

Computational Models of Symbolic Rhythm Similarity: Correlation with Human Judgments¹

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1. INTRODUCTION

A fundamental problem in computational musicology is the design of a mathematical measure, or computational model, of symbolic rhythm similarity. The applications of such a measure include modeling the perceptual mechanisms involved in rhythm recognition by humans, music information retrieval by computers, and the phylogenetic analysis of rhythms in evolutionary studies (Toussaint 2004, 2002; Jan 2007; Dean, Byron & Bailes 2009–2010; Van Den Broek & Todd 2009–10). In this paper a novel approach to describing rhythmic relationships in music is introduced by means of three rhythm similarity experiments. The first involves a group of six distinguished Afro-Cuban timelines that had previously been compared with a variety of mathematical measures of rhythm similarity in the context of the phylogenetic analysis of rhythms (Toussaint 2004, 2002). For some applications it is desirable to obtain a measure that correlates well with human perception of rhythm similarity. With this goal in mind, experiments were performed in which a group of listeners compared and judged the similarity of the same six timelines used in Toussaint (2002). The results obtained from these experiments are compared with those obtained with

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the mathematical measures. The second experiment concerns Mario Rey's (2006) ethnographic study of Afro-Cuban rhythms that are classified into two groups derived from either the *Habanera* or the *Contradanza*. Our goal here was to measure the agreement of Rey's classification with respect to both human perception and mathematical measures of rhythm similarity in order to test whether historically accepted musicological rules determine group similarity that has perceptual and mathematical validity. Both of these experiments involved rhythms with identical-sounding strokes. The third experiment incorporated Middle Eastern and Mediterranean rhythms composed of strokes with two different timbres (*dum-tak* rhythms), thus introducing the simplest form of melody possible into the equation. Furthermore, the rhythms in this set had cyclic time-spans in which the number of pulses varied between six and nine.

A mathematical measure of musical rhythm similarity used frequently in the domain of music information retrieval is the *edit* distance (Orpen & Huron 1992; Lemström & Pienimäki 2007; Mongeau & Sankoff 1990; Crawford 1997–98). Given two sequences of symbols, the edit distance is defined as the minimum number of symbol mutation operations necessary to transform one sequence to the other. However, no studies have been reported previously comparing the edit distance to human perception. A general goal of this study was to determine how well the edit distance correlates with human perception, and how robust this correlation is when subjects are not primed with any underlying meter. One of our more specific goals here is to determine the sensitivity of the fidelity of the edit distance when the rhythms being compared have different numbers of pulses. A second specific goal is to determine if the performance of the edit distance changes when it incorporates information

about different sounds, as in the *dum-tak* rhythms, that is coded simply as just another symbol.

It is well known that the perception of musical rhythm is dependent on the underlying meter in which the rhythm is embedded (Johnson-Laird 1991; Essens 1995; Shmulevich & Povel 2000; Palmer & Krumhansl 1990; Longuet-Higgins & Lee 1982, 1984; Tanguiane 1993). Indeed, it has been well established by these authors that the perception of rhythm is an emergent phenomenon that arises as a result of the mutual interaction (the push and pull) of a rhythm and its metrical interpretation, and hence that meter should be part of the general theories of rhythmic complexity and similarity, at least for untrained Western listeners (Ladinig et al. 2009). These results also resonate well with findings in the visual perceptual domain establishing that the perception of a *figure*, is influenced by the *ground* (or context) in which the figure is embedded (Toussaint 1978). Furthermore, listeners do perceive implied meter even if physical evidence for it does not exist. For instance, it has been shown that isochronous sequences of identical clicks are perceived by Western listeners in either duple, triple, or quadruple time (Bolton 1894). Our goal here is not to study the edit distance in the context of a metrical theory of rhythm, a problem of great interest in itself, but rather to test the robustness of its correlation with human perception, when the listener is free to create any metrical interpretation he or she provides.

2. MEASURING SYMBOLIC RHYTHM SIMILARITY

Rhythm may be represented and studied either *acoustically* or *symbolically*. The typical *acoustic* input is a recording of real auditory sequences. To obtain a computer representation from acoustic input is a difficult problem that first entails detecting the underlying beat and

the onsets of notes (Dixon 2001). Furthermore, in this setting the locations of the resulting onsets are not determined by simple integers or rational numbers, but instead, due to a variety of musical phenomena such as micro-timing, and expressivity, may lie anywhere on the real line (time). The typical *symbolic* input, on the other hand, is notated rhythm, such as in Western music notation, or in box notation, in which the locations of the onsets of notes are known exactly, and the duration intervals between onsets may be described by small integers. This study is concerned with the analysis of rhythm from the symbolic point of view. Thus the mathematical measures of similarity tested are computed on an input consisting of rhythms represented in box notation, i.e., sequences of unit-time symbols. To measure the correlation of mathematical measures with human perception, however, an acoustic input must be created for the listening tests. The acoustic signals used in the experiments consisted of identical clinical sound impulses (much like the sound of two sticks striking each other) created electronically so as to mimic the symbolic input as closely as possible.

Previous studies on symbolic musical rhythm similarity with Afro-Cuban timelines and Flamenco meters generated encouraging results using the *swap* distance. A *swap* is perhaps the simplest mutation operation that may be performed on a rhythm when it is represented in box notation as a binary sequence of elemental *pulses* of two kinds: *onsets* and *rests*. An *onset* is a *sounded pulse*, whereas a *rest* is a *silent pulse*. Note that unlike some usage of the term in the literature, we use the word pulse in a purely mathematical way, and no musical interpretations, such as *strong* pulse, *weak* pulse, or *beat* for example, are implied. Since this study is not concerned with the effects of tempo on perception, throughout this research it is assumed that the duration of one pulse is the same, typically that of a sixteenth note which is

determined by the shortest duration necessary to be able to represent a rhythm. For example the eight-pulse rhythm [x . x . x . . .], unless required for some special comparisons, would be represented as the four-pulse rhythm [x x x .].

A swap interchanges the positions of an onset and a rest that are adjacent to each other in the sequence. For example, the four-pulse cyclic rhythm [x x x .] may be obtained from the rhythm [x x . x] by a single swap operation that interchanges the values (sounds and rests) of the third and fourth pulses in the cycle. The *swap distance* between two rhythms is the minimum number of swaps needed to convert one rhythm to the other. In the statistics literature concerning the problem of measuring the similarity between two permutations of symbols, a swap is called a *pairwise adjacent transposition*, and the swap distance has been used as a measure of disarray or rank correlation (Diaconis & Graham 1977; Kendall 1970). If two rhythms being compared have the same number of onsets this distance is trivial to compute, since for all i the i -th onset of the first rhythm must in effect move, by a suitable sequence of swaps, to the position of the i -th onset of the second rhythm. For example, to convert the sixteen-pulse *clave son* rhythm [x . . x . . x . . . x . x . .] to the sixteen-pulse rap [x . . . x . . x . x . . x . . .] requires three swaps: the second and third onsets of the first rhythm must advance by one pulse, and the third onset must retreat by one pulse. When one rhythm has more onsets than another, the swap distance has been modified in the following way (Toussaint 2003). Let D denote the denser of the two rhythms, and S denote the sparser of the two. Here the density refers to the number of onsets contained in the cyclic rhythm. Then the swap distance between D and S is defined as the *minimum* number of swaps required to convert D to S , with the constraints that every onset of D must move to the location of an onset of S , and every onset of S must accommodate at least one onset of D . As an example,

consider converting the famous “door-knock” rhythm given by [x . x x x . x . . . x . x . . .] to the clave *son* [x . . x . . x . . . x . x . . .]. Here the first, third, fifth, sixth, and seventh onsets of the first rhythm coincide with the first, second, third, fourth, and fifth onsets of the second rhythm, respectively, and thus they remain where they are. On the other hand, the second and fourth onsets of the first rhythm both move to the position of the second onset of the second rhythm, yielding a swap distance of 2.

Although the judgments obtained in previous listening experiments with human subjects using Flamenco meters correlated well with those of the swap distance measure, the Flamenco rhythms were limited in terms of rhythmic variety and the number of rhythms used (Guastavino, Gómez, Toussaint, Marandola, & Gómez 2009). Therefore one goal of the present study was to determine how well this simple distance measure performs on rhythms from different genres, and how it compares with the more generally employable *edit* distance used in music information retrieval applications. The edit distance between two sequences of symbols is defined as the minimum number of *edit operations* required to transform one sequence to the other (Mongeau & Sankoff 1990; Crawford, Iliopoulos, & Raman 1997–98). The edit operations permitted are of three types: *insertions*, *deletions*, and *substitutions*. Insertions and deletions insert and delete, respectively, a symbol anywhere within the sequence. For example, the eight-pulse rhythm [x x . x x . x .] may be obtained from the seven-pulse rhythm [x x . x x . .] by inserting the symbol ‘x’ between the sixth and seventh pulses in the seven-pulse rhythm. A deletion is the inverse operation of an insertion. A substitution replaces one symbol for another. For instance, the eight-pulse rhythm [x x x x x x . .] may be converted to the six-pulse rhythm [x x x . . .] by changing the sixth symbol in the eight-pulse rhythm from ‘x’ to ‘.’ (a substitution) and deleting the first two ‘x’ symbols.

Thus, the edit distance simply permits the comparison of rhythms that have different numbers of pulses as well as onsets, since deletions shorten the duration of a rhythm, and insertions lengthen it.

3. PHYLOGENETIC TREE ANALYSIS

Traditionally, a *phylogenetic* tree, also referred to as an evolutionary tree, is a tree or branching diagram in which the branches indicate evolutionary relationships between biological organisms in a group, based on the measurement of similarity between physical features or genetic material such as DNA molecules, obtained from pairs of organisms in the group. Such trees resemble the dendrograms of traditional cluster analysis, and as such, may be used also for the purpose of measuring and visualizing the similarity relations that exist between the members in a group of biological objects (Carrizo 2004). However, the objects in this study, rather than being biological organisms, are *cultural* objects, namely sequences of symbols that represent musical rhythms. The application of phylogenetic methods to cultural objects, and the study of their evolution is not new. Indeed, such techniques have been applied to a wide variety of cultural objects for some time (Hage et. al. 1998; Mace, Holden, & Shennan 2005).

There exist a variety of different approaches to the construction of phylogenetic trees, ranging from distance-based methods to maximum parsimony, maximum likelihood, and Bayesian inference, to name a few. For our study of musical rhythms the distance-based approach was the most convenient. Such methods assume that a distance matrix is available that contains the distance between every pair of rhythms. The phylogenetic tree is then constructed so that the minimum distance between every pair of rhythms, measured along the

branches in the tree (geodesic), corresponds as closely as possible to the corresponding distance entry in the distance matrix. Within this class of methods we chose to use the popular neighbor joining approach (Saitou and Nei 1987). The software package *SplitsTree-4* provides a powerful framework for computing phylogenetic trees from distance matrices obtained from a group of objects (Huson 1998). One of its virtues is that it may be used to compute more general graphs (or networks) that are not in fact trees. In addition the package allows for the application of several tools including *BioNJ*, a phylogenetic tree computed on the basis of a novel neighbor-joining algorithm (Gascuel 1997).

