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RESEARCH

Sesquialtera in the Colombian Bambuco: Perception and Estimation of Beat and Meter – Extended version

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Bambuco, one of the national rhythms of Colombia, is characterized by the presence of sesquialtera or the superposition of rhythmic elements from a simple and a compound meter. In this work, we analyze bambucos from three perspectives. First, we analyze the perception of beat and meter by asking 10 Colombian musicians to perform beat annotations in a dataset of bambucos. Results show great diversity in the annotations: a total of five metric alternatives (meters or combinations of meters) were found in the annotations, with each bambuco in the study being annotated in at least two different meters. To get a better understanding of which elements influence meter perception in bambucos, elements in three categories (composition, performance and audio production) were identified in our second study, and summarized for our bambuco dataset. In our third study, we use state-of-the-art computational tools for beat and meter analysis to extract beat positions. Given that the algorithms used in the analysis were designed to deal with the rhythmic regularity of a single meter, it is not surprising that tracking performance is not very high. However, a deeper analysis of the onset detection functions used for beat tracking indicates that there is enough information on the signal level to characterize the bi-metric behavior of bambuco. Our beat tracking analysis on bass tracks as well as our analysis of downbeat estimation indicate that while current computational tools cannot directly handle the bi-metric elements in bambuco, they provide valuable information that can be used for musicological analysis.

Keywords: Computational musicology; beat tracking; bambuco; meter perception

1. Introduction

The focus of this work is the bambuco, one of the national rhythms of Colombia, characterized by the superposition of musical elements in two meters, a simple meter (3/4), and a compound one (6/8). This phenomenon is called sesquialtera, and while it is not unique to the bambuco (Brandel, 2006; Locke, 1982; van der Lee, 1995),[1] this work focuses on perceptual and computational aspects particular to the Colombian bambuco. Nonetheless, the analysis procedures and the computational tools developed as part of this work are applicable for many of the Latin American, Iberian, and African genres that share these characteristics. Our goal is to better understand how meter in bambuco is perceived by cultural insiders. To do so, we conducted a study where Colombian musicians were asked to tap the beat of a selection of bambucos. Participants also answered a short questionnaire about their experience finding the beat on this set of bambucos (Section 2.2.1). Based on the findings from the perceptual study, a selection of bambucos in trio format was analyzed to identify elements that contribute to meter perception. Elements in three categories were considered: composition, performance, and audio production (Section 2.2.2). Finally, we investigate the use of state-of-the-art computational tools to automatically extract beat and meter information, and quantify tendencies of bambucos to follow a given meter (Section 2.2.3).

This work builds upon work originally published by Cano et al. (2020), and extends it by including a new dataset (Trio Dataset), and three new studies (characterization of meter perception in bambucos, instrument-specific beat tracking on separated bass tracks, and binary beat estimation from beats in 3/4). In conjunction, the contributions of this work are summarized as follows: (1) To the authors' knowledge, the meter perception study included in this work (originally published as Cano et al. 2020) is the first of its kind. (2) We propose an analysis procedure to characterize meter perception in bambucos based on a set of parameters from three categories: composition, performance, and audio production. (3) We present an objective evaluation of computational tools for rhythm analysis on bambucos, and highlight analysis

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possibilities for future research. (4) All the data including audio files, transcriptions, annotations, and code have been made publicly available to enable future research on the topic.

1.1 Sesquialtera

There are several terms in the literature that refer to rhythmic behaviours closely related to those addressed in this work: birhythmia, sesquialtera and hemiola. (van der Lee, 1995) differentiates vertical rhythmic superpositions from rhythmic alternations, with the former referred to as byrhythmia, and the latter as sesquialtera. (Ramón y Rivera, 1980) accepts birhythmia as a generic term for both phenomena, but uses sesquialtera for the vertical superposition, and hemiola only for the generation of binary accents within ternary meters. In contrast, (Varney, 1999) accepts hemiola as a generic term for both phenomena.

In this article, the term sesquialtera is used in a broad sense, including superposition and alternation of rhythmic elements in a simple meter (3/4), and a compound one (6/8).

1.2 The bambuco

There are references about the presence of bambuco in Colombia dating back to the mid 19th century; however, despite numerous discussions about its origin and musicological characteristics, there is no clarity today about the real origin of this music. Is it indigenous, African or Hispanic? Is it urban or peasant mestizo? Despite this uncertainty, the reality is that little by little bambuco became a regional and musical symbol of identity. Like all the great Latin American genres that fulfilled this purpose towards the end of the 19th century and the first half of the 20th (e.g., habanera, joropo, chacarera), to become a worthy representative of this imagined regional identity, and of those who coined it, the bambuco had to undergo a transformation process referred to as "whitening" (Wade, 1997). In music, whitening can be understood as a progressive adherence to the bourgeois ideal of chamber music. This particular process has been studied by the Colombian ethnomusicologist Santamaría Delagdo (2014:86): 'When relocating to the city since the mid-19th century, the bambuco progressively stopped being popular dance music and became music to be performed and listened to in an atmosphere of literary or concert gatherings.

Bambucos show musical elements typical of ancient Spanish-Iberian and Colombian peasant dances, typified as sesquialteras, whose main characteristic is a bi-metric behavior (3/4–6/8) within the melodic line or between the melodic line and other elements in the musical texture. This behavior can be observed in the example in **Figure 1**, where the guitar accompaniment has elements from both 6/8 and 3/4. Another characteristic element of bambucos is the presence of *caudal* syncopation in its phrases (the sixth eighth-note in a measure tied to the first eighth-note of the following measure – see **Figure 1**), which can result in the perception of a delay or a harmonic anticipation (Pardo Tovar and Pinzón Urrea, 1961). Another element of bambuco which adds to its rhythmic complexity is the characteristic phenomenal accent of the third pulse in the accompaniment patterns used in 3/4 meter.[2] This leads to the perception of a downbeat that is not the first pulse of the bar.

Of the instruments that usually participate in the performance of this type of bambuco (such as bandolas, tiples, and guitars),[3] the main role of the rhythmic accompaniment is usually delegated to the tiple. The tiple is a plucked string instrument slightly smaller than a guitar, with 12 strings grouped in four tripled courses. One of the instrument's most characteristic idiomatic playing techniques is the *aplatillado*, which is achieved by bringing the nails closer to the strings to alter their timbre. With an alternating up and down hand strumming and the *aplatillado* shown in **Figure 2**, textural elements are generated that can sometimes add complexity to the perception of rhythm. This is similar to what happens in the charango (traditional string instrument) in certain Bolivian music (Stobart and Cross, 2000).

When it comes to characteristic ways of handling rhythm, Ramón y Rivera proposed the term "free rhythm" in the context of Latin American music to refer to a certain elasticity in the unit of time, in breathing, and in the execution of rhythmic groups (as opposed to a rhythmic reference subject to a measure or bar) (Ramón y Rivera, 1980). This rhythmic freedom is observed in the set of recordings that are part of this study, and that account not only for particularities of the genre, but also for the period in time when these recordings were made, where a metronomic guide was not necessarily enforced in the recordings. Additionally, tempo and micro-timing in bambuco appear to work in general in a flexible way, with even subtle differences between the timing of the melody and that of the various elements of the accompaniment. These freedoms could be associated with the *rubato* of European music or with the floating rhythm of jazz;

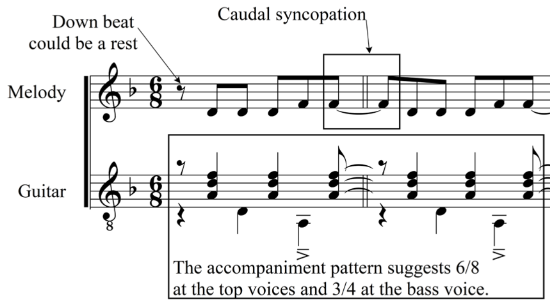

Figure 1: Bambuco example. The downbeat, caudal syncopation and a guitar accompaniment pattern are displayed.

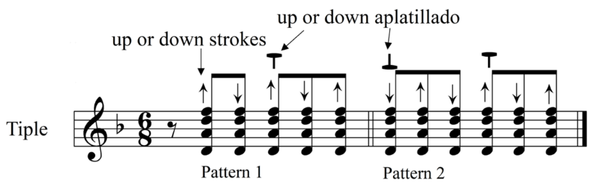

Figure 2: Example of a tiple accompaniment pattern.

however, it is a different phenomenon that contributes to the rhythmic complexity of bambuco.

