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Cultural macroevolution of musical instruments in South America

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Musical instruments provide material evidence to study the diversity and technical innovation of music in space and time. We employed a cultural evolutionary perspective to analyse organological data and their relation to language groups and population history in South America, a unique and complex geographic area for human evolution. The ethnological and archaeological native musical instrument record, documented in three newly assembled continental databases, reveals exceptionally high diversity of wind instruments. We explored similarities in the collection of instruments for each population, considering geographic patterns and focusing on groupings associated with language families. A network analysis of panpipe organological features illustrates four regional/cultural clusters: two in the Tropical Forest and two in the Andes. Twenty-five percent of the instruments in the standard organological classification are present in the archaeological, but not in the ethnographic record, suggesting extinction events. Most recent extinctions can be traced back to European contact, causing a reduction in indigenous cultural diversity.

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Introduction

Music production is a universal feature of human cultures (Mehr et al., 2019). The cultural evolution of music is a growing new field ripe to develop, considering the success of the comparative method in other disciplines, from evolutionary and cultural anthropology to linguistics (Nettl, 2010). Non-material aspects of music like scales, tunes and melodies have been subject to cultural evolution studies in recent years (Savage, 2019). Songs have for instance been statistically examined with aspects of pitch such as harmonic content, melody and tonal arrangements as well as timbre, with novel analytical tools that permit quantification and comparisons in space and time (Leroi and Swire, 2006; MacCallum et al., 2012; Serrà et al., 2012; Savage and Brown, 2013; Mauch et al., 2015; Savage and Atkinson, 2015; Mehr et al., 2019; McBride and Tlustý, 2020).

The diversity of musical instruments is a testament to human creativity and innovation (Montagu, 2007). Their history can be traced back to the archaeological record of at least 35,000 years ago (Conard et al., 2009; Morley, 2013). Hypotheses based on the diversity and distribution of organological traits can potentially be consolidated or refuted with empirical data (Aguirre-Fernández et al., 2020). Musical instruments can be also analysed to reconstruct the musical past erased by historical processes of colonization. For example, previous organological studies in an archaeological context focused on experimental sound analyses and revealed the absence of fixed scales in the central and southern Andes (Gruszczyńska-Ziółkowska, 2002), as well as absence of melodies, reflecting musical systems dealing only with timbre (Pérez de Arce, 2000).

We can use organological data to study human cultural innovation and its transfer among human groups in space and time. Several methods are available to examine if and how the network of instrument relationships relates to the biological and cultural diversity of the people who play them. A fruitful approach is the mapping of characters in phylogenies, with statistical analyses of correlation (Nunn, 2011; Brown et al., 2014; Bégat et al., 2015). Some musicological traits have previously been linked to diversity in languages and/or genetics in other regions of the world: simple clustering techniques have been used to compare the distribution of instruments and language families in Oceania (Mclean, 1979), Taiwanese polyphonic group songs have been linked with local mitochondrial DNA variation (Brown et al., 2014), correlations between song styles and mitochondrial DNA diversity have been detected in Japan (Savage et al., 2015b), and broad range comparisons have been performed between music structure and style, linguistic features and genetic diversity in Northeast Asia (Matsumae et al., 2021).

The most widely used framework of organology, the study of musical instruments and their classification (Kartomi, 1990), is that of von Hornbostel and Sachs (1914). This system is based on the way sound is produced. Excluding electrophones (Sachs, 1940), four top-level categories are relevant here: idiophones (vibration of the instrument itself e.g., a rattle), membranophones (vibration of a membrane, e.g., a drum), chordophones (vibration of strings, e.g., a guitar), and aerophones (vibration of wind, e.g., a flute).

Our study concerns South America's rich native instrument diversity, as documented from the archaeological and ethnographic records (Fig. 1). Following South America's colonization by humans at least ~15–25 thousand years ago (Dillehay, 2009; Ardelean et al., 2020), a unique record of the invention in arts and sciences developed in this large landmass (Kubler, 1984; Mann, 2006). The earliest evidence of musical instruments comes from the coast of Ecuador (Las Vegas Culture, ca. 5000 BCE; Pérez de Arce, 2015) and Peru (Chilca, ca. 3700 BCE; Mansilla Vásquez, 2009). Figure 2 maps major sites and cultures in South America

where instruments and sound devices have been reported; the larger density to the West may reflect a bias in archaeological excavation effort and preservation conditions. The onset of globalization and exposure to European and African influences for the past four centuries has affected most of that diversity, contributing to both the extinction and creation of new instruments; for example, chordophones radiated in South America only after European contact (Izikowitz, 1935). South America provides a rich and challenging area in which innovation and diffusion can be addressed within a defined, but diverse geographic scope, as has been done for languages (Walker et al., 2012), archaeological cultures (Gregorio de Souza et al., 2020), and language/gene coevolution (Amorim et al., 2013). From an organological perspective, the startling and unmatched diversity of aerophones in South America has been previously noted (Olsen, 2004; Olsen and Sheehy, 2008; Beaudet, 2011), but never comprehensively quantified and analysed.

In this paper, we present an exploratory quantitative assessment of native musical instruments and examine their distribution in time and space. Our goal is to explore changes in diversity and extinctions of single instruments, and connections with linguistic relatedness, by tying the instrument diversity to the human groups who produce them. We explored diversity patterns of musical instruments in South America with three case studies of quantitative analysis involving novel datasets: (1) a list of instruments based on the von Hornbostel and Sachs classification system (1914), expanding the most current database of musical instruments (and sound devices) with recent descriptions focusing on South America; (2) a musical instrument database based on the prominent work by Izikowitz (1935), updated with current socio-linguistic information; and (3) a database of panpipe features, expanding that by Aguirre-Fernández et al. (2020). These datasets were contrasted with linguistic and cultural information and explored through different methods.