The methodology used in the study reported here is reminiscent of previous methods applied in the pitch domain by Quinn (2001), and Mavromatis and Williamson (1999a, 1999b). These authors were motivated by a desire to visualize the relationships between chords, and hence applied traditional cluster analysis methods to compare a variety of measures of chord similarity. Our study focuses on rhythms, and is motivated also by the desire to infer phylogenies of collections of rhythms, thus propelling us to use phylogenetic analysis, supported by Mantel tests, in lieu of cluster analysis. Both methods generate trees in the process. However, the trees differ from each other. A cluster analysis tree is a statement about the grouping of a collection of rhythms according to distances computed between all pairs of rhythms and pairs of sub-clusters of rhythms. The main drawback of cluster analysis trees is that they implicitly assume a constant rate of evolution of the rhythms in all branches of the tree. They are useful for visualizing the rhythms but limited for inferring phylogenies. A phylogenetic tree, on the other hand, is a statement about the evolutionary relationship between a collection of rhythms. Phylogenetics trees, such as those produced by the *BioNJ* algorithm used here, do not assume that the rate of evolution is the

same in all branches of the tree, and are more suitable for inferring phylogenies as well as reconstructing ancestral rhythms.

4. STATISTICAL ANALYSIS

A phylogenetic tree of a collection of rhythms provides a compelling visualization of the various relationships that exist between all the rhythms, as well as of their possible evolutionary phylogeny. However, it is not without its limitations. If the distances that make up the distance matrix do not permit an *exact* representation in the form of a tree in two-dimensional space, the algorithms construct an *approximate* representation that minimizes the differences between the distances in the matrix and those in the tree, thus introducing some error in the actual drawing of the tree. Furthermore, by itself the tree does not provide a quantitative measure of the similarity between the two distance matrices being compared. For this purpose there exist two appropriate statistical tests: the Mantel test (Dietz 1983; Hage et al. 1998), and the Procrustes test (Schneider & Borlund 2007a, 2007b). Both tests belong to the family of permutation tests for measuring the association between two distance matrices. They are designed to be used in situations where the elements in the matrix are not independent, as is the case in our rhythm study, thus ruling out conventional correlation tests. The Mantel test is designed to compare and evaluate the degree of monotonicity between different similarity measures, and uses a distance (dissimilarity) matrix as input. Procrustes analysis, on the other hand, is designed to compare and evaluate the resemblance between ordination results based on different similarity measures, and is used for comparing the shapes of geometric configurations of points. Since in our study the rhythms are not represented as points in some feature space, but rather yield a distance matrix, and our goal is

to compare the rhythm similarity measures themselves, the Mantel test was deemed more appropriate. Accordingly, in this work all the Mantel tests were performed using the software developed by Eric Bonnet and Yves Van de Peer, with 10,000 repetitions each (Bonnet & Van de Peer 2002).

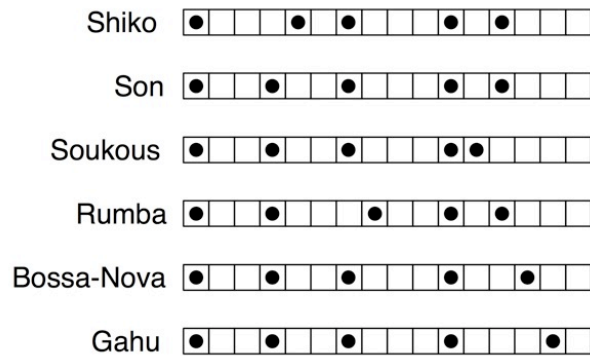
5. EXPERIMENT 1: AFRO-CUBAN TIMELINES

5.1 Rhythms and Computational Models

The first experiment used a group of rhythms consisting of six distinguished Afro-Cuban timelines previously investigated by Toussaint (2002). These six timelines, all of which consist of five onsets in a sixteen-pulse cycle, are shown in Figure 1. These six rhythms were previously used to explore several mathematical approaches to rhythm analysis, including geometric feature extraction, automatic classification via decision trees, comparison of objective, information-theoretic, cognitive, and performance complexity measures, rhythm similarity and grouping, as well as phylogenetic and combinatorial analyses (Toussaint 2002). The rhythms were chosen because they represent some of the most important timelines (rhythmic ostinatos) used in traditional as well as the world music of today, and such timelines are effective markers of the structural evolution of rhythms, and their cultural transmission. Indeed, in describing timeline patterns such as these, Gerhard Kubik (1999, 56), states: “their mathematical structures are *cultural invariables*.”

Of the various mathematical measures of rhythm similarity previously explored with these rhythms, the *swap* distance appeared to be the most promising from the conceptual, computational, and music-theoretical points of view (Toussaint 2002). However, the

Figure 1. The six distinguished Afro-Cuban timelines (in box notation)



listening experiments with human subjects that were previously carried out to determine how well the swap distance correlates with human judgments of perceptual similarity were limited to the comparison of the swap distance with the chronotonic distance (Guastavino et al. 2009). These authors found that the swap distance performed better than the chronotonic distance, and matched human performance fairly well. However, the rhythms used were restricted to twelve-pulse (ternary) flamenco meters. Here the swap distance is compared to human perception using a completely different family of rhythms (sixteen-pulse). Furthermore, no previous studies compared the swap distance with the *edit* distance, in terms of their ability to predict perceptual similarity. The purpose of Experiment 1 was to fill these gaps.

The motivation for comparing the swap and edit distances is two-fold: the practical payoff, and what it tells us about rhythm perception. Consider first the practical payoff. For many applications in the field of music technology a computationally efficient algorithm for measuring rhythm similarity (in the context of technology, the faster the better) is desirable. The swap distance is straightforward to calculate, and computationally extremely efficient, requiring only a number of operations that is linearly proportional to the number of pulses in

the rhythms. The edit distance, on the other hand, is more difficult to compute, requiring dynamic programming and a number of operations that is proportional to the square of the number of pulses in the rhythms. From this point of view, and other things being equal, the swap distance would be preferred over the edit distance.

It is worth pointing out that although the swap distance is much simpler to compute than the edit distance, and also conceptually simpler, in the sense that it contains a single operation (swap) rather than three operations (substitution, insertion, deletion), this does not imply that the swap operation is incapable of generating as much rhythmic variety as the edit distance for rhythms with fixed numbers of onsets and pulses. First note that a swap that changes $[x \ .]$ to $[. \ x]$ may be implemented by the edit distance with either two substitutions, or with a deletion followed by an insertion. The structural result of performing these operations ends up being the same for both the swap and edit distance measures but the cost is different with each. Furthermore, although it is tempting to conclude at first glance that swaps are limited to transpositions of existing durations, this is not the case. Consider for example the rhythm $X = [x \ . \ . \ x \ . \ x]$ with durations (421). Swapping the fourth and fifth pulses yields the rhythm $Y = [x \ . \ x \ . \ . \ x]$ with durations (331), which is not a transposition of (421). The power of the edit distance over the swap distance comes rather from the ability of its three operations to alter the number of onsets and pulses in the rhythms that it generates, thus making it applicable to the comparison of a wider class of rhythms.

Concerning rhythm perception, the swap and edit distance measures differ in some of their computational strategies. The swap distance involves repetition of *local* swap operations that bring all the onsets of one rhythm into alignment with those of the other rhythm. The edit distance, on the other hand, tends to involve *grouping* onsets together and

then moving them together as a group, if it will result in the reduction of the total number of operations. The computational strategy of the distance measure that achieves a higher correlation with human judgments provides a candidate for a better model for rhythm perception. A concrete example will clarify the distinction between these two strategies at work. Consider the two twelve-pulse rhythms given by $A = [x \dots x . x . x . x .]$ and $B = [x . . x . x . x . x . .]$. The minimum number of swaps required to convert A to B involves the four local swaps of the second, third, fourth, and fifth onsets of A with their four preceding rests, respectively, yielding a swap distance equal to 4. The edit distance, on the other hand, is equal to 2, and may be obtained as follows. First, a deletion of the rest at pulse 4 in the twelve-pulse rhythm given by $A = [x \dots x . x . x . x .]$ yields the eleven-pulse rhythm $A' = [x . . x . x . x .]$. Second, inserting a rest after pulse 11 in A' yields the rhythm $[x . . x . x . x . .] = B$, the desired result. Note that the single deletion operation of the rest at pulse 4 in rhythm A moves *all* onsets of A into alignment with *all* onsets of B.

The distance matrix for the six rhythms listed in Figure 1, computed with the swap distance, is given in Figure 2, where the bottom row contains the values (labeled TOTAL) of the sums of the distances of each rhythm to all the others. This value is a measure of the uniqueness of each rhythm in the group as a whole. Thus, the *son*, with a value of 6, is the most similar, whereas the *gahu*, with a score of 12, is the most different. More specifically, this number indicates for each rhythm the number of swaps needed to generate all the rhythms in the group. Therefore the *son* is the most parsimonious.

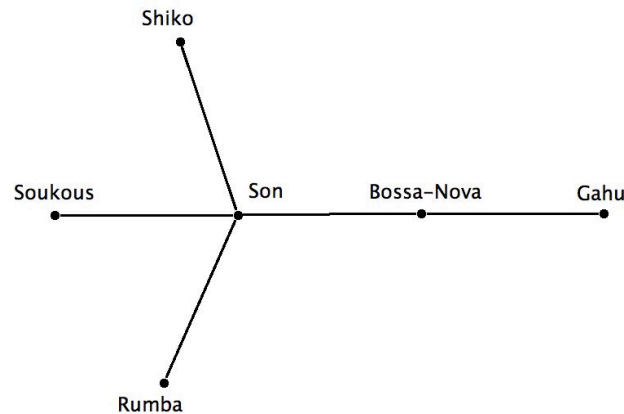
The *BioNJ* phylogenetic tree computed with the swap distance matrix of Figure 2 is shown in Figure 3. This tree provides a concise and immediate visualization of all the relationships present in the distance matrix. The distance between any pair of rhythms in the

Figure 2. The swap distance matrix obtained with the Afro-Cuban timelines

	Shiko	Son	Soukous	Rumba	Bossa-Nova	Gahu
Shiko	0	1	2	2	2	3
Son	1	0	1	1	1	2
Soukous	2	1	0	2	2	3
Rumba	2	1	2	0	2	3
Bossa-Nova	2	1	2	2	0	1
Gahu	3	2	3	3	1	0
TOTAL	10	6	10	10	8	12

BioNJ tree is the length of the shortest path along the tree (geodesic distance) that connects the two rhythms. For example, it is evident at a glance that the *son* is the center of the tree in the sense that it is the unique rhythm that minimizes the maximum distance to any other rhythm, and this maximum is realized by only one rhythm, the *gahu*. In such phylogenetic trees the evolutionary origin is considered to be near the center of the tree, i.e., the point in the tree that minimizes the maximum (or the sum) of the distances to all rhythms. As such there is a strong relationship between the evolutionary origin and the notion of prototypes that minimize the sum of differences to all objects in a collection. In the tree of Figure 3 no new nodes were created, and the *son* is closest to the center, suggesting that the *son* is the prototype for these six rhythms, and that it plays a singular role in their phylogeny. This centrality is also relevant to our understanding of the perception of rhythm. Rhythms close to a central rhythm should be perceived as more similar to it than rhythms far from the center.