1.3 Beat and meter perception

The perception of meter and beat in music is directly associated with the perception of regularity. It is precisely this regularity that allows the listener to create expectations about the musical events in a given time span (Large and Kolen, 1994). While beat perception is mostly linked to a perceived periodicity, meter is additionally linked to an accentuation pattern that differentiates beats from downbeats. Based on these ideas, Western music theory defines a hierarchical relationship between beats, measures (bars), and meter (see **Figure 3**). For certain musical traditions where a unique meter cannot always be clearly defined (such as bambuco but also Bolivian Easter songs (Stobart and Cross, 2000), the Southern Eve dance drumming of the Guinea Coast (Locke, 1982), among others), Western music theory and music notation can often fall short in providing an accurate representation of these musics. In the particular case of the Colombian bambuco, its correct music notation has been the source of many academic discussions (Santamaría Delgado, 2014). Besides the superposition of 3/4 and 6/8 meters, bambuco's characteristic accentuation pattern (due to caudal syncopation and the accentuation of the third beat in 3/4 by the accompaniment) adds another layer of complexity as the traditional definition of downbeats (**Figure 3**) does not always hold in the case of bambuco.

Of particular interest in this context is the work by Stobart and Cross (2000) on rhythm perception of Bolivian Easter songs. The study outlines how cultural outsiders perceived these songs as anacrustic 6/8 rhythms, while footfalls of locals dancing to the rhythm of the music indicated a 2/4 rhythmic perception. The authors highlight that accentuation patterns of the charango (traditional string instrument) accompaniment as well as stress patterns in the local language *Quechua* in which the songs are sung, are possible causes of the differences in perception.

1.4 Music information retrieval (MIR) approaches for rhythm analysis

The computational analysis of musical beat has been widely addressed in the literature, predominately applied to Western popular music (Böck et al., 2019) but also applied to non-Western music (Holzapfel et al., 2014; Srinivasamurthy et al. 2017). Most state-of-the-art algorithms for rhythm analysis have adopted a deep learning approach, with some methods leveraging multi-scale information to model multiple simultaneous metrical levels (Böck & Davies, 2020; Fuentes et al., 2018). While beat tracking accuracy for Western popular music can already be very high, beat tracking of non-Western music presents many more challenges, and performance highly depends on the rhythmic complexity of each music tradition. In the particular case of Latin American music, work on computational analysis of rhythm has either focused on understanding characteristic patterns in micro-timing that implant in local rhythms their unique rhythmic feel, e.g., Brazilian samba (Naveda et al., 2011), and Uruguayan candombe (Jure and Rocamora, 2016), or using rhythmic pattern templates for beat tracking, e.g., Afro-Cuban rhythms (Wright et al., 2008), and Uruguayan candombe (Nunes et al., 2015), or on genre classification (Völkel et al., 2010).

To the authors' knowledge, an in-depth computational analysis of rhythm in the Colombian bambuco has never been performed. This motivated a preliminary beat tracking evaluation, where the goal was to understand how state-of-the-art tools for beat tracking perform when meters superpose in music (see Section 2.2.3). However, we approach this evaluation not with the expectation that the algorithms will succeed in tracking rhythmic patterns they were not originally designed to track; we approach this evaluation with the goal of understanding the potential of these techniques to be expanded into meaningful musicological analysis tools for bambucos and music from the Andes in general.

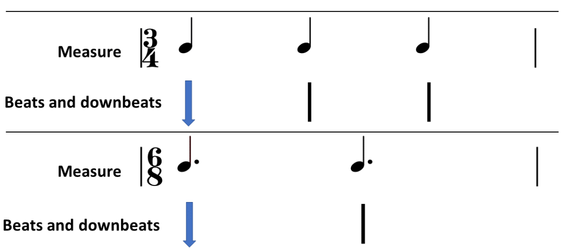

Figure 3: Hierarchical relationship between meter, measures (bars), and beats as defined in Western music theory. In both 3/4 and 6/8, the beats are indicated with vertical lines, and the downbeat with a blue arrow.

2. Bambuco Analysis

2.1 Dataset

Three sets of data were used in this work, one for each of the three studies conducted. The data used in the perceptual and computational studies is part of the ACMUS-MIR dataset,[4] a collection of annotated music from the Andes region in Colombia (Mora-Ángel et al., 2019). For the perceptual study, a selection of 10 bambucos from the **Rhythm Set** of the ACMUS-MIR dataset was used (see **Table 1** for details). The 10 bambucos in the perceptual study were chosen as they clearly exemplify the bi-metric behaviour of the bambuco genre, and include a diversity of instrumental formats (duets, trios, and wind orchestra). Additionally, the majority of the tracks were composed by Luis Uribe Bueno, a representative composer and performer of bambuco in Colombia. As additional annotations, the melody line and the bass of each bambuco in the perceptual study were transcribed. The transcriptions in MIDI format were manually aligned to the audio signal resulting in time-aligned transcriptions. The chord progression of each bambuco was also annotated. See **Figure 4** for an example.

For our second study on the characterization of meter perception in bambucos, a selection of bambucos in trio format was used. Besides setting a common ground, and simplifying the analysis (in comparison to other bambuco formats such as quartets, quintets and large ensembles),

Table 1: Perceptual study dataset. Selection of bambucos from the ACMUS-MIR dataset. Each segment corresponds to a complete musical idea or phrase taken from the original recording. Due to the superposition of 3/4 and 6/8 meters in these bambucos, tempo annotations for both meters are presented. The date column indicates the recording date. For those tracks for which only an approximate recording date is known, the term *circa* is used. For other tracks only the recording decade (e.g. 1960s) is known.

Title	Composer	Tempo 3/4 [bpm]	Tempo 6/8 [bpm]	Duration [sec]	ACMUS-MIR IDs	Date
Mimí	Carlos A. Rosso Manrique	181	121	19.4	rh_0001	circa 1980
Campanitas de mi pueblo	Luis Uribe Bueno	154	102	18.8	rh_0002	circa 1970
El espinaluno	Carlos A. Rosso Manrique	213	142	16.4	rh_0003	circa 1980
El marco de tu ventana	Luis Uribe Bueno	130	89	13.9	rh_0038	1960s
Baile de ranas	Luis Uribe Bueno	153	102	16.5	rh_0039	1960s
Bambuco instrumental	Luis Uribe Bueno	192	128	15.1	rh_0067	1960s
Bambuco instrumental	Luis Uribe Bueno	195	128	20.1	rh_0079	1960s
Bambuco instrumental	Luis Uribe Bueno	199	132	17.0	rh_0080	1960s
Bambuco instrumental	Luis Uribe Bueno	169	113	25.5	rh_0100	1960s
Bochicaniando	Luis Uribe Bueno	184	123	25.6	if_0172	circa 1998

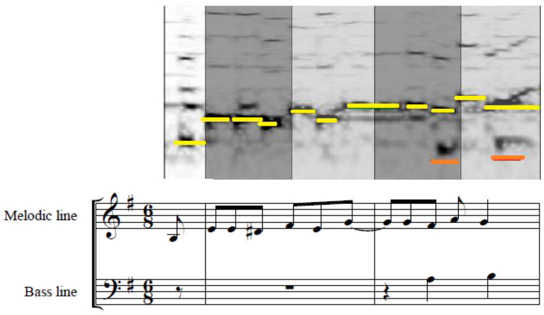

Figure 4: Example transcription of the first two measures of track rh_0067. Conventional music notation and their MIDI representation aligned to the spectrogram is displayed.

the choice of the trio format was motivated by the fact that it is a very widespread instrumental format for bambuco performance, and it offers a simplified scope of the basic components of this music. In the attempt to make a selection as representative as possible, two main bambuco types were identified: traditional bambuco and chamber bambuco. Historically, these two trends occurred sequentially, with the traditional bambuco being prominent since the beginning of the 20th century, and the chamber bambuco gaining strength later on. However, the performance and composition of both types of bambucos remains to be equally prevalent today, with composers and performers often navigating both tendencies. The traditional bambuco is characterized by featuring the bandola as the melodic instrument. The tiple and guitar predominantly assume rhythmic and harmonic roles, eventually performing melodic lines. In the case of the guitar, also eventually performing bass and melodic linking phrases (when linking phrases are performed by the bass, they are known as *pasacalles*).[5] In contrast, melodic, rhythmic and harmonic roles in chamber bambucos are equitably distributed among the three instruments, more counterpoint elements are used, and more complex musical textures are common. In total, 12 trios were chosen for this analysis (see **Table 2** for details). We refer to this dataset as the "Trio Dataset" in the remainder of this work. To make this dataset as representative as possible, the trio dataset was selected from a wide variety of sources. To facilitate future research on this data, YouTube links to each of the bambucos of the dataset are provided in the supplementary material.