Issues in the phylogenetic study of material culture as related to musical instruments

Five fundamental issues concerning the study of material cultural evolution were presented by Tëmkin and Eldredge (2007), after their research on Baltic psaltery and cornets, and have been further elaborated by an expanding body of literature (Lipo et al., 2006; Gray and Watts, 2017; Youngblood and Lahti, 2018). A summary of these critical points, highlighting major limitations and possible solutions, is provided to bring further context to our instrument evolution study.

The first and most significant issue is in the different mode and frequency of interlinear transfer of information between biological and cultural entities, with horizontal transfer heavily influencing the cultural transfer. Cultural transformation has been claimed to be fundamentally different from (vertical) evolution in the past because cultural inheritance can be horizontal/blending (Kroeber, 1923; Moore, 1994). The issue of non-linear vertical evolution is also important in biology, as hybridization and other forms of horizontal gene transfer do occur across the tree of life (Abbott et al., 2013).

The issue of horizontal information transfer in cultural evolution has been examined empirically (Collard et al., 2006). The conclusion has been that cultural transformation can indeed be tree-like, with an abundance of vertical branching patterns, suggesting that horizontal transfer should be tested and not assumed. Simulation studies have further shown that horizontal transfer does not invalidate phylogenetic comparative studies of culture (Currie et al., 2010). Examples from musical datasets show relevant phylogenetic effects: Le Bomin et al. (2016) coded musical data and tested for vertical versus horizontal transmission,

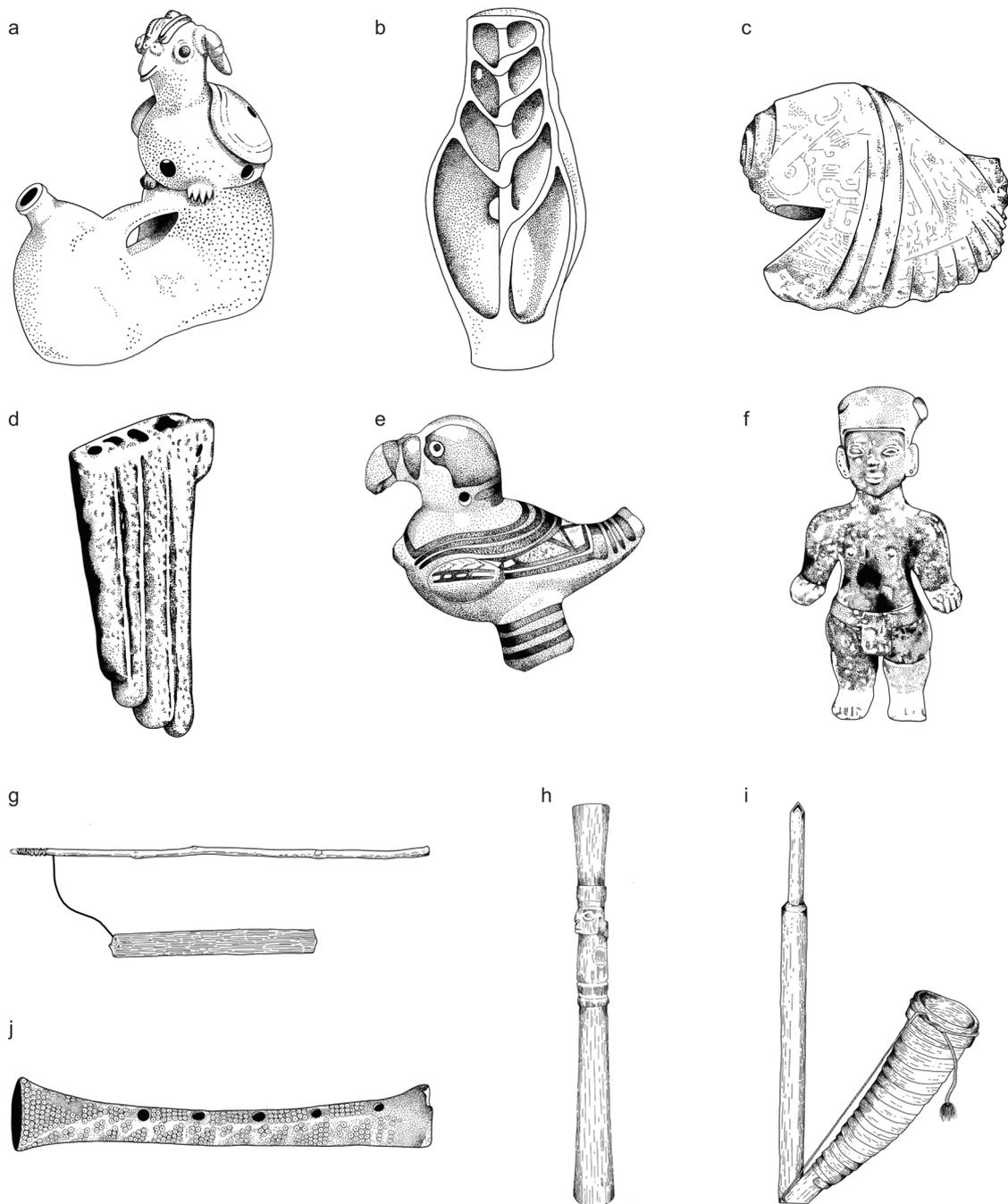


Fig. 1 Examples of pre-Columbian aerophones in South America (not to scale). **a** Double-chambered whistling vessel of La Tolita culture (MAAC-2-2857-85) (Pérez de Arce, 2015). **b** ‘Snail-chambered’ ceramic globular whistle of the Cuasmal culture (CPS-60) (Pérez de Arce, 2015). **c** Conch horn of the Chavín culture. **d** Stone panpipe, Tilcara (Pérez de Arce, 2000). **e** Ocarina in the shape of a parrot (Reiss-Engelhorn-Museen-198) (Hickmann, 2008). **f** Double-chambered ocarina of La Tolita culture (MAAC-1-2996-87) (Pérez de Arce, 2015). **g** Bullroarer from the Apinayé (GM-31.40.266) (Izickowitz, 1935). **h** wood trumpet of the Chimu culture (Reiss-Engelhorn-Museen-120) (Hickmann, 2008). **i** Mapuche trumpet ‘Nolkin’, played by inhalation (Pérez de Arce, 1986). **j** Quena made of bone of the Nasca culture (GM-29.32.4 h) (Izickowitz, 1935).

