Li et al. Heritage Science (2024) 12:264
https://doi.org/10.1186/s40494-024-01377-0

Heritage Science

RESEARCH

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# A "set" of ancient bronze bells excavated in Changsha, Hunan Province, China

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**Abstract**

This article explores the criteria used to ascertain whether or not, and how, ancient Chinese bronze bells might form sets of musical instruments, thus clarifying their original intended use by ancient musicians. The focus is on ten bells unearthed from Changsha city in Hunan province in China, which date to the twelfth century BCE. A range of diverse relationships between these bells provide valuable insights that can be explored. Debate is ongoing among music historians regarding the nature of the bells. Some argue that the ten bells do not constitute a set of musical instruments because their designs and acoustic properties lack sufficient similarity and correlation. Conversely, another group of historians suggests that nine of the ten bells could indeed be seen as a set, but with the tenth bell being an outlier due to its distinct design. The third group of historians contends that the ten bells should be considered a musical set because of their organized sequence of consecutive semi-tones, while the design differences of the bells are less significant and can be overlooked if we focus on their musical functions. In this study, we scrutinize the assumptions made by these music historians, including their definitions of design similarity and the sequence of progressive pitches. Further previously overlooked criteria, such as the geographical proximity of these ten bells and others found in neighboring areas, and the incremental changes in the bell sizes, are also considered. Through the use of these criteria we aim to explore a wide range of relationships between ancient Chinese bells and to reassess what other new evidence the bells may offer to the study of ancient Chinese musical concepts. The concept of the chromatic scale discovered by ancient Chinese musicians was embodied on the casting of bronze bells.

**Keywords** Bell, Ancient China, Changsha, Musical instrument, Pitch, Chromatic scale

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## Introduction

Bronze bells from the twelfth century BCE that have been discovered in South China's Hunan and Jiangxi provinces are some of the most intriguing archaeological finds of the past century. Their exquisite design and sophisticated production techniques rival the craftmanship of any of the finest bronzes produced during the same era. One of the most remarkable features of the bells is their sheer size and weight, which not only indicates extensive use of mineral ores but also testifies to the immense effort that the bell casters put into their production. The bronze bells that were cast in South China during this period were significantly larger and heavier than their northern counterparts [1, 2].

The majority of the excavated bells were discovered just beneath modern ground level at depths ranging from 0.2 to 1.5 m. These and other bells in South China were commonly found in pits situated on hills or along riverbanks that were devoid of any other burial artifacts [1]. When located on hills, they were generally unearthed from the summit to the mid-level, and at the base of the hills. This finding is in stark contrast to their northern counterparts that were typically found in burial sites. Scholars, such as Gao Zhixi, the former director of the Hunan Museum, have inferred from this that the southern bells might have been used as religious paraphernalia that were offered to deities associated with natural phenomena [1].

Bells in South China exhibited significant differences from those in the north after the twelfth century BCE. The northern bells retained their smaller size and held a less important position in their burial contexts, whereas the southern bells, from 1100–1000 BCE onwards, embarked on a drastically different development trajectory. In addition to their large size and weight, their casters gradually cultivated the characteristic design of bells with an almond-shaped cross-section. This produced a fundamental divergence in bell design from the round bells that became prevalent in China after the third century CE [2–5]. Some small clapper bells found in Erlitou in Henan province in China, which date to around 1600 BCE, may also have an almond-shaped profile section. Owing to their small size, this profile feature is not, however, as striking or noticeable as in the southern bells. The larger the bell, the more pronounced its almond-shaped profile section appears.

The almond-shaped profile sections of the large South China bells brought about revolutionary changes in their acoustic properties. Various modern technologies have been employed to study the distinct features of bronze bells [6–12]. Firstly, almond-shaped bells could basically generate two different pitches, by the use of two different strike positions (Fig. 1). This feature was validated in the 1980s by scholars such as Huang Xiangpeng and Ma Chengyuan [3, 13, 14]. Professional musicians' opinions, physical recordings, and laser holographs were utilized to confirm this feature, whose existence has since become an academic consensus. Secondly, when the position of the A-tone is struck at an appropriate angle, an absolute pitch can be generated regardless of the force of the strike, and another absolute pitch, the B-tone, can be produced when position B is struck at an appropriate angle. This feature is significant as bronze bells could have served as the providers of absolute pitches. They were distinguished in this characteristic from other contemporary musical instruments such as flutes or pipes, whose pitches could have been relative and dependent on the players' subtle techniques [4, 15]. As the almond-shaped profile section of a bell can be divided evenly into two sides, a bell has two similarly sized strike areas for its A-tone and four for the B-tone. Thirdly, the almond-shaped bells generally demonstrate greater