For the third study on computational analysis of bambucos, all the bambucos in the **Rhythm Set** of the ACMUS-MIR dataset were used (N = 73). To evaluate beat tracking performance, the annotations from the **Rhythm Set** of the ACMUS-MIR (V1.1) dataset were used. With the awareness that in many cases a unique meter in bambucos cannot be defined, beat annotations in the dataset were performed independently for the two predominant meters, 3/4 and 6/8. For the 73 bambucos, these two sets of annotations were used, each assuming a unique underlying meter (Mora-Ángel et al., 2019).

2.2 Procedure

2.2.1 Meter perception study

A total of 10 Colombian participants took part in the perceptual study (8 male, 2 female, ages 25–50), all of whom had been exposed to bambuco music throughout their lives (cultural insiders). All the participants had musical training, and were either university music students or professional musicians: four guitarists, two bandola players, two pianists, one flutist, one singer. The majority of the participants had previous experience performing bambucos within their musical practices. All participants gave their informed consent before the start of the study. The 10 participants were asked to tap the beat to the selection of 10 bambucos using the computer keyboard in Sonic Visualiser.[6] Participants were given freedom to tap the beats that felt more natural to them. No indications about meter were given to the participants to avoid biasing

Table 2: Trio dataset. The composer, performer and duration of each of the 12 bambucos is presented. Additionally, each bambuco is categorized as either traditional or chamber bambuco. The date column indicates the recording date. For those tracks for which only an approximate recording date is known, the term *circa* is used. Refer to Table 1 in the Supplementary Material for information on availability of the Trio dataset.

Title	Composer	Performer	Type	Duration [sec]	Date
Bambuco en Bm	Adolfo Mejía	Trío Palos y Cuerdas	Chamber	210	2018
Cuadro de bambuco	Samuel Ibarra Conde	Samuel Ibarra Conde	Chamber	283	2019
El parrandista	Peregrino Galindo	Trío Morales Pino	Traditional	114	circa 1970
El republicano	Luis A. Calvo	Colectivo la puerta mágica	Traditional	189	2017
Fusagasugueño	Jaime Romero	Trío Joyel	Traditional	184	circa 1970
Garrapatica	Germán Darío Pérez	Trío Picaporte	Chamber	260	2016
Gloria Beatriz	León Cardona	Trío instrumental colombiano	Chamber	261	1985
Los doce	Álvaro Romero Sánchez	Trío Morales Pino	Traditional	143	circa 1970
Nueva Colombia	Efraín Orozco	Espíritu colombiano	Traditional	156	2000
Pa' Juancho	Germán Darío Pérez	Trío Palos y Cuerdas	Chamber	158	2001
Pilarica	Aristides Romero	Unknown	Traditional	174	circa 1970
Verónica	Gustavo Díez	Trío Agua Dulce	Chamber	154	2012

them. Two sets of annotations were recorded: (1) Beat annotations tapped while listening to the audio (without any visual information) without allowing corrections by the participants (***Audio Only***). (2) Participants were allowed to modify their initial beat annotations in Sonic Visualiser using both audio information and a visual representation of the audio waveform. Participants were allowed to make as many corrections as necessary for them to be satisfied with their annotations (***Audiovisual*** + ***corrections***). If participants were satisfied with the ***Audio Only*** annotations, the correction step was not performed.[7] As part of the perceptual study, each participant also answered a short survey consisting of three questions: (1) Which musical elements guided you when tapping the beat? (2) Was there any element that made the annotation process difficult? and (3) Do you have any observations about the tempo in these bambucos?

2.2.2 Characterization of meter perception in bambucos

Instrumental bambucos of urban origins such as the selection of trios in the Trio Dataset (see **Table 2**), usually have a tripartite form (ABC). Each of the three constituent parts has 16 bars (usually repeated for a total of 32 bars), with 2 phrases of 8 bars each. In this study, each of the three parts (ABC) of the 12 bambucos in the Trio Dataset was analyzed independently (for a total of 36 segments).

In an attempt to characterize the main elements that can contribute to the perception of meter in bambucos, the Trio Dataset was analyzed, and features from three main categories were extracted: (1) compositional elements, (2) performance elements, and (3) audio production elements. The selection of these three categories, as well as the parameters included in each one of them, was informed by the surveys conducted in the perceptual study (see Section 2.2.1), as well as by a detailed musicological analysis. A detailed diagram of the complete set of parameters used in this analysis is shown in **Figure 5**. While compositional elements include aspects determined by composers themselves (e.g., melodic patterns used, textures, role of each instrument), performance aspects refer to those that are not explicitly defined by the composer, and represent an artistic choice by the performers (i.e., in some cases, only the chords and the indication of *bambuco* are given by the composer; the choice of chord positions and accompaniment patterns is left to the performer). These include accompaniment patterns, articulations, dynamics and tempo. Audio production elements, on the other hand, can accentuate aspects of the performance that contribute to meter perception. This includes aspects such as instrument loudness balance, audio effects, and panning.

2.2.3 Computational analysis of beat and meter

The studies presented in this section investigate ways in which state-of-the-art methods for rhythm analysis can be used for musicological analysis of rhythm in bambucos.

Beat tracking in bambucos: As an initial step, we analyze how well beat tracking algorithms can estimate beat positions in bambucos. For this evaluation, two state-of-the-art beat tracking algorithms were used to predict beat positions. The first set of beat tracking estimations was obtained using the Madmom library.[8] In the context of Madmom, we specifically used a multi-model approach that uses recurrent neural networks to track beats (Böck et al., 2014). The second algorithm used for beat estimation was the Multi-Feature Beat tracker (MultiBT) (Zapata et al., 2014) implemented in Essentia (Bogdanov et al., 2013).[9] This algorithm selects between beat estimations from a single beat tracking model with diverse input features. Given the bi-metric characteristics of bambucos, independent ground-truth annotations assuming either a 3/4 or 6/8 meter were used (see Section 2.1). For evaluation we use a subset of metrics from the standard evaluation methods described by Davies et al. (2009).

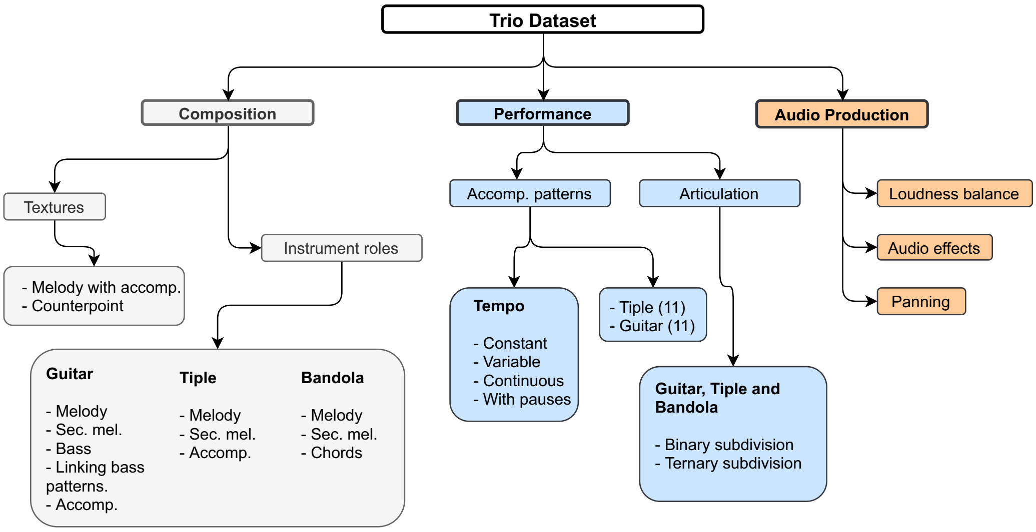

Figure 5: Characterization of factors affecting meter perception in bambucos on the Trio Dataset. Elements in three categories (composition, performance and audio production) were investigated.

