 7). The one instance where their responses are distinctly correlated with a Western mode is for Mōhanam and the Western major, but this simply reflects the similarity of the two modes (see Table 3). For Indian teachers, it is interesting to differentiate between what are considered tone-distribution cues and what are culture-specific cues. Although how often a note is repeated and for how long it is sounded are considered as distributional properties of the note, in a musical context these same properties are assigned to a note based on theoretical considerations, such as its hierarchical position in the rāgam. In general, only the characteristic notes of a rāgam, the tonic and the vādi notes, appear often and for long durations in a melody. Hence, for Indian participants, tone-distribution cues probably overlap with culture-specific cues; that is, the notes that appear most frequently and are sounded for the longest durations are the same ones which occupy hierarchically important positions in a musical scale. Future studies should be directed toward parsing the differences between tone-distribution and culture-specific cues for listeners familiar with the music. Perhaps comparing data between experts and nonmusicians would be useful here as we expect that musicians would probably apply their theoretical knowledge whereas nonmusicians would probably rely more heavily on tone distribution and other structural properties of notes.

WESTERN PARTICIPANTS

The results from our earlier study (Raman & Dowling, 2014) showed that Western listeners, who were unfamiliar with the music, were able to discern grahabēdham modulations most likely by picking up on pertinent tone-distribution cues. In that study, the absence of culture-specific knowledge could have contributed to their higher false-alarm rate, since they lacked the culture-specific cues that signal valid shifts. Their performance on that task and on the present task could reflect one of four types of behavior: (1) They could have utilized culture-specific and veridical cues as did their Indian cohort; that is, they could have engaged in top-down processing of the melodies; (2) they could have been totally oblivious to the modulations; (3) they might have shown sensitivity to the modulation at the level of surface cues, that is, picking up tone-distribution cues, such as frequency of note occurrence and note duration; or (4) they could have applied schematic knowledge of music from their own culture. The first option is unlikely because all Western participants reported that they had never heard Carnātic music before. The second option is also not possible because the results indicated that Western participants were able to discern the shifts with at least moderate success. Thus, the third and fourth options, which involve using tone-distribution cues and applying schematic knowledge from one's culture, are the most likely possibilities. In particular, regarding schematic knowledge, Curtis and Bharucha (2009) found evidence of listeners' transferring schematic knowledge of music from their own culture in understanding structural aspects of unfamiliar music.

Table 2 indicates that Western listeners used the tone-distribution cues of frequency of note occurrence and duration in comprehending the four rāgams when they heard them in Experiment 1. For Ranjani and Sriranjani they relied on tone-distribution cues to a greater extent than Western schematic cues (see Table 8), and this was also the case for Mōhanam, where they also relied more on tone-distribution cues than on the Western minor scales. The one exception to the reliance on tone-distribution cues over schematic cues is with Panthuvarāli, for which they relied more on the Western major scale. Converging evidence for this conclusion from Experiment 1 can be seen in Table 4, where it is clear that the statistically significant z-values between Ranjani versus Panthuvarāli and Mōhanam, and Sriranjani versus Panthuvarāli and Mōhanam, indicate that Western teachers perceived the structure of Panthuvarāli and Mōhanam as closely related to the major scale, and Panthuvarāli as generally related to the three minor modes as well.

An instance of Western teachers applying their schematic knowledge to assimilate the Carnātic rāgams can be seen in their Panthuvarāli profile, which correlated strongly with the major scale, moderately with the natural minor mode, and somewhat with the harmonic and melodic minor modes. The flattened third (E♭) and sixth (A♭) notes offer the most salient cues in differentiating the minor modes from the major scale. This difference is evident in Krumhansl and Kessler's (1982) major and minor profiles and Vuvan et al.'s (2011) minor profiles. Similar to the minor modes, Panthuvarāli has a flattened sixth (Da_1) which provided a highly salient cue for Westerners to consider it as resembling the minor modes (see Figure 2g). On the other hand, unlike the minor modes, Panthuvarāli has a natural third (Ga_2), which completes the major triad C-E-G, thus providing a stronger cue for Westerners to assimilate the rāgam in terms of the major mode. In contrast to Panthuvarāli, the scale of Sriranjani has a flattened third (Ga_1) and a natural sixth (Da_2) and does not include the fifth note (Pa). Also, it shares only four notes with the Western major whereas it shares five notes with the natural minor mode (see Figure 2f). Similar to Castellano et al.'s (1984) study, in which listeners perceived Kāfi—a Hindustāni rāg, equivalent to Sriranjani with the fifth—as strongly related to the minor, we expected Sriranjani to strongly correlate with the natural minor mode. In our study, the Western (and Indian) baseline profiles for Sriranjani only moderately correlated with the major mode and had lower correlations with the minor modes. Tables 2 and 4 indicate that Western teachers perceived Panthuvarāli as more similar to the minor modes than Sriranjani. This could be attributed to the relative salience of cues wherein the flattened sixth (Da_1), in combination with the natural third (Ga_2) and raised fourth (Ma_2) in Panthuvarāli, were probably stronger cues for the minor modes than the combination of flattened third (Ga_1) and natural sixth (Da_2) in Sriranjani.