**Fig. 1** Strike positions of the A-tone and B-tone of the Ningxiang-Shiguzhai-tiger1 bell, one of the five bronze *nao*-bells found in 1959 atop Shiguzhai hill in Changtian village, Laoliangcang town, Huangcai district, Ningxiang county, Changsha city, Hunan province, China. Stored at the Hunan Museum. Accession no. 39206. Photograph by the corresponding author

damping than round-shaped bells. Namely, the resonation of the almond-shaped bells tends to decay faster, resulting in a more rapid, shorter ending of the bell sound in comparison to the longer lasting round-shaped bells that tend to be used for signaling purposes [6]. Fourthly, the two-absolute-pitch feature and the faster ending of bell sounds made them well suited for musical performance [4]. Players could be trained on bells with two absolute pitches with relative ease, as they only needed to learn when and where to strike their bells. More subtle techniques required for other instruments, such as how much air should be blown into a flute, and at what pressure, required a much longer learning period [15]. Several bells assembled together could potentially produce enough notes to play an octave, so reducing the number of instruments needed for a concert. The more rapid ending sounds were more suitable for musical concerts, as a "never ending" sound repeatedly appearing in a melody could have ruined the rhythm. Bells from South China, as a result, became more musically oriented and unique than their northern counterparts. Their distinctive features were not adopted by northern casters until the eleventh-tenth century BCE.

The chronology of the development of southern bells provides a timeline that diverges considerably from political development in North China. According to the textual historical tradition and excavated texts, from 1600 to 900 BCE, the Shang (16th cent.–1045? BCE) and Western Zhou (1045? –771 BCE) dynasties, and other states, gradually emerged in North and Central China, but there were other concurrently existing states in their neighboring areas such as Renfang and Qiangfang [16–21]. Dynastic disruptions and ritual reforms during this period brought significant changes to the design and use of bronzes in North China [1; 22, pp. 96–109; 23, pp. 29–73; 24]. However, southern bells dating to the twelfth to tenth centuries BCE do not seem to have been significantly altered by these dynastic shifts. Instead, they maintained their steady development trajectory by both preserving and innovating from ancient practices. Given that musical practices required long-term training and inherited knowledge, especially during periods when musical notations had not yet been invented, the preservation of and innovation from ancient practices were incredibly crucial for bell musicians and casters. Although our understanding of the dynastic history of South China during this period is limited, due to the scarcity of remaining textual records [17, pp. 78–79; 25, pp. 300–342], the development of these bells demonstrates continuous artistic and musical momentum.

## Laoliangcang Shiguzhai finds in Changsha

Over the past century the county of Ningxiang, now a part of the larger city of Changsha, has yielded numerous ancient bronzes, including vessels and bells. Seventeen bells were found on just one hill, known as "Shiguzhai," in the village of Changtian in the town of Laoliangcang. Shiguzhai hill is relatively small, rising to less than 400 m. These bells, which all date to the twelfth to eleventh centuries BCE, are now dispersed across various museums. While the dimensions of the bells have been measured, unfortunately not all of their tones have been documented.

In 1959 five bells were unearthed from a pit on Shiguzhai hill, from merely one meter below ground level (hereafter "the 1959 find"). The five bells were arranged in two layers; four bells were placed on the lower level, neatly divided into two rows, with a fifth bell placed above them [26, p. 16]. All of the bells were found positioned with their shank at the base and their mouth at the top. The presence of five late Shang style ceramic shards in the same pit suggests the approximate deposit date of the bells [26, p. 16]. Two of these bells are now housed in museums in Beijing; one in the Military Museum of the Chinese People's Revolution and another in the National Museum of China (NMC). The remaining three bells are stored in the Hunan Museum (one of them is shown in Fig. 1, accession no. 39206, hereafter "the Ningxiang-Shiguzhai-tiger1 bell"). Only one of the five bells, the Ningxiang-Shiguzhai-elephant1 bell housed in the Hunan Museum (accession no. 39202), was tested for its two tones. These are recorded as G#3-45 and A#3-23, revealing a major second interval, in one of the volumes of *Zhongguo yinyue wenwu daxi* (hereafter "*Daxi*") [26, p. 16].