Figure 3. The *BioNJ* tree computed with the *swap* distance matrix



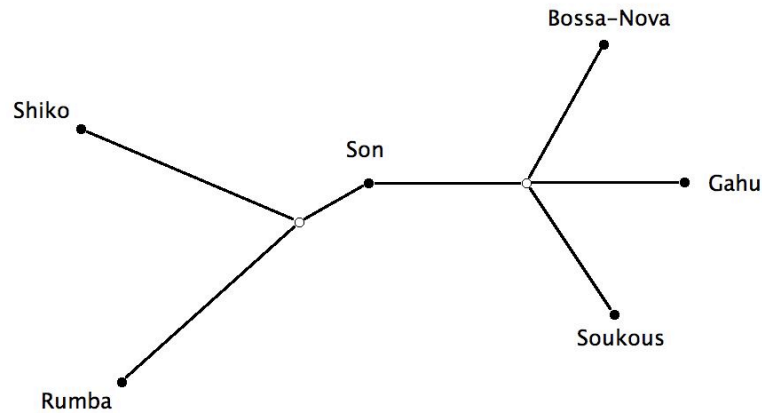
The distance matrix computed with the *edit* distance is shown in Figure 4. Some similarities and differences between this matrix and the swap distance matrix are evident. The *son* is still the rhythm most similar to the others (edit distance = 10). However, the most distant rhythm in the group is no longer the unique *gahu*, but rather the pair consisting of the *shiko* and *rumba* (edit distance = 17).

The *BioNJ* phylogenetic tree computed with the edit distance is shown in Figure 5. Here again the *son* lies clearly at the center of the group. In this tree, on the other hand, the *son* separates two clusters of rhythms as being quite distinct from each other, the first consisting of the *shiko* and *rumba*, and the second comprising the *bossa-nova*, *gahu*, and *soukous*. The solid black circles indicate the rhythms used as input to the *BioNJ* program, and are usually leafs of the tree. The open circles indicate ancestral rhythms from which the leaf rhythms may be derived, and are usually internal nodes of the tree. For distance measures such as the swap and edit distances, it is possible, at least in theory to reconstruct these ancestral rhythms.

Figure 4. The edit (Levenshtein) distance matrix

	Shiko	Son	Soukous	Rumba	Bossa-Nova	Gahu
Shiko	0	2	4	3	4	4
Son	2	0	2	2	2	2
Soukous	4	2	0	4	2	2
Rumba	3	2	4	0	4	4
Bossa-Nova	4	2	2	4	0	2
Gahu	4	2	2	4	2	0
TOTAL	17	10	14	17	14	14

Figure 5. *BioNJ* tree computed with the *edit* distance matrix



5.2 Listening tests

Participants

A total of 16 participants comprising 9 females and 7 males took part in Experiment 1 (mean age = 20.25, range = 18–24). All the subjects were trained musicians (primarily in

classical music). All were undergraduate music students at Harvard University who were paid \$10 for their participation. The average number of years of musical training among all participants was 11.4 years.

Apparatus

The participants sat on a chair and listened to the rhythms using Sennheiser, model PXC 250 noise-cancelling headphones (*NoiseGuardTM*). The headphones were connected to a MacBook Pro laptop Apple computer on which was displayed the graphical user interface of the *Sonic Mapper* software developed by Gary P. Scavone using *Qt* for the user interface and *RtAudio* for audio output (Scavone, Lakatos, & Harbke 2002). The *Sonic Mapper* software offers three alternatives for comparing sounds: two-dimensional similarity mapping, sorting, and the more traditional pairwise comparison tests. In all our experiments pairwise comparisons were used.

Stimulus materials

The sound samples were created using Apple *Garageband*. The rhythms, entered in MIDI format, were exact. Each onset triggered an identical click, which sounded much like pair of high-pitched wooden claves struck together. Each rhythm was played four times in succession at a tempo of 200 pulses per minute, resulting in a sound sample that lasted for 8 seconds. Thus in all rhythms the inter-pulse interval for all patterns was always the same.

In our experimental designs, one factor that may contribute to the variability in listeners' judgments about rhythm concerns carryover effects. There is empirical evidence to show that there are carryover effects affecting a listener's perception in experiments where one rhythm

is presented following another rhythm (Beauvillain 1983; Francis & Ciocca 2003), or when the tempo is varied (Desain, Jansen, & Honing 2000), or when pitch is varied (Pitt & Monahan 1987). In our experiments tempo and pitch were kept constant at all times.

Some may argue that rhythm is not a mere sequence of identical clicks or onsets. However, the music literature is filled with a plethora of definitions of rhythm (Abdy Williams 2009, 24). Rhythm may be studied at a variety of different levels of richness of information that may include any combination of properties such as pitch, intensity, micro-timing deviations, dynamic differences, timbre, texture, harmony, accentuation patterns, and beat/metrical structure (Cooper & Meyer 1960). Here we strip rhythms down to their barest representations as pure durational patterns. Hence we also refer to these rhythms as *durational rhythms*, to emphasize that the structure of their objective input representation is determined purely by duration.

Procedure

Each participant was seated in an isolated, quiet room with a laptop, headphones, and a sheet of instructions. Before the start of the experiment the participant filled out a form with some biographical data. The instructions told the participants that they would be hearing 30 pairs of rhythms, and that they would be asked to compare them using a sliding scale from 1 (most dissimilar) to 10 (most similar). *SonicMapper* presented the pairs of rhythms to the participants in a randomized order. Within this random order each pair of rhythms (A, B) was presented twice, once with rhythm A heard before rhythm B, and once with rhythm B heard before rhythm A. Each test took approximately 20 to 30 minutes to complete. The subjects did not listen to the rhythms before the experiment began, they were not trained to

judge the range of possible similarity and dissimilarity judgments, and they were not given practice trials or taught how to use a similarity scale.

5.3 Results of Experiment 1

The output of the *SonicMapper* consisted of a set of similarity ratings for each pair of rhythms in each of the two orders of presentation for each participant. The median of these similarity ratings, across all the participants, was used in order to reduce the impact of outliers, and the resulting numbers were subtracted from 10 to convert them to “distances.” The resulting distance matrix is shown in Figure 6. The entries at the bottom row (labeled TOTAL) list the sums of the distances from each rhythm (indicated at the top of the columns) to all the other rhythms, summed in *both* directions of presentation, and divided by two. Thus the score of any given rhythm is equal to half the sum of all the values in that rhythm’s row and column. In subsequent calculations the mean scores were compared to the median scores, and they gave virtually the same trees and correlation values.

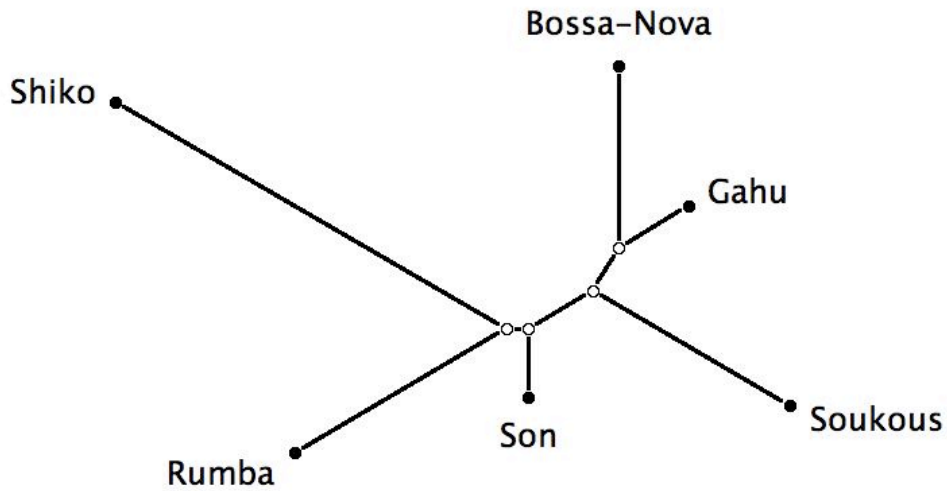
To compute a phylogenetic tree the *BioNJ* program requires as input a symmetric distance matrix. When the matrix is not symmetric (as is the case in Figure 6) the program automatically symmetrizes it by averaging the corresponding pairs of non-diagonal elements. The *BioNJ* tree computed with the symmetrized version of the matrix of Figure 6 is given in Figure 7.

Since the *BioNJ* phylogenetic tree program automatically produces a symmetric matrix from a non-symmetric matrix, we wanted to determine if there was a significant difference in judgments depending on the order in which the pairs of rhythms were presented to the listeners during the experiments. Therefore a Mantel test was performed to measure the

Figure 6. The non-symmetric median distance matrix obtained from the listening tests

	Shiko	Son	Soukous	Rumba	Bossa-Nova	Gahu
Shiko	0	5.04	6.52	6.28	6.32	5.56
Son	5.04	0	2.84	3.84	3.28	2.24
Soukous	7.72	3.68	0	6.28	3.68	3.16
Rumba	6.52	2.20	4.44	0	5.48	3.2
Bossa-Nova	7.84	3.40	4.20	6.00	0	2.32
Gahu	6.52	3.64	4.00	4.52	2.52	0
TOTAL	31.68	17.6	23.26	24.38	22.52	18.84

Figure 7. *BioNJ* tree computed with the symmetrized distance matrix obtained from the listening tests



similarity between the two *directional* matrices in Figures 8 and 9. The two matrices are highly correlated at a very significant level ($r = 0.81$ and $p = 0.003$). We concluded that the

order of presentation does not significantly affect our results, and therefore, in the subsequent two experiments the listeners were presented the rhythms in only one randomized order in order to be able to accommodate a greater number of rhythms without increasing the total time of the listening experiments.

To test for the range of individual differences and variability among subjects, the standard deviations of the raw similarity scores from which the median distance matrix in Figure 8 was obtained, were calculated across all participants. These standard deviations ranged from 1.00 to 2.14, with an average value of 1.54. That these values may be considered to be relatively high, does not imply that the subjects generally disagreed significantly in their comparative judgments. Since the subjects were not trained on how to score their judgments, but were left to their own devices, some used the upper end of the scale, and others the lower end, contributing to the relatively large standard deviations. What is more important than the absolute values of the scores, is a subject's relative judgments of the different pairs of rhythms, within his or her own range of scores. The Mantel test measures the inter-subject correlations of judgments with these relative scores. For example, the two subjects whose ranges of score values differed the most, were P6 with scores ranging from 4.68 to 9.0, and P4 with scores ranging from 1.24 to 7.8. Nevertheless, the Mantel test for these two subjects gave a correlation of 0.50 with $p = 0.05$.