concluding that ‘vertical transmission plays a key role in shaping musical diversity’, as expressed in musical characters such as metrics, rhythm, and melody.

The possible occurrence of horizontal transfer distorting vertical relationships and ‘treeness’ of the data can also be accounted for by some algorithms and has been implemented in biology (Holland et al., 2002; Makarenkov and Legendre, 2004) as well as in the reconstruction of language trees (Wang and Minett, 2005; Hunley et al., 2007; Greenhill et al., 2009). To account for recombination between lineages, different displays

of evolutionary relationships can be considered (i.e. networks, neighbor-net, or densities) (Bryant and Moulton, 2004; Bouckaert, 2010; Baptiste et al., 2013; Gray and Watts, 2017). Split-networks (Huson and Bryant, 2006) are a well-established analytical tool and a common choice when accounting for horizontal transfer; for this reason, it was chosen for the panpipe test case examined here.

A second issue noted by Tëmkin and Eldredge (2007) is that transmission of cultural traits can occur ‘even when a lineage is historically discontinuous’, whereas in biology extinction results



Fig. 2 Map indicating South American archaeological sites and cultures in which pre-Columbian musical instruments or sound devices have been found. Modified and expanded from Hickmann (2008).

in the complete loss of information. Indeed, this difference is evident. In the case of material culture, artefacts (instruments) can cease to be produced and even no longer be around physically, but not be declared 'extinct' if the knowledge for its production persists in some form. An example is the disappearance of the recorder in the 19th century and its renewed production in great quantities at the beginning of the 20th century accompanied by its widespread in musical education (Scheck, 1975). In Chile, it is common to say that a musical tradition like 'baile chino' is 'sleeping', and it can remain so for years until it 'awakes' and a new group is formed, considered to be the same previous one. One must thus factor in such pseudoextinctions contributing to potential discontinuity in the data.

Third, Tëmkin and Eldredge (2007) pointed out that in current phylogenetic methods, algorithms treat taxa as terminal tips of the tree, making ancestors hypothetical and not identifiable. In contrast, in material culture ancestors can be known, for instance when an artefact is used as a prototype and thus represents a direct ancestor. The operational issue of not being able to treat actual ancestors as such has been identified and discussed in biological systematics (Haug and Haug, 2017). Nonetheless, the problem can be circumvented by using the available algorithms as they are if the matter is considered when evaluating the results of an analysis.

Fourth, Tëmkin and Eldredge (2007) noted that current algorithms mostly generate strictly bifurcating trees (Lipo et al., 2006; Darlu et al., 2019). Indeed, bursts of multiple lineages arising at once from the same node may also happen in culture (Gray and

Watts, 2017). Such events are called 'hard polytomies' when illustrated in phylogenies to distinguish them from unresolved tree topologies, known as 'soft polytomies'. Network approaches and appropriate interpretations of polytomies can address this point.

Fifth, Tëmkin and Eldredge (2007) pointed out differences in the generative process of the entities in question. Clearly, the myriad of processes during ontogeny giving rise to a grown organism, with both genetic and environmental influences playing a role, are different from the process of constructing an instrument (Wagner, 2014).

Results

Diversity patterns of musical instruments in South America.

After examining the caveats to consider for our cultural evolutionary analysis of musical instruments, we proceed with our first broad continental screening, examining the diversity of archaeological and ethnographic specimens. We compiled and updated an extensive instrument dataset, including several new entries from sources dedicated to South America. Our 501 entries were divided into three classes: aerophones, membranophones, and idiophones (Fig. 3a). Chordophones were disregarded, as they were arguably absent in pre-Columbian times (Izizowitz, 1935). The current state of documentation is shown in Fig. 3b, including new entries for each class of instrument (49 aerophones, 46 idiophones and four membranophones). The composition of the updated dataset reveals a preponderance of aerophones in