Among all the proposed metrics, we chose the F-measure (F1), along with the continuity measures originally defined by Klapuri et al. (2006); Hainsworth (2004). This allows us to analyze both the ambiguity associated with the annotated metrical level, and the continuity in the beat estimates. The F-measure (F1) is a generic score often used in information retrieval. For beat tracking, it is common practice to use a ±70 ms tolerance window around annotations to consider a beat prediction as correct. The F-measure takes into consideration the number of correct beats, the number of false positives (extra detections), and the number of false negatives (missed detections). Under this metric, completely unrelated beat sequences typically score around 25% by virtue of beats arbitrarily falling within the range of tolerance windows. Continuity-based evaluation considers regions of continuously correct beat estimates relative to the length of the audio signal. This is the case of the Correct Metrical Level Continuity (**CMLc**) measure, which computes the ratio of the longest continuously correct segment to the length of the input. By definition, continuity is defined using a tolerance window of ±17% of the current inter-annotation-interval, considering an estimation as correct if it falls within this window. To include the effect of beats in other segments, a less strict measure considers the total number of correct beats at the correct metrical level without the continuity criteria (**CMLt**) (Davies et al., 2009). Lastly, to account for ambiguity in the metrical level, two additional metrics consider beats occurring at double or half the annotated metrical level, with the same continuity criteria as before. These conditions are considered *allowed* metrical levels resulting in the Allowed Metrical Level Continuity (**AMLc**) metric, and its less strict alternative (**AMLt**) (Davies et al., 2009).[10]

Instrument-specific beat tracking on separated bass tracks: As a follow-up study to the beat tracking evaluation, we conducted a preliminary study of instrument-specific beat tracking. The motivation behind this study was two-fold: (1) There is a tendency for certain instruments to assume specific roles or to perform characteristic rhythmic patterns in bambucos, especially in traditional bambucos as described in Section 2.1. By conducting instrument-specific beat analysis, beat tracking algorithms might potentially be able to estimate beat positions more accurately. (2) For musicological investigations, the understanding of which instrument or instruments are driving the rhythmic tendencies towards a specific meter is of great value. However, in order to effectively perform instrument-specific beat tracking, independent audio tracks for each instrument are necessary. This can be achieved if multi-track recordings are available (which is almost never the case), or by performing sound source separation on the original mixture. Even though great progress has been made in sound separation technologies in the last years (see Cano et al., 2019, for an overview), high quality separation is very challenging, and results may vary a lot depending on the original track. Additionally, with the widespread use of data-driven separation algorithms, results may also vary depending on how much the audio material used for training matches that of the track to be separated. To minimize the difficulty of the separation task, and to maximize the potential for beat tracking on the separated instrument, we focus only on separating the bass in our bambuco dataset. While bass separation is by no means a solved task, the fact that the instrument appears in a well defined frequency region, where the amount of overlap with other instruments is not too high, allows for good separation results. To separate the bass in our bambuco dataset, we use the 4-stem functionality of the Spleeter library (Hennequin et al., 2020), which separates a given track into vocals, drums, bass and other instruments. Only the tracks in the bambuco dataset where a bass instrument is playing are used (36 tracks from the 73 bambucos).[11] To extract beat positions, we use the same beat tracking algorithms and metrics as the ones described in the *Beat tracking in bambucos* study.

Binary beat estimation from beats in 3/4 obtained by beat tracking algorithms: As a final investigation, we evaluate the feasibility of estimating beat positions in 6/8 from automatic estimations of beats in 3/4. The motivation behind this study is as follows: (1) Algorithms for beat tracking available today are usually better suited to track 3/4 than 6/8 meter (see Section 3). This is possibly a consequence of 3/4 meter being more commonly used for algorithm development. While current techniques for beat tracking should be suitable for tracking beats in 6/8, data-driven algorithm development (such as deep learning techniques) is held back by the lack of suitable annotated datasets in 6/8 meter. (2) The mathematical relationship between 6/8 and 3/4, displayed in **Figure 3**, can easily be used in algorithmic form to extract beat information. If accurate beat estimations in 6/8 can be obtained from 3/4 beats, analysis of bi-metric aspects in bambuco will not entirely rely on the availability of a beat tracker that can reliably estimate beats in 6/8.

To perform this analysis, we use a method that jointly estimates beats and downbeats, available in the Madmom library originally proposed by Böck et al. (2016). The method is based on a recurrent neural network to track beats, and a dynamic Bayesian network to model bars. We refer to this algorithm as MadmomDBN. The algorithm takes an optional input parameter that defines the number of beats to be extracted per bar. By defining the number of beats per bar to be equal to three, the beat estimations can be fixed to a 3/4 bar.[12] Besides estimating a given number of beats per bar, the algorithm also returns an estimation of the downbeat or beat ordering in the bar (i.e., 1,2,3). The correct estimation of the downbeat is necessary in order to be able to calculate the beat position in 6/8 from estimations in 3/4. The first beat of a bar coincides in 3/4 and 6/8. The position of the second beat in a 6/8 bar can be estimated based on the positions of the second and third beats in a 3/4 bar. With t_{i1}, t_{i2}, t_{i3} the estimated positions in time of beats one, two and three of bar i in 3/4, respectively, the position of the first beat of bar i in 6/8 is given by $\hat{t}_{i1} = t_{i1}$. Similarly, the position of the second beat of bar i in 6/8 is given by $\hat{t}_{i2} = (t_{i2} + t_{i3})/2$.

3. Results and Discussion

3.1 Meter perception in bambucos

The beat annotations obtained from the 10 participants (Section 2.2.3) were analyzed to determine the underlying meter(s) perceived by each participant in each track. Even though participants were given freedom to tap beats that felt natural to them, each annotation can be directly mapped back to a given meter. This can be understood by looking at **Figure 3**: If a participant taps three beats per bar, these annotations are mapped back to a 3/4 meter. Conversely, if a participant taps two beats per bar, the underlying meter is assumed to be 6/8. In some cases, participants tapped different meters in different bars of the same track, tapping one bar in 3/4 and the following in 6/8, for example. In those cases, we map the annotation as a combination of 3/4 and 6/8. In total, five metric alternatives (meters or combinations of meters) were observed: 3/4 meter, 6/8 meter, a combination of 3/4 and 6/8, "one count" annotations where participants annotated the first beat of the measure (blue arrows in **Figure 3** which correspond to the downbeats in Western traditions but are not necessarily the accentuated beats in bambucos), and a combination between 6/8 and "one count" annotations. These five alternatives are denoted by "3/4", "6/8", "3/4–6/8", "1", and "1–6/8", respectively.

Figure 6 shows a summary of the annotations aggregated for all tracks and participants from the revised annotations (***Audiovisual*** + ***corrections***). It can be seen that for each of the 10 bambucos, at least two different meters or meter combinations were perceived. The 6/8 meter proved to be predominant in the annotations. It should be noted, that as of today, bambuco is written as a convention in 6/8, and hence, there might be a tendency in trained musicians to default to 6/8. It can be seen that five of the 10 participants annotated all the tracks in 6/8 meter. Two of the participants perceived "6/8" and the "3/4–6/8" combination, and two participants perceived a "3/4" meter. Of particular interest is participant eight (p8), who predominantly annotated the bambucos in "1". This is interesting because this is the only type of annotation that avoids resolving the ambiguity in meter perception as the first beat coincides in "6/8" and "3/4" (see **Figure 3**). The practice of counting music in "1" is often related to music in fast *tempi*, where counting all beats in a bar might no longer be comfortable. However, this is not the case here. **Table 1** shows the *tempo* distribution of our bambuco dataset. The fastest bambuco in our dataset is rh_0003, which is mostly annotated in "6/8", with p8 choosing the "1–6/8" alternative in this case. Participant p8 annotated seven bambucos in "1", all of them with slower tempi than rh_0003.