A further group of ten bells was retrieved on the 7th of June 1993 (hereafter "the June 1993 find"). The pit in which they had been deposited, at 1.5 m beneath ground level, lies at the northwestern part of the summit of Shiguzhai hill, facing the distant Wei River. This pit is located about fifty meters from the pit discovered in 1959. The pit purportedly contained ten bells only, spatially deposited in three groups plus one solitary bell. Each group had three bells nested within each other, with a single bell placed on top of these nine, at just 0.5 m below the surface. The bells were accessioned by the Changsha Museum (CsM), which used two different accessions numbers (no. 1633 in Fig. 2; no. 1632.6 in Fig. 3), because the museum curators believed that one bell did not belong to the same "set" as the other nine bells [27]. In 1994, the Wuhan Conservatory of Music conducted a tonal analysis of the bells and published their results with the Changsha Museum in 1997 [27]. The corresponding author of this article tested the bells

**Fig. 2** Bell no. CsM III of the ten Shiguzhai bells found in June 1993. Stored at the Changsha Musuem. Accession no. 1633. Photograph by the corresponding author

again in 2022, with the results shown in Table 1 below (refer to bells CsM I to X).

The final two bells of the seventeen under examination were found in August 1993 (hereafter "the August 1993 find"). It is believed that two people from the Chuanshan village of the Fengmuqiao town, inspired by the find in June, started privately searching for bells in that area. Using a detector they successfully located two bells on the hilltop, reportedly just 0.4 m below ground and only twenty meters away from the pit of the June 1993 find. Although ancient bronzes deposited below the ground in China are classified as public assets, and their discovery should be reported to the government, the two villagers secretly dug the bells up and attempted to sell them privately. Soon afterwards, one of the bells was confiscated by the Ningxiang Cultural Relics Management Office, while the other was retrieved two years later, in 1995, from antique dealers in Shenzhen in Guangdong province [26, p. 22]. These two bells were subsequently accessioned by the Ningxiang Office (no. 0796, and no. 0667 in Fig. 4). As of 2024, bell no. 0667 is part of the collection of the Changsha Museum, while the other is housed in the Ningxiang Tanheli Bronze Museum. No public pitch testing report of the two bells has so far been published by these museums. In 2022, the corresponding author tested bell no. 0667 and recorded the bell's two tones as A#3-31 and B3-49. This bell is referred to here as "Ningxiang-Shiguzhai-Feng2," with the untested bell referred to as "Ningxiang-Shiguzhai-Feng1".

All of these seventeen bells were closely linked both geographically and temporally. Although the bells were dug up at several different times, their provenance is well documented, with all of them tracing to an area of approximately 1000–1500 square meters at the top of Shiguzhai hill. The design and production techniques used suggest they were likely to have been crafted in the twelfth century BCE [1, 4, 5, 33, 34]. The dates of their production and deposition could also have been very close to each other. The similar methods and choices of location used to deposit the bells suggest that the people who deposited them were probably members of the same community who shared highly similar cultural and religious preferences.

## Definition of a set of bells

We shall first examine the various criteria used to define a set of bells. These criteria include bells that share similarities in design, size, shape, and production techniques, as well as bells deposited in the same archaeological sites, bells producing pitches with compatible intervals, and other attributes. We will explore ongoing debates regarding these criteria and propose new definitions that can enable us to better identify "sets" of bells.

Our understanding of bells from this period depends greatly on the perspective from which we approach them. If these bells are viewed merely as individual signaling instruments, then aspects such as their size, shape, and design are inconsequential. If, however, they are regarded as a coordinated group of signaling instruments, their size becomes significant, as a larger sounding body may produce louder sounds. The scenario changes substantially when we consider these bells as a set of musical instruments that were intended to be grouped together. In this case, their size, shape, designs, pitches, and spatial context of where they were deposited are all crucial elements. The dimensions of each bell then cannot be the same as every other one, as the creation of a melody necessitates changes in sound, which are facilitated by varying bell sizes. This implies that when searching for sets of musical bells, we should also look out for bells of differing sizes, which may produce progressively varying pitches. The designs and spatial context of the bells can also provide additional clues. Bells with similar designs may also have been intended as luxurious display items

**Fig. 3** Bell no. CsM IX of the ten Shiguzhai bells found in June 1993. Stored at the Changsha Musuem. Accession no. 1632.6. Photograph by the corresponding author

or religious offerings. In this article, however, our primary focus is on identifying musical bells that could be categorized as organized groups of bells, just as they had been originally intended by their ancient casters.