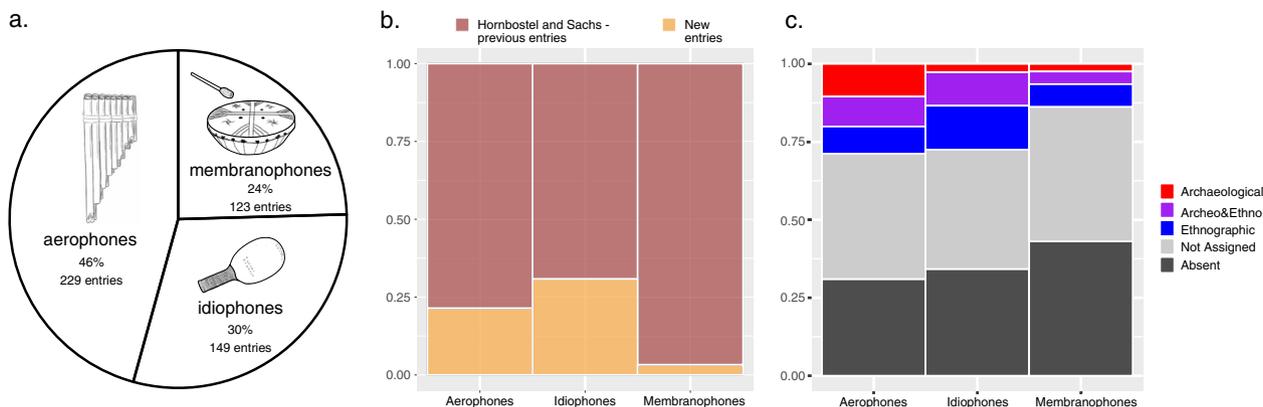


Fig. 3 Distribution of instruments according to the von Hornbostel and Sachs (1914) classification. **a** Number of entries for each instrument class in the global classification. **b** relative contribution of instruments (from Perez de Arce and Gili, 2013) compared to the von Hornbostel–Sachs (1914) classification and its revisions (MIMO consortium 2011; CIMCIM, 2017). **c** proportion of South American instruments per class, subdivided between historical/ancient presence (archaeological) and more recent use documented from ethnographic sources.

South America, which account for more than 50% of the instrument entries in the continent (66 out of 124). These 66 entries represent about 40% of the global aerophone coverage in our dataset. Only 30% of the South American aerophones are present in the ethnographic record only, possibly associated with relatively recent innovations or information loss (Fig. 3c). The second most represented instrument class in South America are idiophones (41 entries, 33%) and of those, 50% are present either only archaeologically, or both archaeologically and ethnographically, whereas the other 50% have been recorded to occur exclusively ethnographically.

The ethnological record documents how instrumental diversity in South American communities has sometimes decreased from the time of the European invasion and subsequent colonial times. The archaeological record, mostly consisting of instruments made of ceramic or bones, presents a diversity of mostly aerophones that is unique and with a history going back millennia (Olsen, 2004). In our survey, the number of instrumental extinctions (i.e. instruments that are present in the archaeological record alone and are not found in any ethnographic records) includes 31 entries of the extended von Hornbostel–Sachs (1914) classification (25% of the recorded South American instruments). These instruments, which possibly went extinct in early ethnographic times, include 24 aerophones, four idiophones and three membranophones (data and code provided under the link in ‘data availability section’).

Geographical and linguistic patterns associated with musical instruments. After a systematic mapping of instrument diversity in the continent, we begin with a phylogenetic exploration of instruments sets in different South American societies. For this and the following case study, we employ different datasets. These datasets are associated to information that makes it possible to link instruments to the humans who produced them. We, therefore, consider human societies, or cultures, as taxa in our evolutionary and relationship comparisons.

We revised the work of Izkowitz (1935), a compendium of available published descriptions and museum specimens at the time, condensing it into a presence/absence dataset of 57 instruments, compiled for 144 societies (data and code provided under the link in ‘Data availability’ section). Each society is assigned to a language family according to the language spoken, and to its geographic coordinates via its linguistic link. The composition of this dataset is 74% aerophones, 21% idiophones

and 5% membranophones (chordophones are not considered—see the previous section). These proportions are comparable to the von Hornbostel–Sachs (1914) classification for the abundance of aerophones but differ in the small number of membranophones described. The geographic coverage for the societies included in the analysis and the proportion of instruments described for each society is illustrated in Fig. S1 (Supplementary Electronic Document), which shows a concentration of cultures in the north-western area of the continent. The distribution of each instrument on a map is shown in Fig. S2, whereas Fig. 4 shows some examples of different distributions. Most instruments have a continental ubiquitous distribution (like the panpipe and the rattle), while a few have a geographically restricted distribution, such as the Aztec flute, found only in the Chibchan speakers of northern South America, the Chaco clarinet, found around the Gran Chaco region and the flat roots as signal instruments used in the northwest of the Amazonian basin. A few instruments have a discontinuous distribution, present in two very distant regions: like the Timbira flute, found in societies speaking Nuclear-Macro-Je languages in the central-east of Brazil and in the Cashibo of Peru, or the simple end flute, found in the Chibchan speakers of northern South America and in the southern regions of Chaco and Patagonia.

Based on the different instrument sets, we computed musical distances between societies and visualized them with a Neighbour Joining tree (Fig. 5). The large basal polytomy and the low bootstrap values indicate that the data do not support a strong phylogenetic signal. We can nevertheless focus on branches where similarities between societies are based on a shared set of instruments. Geographic distance is also relevant to understand the possible evolutionary dynamics in play. In pairs that are not in geographic proximity, sharing by horizontal transfer due to contact is less likely. The same sets of instruments shared across large geographic distances could be due to culturally mediated horizontal contact, such as trade, or due to shared cultural history, such as for speakers of the same language family. The appearance of the same instrument in societies that are not geographically or culturally close can be also interpreted as independent innovation, or a sign of past proximity predating current distance (see discontinuous distributions of Fig. 4). We, therefore, examined the relationship between geographic and instrument distances (Fig. S3), show a minor, but significant correlation (R squared 0.01942, p value < 0.001). It is noticeable that close geographic proximity does not necessarily correspond to a similar set of instruments, as can be seen for the pairs that are