Comparing the three distance matrices of Figures 2, 4, and 6 it may be observed that in all three cases the *son* has the lowest TOTAL score, indicating that it is the rhythm most similar to the others. The comparability between the two matrices ends there however. The rhythm most different from the others is the *gahu* for the swap distance, but the *shiko* (and *rumba*) for the edit distance and the human judgments. Comparing the three corresponding

Figure 8. First directional distance matrix obtained from the listening tests

	Shiko	Son	Soukous	Rumba	Bossa-Nova	Gahu
Shiko	0					
Son	5.04	0				
Soukous	7.72	3.68	0			
Rumba	6.52	2.20	4.44	0		
Bossa-Nova	7.84	3.40	4.20	6.00	0	
Gahu	6.52	3.64	4.00	4.52	2.52	0
TOTAL	33.64	17.96	24.04	23.68	23.96	21.20

Figure 9. Second directional distance matrix obtained from the listening tests

	Shiko	Son	Soukous	Rumba	Bossa-Nova	Gahu
Shiko	0	5.04	6.52	6.28	6.32	5.56
Son		0	2.84	3.84	3.28	2.24
Soukous			0	6.28	3.68	3.16
Rumba				0	5.48	3.20
Bossa-Nova					0	2.32
Gahu						0
TOTAL	29.72	17.24	22.48	25.08	21.08	16.48

BioNJ trees of Figures 3, 5, and 7 it is noteworthy that both the edit distance and human judgments cluster the rhythms into two groups separated by the *clave son*, one group consisting of the *shiko* and *rumba*, and the second group consisting of the *bossa-nova*, *gahu*, and *soukous*. Mantel tests (one tailed) computed for the three pairs of distance matrices yield

the correlation coefficients and their significance values shown in the table below. These tests suggest that the swap distance is not as good as the edit distance as a model for perceptual rhythm similarity. The edit distance yields a high correlation of 0.766 at a highly significant level of $p = 0.017$.

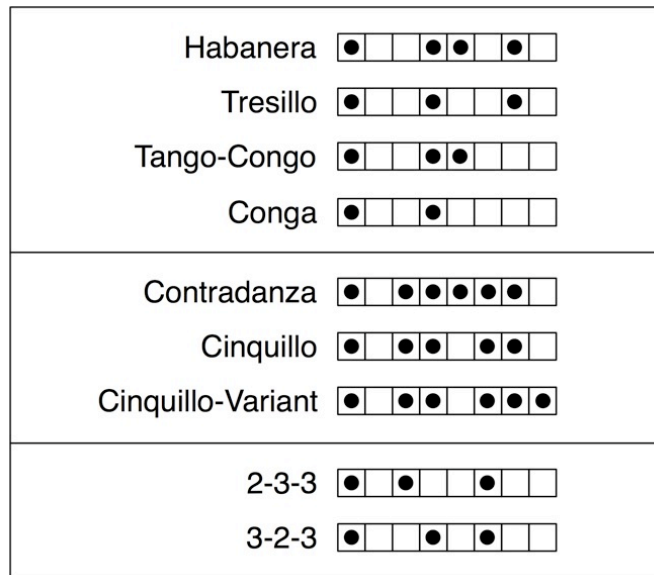
	Swap Distance	Edit Distance
Human	$r = 0.34$	$r = 0.766$
Judgments	$p = 0.183$	$p = 0.017$
Swap Distance		$r = 0.556$ $p = 0.066$

6. EXPERIMENT 2: THE HABANERA AND CONTRADANZA RHYTHMIC GROUPS

6.1 Rhythms and Computational Models

The rhythms used in Experiment 2 were taken from Mario Rey's ethnographic study of Cuban art music (Rey 2006). Mario Rey classified a collection of the most frequently used Afro-Cuban rhythms into two groups derived from either the *Habanera* or the *Contradanza*. Our first goal was to measure the degree of agreement between Rey's classification and human perceptual judgments, as well as with the mathematically based edit distance, in order to test whether the musicological grouping rules described by Rey have any perceptual or mathematical validity. The nine rhythms used in Experiment 2 are shown in Figure 10. The four rhythms at the top are considered by Rey to be derived from the *habanera*. Indeed, the

Figure 10. The seven Afro-Cuban rhythms from Mario Rey’s study in box notation, and two rotations of the *tresillo* (bottom)



tresillo may be derived from it by deleting (silencing or eliding) the third onset (strong beat), the *tango-congo* by deleting the last onset, and the *conga* by deleting the two last onsets. The rhythms in the middle group are considered by Rey to be derived from the *contradanza*. The *cinquillo* may be derived from the *contradanza* by deleting the fourth onset (strong beat) of the *contradanza*, and the *cinquillo-variant* may be obtained by deleting the fourth onset and inserting an onset at pulse number eight. Rey also suggested that the *habanera* and *contradanza* rhythms were the ancestral rhythms in their respective groups. Indeed, Rey uses the term “parent” rhythms to describe these two rhythms. He points out that it is a common practice in African derived rhythms to “represent the strong portion of the beats with silences” (Rey 2006), also referred to as the “silent downbeat” (Agawu 2006, p. 31). In Rey’s music theoretic analysis the rhythms “within each group structurally coincide when mapped onto the basic parent rhythms” (Rey 2006). Our second goal in Experiment 2 was to

determine if phylogenetic trees that use the edit distance support Rey's analysis. The last group of two rhythms at the bottom of Figure 10 were added to Rey's collection because they are rotations of the *tresillo* and are used all over the world.

The edit distance matrix and corresponding *BioNJ* tree computed from these nine rhythms are shown in Figures 11 and 12, respectively. The tree in Figure 12 exhibits two main clusters in which the first cluster, comprising the *contradanza*, *cinquillo*, and *cinquillo-variant*, is widely separated from the second cluster consisting of the remaining rhythms. This second cluster contains the singleton 2-3-3 rhythm widely separated from the remaining rhythms. In the remaining rhythms two sub-clusters are also evident: the pair making up the *tango-congo* and *habanera*, and the pair consisting of the *conga* and the 3-2-3 rhythm.

6.2 Listening tests

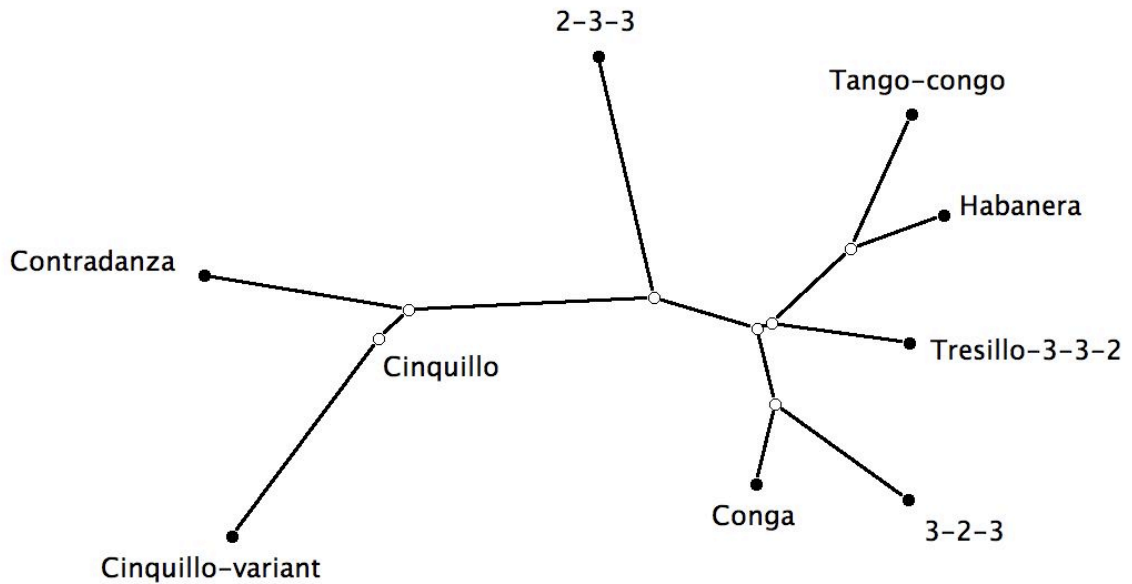
Participants

A total of 16 participants comprising 8 females and 8 males took part in Experiment 2 (mean age = 29.5, range = 18–57). Half of the subjects were Radcliffe Fellows at the Radcliffe Institute for Advanced Study at Harvard University, and half were undergraduate music students at Harvard University, who were paid \$10 for their participation. The Radcliffe Fellows represented a wide assortment of academic disciplines. The average number of years of musical training among all participants was 9.1 years.

Figure 11. The edit distance matrix of Mario Rey’s Cuban rhythms

	2-3-3	3-2-3	Cinquillo- Variant	Cinquillo	Conga	Contradanza	Habanera	Tango- Congo	Tresillo
2-3-3	0	2	3	2	2	3	3	3	2
3-2-3	2	0	3	2	1	3	2	2	2
Cinquillo- Variant	3	3	0	1	4	2	3	4	3
Cinquillo	2	2	1	0	3	1	2	3	2
Conga	2	1	4	3	0	4	2	1	1
Contradanza	3	3	2	1	4	0	2	3	3
Habanera	3	2	3	2	2	2	0	1	1
Tango-Congo	3	2	4	3	1	3	1	0	2
Tresillo	2	2	3	2	1	3	1	2	0
TOTAL	20	17	23	16	18	21	16	19	16

Figure 12. The phylogenetic tree computed from the edit-distance matrix of Mario Rey’s Afro-Cuban rhythms



Apparatus

The apparatus used in Experiment 2 was the same as in Experiment 1, except that two participants were tested at the same time in different rooms. Half of the participants used Sennheiser, model PXC 250 noise-cancelling headphones (*NoiseGuardTM*), and the other half used SONY, model MDR-NC7 noise-cancelling headphones.

Stimulus materials and procedure

The sound samples were created with parameters identical to the Afro-Cuban sound samples of Experiment 1. The experimental procedure was also exactly the same as in Experiment 1, except that 36 pairs of rhythms were presented, and each pair of rhythms was presented only once. As in Experiment 1, for each participant the order of presentation of the rhythm-pairs, and the order of presentation of each rhythm within each pair, was automatically randomized by *SonicMapper*.