From the 100 annotation instances in this study (10 tracks × 10 participants), a total of 10 instances showed different meters when comparing the (***Audio Only***) annotations with the revised annotations (***Audiovisual*** + ***corrections***). Three instances were modified from "3/4–6/8" to "6/8", two instances were modified from "6/8" to "3/4–6/8", two from "3/4" to "6/8", two from "6/8" to "1", and one from "6/8" to "3/4". These results further indicate the dynamic nature of meter perception in bambucos.

In terms of the survey conducted as part of this study, responses show a tendency to use harmony (where in the

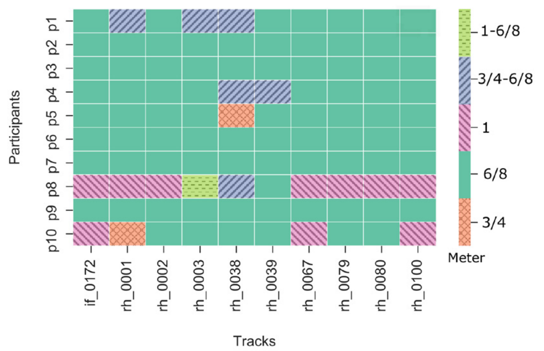

Figure 6: Perceived meter aggregated for the 10 tracks and 10 participants in the study. Five distinct meters or meter combinations were observed.

bar the harmonic changes occur), as well as a tendency to rely on parts of the musical discourse that are close to their personal experience (guitar or tiple players, for example, focused more on the accompaniment patterns of the guitar and the tiple). According to the participants, the main difficulties of the analysis process in addition to flexibility in *tempo* were the conception of the phrasing present in the sample, the *ritardandos* and *accelerandos* performed between different parts of the musical texture (melody and accompaniment), and the quality of the recordings. Finally, the participants observed that the *tempo* in these recordings behaves in an organic way, far from the metric rigor typical of the practices of current academic musicians. This organic handling of *tempo* is no longer frequent in the way the bambuco is performed today. This transformation could be related to the changes in recording techniques, and the prescriptive function of the academic institutions and the musical events in which this type of music circulates. Responses from this survey served as the foundation for the *Characterization of meter perception in bambucos* (see Section 2.2.2). The three main categories (composition, performance and audio production), as well as some of the elements considered in each category, were revealed in the surveys.

3.2 Characterization of meter perception in bambucos

In this section, we summarize the main findings of the characterization study, highlighting the main observations for each of the three categories considered: composition, performance, and production. Additionally, the prevalence of each of the elements analyzed in the study is summarized in **Figures 8, 9**, and **10**. In each figure, the number of bambucos in which a particular element was observed is shown as a percentage (a total of 36 bambuco segments were analyzed – 12 trios × 3 parts (ABC)). The entire table with a detailed summary is presented in the supplementary material.

Compositional elements: From the perspective of the composition, diverse ways of working with the ensemble are observed, with melodic and accompaniment patterns (some with binary prolation and some with ternary), and instrumentation (binary and ternary patterns can appear in different instruments) being possible factors that influence meter perception. When the texture of the ensemble is configured as "melody with accompaniment" (72.2% of the samples – see **Figure 8**), meter (either 3/4 or 6/8) can appear to be more clearly defined, given that the roles of the guitar, tiple and bandola are also well established. The melodic-rhythmic role of the bandola, and its prevalence in the higher frequencies of the ensemble can often be a defining factor when it comes to binary or ternary perception. When the tiple acts as an accompaniment instrument, with frequent use of *apagados* (i.e., right hand muted strokes) and *aplatillados*, its presence in the mid-frequencies of the ensemble can often influence binary perception. The guitar, being prominent in the mid-low frequencies of the ensemble, can often play an important role in the definition of the 3/4 meter. There is a duality, for example, when binary patterns in the bandola come together with the ternary patterns in the guitar bass lines. The tiple, in this case, has the role to bring balance and cohesion to the ensemble. There is also a duality when melodic lines with eighth notes articulated in groups of two (which would be expected to give a ternary perception), provide instead a clear definition of binary meter due to the melodic contour and its agogic accents. As described in **Figure 7**, we observed a great diversity of accompaniment patterns (Refer to the Table in the supplementary material for the complete list of patterns). The tiple can also take a percussive role in the trio, bringing cohesion to all harmonic and rhythmic elements in the piece. It is the tiple accompaniment patterns that provide coherence to the versatility typical of the bambuco genre.

When the texture of the ensemble is contrapuntal (33.3% of the samples – see **Figure 8**), meter perception depends on the balance between the elements in the composition. Contrapuntal elements usually appear between the bandola and the tiple, two instruments with steel strings and bright timbres, that can achieve a balance, and clearly define articulation, dynamics, and rhythmic patterns. While the role of the guitar is slowly becoming more prominent over time, it has generally taken a more discreet role, often providing a stable rhythmic foundation, with relatively constant patterns, and chords with accentuated bass notes.

Performance elements: There is a wide variety of performance elements that can influence meter perception, including phrasing, articulation, accentuation, and performance techniques (e.g., aplatillado). If within a given bar, for example, the articulation of the melodic line creates two groups of three notes, binary meter perception will likely be prevalent. If on the other hand, the articulation creates three groups of two notes, perception will gravitate around a 3/4 meter (see **Figure 9** for the prevalence of binary and ternary subdivisions for each instrument). Similarly, if the tiple accentuates the first chord in each group of three notes, meter perception is likely to be predominantly binary (6/8). In terms of the melodic line, accents created by the melodic contour, types of attacks used, and stroke directions are elements that can also contribute to meter perception. For the accompanying instruments, the performer's selection of melodic, rhythmic and harmonic accompanying patterns are possibly the most prominent elements. *Tempo* variations in the performance add an extra layer of complexity to meter perception, the use of *rubato, accelerando* and *ritardando*, the use of *fermatas* (which are very characteristic in bambucos from the early 20th century but not so common today), and the lengthening and accentuation of the third beat in 3/4 (as observed in caudal syncopation) all can have an important influence on meter perception.

Production elements: In general, there is a tendency to an austere simplicity in the production that enhances the natural timbre of the instruments. The balance of the mix tends to enhance the melody, especially in the traditional bambucos, and to be more equitable between the instruments in chamber bambucos. Equalization can also emphasize aspects of the mix that could give