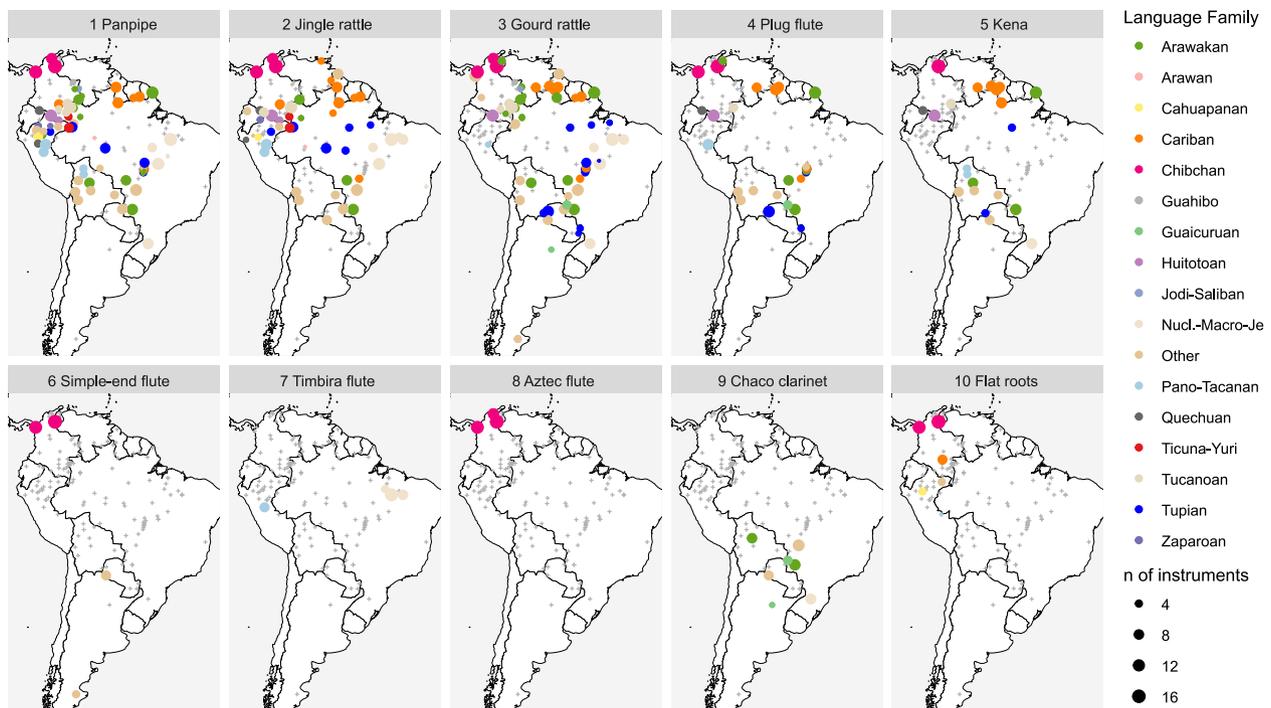


Fig. 4 Distribution of musical instruments. Distribution of 10 of the 57 instruments of the Izikowitz database, characterized by differential patterns. ubiquitous (1-5), discontinuous (6-7), or region-specific (8-10).

found between 0 and 30 km of distance, which all have instrument distance values above 0.5. The same set of instruments (pairwise distance = 0) is found in several pairs of societies, also on geographic distances above 4000 km: these pairs mostly include societies that have only one instrument, for which fine comparisons are more difficult and less informative. Strong associations, backed up by high bootstrap values, are found with the Gaviao-Pykopje and Timbira-Creapimcatage (two groups that speak Nuclear-Macro-Je languages and are recorded as living at ~450 km of distance) who share the same set of four instruments. Motilon and Dule (Chibchan family, ~450 km distance) have 14 instruments in common. Cocama and Kambeba (Tupian family, ~500 km distance) have four instruments in common. Tariana and Mehinako (Arawakan family, >2000 km distance) have three instruments in common. The larger clustering of speakers of the same language family is the one found between Caribbean speakers Macushi, Patamona, Pemon and Soto, who occupy regions with a range of ~300 km and share four instruments (transverse flutes, bamboo trumpets, gourd rattle, and kena).

The closest distances between instrument sets (below 0.5) are displayed on a map in Fig. S4. The closest similarities involve groups across the Amazonian basin, connecting societies separated by a large geographic distance on East-West direction, mostly on similar latitude intervals. Corridors along the same ecoregion, in the Amazonian Basin, represent a possible preferential path of population contact. The network of close pairwise distances includes connections with the north and the East of Colombia and the northwest of the Amazonian basin.

Networks based on panpipe trait variation, compared against cultural areas. Panpipes are extensively distributed in the continent and are therefore a particularly useful source for comparisons between human societies. We created a panpipe profile for each society in our dataset based on the features detailed in Aguirre-Fernández et al. (2020). We considered societies again as

taxa, keeping those where panpipes are present, and for each society, we annotated the type of panpipes, based on the presence or absence of a set of features. Each society was then assigned to one of the considered cultural areas, referring to the areal system proposed by Murdock (1951) on the basis of linguistic and cultural traits (e.g. food production, society structure, kinship). The panpipe profiles were analysed starting from a matrix of distance and applying a phylogenetic network approach, which allows for reticulations between nodes. The branching patterns generated by the Splitstree method return a realistic picture of the principal evolutionary relationships together with possible effects of horizontal transfer/contact. The resulting network (Fig. 6) is clearly star-like, but major branches of closer relatedness broadly overlap with some cultural areas and macro-ecogeographic regions, particularly those in the Andean region. The global delta score is 0.32 (the theoretical range is from zero to one, with treelikeness approaching zero and a network shape being closer to one). The Peruvian cultural area agglomerates many societies into an ‘Andean cluster’, with a distinct subgroup including archaeological cultures. Notably, northern Andean societies such as Cajamarca and ‘Quechua North Andes’ (which includes Quechua speakers from northern regions of Ecuador and Colombia) are found on the opposite side of the network, along with members of other northern cultural areas such as the Isthmian, Colombian, and Loreto cultural areas. We distinguish two tropical forest clusters: cluster 1 is formed by the cultural areas flanking the Andes (Loreto, Caqueta, and Jurua-Purus), whereas cluster 2 is the most diverse and heterogeneous region of the network, representing many cultural areas of the Amazon basin and reaching the eastern limits of the continent (Guiana, Pará, Goiás). Delta scores for the individual societies (Supplementary Electronic Document) range from 0.26 to 0.42. The lowest delta scores are associated with Chancay, Aymara-Chile and Bolivia, all belonging to the Andean cluster, followed by Oyampik, Wayana and Kuikuru from the tropical forest cluster, thus indicating a treelike signal is higher in those cases. The highest delta scores are