## Bells with similar designs as a set

There has, until now, been no collective analysis of the seventeen bells as a group. Gao Zhixi had previously categorized various bells found in South China, which included, for typological comparison, some of these seventeen [1]. He did not, however, delve into whether the bells he was comparing were intended to form any "set(s)." The 1993 finds were additional new evidence to him, but this has yet to be comprehensively investigated. The ten bells of the June 1993 find were analyzed by former curators of the Changsha Museum, who argued that these bells should be split into two distinct sets. In their analysis the Fig. 2 bell adorned with the *taotie* pattern is categorized as a standalone piece, while the nine bells that all feature strikingly similar designs comprise another set (Fig. 5) [27]. Music historian Chen Quanyou holds a similar view [35]. The designs of these nine bells are indeed distinctively similar, as each bell surface features thirty-six evenly distributed bubbles that protrude from a background pattern filled with spirals. The two strike positions of the A-tone, or the top central parts of the bell's mouth, are usually highlighted with a bulging rectangular section filled with spirals. The strike positions of the B-tone are filled either with background spirals or with animal motifs that bulge out from the background.

These scholars, such as Chen Quanyou and former curators of the Changsha Museum, seem to have taken further criteria into account in addition to the initial criterion of design similarity. It is understandable why some might consider the Fig. 2 *taotie*-patterned bell to be different from the Fig. 3 bell on the basis of design differences [26, 35]. However, the Fig. 1 bell from the 1959 find resembles the Fig. 4 bell from the August 1993 find, and they were found in almost the same location, specifically, in two pits fifty meters apart from each other at the top of Shiguzhai hill. It is surprising that no one has proposed that they should be classified as the same set. If we were to accept this argument that bells with similar designs should be considered as part of the same set, then numerous other bells with decorative patterns akin to those of the bells in Figs. 2 and 3 bells should also be included. Yet, up until the present day, scholars have merely compared these bells for typological studies without discussing whether all of the seventeen bells should be classified as belonging to the same musical set(s). This omission suggests that either this argument is flawed, or that the scholars have other considerations at play.

**Table 1** Pitch test of some bells found in the Ningxiang county

| Corresponding author's new no. and appellation | Ningxiang-Shiguzhai-elephant1 | Ningxiang-Shiguzhai-Feng2 | CsM I | II | III | IV | V | VI | VII | VIII | IX | X |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A-tone (Hz; one to two of them will be turned into musical notes) | G#3–45 | A#3–31 (229; 228) | C#4 + 18 (280; 279) | C#4 + 18 (280; 279) | D#4 + 10 (313; 312) | D#4 + 10 (313; 314) | E4-24 (325; 326, 327) | F#4–28 (364; 363) | F#4–38 (362; 363, 364) | F#4 + 42 (379; 381, 377) | G4 + 44 (402) | G#4–22 (410) |
| B-tone (the number before the semi-colon is the frequency that is the clearest or most often occurred) | A#3–23 [not tested by the corresponding author, so no Hz is given.] | B3-49 (240; 237, 235, 233, 230, 229, 228, 227, 226) | C#4 + 36 C4 + 48 (283; 282, 280, 278, 276, 274, 269) | D4 + 14 C#4 + 18 (296; 302, 290, 288, 286, 283, 280) | F4 + 4 D#4–29 (350; 347, 343, 337, 335, 330, 321, 315, 306) | E4-19 D#4–1 (326; 323, 319, 315, 313, 311) | F4 + 28 E4-19 (355; 360, 358, 351, 347, 342, 338, 333, 330, 328, 326) | F#4 + 32 F#4–19 (377; 380, 375, 373, 370, 368, 366) | G#4–39 G4 + 44 (406; 404, 402) | G#4–26 G4 + 48 (409; 410, 408, 403) | G#4 + 32 G4 + 48 (423; 420, 412, 409, 403) | A4-12 G#4–10 (437; 434, 431, 427, 423, 420, 413) |
| Accession no | HnM 39202 | Wenguansuo 0667 | CsM 1632.9 | 1632.5 | 1633 | 1632.8 | 1632.7 | 1632.4 | 1632.3 | 1632.2 | 1632.6 | 1632.1 |
| Side length (*xianchang*) | 44.5 | ? | 34 | 31 | 31.5 | 31 | 31 | 29.5 | 28 | 28.3 | 29 | 23.3 |
| Spine length (*zhongchang*) | 40 | ? | 29.6 | 27.5 | 28 | 27.5 | 27 | 26.5 | 25.5 | 24.8 | 26 | 21 |
| Girth of lip-mid-hip (LMH) | ? | ? | 99–90-79 | 90.2–84-72 | 96.5–89.5–79.5 | 90–83-72.5 | 90.5–83.5–71 | 84.5–79-69.5 | 84–75.4–63.3 | 80.5–74.5–64.2 | 86.5–80.5–70.2 | 66.5–61.5–54.3 |
| *Xianjian, gujian* (cavity) | ? | ? | 33.5, 19 | 32, 21 | 32, 23 | 30, 21 | 32, 20 | 28.5, 20 | 28.5, 18.7 | 27, 19 | 29.5, 20 | 23, 15 |
| *Wuxiu, wuguang* (cavity) | ? | ? | 24, 19 | 24, 16 | 25.5, 18 | 24, 16 | 24, 15 | 23, 15.5 | 23, 13.5 | 21.5, 14.5 | 23, 16.5 | 18, 13 |
| Overall height | 70 + | 80 | 53.5 | 48.5 | 54 | 51.6 | 50 | 48 | 45.7 | 47 | 49.5 | 36.5 |