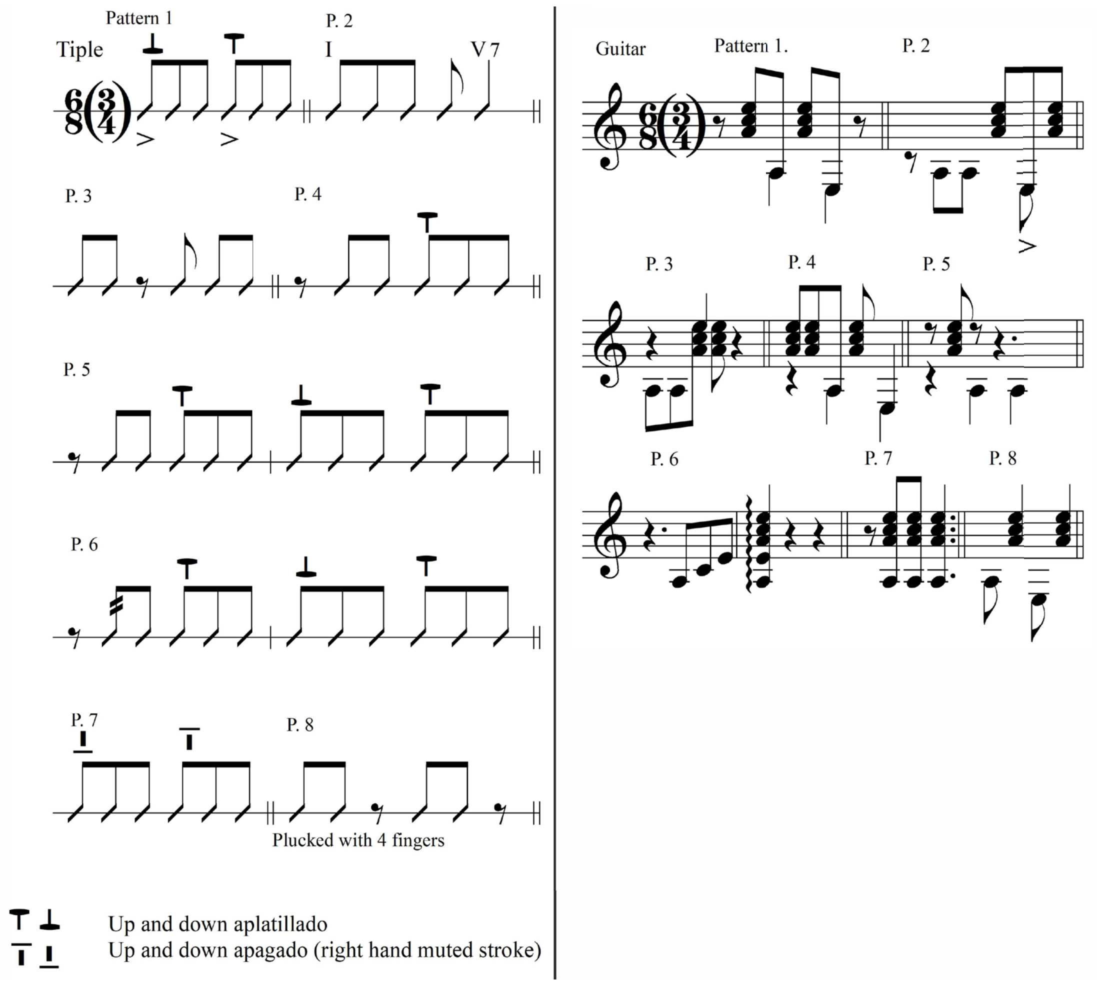

Figure 7: Selection of accompaniment patterns (P) identified in the Trio Dataset for the tiple (left) and the guitar (right). Refer to the Table 2 in the Supplementary Material for the complete list of patterns.

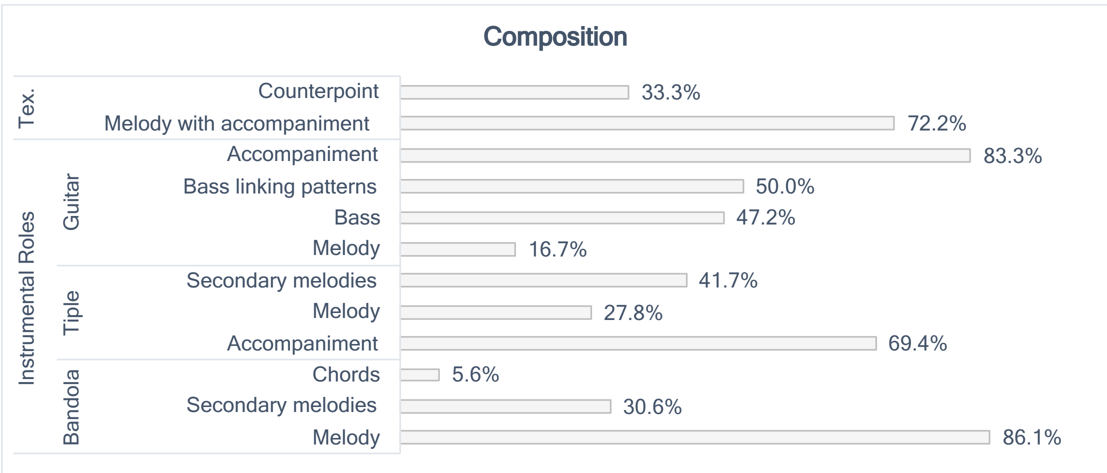

Figure 8: Percentage of bambucos using each compositional element analyzed in the Trio Dataset. In the figure, "Tex." stands for textures. Given that some elements in the same category (e.g., counterpoint and melody with accompaniment) can appear in the same bambuco segment, the percentages per category do not necessarily add up to 100%.

different meter perceptions. If the mid-frequencies are boosted, the binary perception could be enhanced by the tiple accompaniment; in tracks where the low-frequencies are boosted, there can be a predominance of 3/4 perception if there is a rhythmic guitar. Perception will depend on the role assumed by each instrument. In terms of effects, the more traditional recordings use reverb in the mix, while more contemporary bambucos tend to apply delay effects, especially in the bandola. While the impact on rhythmic perception of these

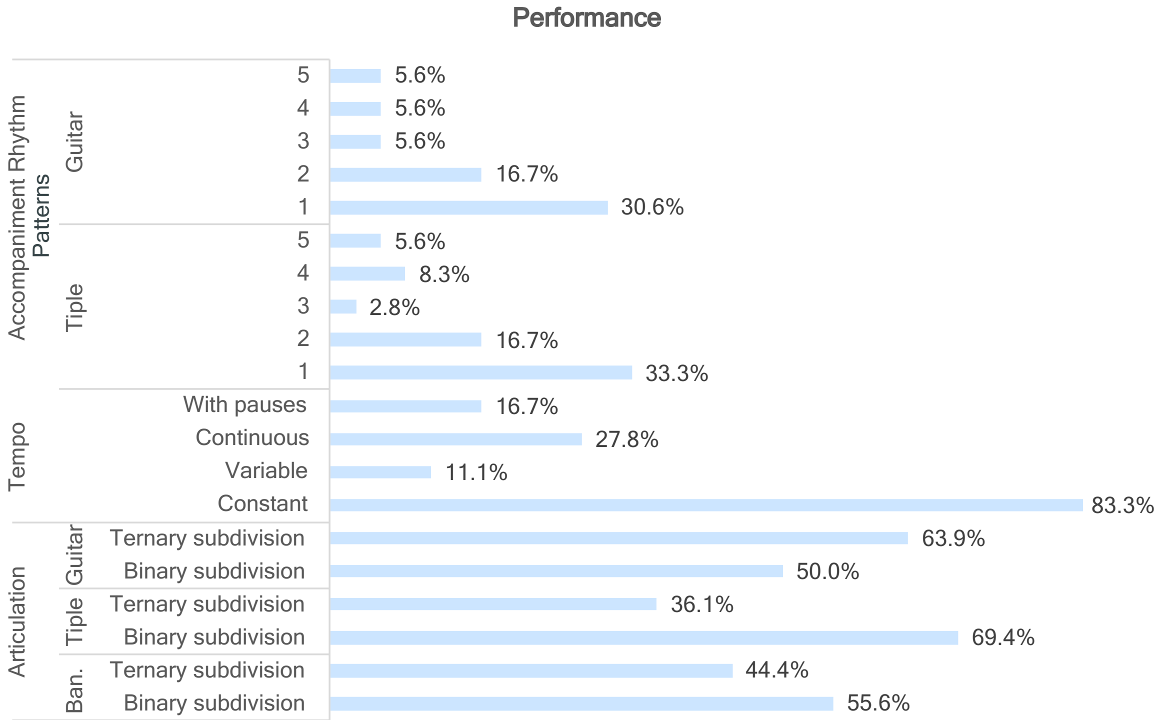

Figure 9: Percentage of bambucos using each performance element analyzed in the Trio Dataset. In the figure, "Ban." stands for bandola. Given that some elements in the same category (e.g., ternary subdivision and binary subdivision) can appear in the same bambuco segment, the percentages per category do not necessarily add up to 100%.

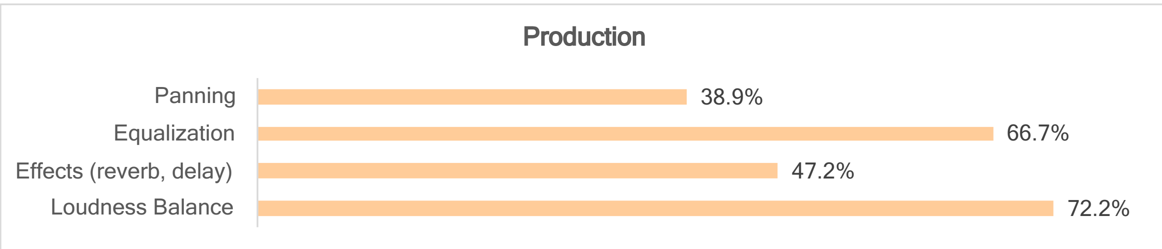

Figure 10: Percentage of bambucos using each production element analyzed in the Trio Dataset.

effects might be subtle, they in fact contribute to a sense of rhythmic complexity. In terms of panning, traditional recordings, whether stereo or mono, try to maintain mono compatibility, making the perceptual separation of instruments more difficult. In some recordings, the stereo panning is widened, allowing for better perceptual separation between instruments.