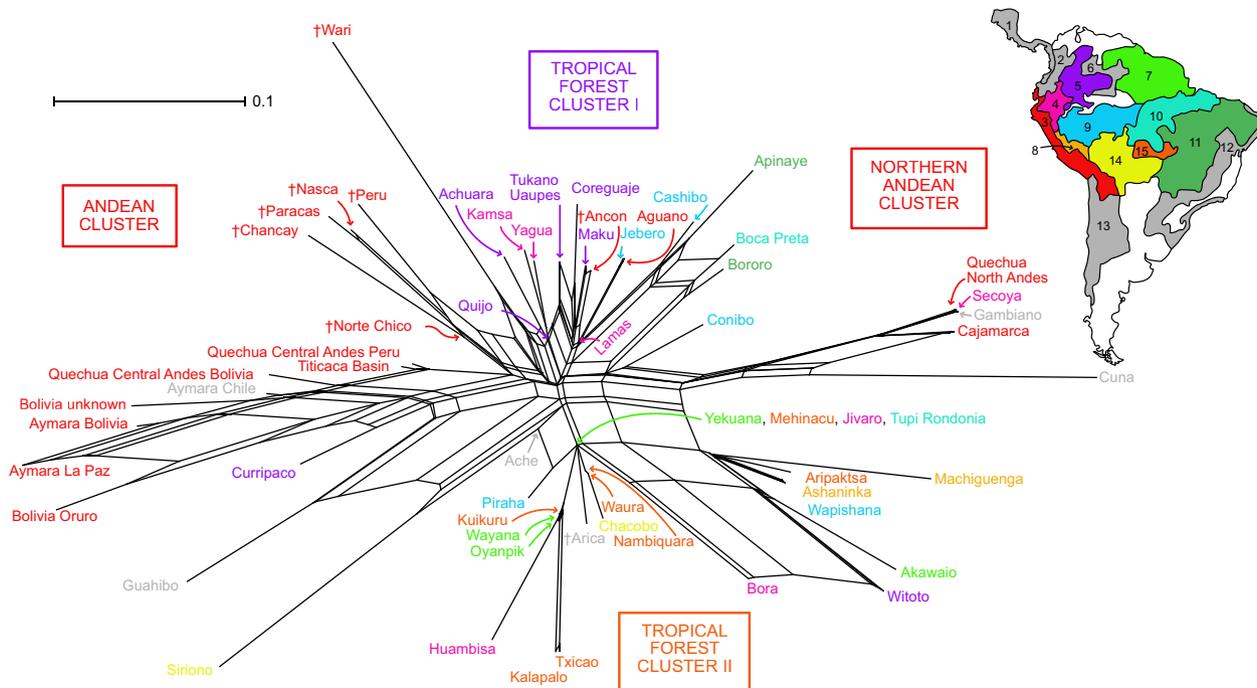


Fig. 6 A neighbor-net constructed from the concatenation of 13 panpipe features discretized in 53 character states for 61 societies, based on observations of 375 panpipes. The colours relate to the cultural areas described by Murdock (1951), as illustrated in the map: (1) Isthmian; (2) Colombian; (3) Peruvian; (4) Loreto; (5) Caqueta; (6) Savanna; (7) Guiana; (8) Montaña; (9) Jurua-Purus; (10) Pará; (11) Goiás; (12) Eastern lowland; (13) Chilean; (14) Bolivian; and (15) Xingú. The scale bar illustrates the distance among branches.

Europe and slightly lower than that of east Asia (Savage et al., 2015a). The apparent discrepancy between the analysis of recordings (Savage et al., 2015a) and our accounting of high aerophone instrument diversity is a matter that requires further study in both terms of primary data, but also in the understanding of organological versus song diversity, an important and unresolved matter.

When considering the ethnographic and archaeological records, it is clear that these are not comparable, given the preservational bias of the latter (Perreault, 2019). The great majority of archaeological remains of sound devices in the Americas are made of ceramic (Hickmann, 2008), and the record from forested areas of the continent, in particular the Amazon region with rich organological diversity, is very limited. Notwithstanding the huge amounts of missing data, it is important to consider what is indeed available, as this serves to provide some temporal threshold for the occurrence of some instruments and their distribution in past times, as well as records of extinction (Zhang and Mace, 2021).

The pre-Columbian use and development of musical instruments in South America may have been influenced by cultural exchange with other continents (Riley et al., 1976). The possibility of long-range geographical connections between human groups using panpipes has already been explored (Aguirre-Fernández et al., 2020). Pre-Columbian contacts between the Americas and the Pacific have also been suggested based on domesticated species such as the sweet potato (Roullier et al., 2013) and chicken (Storey et al., 2007), and left traces in the genetic makeup of Pacific islanders (Ioannidis et al., 2020).

This subject of transpacific contact remains controversial in spite of the growing independent lines of evidence that support it (Jones et al., 2011). In terms of musical instruments, the challenge lies in finding relevant archaeological data regardless of its incompleteness (Perreault, 2019). In addition, studies on cultural transmission dynamics (Scanlon et al., 2019) applied to musical instruments would help understand the transmission

mechanisms in place and the likelihood of transmission patterns (e.g., imitation from family members; Chitwood, 2014).