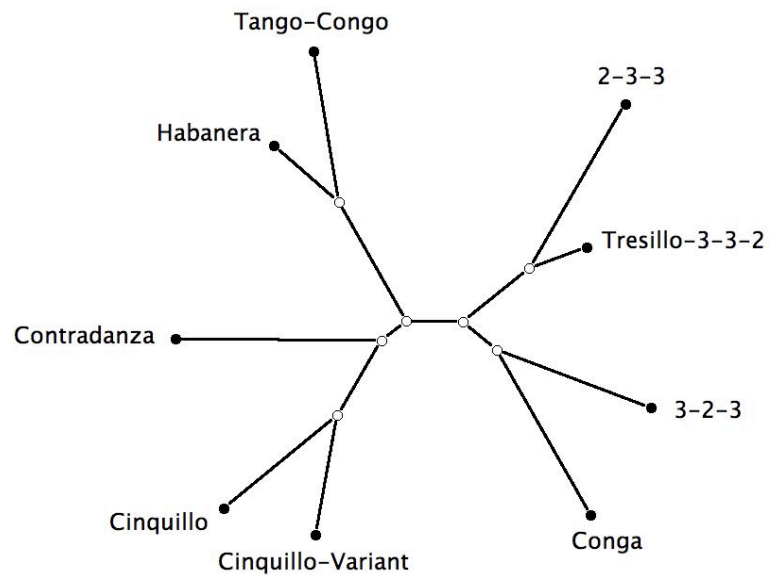
6.3 Results of Experiment 2

The distance matrix for Experiment 2 shown in Figure 13 was computed in the same manner as that for Experiment 1. The corresponding *BioNJ* tree is shown in Figure 14. Recall that one of the main goals of Experiment 2 was to test whether Mario Rey's musicological classification of the seven rhythms listed in the top two boxes in Figure 10 has any mathematical or perceptual validity. Our results support this hypothesis. The *BioNJ* tree in Figure 14 separates the three-rhythm group comprising the *cinquillo*, *cinquillo-variant*, and *contradanza* from the four-rhythm group consisting of the *habanera*, *tresillo*, *tango-congo*, and *conga*. This clustering is in agreement with that obtained using the edit distance

Figure 13. Distance matrix obtained from the listening tests with Mario Rey’s rhythms

	2-3-3	3-2-3	Cinquillo- Variant	Cinquillo	Conga	Contradanza	Habanera	Tango- Congo	Tresillo
2-3-3	0	4.52	5.16	4.64	5.80	4.64	5.76	5.80	2.36
3-2-3	4.52	0	5.12	4.68	3.32	4.72	4.08	5.40	3.60
Cinquillo-Variant	5.16	5.12	0	2.52	4.44	3.72	4.60	5.28	3.56
Cinquillo	4.64	4.68	2.52	0	5.60	4.28	5.04	5.32	3.96
Conga	5.80	3.32	4.44	5.6	0	5.92	4.48	4.24	2.28
Contradanza	4.64	4.72	3.72	4.28	5.92	0	4.24	4.44	5.00
Habanera	5.76	4.08	4.60	5.04	4.48	4.24	0	2.24	3.92
Tango-Congo	5.80	5.40	5.28	5.32	4.24	4.44	2.24	0	6.04
Tresillo	2.36	3.60	3.56	3.96	2.28	5.00	3.92	6.04	0
TOTAL	38.68	35.44	34.4	36.04	36.08	36.96	34.36	38.76	30.72

Figure 14. The *BioNJ* tree computed from the distance matrix of Figure 13



shown in Figure 12, although these two groups are more widely separated by the edit distance than by the human similarity judgments. This finding suggests that perhaps the categorizations of rhythms constructed by musicologists are guided more by discrete musicological rules than by the more graded categories of perception, and that the edit distance better captures such rules. On the other hand, one critical feature that distinguishes these two groups is simply the number of onsets contained in the rhythms: the *cinquillo*, *cinquillo-variant*, and *contradanza* each contain more onsets than each of the rhythms in the other group, and the edit distance may simply be more sensitive to this feature of the rhythms than human listeners are.

It should also be noted that both the edit distance and human judgments yield the same partition of Rey's four-group cluster into two sub-clusters of two rhythms each, one consisting of the *tango-congo* and *habanera*, and the other comprising the *conga* and the 3-2-3 rhythm [x . . x . x . .]. The two *BioNJ* trees differ concerning the pair consisting of the *tresillo* and the 2-3-3 rhythms given respectively by [x . . x . . x .] and [x . x . . x . .]. The human judgments place the 2-3-3 rhythm in a subgroup along with the *tresillo*, whereas the edit distance creates a solitary cluster for it. Nevertheless, the overall similarities between the two trees are marked. Indeed, the Mantel test performed on the corresponding distance matrices yields a correlation coefficient of 0.594 at a significance level of 0.0002 (one-tailed test).

From the distance matrices in Figures 11 and 13, it may be observed that both the human judgments as well as the edit distance highlight the *tresillo* rhythm [x . . x . . x .] as having the lowest TOTAL score values (16 for the edit distance, and 30.72 for the human judgments). Note however that for the edit distance this value is also realized by the

habanera [x . . x x . x .] and the *cinquillo* [x . x x . x x .]. As an aside it is worth pointing out that the *tresillo* consists of the first eight pulses (measure) of the world-famous *clave son* timeline given by [x . . x . . x . . . x . x . . .], a rhythm that is considered to have conquered the world (Toussaint 2010).

Recall that Mario Rey, in his qualitative ethnographic study, considers the *habanera* and *contradanza* to be the ancestral rhythms (“parents”) of the upper two groups of rhythms illustrated in Figure 10. However, the perceptual information characterized by the distance matrix and *BioNJ* tree obtained from the human judgments does not support these claims, but rather suggests that the *tresillo*, by virtue of being the most parsimonious rhythm, is the ancestor of the entire group. On the other hand, the more objective criteria given by the distance matrix (Figure 11) and *BioNJ* tree (Figure 12) obtained from the edit distance, tell a different story. Here three rhythms are tied for being most parsimonious, with TOTAL scores equal to 16: the *tresillo*, the *habanera*, and the *cinquillo*. This suggests that, along with the *tresillo*, the *habanera* is also a likely contender for the ancestral rhythm of the first group, in partial support of Rey’s claim. On the other hand, contrary to Rey’s claim, the edit distance selects the *cinquillo* rather than the *contradanza* as the ancestral rhythm for the second group in Rey’s classification. These findings suggest again that, like the categorizations of rhythms constructed by musicologists, it may be that the genealogies they formulate are guided more by explicit musicological rules passed down by teachers than by perceptual similarities. After all, the edit distance permits ancestral rhythms to have either fewer or more onsets than its descendants, whereas in Rey’s analysis it appears that his definition of parent rhythms implies that they contain the onsets of their offspring, notwithstanding the *cinquillo-variant*.

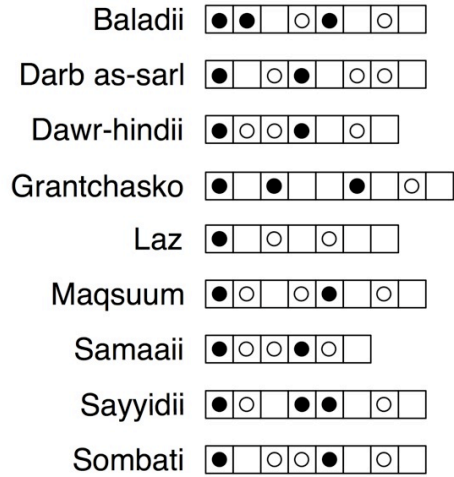
To test for the range of individual differences and variability among subjects, the standard deviations of the raw similarity scores from which the median distance matrix in Figure 13 was obtained, were calculated across all participants. These standard deviations ranged from 1.35 to 2.26, with an average value of 1.7, slightly higher than for Experiment I. Furthermore, there were some real outliers among the listeners, subjects that did not agree with each other at all. For example, the two subjects whose ranges of score values differed the most, were those labeled A3 and B7, with scores ranging from 3.1 to 8.8 and 2.0 to 6.7, respectively. The Mantel test for these two subjects gave a correlation of -0.44 with $p = 0.008$.

7. EXPERIMENT 3: THE MIDDLE EASTERN AND MEDITERRANEAN RHYTHMS

7.1 Rhythms and Computational Models

Experiment 3 used a set of dance rhythms, shown in Figure 15, that are completely different from the timelines used in the first two experiments. Unlike the other two sets of rhythms, these nine Middle Eastern and Mediterranean rhythms consist of two sounds, a low mellow sound called *dum*, and a dry high-pitched sound called a *tak*. For this reason these rhythms are often referred to as *dum-tak* rhythms (Shiloah 1995; Touma 1996; Middle Eastern Rhythms FAQ, <http://www.khafif.com/rhy/>, accessed Jan. 13, 2011). The *dum* is normally struck in the center of the drum skin, whereas the *tak* is played on the rim of the drum. In the box-notation in Figure 15 the *dum* is notated with a black-filled circle, and the *tak* with a white-filled circle. Note that the nine rhythms in combination contain an almost equal number of *dum* (20) and *tak* (22) sounds.

Figure 15. The Middle Eastern and Mediterranean rhythms in box notation. Black circles denote *dum* sounds, and white circles *tak* sounds



It is a well-established phenomenon in musical listening behavior that listeners may attend selectively, by giving more weight, to sounds that occur more frequently during an experiment. Since the *dum* and *tak* sounds in our experiment occur with essentially equally frequency, such attending is less likely. More importantly, note also that, unlike the two other sets of rhythms, these rhythmic cycles have different cardinalities of pulses, and hence possess much greater metrical ambiguity (London 2004). One pattern, the *samaai* has six pulses, the *grantchasko* has nine pulses, the *dawr-hindii* and *laz* each have seven pulses, and the remaining five rhythms all have eight pulses. Using metrically ambiguous rhythms that have unequal numbers of onsets, and unequal numbers of pulses in their cycles provides a more challenging test to the design of successful mathematical measures of rhythm similarity that are robust across metrical hypotheses constructed by the listeners, especially listeners such as those used in this study, with biases favoring Western metrical music.

Since the edit distance allows for symbols to take on any number of values, it is natural to employ it here in two versions. In the two-symbol version the rhythm is considered to

consist of sounded and silent pulses only, without distinguishing between the *dum* and the *tak*. In the three-symbol version the rhythm consists of *dum*, *tak*, and silent pulses. Therefore in the two-symbol similarity calculations the three rhythms *baladii*, *maqsuum*, and *sayyidii* are obviously all identical. One of the goals of this experiment was to determine whether, and by how much, the results would improve if the rhythms were encoded with three rather than two symbols in order to distinguish them from each other. The two-symbol and three-symbol edit distance matrices computed with the nine rhythms of Figure 15, along with their corresponding *BioNJ* trees are given in Figures 16–19.

7.2 Listening tests

Participants

A total of 16 participants comprising 8 females and 8 males took part in Experiment 3 (mean age = 24.1, range = 18–58). Two subjects were Radcliffe Fellows at the Radcliffe Institute for Advanced Study at Harvard University, and fourteen were undergraduate students at Harvard University, who were paid \$15 for their participation. The average number of years of musical training among all participants was 10.9 years.