3.3 Computational analysis of beat and meter

Beat tracking in bambucos: Two independent evaluations are presented in **Table 3** for each of the two beat tracking algorithms. The top row presents results obtained when ground-truth annotations assuming an underlying 3/4 meter are used. The bottom row presents results with ground-truth annotations in 6/8. Metrics that enforce continuity (CMLc and AMLc) are in all cases lower than their less strict counterparts (CMLt and AMLt). Additionally, metrics that allow estimation in different metrical levels (AMLc and AMLt) are also higher than the ones that enforce a correct one (CMLc and CMLt). These results indicate that on certain occasions, the

Table 3: Beat tracking evaluation metrics obtained with Madmom and MultiBT. Results are presented using two sets of ground-truths: 3/4 and 6/8. All metrics presented have a maximum score of 100%.

	Algorithm	F1	AMLc	AMLt	CMLc	CMLt
3/4	Madmom	75.06	60.76	77.05	50.89	64.27
	MultiBT	42.79	23.32	25.24	12.43	14.33
6/8	Madmom	41.13	9.23	10.71	5.64	5.72
	MultiBT	45.15	42.87	51.76	32.38	35.54

algorithms are tracking a higher metrical level, detecting the first beat of the bar as the underlying beat (similar to the "1" annotations in the perceptual study). As previously mentioned, this is the only beat where 6/8 and 3/4 coincide. When focusing on those metrics that only consider the correct estimations, and not the false positives and false negatives, namely AMLc, AMLt, CMLc and CMLt, Madmom appears to be consistently better at estimating beats in 3/4 than in 6/8. In contrast, MultiBT shows better performance for 6/8 for the same set of metrics.

Evaluation results confirmed our initial hypothesis that the bi-metric nature of our dataset is greatly responsible for the relatively poor performance of the beat tracking algorithms. To better understand the potential of beat tracking algorithms when working with our dataset, we analyzed the onset detection functions, as obtained by the spectral flux or the superflux algorithms, of the 10 bambucos in the perceptual study. Onset detection functions are intermediate signal representations often used in beat tracking algorithms that highlight time instants of the signal where onsets might be present. A peak in the onset detection function suggests that there is a high probability of an onset occurring in that position. With this analysis, the goal was to understand whether valuable information could be found on the signal level to characterize the bi-metric behaviour of bambucos. **Figure 11** shows a segment of the onset detection function obtained with superflux on track rh_0002. The ground-truth beat annotations in 6/8 and in 3/4 are also displayed for reference. It should be noted that the annotations in 3/4 and 6/8 were extracted independently by different annotators, and hence the downbeats (which in theory should coincide) do not exactly overlap in all cases. Strong peaks in the onset detection function can be observed in most beat positions from the ground-truth annotations (dotted orange line (3/4) and solid green line (6/8) lines). This suggests that regardless of the rhythmic complexity, there is information that can be exploited to characterize the metric behavior of bambucos. For reference, the beat estimations obtained by Madmom and MultiBT (dashed lines) are also shown in the figure. The Difficulty of the task is further confirmed by the fact that, not surprisingly, the estimations obtained by Madmom and MuiltiBT also tend to overlap with peaks in the onset detection function. It is important to note that the analysis of onset detection functions is only valid for those beats that coincide with attacks, which is not the case for rests and syncopated rhythms. However, this preliminary analysis indicates that valuable information for bi-metric music analysis can indeed be extracted directly from the signal.

Instrument-specific beat tracking on separated bass tracks: A total of 36 separated bass tracks obtained with the Spleeter library were used for extracting beat positions with the Madmom and MultiBT algorithms. Using the F1 evaluation metric on the Madmom detections, we observed that for some bambucos, the algorithms performed very poorly. Informal listening tests confirmed that poor beat tracking results occurred on tracks whose bass separation quality was also very poor. From the 36 separated bass tracks, seven bambucos with an F1 score below 40% were identified as tracks with no relevant information after the source separation process, and were discarded for this analysis.[13] Beat tracking results are displayed in **Table 4** using independent ground-truths in 3/4 and 6/8. Results obtained from the bass separated tracks show a strong prevalence of the 3/4 meter compared to 6/8, with metrics obtained with both algorithms consistently higher for the simple meter. A comparison of the results obtained for the original mix (marked with -M in **Table 4**), and those obtained for the bass shows that the metrics are slightly lower for the separated bass tracks than for the mix in both meters. These results suggest that the algorithms exploit information from other instruments besides the

Table 4: Instrument-specific beat tracking on separated bass tracks, and original mix (denoted -M in italic) for comparison: evaluation metrics obtained with Madmom and MultiBT. Results are presented using 3/4 and 6/8 as ground-truth. All metrics presented have a maximum score of 100%.

	Algorithm	F1	AMLc	AMLt	CMLc	CMLt
3/4	Madmom	81.07	63.58	73.51	57.34	67.62
	Madmom-M	*89.56*	*75.41*	*85.34*	*70.55*	*80.49*
	MultiBT	60.65	44.27	53.52	32.59	40.53
	MultiBT-M	*47.00*	*24.72*	*26.93*	*18.60*	*20.65*
6/8	Madmom	39.88	12.08	13.40	6.54	7.47
	Madmom-M	*44.10*	*10.74*	*10.79*	*9.30*	*9.30*
	MultiBT	32.07	19.60	25.16	9.77	11.45
	MultiBT-M	*46.58*	*45.82*	*52.00*	*34.26*	*36.12*

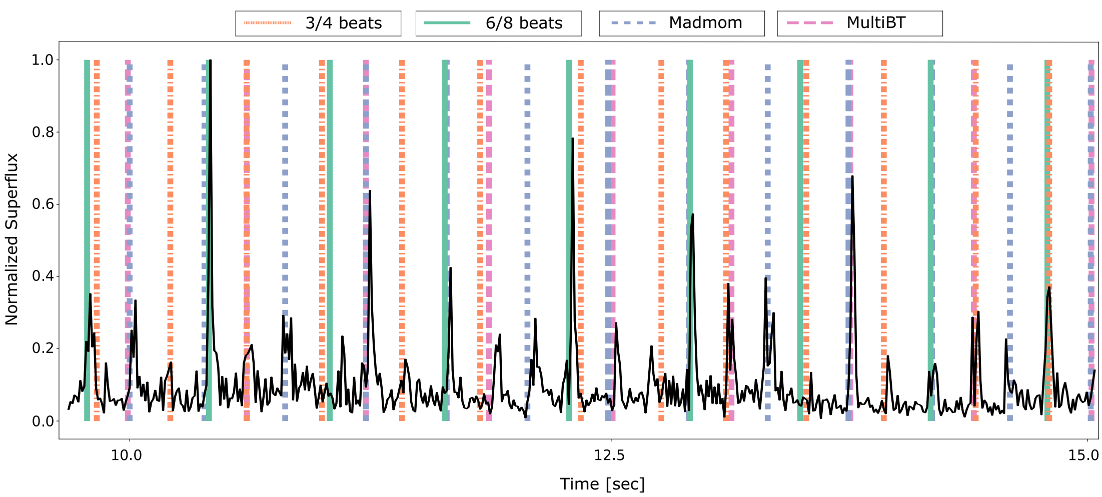

Figure 11: Onset detection function extracted using superflux on a segment of track rh_0002. Ground-truth annotations in 3/4 and 6/8 are shown, as well as beat estimations obtained with Madmom and MultiBT.

bass to extract beat positions in both meters. Ultimately, our goal is to be able to model instrument-specific meter tendencies that often relate to the specific role each instrument takes in the musical texture. While these results allow us to understand that other instruments besides the bass contribute beat information in both meters, it is not possible to disentangle these results from the fact that both beat trackers perform better in 3/4 than in 6/8. We hypothesize that the bass very frequently assumes rhythmic patterns that emphasize the 3/4 meter; however, more in depth studies are required to accurately characterize the phenomenon.