The decline in instrument diversity (particularly of idiophones and membranophones) described by our estimate of extinction (25% of the standard classification, possibly an underestimation of the actual past diversity, due to the preservation bias mentioned before) may reflect a cultural bottleneck. Historical (Mann, 2006) and population genetic data from living and ancient individuals (O'Fallon and Fehren-Schmitz, 2011; Llamas et al., 2016) document a sharp reduction of population size following the European contact, which may have led to that cultural bottleneck. On the other hand, post-Columbian times brought South American communities in contact with a completely new range of instruments and musical influences, mostly from Europe and Africa, leading to horizontal transfer of organological information, transculturation and ultimately a shift in the South American instrumental collection. The second wave of cultural change is likely to have started within the past century. Distinct societies have forcedly or voluntarily integrated into the socio-political and economic context of the modern South American national states, their territories were reduced or destroyed as driven by agriculture and gold mining, and there has been violent persecution or dissolution of communities and their traditions (Davis, 2009). The mechanisms behind as well as the tragic effects of these developments have been studied with respect to the impoverishment of networks of indigenous knowledge (Cámara-Leret et al., 2019), but remain to be highlighted from a musicological point of view. These cultural transformations might have reduced the overall diversity while channelling new forms of integration of old traditions into new urban contexts, and promoting cultural innovations that would be reflected in the 40% of instruments that are present only ethnographically.

The quantitative methods applied by our analysis revealed that musical instruments can retain similarities and connections shaped not only by geographic proximity but also by the linguistic/cultural affiliation of the people who played them, even at

large geographic distances. Figure 5 shows some branches where ethnic groups who speak related languages also share similar sets of instruments. Four Carib-speaking populations of the Guianas and Venezuela have similar sets of instruments: the groups considered share a close linguistic relatedness, with three of them speaking a language of the Pemongan subfamily. This connection could be backed up by an important role for musical instruments in these societies, promoting conservativeness through time, or by strong (and maybe more recent) historical exchanges. The search for continental-scale phylogenetic patterns does not return clear tree-like topologies (Fig. 5). Reasons behind this may include: (1) the paucity of musical instruments used in the analysis, and the non-systematic mapping from the ethnographic record available; (2) the effects of horizontal transmission, which are difficult to quantify with the available data—a study of this matter would require a typological review that aims at prioritizing which features are most stable in vertical transmission; and (3) the peculiar historical trajectories of the continent, which may favour the independent evolution of cultural features above linguistic and genetic relatedness. A large number of languages and language families (second only to Oceania; Hammarström et al., 2020) and associated cultures can be seen as a driver for rapid cultural change. This variable cultural landscape might account for the higher chances of unrelated pockets of instrument diversity, which can be in turn emphasized by random drift, identity marking, and independent innovations.

The neighbour-net analysis of panpipes (Fig. 6) allows for flexibility towards horizontal transfers and contact events overriding the evolutionary backbone, which is commonly expected in cultural traits (Moulton and Huber, 2009). The panpipe dataset benefits from a more systematic and robust analysis of the traits that are present or absent in the different specimens described, with multiple specimens associated with each society. The phylogenetic approach provides remarkable insights to broad areas of cohesiveness in panpipe construction, even if a similar limitation in the number of features analysable on a large scale is in place (13 panpipe features discretized in 53 character states). The subdivision of the large Andean cluster (corresponding to the Peruvian cultural area identified in Murdock, 1951) into a northern and a southern block mirrors the linguistic and genetic evidence of northern and southern spheres of influence in the Central Andes, as identified by Stanish (2001) and confirmed by linguistic and genetic evidence on population structure established <2000 years ago (Nakatsuka et al., 2020; Urban and Barbieri, 2020). A separate cluster corresponds to the ancient societies of the Peruvian cultural area, of which the panpipe record is reconstructed by archaeological specimens only: possible preservation bias or the lack of European influence can be elements in favour of their distinction from the rest of the Andean populations.

Finally, there is a shared cultural influence in panpipe production focused in northeast Amazonia, separated from a more central/southern core: a geographical pattern illustrating the cultural diversity in such a large area as Amazonia (Fausto, 2020; Pearce et al., 2020). Amazonia has been traditionally considered home to relatively homogeneous, albeit isolated groups, but recent archaeological and genetic work demonstrates the multi-layered diversity of the region, highlighting the presence of ancient structure and complex societies (Heckenberger and Neves, 2009; Arias et al., 2018; Posth et al., 2018; Barbieri et al., 2019). The cultural areas recognized here (Murdock, 1951) are subject to debate, as outlined in Weiss (1980); a broader scheme includes the three major cultural and eco-geographical areas (grasslands, tropical forest and desert-mountain). As discussed for instruments in Kartomi (1990), micro-taxonomic work needs to be further developed in order to reach the ground needed for historical questions to be unambiguously answered.

Our continental study presented exploratory angles to encourage more fine-scale testing approaches. Systematic, quantitative organology as part of comparative musicology (Savage and Brown, 2013) has the advantage of incorporating rich and complex material evidence. The use of concepts and rigorous quantitative methods will help uncover patterns and mechanisms underlying human innovation, which are impossible to achieve with traditional discursive descriptions of historical phenomena. Further, analytical approaches have the advantage of explicit assumptions and reproducibility. However, powerful methods are not sufficient to achieve meaningful results: they must be accompanied by robust data collection and curation. Current efforts such as the Musical Instrument Museums Online (<https://mimo-international.com/MIMO/>) pave the way to global quantitative studies in organology. Promising ways forward also reside in quantifying more intricate instrumental traits to characterize instrumental features and diversity. Examining the interior of instruments using non-invasive imaging techniques (Hickmann, 2008; Borman and Stoel, 2009; Fuchs et al., 2016) and analysing the sounds produced by instruments enables an expansion of their characterization (Gruszczyńska-Ziółkowska, 2009).