Apparatus, stimulus materials, and procedure

The apparatus used in Experiment 3 was the same as in Experiment 2. The sound samples were created in the same way as in the first two experiments, but instead of a wooden clave-like click, a low *dum* sound (like a hand hitting the center of a drum), and a higher *tak* sound (similar to a hand striking the edge of a drum) were used. The tempo was kept constant for each sound sample so that they ranged in duration from 8 to 11 seconds

Figure 16. The two-symbol edit distance matrix for the Middle Eastern and Mediterranean *dum-tak* rhythms

	Baladii	Darb-as-sarl	Dawr-hindii	Grantchasko	Laz	Maqsum	Samaaii	Sayyidii	Sombati
Baladii	0	2	1	2	3	0	2	0	2
Darb-as-sarl	2	0	2	2	2	2	2	2	2
Dawr-hindii	1	2	0	3	3	1	1	1	1
Grantchasko	2	2	3	0	2	2	4	2	2
Laz	3	2	3	2	0	3	3	3	2
Maqsum	0	2	1	2	3	0	2	0	2
Samaaii	2	2	1	4	3	2	0	2	2
Sayyidii	0	2	1	2	3	0	2	0	2
Sombati	2	2	1	2	2	2	2	2	0
TOTAL	12	16	13	19	21	12	18	12	15

Figure 17. The *BioNJ* phylogenetic tree computed from the two-symbol edit-distance matrix for the Middle Eastern and Mediterranean *dum-tak* rhythms

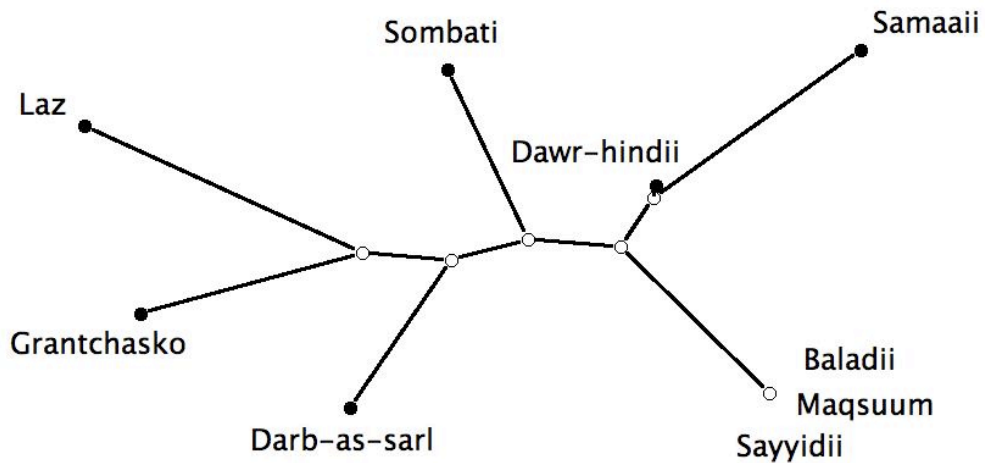
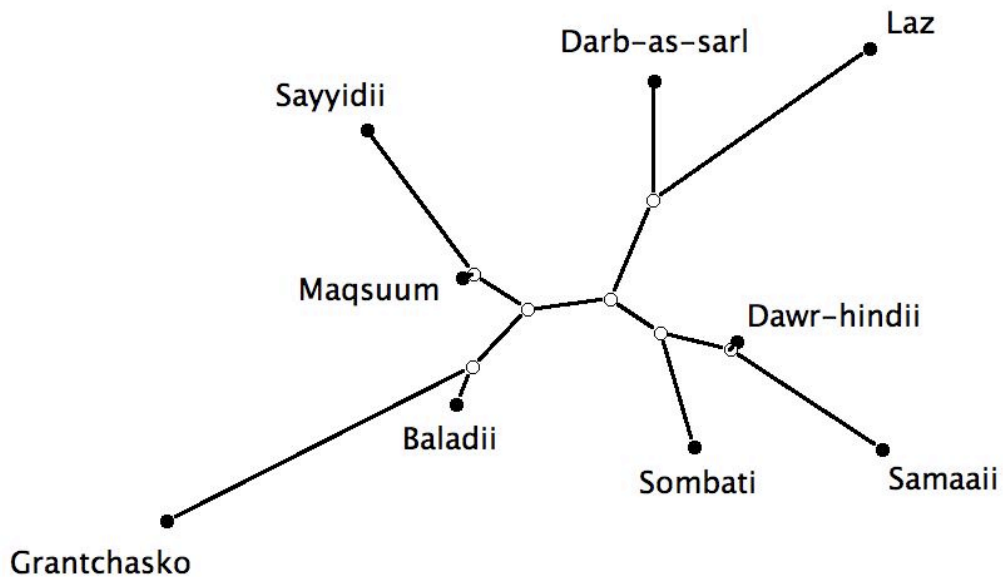


Figure 18. The three-symbol edit distance matrix for the Middle Eastern and Mediterranean *dum-tak* rhythms

	Baladii	Darb-as-sarl	Dawr-hindii	Grantchasko	Laz	Maqsum	Samaaii	Sayyidii	Sombati
Baladii	0	2	2	2	3	1	3	2	2
Darb-as-sarl	2	0	2	4	2	2	3	3	2
Dawr-hindii	2	2	0	4	3	1	1	2	1
Grantchasko	2	4	4	0	4	3	5	3	3
Laz	3	2	3	4	0	3	3	4	3
Maqsum	1	2	1	3	3	0	2	1	2
Samaaii	3	3	1	5	3	2	0	3	2
Sayyidii	2	3	2	3	4	1	3	0	3
Sombati	2	2	1	3	3	2	2	3	0
TOTAL	17	20	16	28	25	15	22	21	18

Figure 19. The *BioNJ* phylogenetic tree computed from the three-symbol edit-distance matrix for the Middle Eastern and Mediterranean *dum-tak* rhythms



depending on the number of pulses contained in the rhythmic cycle. The experimental procedure was identical to that of Experiment 2.

7.3 Results of Experiment 3

The distance matrix for Experiment 3 was computed in the same manner as that for Experiments 1 and 2. The matrix and resulting *BioNJ* tree are shown in Figures 20 and 21, respectively. To test for the range of individual differences and variability among the subjects, the standard deviations of the raw similarity scores from which the median distance matrix in Figure 21 was obtained, were calculated across all participants; they ranged from 1.17 to 2.38, with an average value of 1.82, almost the same as for Experiment 2. In this experiment there were subjects that used very different portions of the scale in making their judgments. For example, subject B2 had scores ranging from 1.0 to 6.28, whereas subject B8 had scores ranging from 5.16 to 8.84, with almost no overlap region in common between the two. However, their relative judgments agreed strongly; the Mantel test calculated with their similarity matrices gave a correlation coefficient of 0.582 with $p = 0.005$.

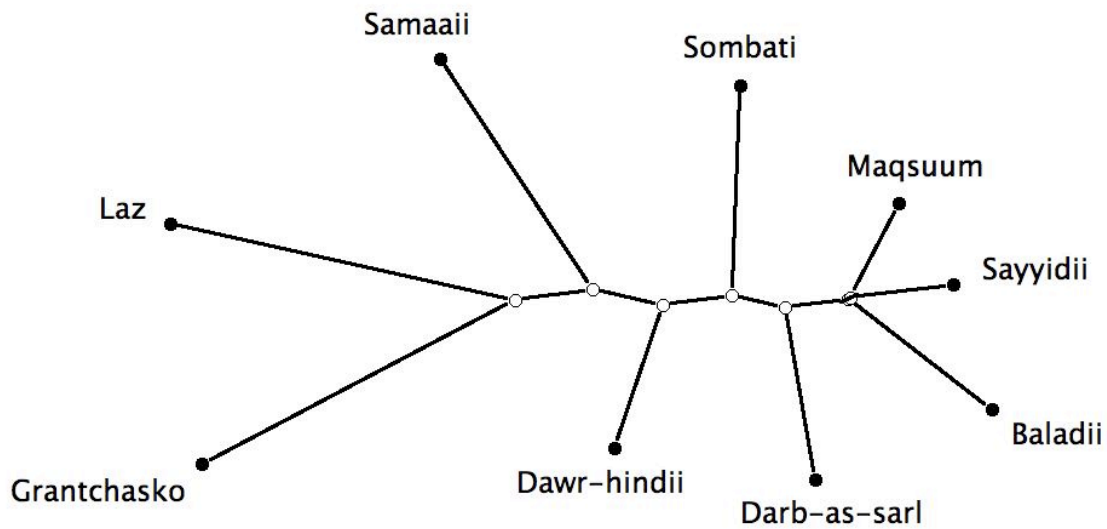
The main goal of Experiment 3 was to test the effectiveness of the edit distance to predict human perceptual judgments when the rhythms contain non-Western meters and different numbers of pulses in their cycles. We also wanted to compare the two-symbol edit distance with the three-symbol edit distance when the rhythms contain two different sounds to see if the straightforward application of the edit distance can capture and exploit the added information contained in the different sounds.

The three distance matrices in Figures 16, 18, and 20, corresponding to the two-symbol and three-symbol edit distances, and the human judgments, have two noteworthy

Figure 20. The distance matrix obtained from the listening tests for the Middle Eastern and Mediterranean *dum-tak* rhythms

	Baladii	Darb-as-sarl	Dawr-hindii	Grantchasko	Laz	Maqsum	Samaaii	Sayyidii	Sombati
Baladii	0	3.36	3.84	7.40	7.36	2.60	6.28	2.56	5.88
Darb-as-sarl	3.36	0	4.00	6.56	7.56	3.52	5.84	3.04	3.96
Dawr-hindii	3.84	4.00	0	6.80	6.80	3.64	3.52	5.48	3.56
Grantchasko	7.40	6.56	6.80	0	6.32	6.52	6.80	7.04	7.40
Laz	7.36	7.56	6.80	6.32	0	6.60	5.88	7.32	6.96
Maqsum	2.60	3.52	3.64	6.52	6.60	0	5.64	1.88	3.40
Samaaii	6.28	5.84	3.52	6.80	5.88	5.64	0	6.48	6.04
Sayyidii	2.56	3.04	5.48	7.04	7.32	1.88	6.48	0	3.04
Sombati	5.88	3.96	3.56	7.40	6.96	3.40	6.04	3.04	0
TOTAL	39.28	37.84	37.64	54.84	54.8	33.8	46.48	36.84	40.24

Figure 21. *BioNJ* tree computed with the distance matrix obtained from the listening tests for the Middle Eastern and Mediterranean *dum-tak* rhythms



commonalities. First, all three yield the *maqsum* rhythm as the most parsimonious of the group, having TOTAL scores of 12, 15, and 33.8, respectively. Naturally, the *sayyidii* and the *baladii* also have scores of 12, since they are considered to be identical to the *maqsum* by the two-symbol edit distance. Second, all three yield the *laz* and *grantchasko* as the two most different rhythms of the group. Note that the *grantchasko* is the longest rhythm, the only rhythm that has nine pulses, and the only rhythm containing three well-separated *dum* sounds. Also the *laz* is the unique rhythm containing only one *dum* sound.

Comparing the three *BioNJ* trees we observe that the tree obtained from the listening tests is slightly more similar to the tree calculated with the two-symbol edit distance than with the three-symbol edit distance, although the difference is probably not significant. The human judgments placed the *maqsum*, *sayyidii*, and *baladii* in one tight cluster (Figure 21). The three-symbol edit distance also clustered them together, but included the *grantchasko* in the group (Figure 19). The human judgments and the two-symbol edit distance both placed the *grantchasko* and *laz* into one cluster, whereas the three-symbol edit distance located them in different clusters at opposite ends of the tree. Finally, the listening tests and the two-symbol edit distance both created a solitary cluster for the *sombati*, whereas the three-symbol edit distance lumped it together in a cluster with the *dawr-hindii* and *samaii*.