Binary beat estimation from beats in 3/4 obtained by beat tracking algorithms: The 73 bambucos in our dataset were processed using the MadmomDBN algorithm with the number of beats per bar set to three to force the algorithm to track beats in 3/4. For a successful estimation of beats in 6/8, two requirements must be met: (1) Beat positions in 3/4 need to be accurately estimated, (2) The downbeat or beat ordering in the bar needs to be known or accurately estimated. From the 73 bambucos, only 42 bambucos satisfied the first condition. The selection of 42 bambucos was performed first by manual inspection, where out-of-phase estimations (beat positions extracted in the upbeat positions) were discarded. The F1 score of the remaining bambucos was calculated and only those with a score above 60% were used in this study (N = 42). To verify whether the second condition was met for any of the selected bambucos, the beat ordering returned by MadmomDBN was manually inspected. From the 42 bambucos, the beat ordering (and hence, the downbeat estimation) of 10 bambucos (23%) was correctly estimated as [1-2-3]. From the remaining tracks, 30 bambucos (71.4%) obtained beat orderings corresponding to [3-1-2], and 2 bambucos (4.7%) obtained beat orderings of [2-3-1]. These results show from a computational perspective that the first beat in bambucos is, in most case, not the most accentuated one and can often be a rest. This explains the strong prevalence of [3-1-2] orderings in the extracted beats, essentially shifting the (estimated) downbeat to the second beat in the 3/4 bar. In the particular case of bambuco analysis, an alternative computational solution to resolve the ambiguity in downbeat estimation could be chord change detection. While the first beat of the bar is not necessarily accentuated in bambucos, chord changes normally coincide with the bar line. This is however left for future investigation.

In order to maximize the number of tracks used in the final estimation, we included a parameter in our extraction algorithm that allowed musicologists to provide the right permutation for the beat positions. By simply typing 1 for [1-2-3], 2 for [2-3-1] or 3 for [3-1-2], the right ordering of the beats in the bar could be easily corrected. This allowed us to use the 42 bambucos for the binary beat estimation. Results of the estimation of beat positions in 6/8 are displayed in **Table 5**. It can be seen that beat tracking metrics are consistently high, demonstrating that if a good estimation in 3/4 can be obtained (which is the case for the Madmom algorithm – see **Table 3**), beat positions in 6/8 can be very accurately estimated using this simple approach. This opens the possibilities of analysis for musics

Table 5: Estimation of beat positions in 6/8 from estimations in 3/4: evaluation metrics obtained with MadmomDBN for estimated 6/8 beats. All metrics presented have a maximum score of 100%.

	Algorithm	F1	AMLc	AMLt	CMLc	CMLt
$\frac{6}{8}$	MadmomDBN	92.13	88.47	91.59	88.47	91.59

that exhibit bi-metric components since a computational method that estimates beats in both meters is not strictly necessary (as was originally hypothesized). While this approach still requires the correct estimation of the downbeat, our results show that information from the automatic extraction can be leveraged to obtain accurate results. Additionally, by including other sources of information such as chord changes, downbeat estimation results could potentially be improved.

4. Conclusions

This work presented an analysis of beat and meter in the Colombian bambuco, a rhythm characterized by the presence of musical elements in two different meters. Our perceptual study confirmed that even for human listeners, there is not a unique understanding of the rhythmic structures of the genre. Even though current conventions assume a 6/8 meter when writing bambucos, our perceptual study confirmed that reality is much more complex than that. A total of five metric alternatives were found in the annotations produced by the participants in the study. Additionally, our characterization of meter perception in bambuco, which included elements in three categories (composition, performance and audio production), further evidenced the complexity of the interactions that contribute to meter perception.

Not surprisingly, results from the computational analysis confirmed that beat tracking models developed to deal with the regularity of a unique meter, do not fully characterize the complex rhythmic interactions in bambucos. However, our beat tracking analysis as well as the analysis of bass tracks, and the estimation of beats in 6/8 from 3/4 beats showed that computational tools can facilitate an in-depth analysis of meter and rhythm in bambucos. As a way of summarizing the results from the computational analysis, **Figure 12** shows bambuco rh_0179 with ground-truth beat annotations. The onset detection function, the beat and downbeat estimations (activations) obtained with MadmomDBN are also displayed as heat maps. Understanding the way in which onsets translate into beats and downbeats, and how that compares to human annotations is the heart of this investigation.

It is clear from the findings in this study that the development of tools for rhythm analysis of bambucos –or of any other music tradition that shares similar rhythmic properties– cannot be approached from a binary decision (right/wrong) perspective. This calls for rhythm analysis tools with an exploratory nature, where the existence of several truths is permitted, and the choice of the most relevant one is both task- and context-dependent. Our hope is that this study as well as the data and annotations collected in it, will serve as a preliminary step in the

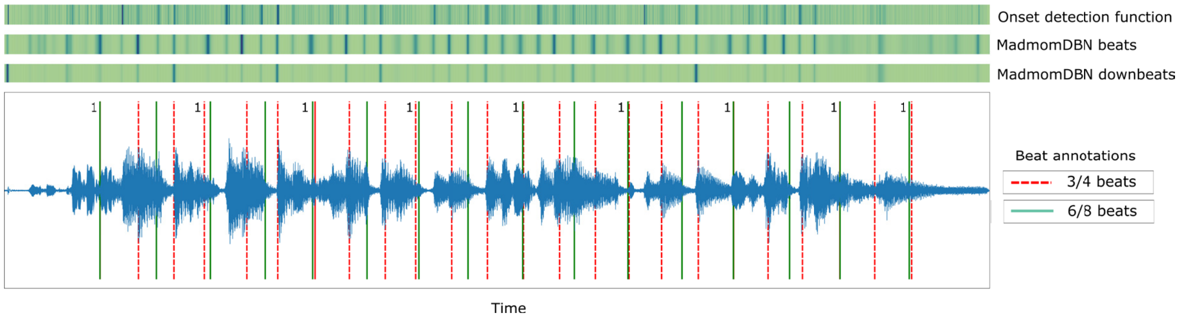

Figure 12: Computational rhythm analysis of bambuco rh_0179. Ground-truth annotations in 3/4 and 6/8 are displayed on the waveform. The downbeats are indicated with a "1". Additionally, the aligned onset detection function (superflux), and the MadmomDBN beat and downbeat activations are displayed as heat maps. It can be seen that for this example the downbeat activation is always higher on beat 3 than on beat 1 of a 3/4 meter (red lines).

development of computational tools for musicological analysis of bambucos and Andean music.

Notes

1 Sesquilatera is a phenomenon profusely present in music styles from sub-Saharan Africa, the Iberian Peninsula, and Latin America.

2 We use the nomenclature proposed by Lerdahl and Jackendoff (1996) who distinguish three types of accents: phenomenal accents, structural accents, and metrical accents.

3 Instrument descriptions available: https://acmus-mir.github.io/andes-music/.

4 ACMUS-MIR Dataset (V1.1): https://zenodo.org/record/3965447.

5 This role of the guitar is know as *marcante* guitar (meaning guitar "that marks" in Spanish). This role is often performed with a slightly larger guitar using its own performance techniques.

6 Sonic Visualiser is available at: https://www.sonicvisualiser.org/.

7 Audio and annotations for the perceptual study: https://zenodo.org/record/3829091#.Xxd3IZ7TuUk.

8 Link to Madmom library: https://madmom.readthedocs.io/en/latest/.

9 Link to Essentia: https://essentia.upf.edu/.

10 Code available: https://github.com/ACMUS-MIR/publications-resources/tree/master/TISMIR2021.

11 The guitar often performs bass lines as part of the accompaniment in bambucos. However, preliminary test showed that bass separation when only the guitar is playing the bass line was very poor. For this reason only tracks where a bass is present are used in this study.

12 It must be noted that defining the number of beats to be estimated by MadmomDBN to be six, will result in estimations of a 6/4 bar and not of a 6/8 one. For this reason, beat estimations in 6/8 cannot be explicitly made.

13 The F1 measure for beat tracking is used here as a metric for discarding poor separation results. We chose this approach since metrics to evaluate separation quality (e.g., SI-SDR, SDR, SIR) require the original bass recordings as reference. Since the original bass tracks are not available, we use the F1 as proxy.

Additional Files

The additional files for this article can be found as follows:

- **Supplementary Material.** Table 1. DOI: https://doi.org/10.5334/tismir.118.s1
- **Supplementary Material.** Table 2. DOI: https://doi.org/10.5334/tismir.118.s2

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Competing Interests

The authors have no competing interests to declare.

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