Methods

Diversity patterns of musical instruments in South America.

The database presented here (data and code provided under the link in 'Data availability' section) is based on the von Hornbostel and Sachs classification (1914), as reviewed by the Musical Instruments Museums Online consortium (MIMO Consortium, 2011) and the addenda proposed by the International Committee of Museums and Collections of Instruments and Music (CIMCIM, 2017). We expanded this database for South America based on the translation of von Hornbostel and Sachs (1914) into Spanish by Vega (1946), with contributions from Bolaños et al. (1978) and Pérez de Arce and Gili (2013). Twelve additional entries were included based on unpublished organological work by José Perez de Arce. Chordophones are not included in our analysis, as they are absent in the archaeological record (Izikowitz, 1935) and derive from post-Columbian Iberian prototypes (Olsen and Sheehy, 2008). The units of analysis are native, pre-colonial musical instruments. The aims of this section are to integrate new data from South America, including sources published in Spanish (these entries could be considered in future versions of the H-S classification) and to characterize the diversity of this newly consolidated dataset through instrument classes (aerophones, membranophones and idiophones) and through time (archaeological and ethnological records).

Geographical and linguistic patterns associated with musical instruments.

We revised the material of Izikowitz (1935) to build a matrix and code the presence/absence of 57 types of instruments in 144 societies or ethnic groups (data and code provided under the link in the 'Data availability' section). Character state 1 marks the definite presence of an instrument in the ethnographic record and 0 marks the lack of evidence for a particular instrument, according to Izikowitz. The aim of this section is to explore the relatedness between societies according to their instrument sets, accounting for geographic and linguistic proximity.

The units of analysis in this section are societies: the society names or locations indicated by Izikowitz (1935) were associated with their linguistic affiliation as reported in Glottolog v. 4.2.1 (Hammarström et al., 2020). We refer to ethnic groups or cultures to identify the people who produced the musical instruments under examination. The association to Glottolog codes was used to extrapolate approximate geographic

coordinates and generate a map with the approximate location of the ethnic groups—or better, the language they speak.

We used R to calculate distances between the sets of instruments present in each society and generate a Neighbour-Joining tree. Bootstrap values were calculated as the proportion of times the same node was reconstructed over 1000 iterations. Maps visualizations are made in R. Data and scripts to generate the analysis are found under the following Github link: https://github.com/chiarabarbieri/SouthAmerica_MusicInstruments.

Networks based on panpipe trait variation, compared against cultural areas. We extracted the South American panpipe sample of Aguirre-Fernández et al. (2020) and added further panpipe data based on online queries (American Museum of Natural History and Pitt Rivers Museum), direct observation (Centro de la Diversidad Cultural, Caracas) and information sent by collection curators (Museum für Völkerkunde, Dresden). The dataset used here included 375 objects and 13 instrument features subdivided into 53 different character states. The 375 objects represent 61 societies/cultures in 12 countries. The information that accompanies objects in collections (e.g. ethnic labels and geographical locations) is of variable quality and ethnic terms were standardized using the ethnological dictionary of Olson (1991), but some groupings were designed based mostly on linguistic and geographic boundaries. (e.g., the language/language family Aymara, which covers a vast territory, is subdivided into geographic areas: Bolivia, Chile and La Paz). The panpipe profiles are the operational taxonomic units used in this study and consist of scoring the most frequent value (mode) of a given panpipe feature (see list below) for a given society of culture; in the case that the most frequent value is represented by two or more feature categories, the value was left as unknown ('?'). The matrix is available at the link in the 'Data availability' section. The list of features is detailed in the Supplementary Electronic Document. The units of analysis are again defined as societies. The aim of this study is to compare the relatedness between the most popular panpipe features in each society. This approach develops from the one followed in Aguirre-Fernández et al. (2020), which used the panpipe instruments as units of analysis. The phylogenetic affinities of the panpipe profiles were illustrated using a neighbor-net analysis (a distance-based method under the split networks framework) using SplitsTree 4.16 (Huson and Bryant, 2006) with the standard parameters, including uncorrected p character transformations, least-squares variance, and equal angle splits. The delta values were calculated using the 'compute delta score' function under the analysis tab in SplitsTree.

Data availability

The data and code for the analyses are available at https://github.com/chiarabarbieri/SouthAmerica_MusicInstruments. Including: Supplementary Table S1: Classification of instruments according to von Hornbostel and Sachs (1914), subsequent revisions and new data for South America. Supplementary Table S2: Instrument repertoire based on the work of Izikowitz (1935) on ethnographic data, and information on the societies for which the instrument data is found (57 types of instruments in 144 societies or ethnic groups). Supplementary Table S3: Data matrix of panpipe profiles. The dataset includes 13 instrument features subdivided in 53 different character states, annotated for 61 societies or ethnic groups.

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Author contributions

MRS-V conceived and supervised the study. MRS-V, AG, CB and GA-F wrote the first draft of this paper. JPA collected published and unpublished data for the instruments classification database (Table S1), assembled by AG and JPA. HM provided access and information on musical instruments from Venezuela and archaeological records of them. The Izikowitz dataset (Table S2) was assembled and initially analysed by AG. The panpipes dataset (Table S3) was assembled and analysed by GA-F. Both CB and GA-F worked on subsequent versions of the manuscript and performed further data analyses and visualization. GA-F, CB and MRS-V interpreted the results and wrote the paper with contributions from AG and JPA. All authors revised and accepted the final version of this manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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