These results suggest that the edit distance still manages to perform well for more complex rhythms than those used in Experiments 1 and 2, and that the two-symbol edit distance may be superior to the three-symbol edit distance when the latter is used in this way. The table below gives the correlation coefficients and their levels of significance obtained with the Mantel test (one tailed). However, even if the difference between the two-symbol and three-symbol edit distances is statistically significant, the difference is rather small, since

it amounts to only 0.04% of the variance accounted for. These results suggest that for the edit distance to succeed in incorporating accents, it should not treat them merely as an additional symbol, but rather it should be modified in a more sophisticated manner than the way it was used here.

	two-symbol Edit	three-symbol Edit
	Distance	Distance
Human	$r = 0.677$	$r = 0.636$
Judgments	$p = 0.001$	$p = 0.0015$
two-symbol Edit		$r = 0.760$
Distance		$p = 0.0002$

8. CONCLUSIONS AND FUTURE DIRECTIONS

There appears to be little doubt that even the greatly simplified *durational rhythms*, i.e., rhythms that have been stripped of all information other than time, and that possess exact inter-onset intervals determined by small integer ratios, exhibit a high degree of perceptual complexity. Furthermore, there is no doubt that at first glance the edit distance appears to be too simple or naïve to capture the perceptual complexity of real durational rhythms. Nevertheless in all three experiments with very different sets of rhythms the edit distance performed admirably well. One is tempted to feel that this is too good to be true; however, one should not be fooled by the apparent simplicity of the edit distance. It is well known that mathematical rules or formulas that appear to be very simple may in fact generate unbounded complexity (Mandelbrot 1982; Boettiger & Oster 2009). Although the evidenced correlations

speak for themselves, this is not to say that the edit distance is without its weaknesses. Indeed, one may construct examples in which the edit distance yields results that contradict human perception judgments. Consider for instance the following three sixteen-pulse rhythmic patterns:

$$A = [x \dots x \dots x \dots x \dots x \dots]$$

$$B = [x \dots x \dots x \dots x \dots x \dots]$$

$$C = [x \dots x \dots x \dots x \dots x \dots]$$

The edit distance between rhythmic patterns A and C is 3, and may be derived as follows:

$$\begin{aligned} A &= [x \dots x \dots x \dots x \dots x \dots] \text{ (delete a rest after onset 2)} \\ &= [x \dots x \dots x \dots x \dots x \dots] \text{ (substitute onset 5 with a rest)} \\ &= [x \dots x \dots x \dots x \dots x \dots] \text{ (insert an onset after pulse 13)} \\ C &= [x \dots x \dots x \dots x \dots x \dots] \end{aligned}$$

The edit distance between rhythmic patterns A and B is 5, and may be derived as follows:

$$\begin{aligned} A &= [x \dots x \dots x \dots x \dots x \dots] \text{ (delete a rest between onsets 1 and 2)} \\ &= [x \dots x \dots x \dots x \dots x \dots] \text{ (insert a rest between onsets 2 and 3)} \\ &= [x \dots x \dots x \dots x \dots x \dots] \text{ (delete a rest between onsets 3 and 4)} \\ &= [x \dots x \dots x \dots x \dots x \dots] \text{ (substitute onset 5 for a rest)} \\ &= [x \dots x \dots x \dots x \dots x \dots] \text{ (insert an onset after pulse 13)} \\ B &= [x \dots x \dots x \dots x \dots x \dots] \end{aligned}$$

In other words, rhythm A (the *clave son*), is dictated by the edit distance to be more similar to rhythm C than to rhythm B. Contrary to this however, most listeners consider rhythm A to be more similar to rhythm B than to rhythm C.

Turning to the results from the experiments reported here, although the edit distance and human judgments yield the same global clustering of the six Afro-Cuban rhythms, evidenced in Figures 5 and 7, the edit distance fails to reflect more refined local variations evident in the tree obtained from the human judgments. Within the three-group cluster comprising the *bossa-nova*, *gahu*, and *soukous*, the human judgments yield a sub-cluster consisting of the *bossa-nova* and *gahu* (see Figure 7), which the edit distance fails to capture. Also the human subjects judged the *shiko* to be more distant from the *son* than the *rumba*, but according to the edit distance they are equally distant. Along the same lines, in Experiment 2 the human judgments placed the 2-3-3 rhythm in a cluster with the *tresillo* (Figure 14), but the edit distance created a solitary cluster for it (Figure 11).

It is conceivable that the good correlations obtained in Experiments 1 and 2 are due to the fact that a rather constrained set of rhythms sharing a similar metric environment has been used. In Experiment 1, all the rhythms have sixteen pulses and five onsets, and in Experiment 2, eight-pulse long patterns are used where the two groups have significantly different numbers of onsets (2–4 onsets in the first group and 5–6 onsets in the second group). Therefore, concerning Rey's categorization, a trivial rule that merely counts the number of onsets can separate these two classes, and the edit distance may implicitly be doing just that. Of course, we used these rhythms precisely because they form part of Rey's ethnographic study. Moreover, the number of onsets in a pattern may be a perfectly valid feature that determines rhythm similarity, although it tends to measure superficial rather than

deep structure. However, we may ask if good correlations to human judgments would still be obtained if more varied rhythms (including random patterns) were included in the experiment. This issue will be addressed in a future study.

Experiment 3 suggests that the two-symbol edit distance may be a slightly better model of perception ($r = 0.677, p = 0.001$) than the three-symbol edit distance ($r = 0.636, p = 0.0015$). This does not imply however, that using the additional information provided by differentiating the two sounds necessarily degrades performance, or is even useless for the task. Besides the fact that the difference may not be significant, it may merely indicate that this way of coding this information (by means of two distinct symbols in the edit distance computations) may not be the best approach. Hopefully the results presented here will clarify the strengths and weaknesses of the edit distance, and motivate its modification so that it is impervious to counterexamples, and provides an even better match with human judgments. One possible solution might be to assign suitable weights to the various operations of the edit distance that depend on perceptual temporal universals. However, such research is left for the future.

The results obtained here also suggest a new approach to the investigation of cultural prototypes. While discourse on the topic of prototypicality is preliminary at this stage, the following discussion stimulated by the present research, is offered as a starting point for future research in this direction.

There exist various parameters for prototypicality, such as commonality or anteriority. For instance, a dog may be a prototypical member of the category ‘mammal’ because it is encountered more often in urban environments, rather than being necessarily the most highly representative instance of a mammal. Inuits in the North Pole may have a very different

mammal prototype. Analogously, a specific musical pattern may be the prototype of a motivic/thematic category simply because it appears at the beginning of a musical work. The term prototype is used here in a limited way to refer to a *good* exemplar or a highly representative instance of a category (Rosch 1975; MacLaury 1991). Trehub and Unyk (1991) emphasize cross-cultural and developmental strategies for identifying *natural* music prototypes, by which they mean those that have a biological core rather than one derived from experience. They suggest that in those instances where categories can be defined, such as Rey's categorization of Afro-Cuban rhythms, and the Middle Eastern and Mediterranean rhythms analyzed above, the best prototypes should be those that are maximally similar to the other members in the category. They also suggest that if the prototypes have a biological significance, they should bring into evidence cross-cultural, as well as developmental, similarities in their perception. Accordingly research to determine candidates for prototypes has in the past focused on searching for patterns that exist across different cultures and developmental stages. In particular Trehub and Unyk (1991) review the literature on the identification of *good* melodies in general, and prototypical lullabies in particular. The approach to the study of rhythmic prototypes presented here offers a novel quantitative method to obtain one type of natural prototypes, namely those that are maximally similar to all other rhythms in a category, in the sense that they minimize the sum of the edit distances to all the other rhythms in the category.

For the category of the six distinguished timelines consisting of five onsets and sixteen pulses, all three distance matrices for the swap distance, edit distance, and listening experiments given in Figures 2, 4, and 6, respectively, single out the *clave son* as the best prototype. For the category consisting of Mario Rey's Afro-Cuban rhythms, the listening

experiments isolate the *tresillo* [x . . x . . x .] as the best prototype (Figure 13), but the edit distance (Figure 11) also yields the *habanera* [x . . x x . x .] and *cinquillo* [x . x x . x x .] as candidates tied with the *tresillo* for the position of best prototype.

For the category of Middle-Eastern and Mediterranean *dum-tak* rhythms the listening experiments and the three-symbol edit distance both select the *maqsum* as the best prototype. However, the two-symbol edit distance naturally includes the *baladii* and the *sayyidii* as equal contenders, since all three rhythms have the same rhythmic pattern [x x . x x . x .]. In the three instances the prototype rhythms obtained by minimizing the sum of the edit distances, confirm existing musicological evidence of their distinguished status. The *clave son* has a noteworthy eight-hundred-year history of universal appeal (Toussaint 2010). The *tresillo*, and *cinquillo*, the ancient Greek *dochmiac* and *hypodochmius* patterns, respectively (Abdy Williams 2009; West 2005, 144) are rhythms found in traditional music in many parts of the world (Toussaint 2005). The *maqsum* pattern is known throughout the Middle East (Hagoel 2003). Note that the duration pattern of the *maqsum* rhythm is a rotation of the *cinquillo*, and thus both belong to the same rhythm necklace. The fact that the edit distance generates this pattern as the best prototype in two distinct musical cultures (genres, categories) such as Afro-Cuban rhythms and Middle-Eastern and Mediterranean rhythms provides objective and quantitative evidence to support the hypothesis that this rhythm necklace may indeed be a universal music prototype.

As already stated in the introduction, the current study ignores the issue of meter altogether. Hence it remains unclear how meter may influence the perceptual results and its effect on the edit distance. We have also ignored the related topic of syncopation, which results from the interaction between the measurable rhythm and the perceived, anticipated

meter (Fitch & Rosenfeld 2007; Honing 2006; Smith & Honing 2006). In a future study we plan to evaluate the edit distance and mathematical measures of syncopation (Thul & Toussaint 2008) as a function of both the perception of the underlying meter and the perception of syncopation.

In the experiments reported here most of the listeners had a strong Western Classical Musical bias, evidenced by their backgrounds. From cross-cultural studies it is known that these listeners probably bring to these listening tests a tacit but definite bias to hear rhythms in either 4/4 and 3/4 meters, or minor variations thereof (Stobart & Cross 2000; Stevens 2004). Nevertheless, in Experiment 3 the edit distance gave a high and significant correlation with human perception. It is possible that listeners acculturated in Middle Eastern and Mediterranean music idioms such as asymmetrical meters would generate different distance matrices. In a future experiment we plan to test the edit distance using these same rhythms but with listeners from the Middle East.

REFERENCES

- Abdy Williams, C. F. 2009. *The Aristoxenian Theory Of Musical Rhythm*. New York: Cambridge University Press.
- Agawu, K. 2006. "Structural Analysis Or Cultural Analysis? Competing Perspectives On The 'Standard Pattern' Of West African Rhythm." *Journal of the American Musicological Society* 59.1: 1–46.
- Beauvillain, C. 1983. "Auditory Perception Of Dissonant Polyrhythms." *Perception and Psychophysics* 34.6: 585–592.
- Berenzweig, A., Logan, B., Ellis, D. P. & Whitman, B. 2004. A Large-Scale Evaluation Of Acoustic And Subjective Music-Similarity Measures. *Computer Music Journal* 28.2: 63–76.