To provide converging evidence that Westerners were using their own schematic knowledge in judging pitches in the four Carnātic rāgams, and not simply relying on actual structural properties of the rāgams as heard by Indian listeners, we wanted to make sure that Western teachers' correlations between their profiles for those rāgams and the Western modes were stronger than those for Indian teachers. As expected, only the Indian baseline profile of Mōhanam strongly correlated with the Western major scale, whereas Sriranjani and Panthuvarāli correlated only moderately, and Ranjani did not correlate significantly with the major mode (see Table 3). This pattern suggests that schematic transfer by the Western listeners was occurring in two instances: (1) Correlation of Ranjani with the Western major scale. The Indian baseline profile for Ranjani did not correlate with the major scale, whereas the Western baseline profile did correlate moderately. (2) Correlation of Panthuvarāli with the Western major and minor modes. The Indian baseline profile for Panthuvarāli correlated moderately with the major scale, whereas the Western baseline profile correlated strongly with the major mode, moderately with natural minor, and approached significance with harmonic and melodic minor modes. To conclude, Western teachers appeared to transfer Western schematic knowledge in assimilating rāgams Ranjani and Panthuvarāli.

In Experiment 2, with the rāgamālikā excerpt, Western participants' responses at the five time periods of Ranjani were largely undifferentiated, which is perhaps reflective of the trouble they had with identifying the scale notes of Ranjani in Experiment 1 as noted above (see Figures 4b and 2a). On the other hand, the predicted response pattern is seen with Sriranjani (also see Figure 2b). With the grahabēdham excerpt, Western participants successfully tracked the modulations (see Figure 5b). Note that Table 9 indicates that the Western baseline profiles for rāgams Panthuvarāli and Mōhanam are strongly related, but not so in Experiment 2 when the tonic was shifted for Mōhanam. The modulating context in which the rāgams were presented appeared to influence Western participants' judgments. When the rāgams were presented as separate excerpts in Experiment 1, the Western teachers perceived them as strongly related, whereas in Experiment 2 when the rāgams were presented one after the other, and with different tonal centers, as parts of the same excerpt, this perception changed, and thus they were able to identify the shifts successfully.

In Experiment 2, the Western teachers tracked the modulations more clearly than the Indian teachers (see Figures 4 and 5), which was the opposite of our prediction. Based on the results of our earlier study (Raman & Dowling, 2014), we expected Western participants to be more successful at recognizing modulations in the grahabēdham than in the rāgamālikā excerpt, and this turned out to be the case (see Figures 4b vs. 5b). Western participants are probably adept at recognizing shifts of tonal center because of its popular occurrence in Western classical and popular music. Furthermore, we have presented converging evidence above that Western teachers were able to use their schematic knowledge especially with rāgams Panthuvarāli and Mōhanam.

As mentioned earlier, the drone provides a strong surface cue especially in the grahabēdham excerpt as it is anchored to the first rāgam; thus, we might expect Western participants to show weaker responses to the second rāgam. The results show that to the extent that Western participants are using this strong surface cue, we might suppose that they are using it to differentiate the new rāgam from the original rāgam.

In both the rāgamālikā and grahabēdham excerpts, all participants heard the first rāgam twice and the other rāgam only once. We might expect the profile for the initial rāgam to be more robust when the repetition occurred, but this was not the case. Steiger's z-tests for dependent samples indicated that with both Indian and Western participants, there was no difference between time periods when the first rāgam was well established at T1 and T5 with rāgamālikā, $z = 0.19$ and 0.00, and with grahabēdham, $z = 0.32$ and -0.10 (see Figures 4 and 5).