Most of the recorded data was measured and tested by the corresponding author in August 2022 in the exhibition gallery of the Changsha Museum

Temperature of the testing location: 22 °C

All measurements are presented in centimeters, unless indicated otherwise

In the LMH section, the term "lip" refers to the girth of the mouth of the bell, "mid" indicates the girth of the section beneath the top two rows of knobs, and "hip" denotes the girth of the lowest section of the bell's sounding body

A4 = 440 Hz

Overtones of any resonance are not considered the intended tones of a bell; only the fundamental tone is documented

For testing [3, 6–8, 28–31], each bell was placed on the floor with its shank at the base. The A-tone strike position on one side of the bell was struck three times, followed by three strikes on the other side. The corresponding author then tested the four B-tone strike positions, striking each position three times. The sound generated by the bells was recorded and analyzed using the internal recording device of a Samsung Galaxy Book Pro laptop and the audial software "Audacity" [32]

**Fig. 4** The Ningxiang-Shiguzhai-Feng2 bell (left) and -Feng1 bell (right), found in August 1993 atop Shiguzhai hill, Ningxiang county. Stored at the Changsha Musuem and Ningxiang Tanheli Bronze Museum. Accession no. of the Ningxiang wenguansuo *zong*-0667 and *zong*-0796. Photographs by the corresponding author

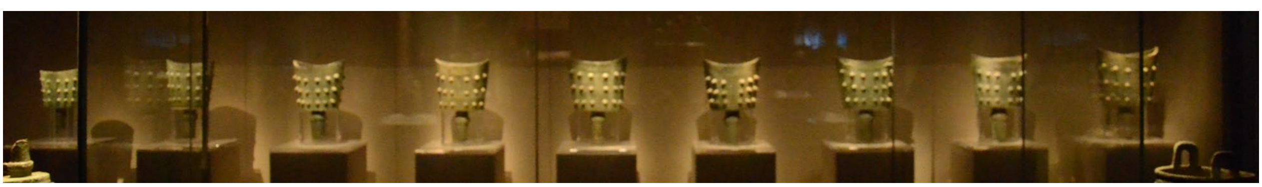

**Fig. 5** Nine of the ten Shiguzhai bells found in June 1993. Changsha Museum. Photograph by the corresponding author

## Bells with geographical proximity as a set

The factor of geographical proximity presents a significant challenge for scholars. There is a tendency for archaeologists to focus solely on items discovered within the same spatial context. This has been the case when discussing these seventeen bells and other bells with similar designs that were, however, found at other sites in Hunan, Jiangxi, and Fujian [1]. It seems that Chen Quanyou's interest was predominantly in bells with similar designs discovered within the same pit. He did not, however, provide any satisfactory explanation as to why the bells from the 1959 and August 1993 finds could not be compared.