- Boettiger, A. N. & Oster, G. 2009. Emergent Complexity In Simple Neural Systems. *Communicative & Integrative Biology* 2.6: 1–4.
- Bolton, T. L. 1894. “Rhythm.” *The American Journal of Psychology* 6: 145–238.
- Bonnet, E., & Van de Peer, Y. 2002. “zt: A Software Tool For Simple And Partial Mantel Tests.” *Journal of Statistical Software* 7.10: 1–12.
- Carrizo, S. F. 2004. “Phylogenetic trees: an information visualization perspective.” *Proceedings of the Second Conference on Asia-Pacific Bioinformatics* 29: 315–320.
- Cooper, G. & Meyer, L. B. 1960. *The Rhythmic Structure Of Music*. Chicago: The University of Chicago Press.
- Crawford, T., Iliopoulos, C. S., & Raman, R. 1997–98. “String-Matching Techniques For Melodic Similarity And Melodic Recognition.” *Computing in Musicology* 11: 73–100.
- Dean, R. T., Byron, T., & Bailes, F. A. 2009–2010. “The Pulse Of Symmetry: On The Possible Co-Evolution Of Rhythm In Music And Dance.” *Musicae Scientiæ* Special Issue on Music and Evolution: 341–367.
- Demorest, S. M. & Serlin, R. C. 1997. “The Integration Of Pitch And Rhythm In Musical Judgment: Testing Age-Related Trends In Novice Listeners.” *Journal of Research in Music Education* 45.1: 67–79.
- Desain, P., Jansen, C., and Honing, H. 2000. “How Identification Of Rhythmic Categories Depends On Tempo And Meter.” In *Proceedings of the Sixth International Conference on Music Perception and Cognition*. Keele, UK: Keele University Department of Psychology.
- Diaconis P., & Graham, R. L. 1977. “Spearman’s Footrule As A Measure Of Disarray.” *Journal of the Royal Statistical Society* B-39.2: 262–268.
- Dietz, E. J. 1983. “Permutation Tests For Association Between Two Distance Matrices.” *Systematic Zoology* 32.1: 21–26.
- Dixon, S. 2001. “Automatic Extraction Of Tempo And Beat From Expressive Performances.” *Journal of New Music Research* 30.1: 39–58.

- Essens, P. 1995. "Structuring Temporal Sequences: Comparison Of Models And Factors Of Complexity". *Perception and Psychophysics* 57.4: 519–532.
- Ferraro, P., & Hanna, P. 2007. "Optimizations Of Local Edition For Evaluating Similarity Between Monophonic Musical Sequences." *Proceedings of the 8th International Conference on Information Retrieval*. Pittsburgh PA, U.S.A.
- Fitch, W. T., & Rosenfeld, A. J. 2007. "Perception And Production Of Syncopated Rhythms." *Music Perception* 25: 43–58.
- Francis, A. L. & Ciocca, V. 2003. "Stimulus Presentation Order And The Perception Of Lexical Tones In Cantonese." *Journal of the Acoustical Society of America* 114.3: 1611–1621.
- Gascuel, O. 1997. "BIONJ: An Improved Version Of The NJ Algorithm Based On A Simple Model Of Sequence Data." *Molecular Biology and Evolution* 14.7: 685–695.
- Guastavino, C., Gómez, F., Toussaint, G. T., Marandola, F., & Gómez, E. 2009. "Measuring Similarity Between Flamenco Rhythmic Patterns." *Journal of New Music Research* 38.2: 129–138.
- Hage, P., Harary, F., & Krackhardt, D. 1998. "A Test Of Communication And Cultural Similarity In Polyhesian Prehistory." *Current Anthropology* 39.5: 699–703.
- Hagoel, K. 2003. *The Art Of Middle Eastern Rhythm*. Kfar Sava, Israel: OR-TAV Music Publications.
- Honing, H. 2006. "Computational Modeling Of Music Cognition: A Case Study On Model Selection." *Music Perception* 23.5: 365–76.
- Huson, D. H., & Bryant, D. 2006. "Application Of Phylogenetic Networks In Evolutionary Studies." *Molecular Biology and Evolution* 23.2: 254–267.
- Huson, D. H. 1998. "*SplitsTree*: A Program For Analyzing And Visualizing Evolutionary Data." *Bioinformatics* 14.10: 68–73.
- Jan, S. 2007. *The Memetics Of Music: A Neo-Darwinian View Of Musical Structure And Culture*. Aldershot, England: Ashgate Publishing.

- Johnson-Laird, P. N. 1991. "Rhythm And Meter: A Theory At The Computational Level." *Psychomusicology* 10.2: 88–106.
- Kendall, M. 1970. *Rank correlation methods*. London: Griffin.
- Kubik, G. 1999. *Africa and the blues*. Jackson: University Press of Mississippi.
- Ladinig, O., Honing, H., Háden, G., & Winkler, I. 2009. "Probing Attentive And Pre-Attentive Emergent Meter In Adult Listeners With No Extensive Music Training." *Music Perception* 26.4: 377–386.
- Lemström, K., & Pienimäki, A. 2007. "On Comparing Edit Distance And Geometric Frameworks In Content-Based Retrieval Of Symbolically Encoded Polyphonic Music." *Musicae Scientiae Discussion Forum* 4A: 135–151.
- Lipo, C. P., O'Brien, M. J., Collard, M., & Shennan, S. J., Eds. 2006. *Mapping Our Ancestors: Phylogenetic Approaches In Anthropology And Prehistory*. New Brunswick: Transaction Publishers.
- London, J. 2004. *Hearing In Time*. New York: Oxford University Press.
- Longuet-Higgins, H. C. & Lee, C. S. 1984. "The Rhythmic Interpretation Of Monophonic Music." *Music Perception* 1.4: 424–41.
- _____. 1982. "The Perception Of Musical Rhythms." *Perception* 11: 115–128.
- Mace, R., Holden, C. J., & Shennan, S., Eds. 2005. *The Evolution Of Cultural Diversity: A Phylogenetics Approach*. London: UCL Press.
- MacLaury, R. E. 1991. "Prototypes Revisited." *Annual Review of Anthropology* 20: 55–74.
- Mandelbrot, B. B. 1982. *The Fractal Geometry Of Nature*. W.H. Freeman and Company.
- Mantel, N. 1967. "The Detection Of Disease Clustering And A Generalized Regression Approach." *Cancer Research* 27: 209–220.
- Mavromatis, P., & Williamson, V. 1999a. "Toward A Perceptual Model For Categorizing Atonal Sonorities." *The Annual Conference of the Society for Music Theory*, Atlanta, Georgia.

- _____. 1999b. "Categorizing Atonal Sonorities: Multidimensional Scaling, Tree-Fitting And Clustering Compared." *The Annual Conference of the Society for Music Perception and Cognition*, Evanston, Illinois.
- Mongeau, M., & Sankoff, D. 1990. "Comparison Of Musical Sequences." *Computers and the Humanities* 24: 161–175.
- Orpen, K. S., & Huron, D. 1992. "Measurement Of Similarity In Music: A Quantitative Approach For Non-Parametric Representations." *Computers in Music Research* 4: 1–44.
- Palmer, C. & Krumhansl, C. L. 1990. "Mental Representations For Musical Meter." *Journal of Experimental Psychology - Human Perception and Performance* 16:4: 728–41.
- Pitt, M. A. & Monahan, C. B. 1987. "The Perceived Similarity Of Auditory Polyrythms." *Perception and Psychophysics* 41.6: 534–546.
- Quinn, I. 2001. "Listening To Similarity Relations." *Perspectives of New Music* 39.2: 108–158.
- Rey, M. 2006. "The Rhythmic Component Of *Afrocubanismo* In The Art Music Of Cuba." *Black Music Research Journal* 26.2: 181–212.
- Rosch, E. 1975. "Universals And Cultural Specifics In Human Categorization." In *Cross-Cultural Perspectives on Learning*, edited by R. Breslin, S. Bochner, & W. Lonner. New York: Halsted Press.
- Saitou, N., & Nei, M. 1987. "The Neighbor-Joining Method: A New Method For Reconstructing Phylogenetic Trees." *Molecular Biology and Evolution* 4: 406–425.
- Scavone, G. P., Lakatos, S., & Harbke, C. R. 2002. "The *Sonic Mapper*: An Interactive Program For Obtaining Similarity Ratings With Auditory Stimuli." *Proceedings of the International Conference on Auditory Display*. Kyoto, Japan.
- Schneider, J. W. & Borlund, P. 2007a. "Matrix Comparison, Part 1: Motivation And Important Issues For Measuring The Resemblance Between Proximity Measures Or Ordination Results." *Journal of the American Society for Information Science and Technology* 58.11: 1586–1595.

- _____. 2007b. "Matrix Comparison, Part 2: Measuring The Resemblance Between Proximity Measures Or Ordination Results By Use Of The Mantel And Procrustes Statistic." *Journal of the American Society for Information Science and Technology*, 58.11: 1596–1609.
- Shiloah, A. 1995. *Music In The World Of Islam: A Socio-Cultural Study*. Aldershot, England: Scolar Press.
- Shmulevich, I. & Povel, D.-J. 2000. "Measures Of Temporal Pattern Complexity." *Journal of New Music Research* 29.1: 61–69.
- Smith, L. M. & Honing, H. 2006. "Evaluating And Extending Computational Models Of Rhythmic Syncopation In Music." In *Proceedings of the International Computer Music Conference*. New Orleans, LA: 688–91.
- Stevens, C. 2004. "Cross-Cultural Studies Of Musical Pitch And Time." *Acoustical Science & Technology* 25.6: 433–438.
- Stobart H. & Cross, I. 2000. "The Andean Anacrusis? Rhythmic Structure And Perception In Easter Songs Of Northern Potosí, Bolivia." *British Journal of Ethnomusicology* 9: 63–94.
- Talianová, M. 2007. "Survey Of Molecular Phylogenetics." *Plant Soil Environment* 53.9: 413–416.
- Tanguiane, A. S. 1993. *Artificial Perception And Music Recognition*. Berlin: Springer-Verlag.
- Thul, E. & Toussaint, G. T. 2008. "Rhythm Complexity Measures: A Comparison Of Mathematical Models Of Human Perception And Performance." *Proc. 9th International Conference on Music Information Retrieval*. Philadelphia, PA, September 14–18: 663–668.
- Touma, H. H. 1996. *The Music Of The Arabs*. Portland: Amadeus Press.
- Toussaint, G. T. 2011. "The Rhythm That Conquered The World: What Makes A "Good" Rhythm Good." *Percussive Notes*, in press.
- _____. 2005. "The Euclidean algorithm generates traditional musical rhythms." In *Proceedings of BRIDGES: Mathematical Connections in Art, Music, and Science*. Banff, Alberta, Canada: 47–56.

- _____. 2004. "A Comparison Of Rhythmic Similarity Measures." In *Proc. 5th International Conference on Music Information Retrieval*. Barcelona, Spain: 242–245.
- _____. 2003. "Algorithmic, Geometric, And Combinatorial Problems In Computational Music Theory." *Proceedings of X Encuentros de Geometria Computacional*. University of Sevilla, Sevilla, Spain: 101–107.
- _____. 2002. "A Mathematical Analysis Of African, Brazilian, And Cuban Clave Rhythms." *Proceedings of BRIDGES: Mathematical Connections in Art, Music and Science*. Towson University, Towson, MD: 157–168.
- _____. 1978. "The Use Of Context In Pattern Recognition." *Pattern Recognition* 10: 189–204.
- Trehub, S. E., & Unyk, A. M. 1991. "Music Prototypes In Developmental Perspective." *Psychomusicology* 10: 73–87.
- Van Den Broek, E. M. F., & Todd, P. M. 2009–10. "Evolution Of Rhythm As An Indicator Of Mate Quality." *Musicae Scientiæ*, Special Issue on Music and Evolution: 369–386.
- West, M. L. 2005. *Ancient Greek Music*. Oxford: Clarendon Press.
- Witten, I. H, Manzara, L. C., & D. Conklin, D. 1994. "Comparing Human And Computational Models Of Music Prediction." *Computer Music Journal* 18.1: 70–80.