Two ways in which the transfer of schematic knowledge for Western participants may have occurred are suggested by Dowling's (1978; Dowling & Harwood, 1986) model of the cognitive organization of scales. First, both the Indian and Western systems share the tonal material of the chromatic scale of semitones underlying the selection of pitch classes to be put to use. Then at the third level of Dowling's model—the level of tuning systems—where a set of pitch classes from the tonal material is chosen to form the basis of a series of modal scales (e.g., the white notes on the piano keyboard), there are partial overlaps. For example, both the Western Dorian and major pentatonic modes share a tuning system with the Carnātic rāgams Sriranjani and Mōhanam. It is at the fourth level of Dowling's model, modal scales, that there are even more pronounced cultural differences in scale organization. Schematic transfer for Western participants was limited here due to the few modes (i.e., major and minor) available. For example, the Western major pentatonic mode and Mōhanam are equivalent at the level of modal scales, but modes such as Ranjani and Panthuvarāli are distinctly unfamiliar and do not have a Western equivalent. In this study, the Western baseline profiles of Sriranjani and Mōhanam were almost identical to the Indian profiles (see Figures 2b and 2d). Thus, there is evidence that in certain instances Western listeners transferred schematic knowledge of music from their culture at the level of the tuning system, and that knowledge in these cases was a good match to the music of the unfamiliar culture.

In other instances the importation of Western schematic knowledge did not produce a good fit to the Indian rāgams. As noted above, Ranjani and Panthuvarāli do not have equivalent tuning systems in Western music. Nevertheless, in Experiment 1, Western teachers applied their schematic knowledge and, in comparison to Indian teachers' baseline profiles, gave higher ratings to certain non-scale notes in their Ranjani and Panthuvarāli profiles, which happen to be in-scale pitches in the Western major scale (see Figures 2a and 2c). This suggests that they were perceiving those two rāgams in terms of the familiar Western major mode. This result is similar to that found by Curtis and Bharucha (2009).

THEORETICAL ISSUES

We now turn to address a few theoretical issues raised in the Introduction of this article. An important objective of cross-cultural research is to determine whether we can generalize theories and principles developed in one culture across other cultures. This study supports the fact that certain aspects of music cognition, such as the principles underlying tonal hierarchy, the resultant tonal maps, and melodic expectancies, developed on the basis of Western music can be applied to Carnātic music as well. However, certain other aspects, such as determining the structure of scales and melodic patterns, are culture-specific. The results also support Krumhansl and Cuddy's (2010) third proposition in that the conceptual framework and theory of tonal hierarchies can be generalized in large part to Carnātic music. Western listeners were clearly able to apply these principles to assimilate Carnātic rāgams. Further, Toiviainen and Krumhansl's (2003) concurrent probe-tone technique proved very well suited to exploring these cross-cultural issues involved with the tonal hierarchy. It is clear from these results that the schematic knowledge, and hence, the acculturation, of the Indian and Western listeners is different in detail, though sharing certain aspects, such as those of some tuning systems.

One important limitation of this study is the presence of a confound between familiarity and nationality. All Indian participants were familiar with the rāgams and the excerpts in Experiment 1, and with the rāgamālikā excerpt (but not the grahabēdham excerpt) in Experiment 2, but Western participants were not. Hence, evidence for Indian teachers' use of culture-specific schematic cues could not be differentiated from veridical cues. Could familiarity with the music have led to less marked profiles for the Indian teachers when compared to their Western cohort? Further research needs to address the effect of prior knowledge of the music on such a rating task. A second study could examine if similar effects can be observed with Indian teachers with unfamiliar melodies and rāgams. A related issue concerns whether veridical cues are truly culture-specific. Can we parse culture-specific and veridical cues? Perhaps training Westerners to become familiar with the Carnātic melodies in the study could throw light on the issue.

Future studies need to focus on comparisons across cultures between profiles of musicians and nonmusicians obtained using the concurrent probe-tone technique. A cross-cultural study with musical expertise and familiarity with the music as independent variables could provide valuable information on the acquisition and use of the tonal hierarchy. Earlier research (e.g., Bigand & Poulin-Charronnat, 2006; Halpern et al.,

1996) showed that nonmusicians have an implicit understanding of tonal hierarchies and that this understanding becomes more sophisticated with music training. In the proposed study, nonmusicians who are unfamiliar with the music would have to rely on basic surface cues and schematic knowledge that they gained only through listening but not practicing music from their culture. Towards this, we have already acquired data from both Indian and Western nonmusicians and are in the process of analyzing the data.

Conclusion

The primary goal of this study was to track participants' responses to modulations in Carnātic music while identifying the various cues that listeners utilized in order to discern these modulations. To accomplish this, we obtained baseline profiles of four rāgams (modes) from Experiment 1 and compared these against profiles of modulating excerpts in Experiment 2. Both Indian and Western participants employed tone-distribution cues of frequency of note occurrence and note duration in order to comprehend the structure of the rāgams. In addition, Indian participants used culture-specific knowledge, and Western participants applied aspects of their own culture-specific knowledge to the unfamiliar melodies.

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Appendix A

LIST OF SONG TITLES AND ARTISTS

TABLE A1. *Experiment 1: Creating Baseline Profiles*

Title	Rāgam	Artist	Instrument	Tempo (MM)
Ranjani niranjani[a]	Ranjani	U. Srinivas	Mandolin	92
Gajavadhana[b]	Sriranjani	Kadri Gopalnath	Saxophone	99
Sārasāksha[c]	Panthuvarāli	Kadri Gopalnath	Saxophone	98
Nannu pālimpa[d]	Mōhanam	E. Gayathri	Veenā	80

Note. MM = Metronom Mälzel; number of beats per minute.
[a]Actual version of the song: https://www.youtube.com/watch?v=sEJ54xZuLP4 (last accessed May 29, 2015)
[b]A version of the song: https://www.youtube.com/watch?v=PwD35KfhtQk (last accessed May 29, 2015)
[c]Actual version of the song: https://www.youtube.com/watch?v=SNgQrCJt9kI (last accessed May 29, 2015)
[d]A version of the song: https://www.youtube.com/watch?v=4rAubUcfva4 (last accessed May 29, 2015)

TABLE A2. *Experiment 2: Tracking Modulations*

Title	Artist	Instrument	Tempo (MM)
Ranjanimālā[a] (Ranjani, Sriranjani)	Chitti Babu	Veenā	102[c]
Grahabēdham in Panthuvarāli[b] (to Mōhanam)	E. Gayathri	Veenā	78[d]

Note. MM = Metronom Mälzel; number of beats per minute.
[a]Actual version of the song: https://www.youtube.com/watch?v=eUrikZHhGSY (last accessed May 29, 2015)
[b]Private recording; refer to web links in Table A1 for the corresponding rāgams.
[c]The tempo 102 is for every dotted quarter, that is every beat.
[d]Since this is an unmetered song, the tempo is an approximation.

Appendix B

CORRELATIONS (PEARSON'S r) BETWEEN THE BASELINE PROFILES OF INDIAN AND WESTERN PARTICIPANTS FROM EXPERIMENT 1

Rāgam	r-value	95% CI
Ranjani	.75**	[.31, .93]
Sriranjani	.92**	[.73, .98]
Panthuvarāli	.81**	[.44, .94]
Mōhanam	.88**	[.62, .97]

Note. CI = confidence interval.
$^{**}p < .01$

Appendix C

CORRELATIONS (PEARSON'S r) BETWEEN THE BASELINE PROFILES OF ALL PAIRS OF RĀGAMS FROM EXPERIMENT 1 AND FISHER'S z-VALUES FOR INDEPENDENT SAMPLES (NEGATIVE z-VALUES INDICATE THAT THE SECOND RĀGAM OF THE PAIR HAS A HIGHER CORRELATION COEFFICIENT)

Rāgam	Indian	Western	z-value
Ranjani vs. Sriranjani	.37	.46	−0.23
Ranjani vs. Panthuvarāli	.28	.60*	−0.86
Ranjani vs. Mōhanam	.55+	.51+	0.12
Sriranjani vs. Panthuvarāli	−.003	.38	−0.86
Sriranjani vs. Mōhanam	.48	.26	0.54
Panthuvarāli vs. Mōhanam	.64*	.93**	−1.91+

$^{*}p < .05$ $^{**}p < .01$ $^{+}.05 < p < .10$

Appendix D

CORRELATIONS BETWEEN TONE-DISTRIBUTION PROFILES AND WESTERN MAJOR AND MINOR PROFILES

TABLE D1. *Correlations (Pearson's r) between the Profiles of Frequency of Note Occurrence (F) and Note Duration (D) from Table 1, and Krumhansl and Kessler's (1982) Western Major (M) and Vuvan et al.'s (2011) Natural (N), Harmonic (H), and Melodic (MM) Minor Profiles for the Four Rāgams in Experiment 1.*

Rāgam	F vs. D	F vs. M	F vs. N	F vs. H	F vs. MM	D vs. M	D vs. N	D vs. H	D vs. MM
Ranjani	.97**	.45	.11	.24	.30	.56+	.20	.22	.29
Sriranjani	.94**	.18	.27	−.17	.25	.29	.16	−.14	.21
Panthuvarāli	.94**	.37	.07	.34	.04	.57+	.34	.51+	.33
Mōhanam	.94**	.74**	.16	.001	.06	.82**	.26	.10	.12

**$p < .01$ +$.05 < p < .10$

TABLE D2. *Correlations (Pearson's r) between Krumhansl and Kessler's (1982) Western Major (M) and Vuvan* et al.*'s (2011) Natural (N), Harmonic (H), and Melodic (MM) Minor Profiles.*

Profile	*r*-value
M vs. N	.43
M vs. H	.31
M vs. MM	.37
N vs. H	.57+
N vs. MM	.80**
H vs. MM	.81**

**$p < .01$ +$.05 < p < .10$