It is the case that previous scholars have not adequately addressed why those ten bells were deposited together into one pit, and why the seventeen bells were buried on Shiguzhai hill. Despite the fact that they were not archaeologically excavated under scientifically controlled circumstances, the locations of their discovery and their methods of deposition cannot be simply dismissed. It seems apparent that there must have been particular reasons for their collective burial on Shiguzhai hill.

## Bells with progressive pitches as a set

The ten bells from the June 1993 find have been grouped together for the demonstrable reason that they produce progressive pitches spaced at even intervals (refer to bells CsM I to X in Table 1). Here these bells are re-arranged according to their pitches, as recorded when tested by the corresponding author of this article in 2022. Previous scholars disputed that these bells formed a set, arguing that their pitches lacked an orderly format, their two-tone feature was underdeveloped, and there was no conspicuous mark to signify the B-tone on the bells [26, p. 24; 35]. The former curators of the Changsha Museum proposed that the nine bells formed a set, while art historian Robert Bagley further argued that the ten bells in total had indeed formed a musical set [4, 5]. Bagley further conjectured that the 1997 testing record of the ten bells demonstrated that in the twelfth century BCE their casters had attained the chromatic scale [4]. This predates not only the first successful mathematical calculation of the chromatic scale by Prince Zhu Zaiyu (1536–1611 CE) and other European musicians in the sixteenth century CE, but also the evidence of the realization of the chromatic scale shown in the inscriptions on the bells of Marquis Yi of Zeng that were produced around 433 BCE [4, 36, pp. 147–207, 234–8; 37, 38]. Bagley's theory requires confirmation from re-testing of the ten bells, and it is probable that additional evidence from other bells could further substantiate his theory.

There are several methodological assumptions and practices in need of clarification. Firstly, we will employ the international scientific pitch notation to document the pitches of the bells. The traditional Chinese names of the pitches were probably invented after the twelfth century BCE and so cannot be confidently used as pitch names for this period. We recorded the fundamental frequency of the vibration of the bells in hertz, and converted them into musical notes, with 440 Hz equating to A4.

Secondly, it is crucial to clearly describe the striking and recording methods for reference by future tests. We do not strive for a completely noiseless environment, as ancient bell players and their audiences would not have enjoyed such conditions all the times. Playing the bells in an ordinary, quiet interior setting is therefore deemed sufficient. A bell for testing is set up on the floor with its shank at the base. The A-tone strike position on one side of the bell is struck three times, followed by three strikes on the other side. Since there are four B-tone strike positions, striking each three times means that a total of twelve B-tones are recorded. The internal recording device of a laptop computer (Samsung Galaxy Book Pro) and the audial software "Audacity" were used to record and analyze the sounds generated by the bells. Digital sampling setting is as follows: sampling frequency adopted by the computer is 44,100 Hz, bit depth is 32 bit [29–31]. When the digital sampling frequency is set at 44,100 Hz, the computer can only record sounds under 22,050 Hz, and the ordinary human ear can capture sounds ranging from 20 to 20,000 Hz. The highest frequency of bells tested does not exceed 500 Hz, thus this sampling setting is appropriate. The frequency of each sound generated is documented in Table 1, and repeated sound frequencies are not recorded. If only one sound frequency is found for the A-tone, it indicates that the same sound frequency was produced with each of the six strikes. It is evident that the B-tone can have multiple possible frequencies, indicating richer vibrational profiles of the almond-shaped bell. For the B-tone, only the one to two frequencies deemed by the corresponding author of this article to be relevant are converted into musical notes.

Thirdly, the sound frequency analysis in Audacity needs explanation. For example, Figs. 6 and 7 showcase charts of the frequency analyses of the sounds generated by striking the A- and B-tone positions of two of the ten Shiguzhai bells from the June 1993 find. They display the frequency spectra of the vibration of the bell tones. The vibration of the bell generates the fundamental tone, shown in Figs. 6 and 7, as the first major peak, together with a number of overtones, which are set aside for future exploration. The frequency analysis considers the first major peak for each of the two tones of each bell. Occasionally, the fundamental tone of a given B-tone may not be as noticeable as that of the A-tone and the first major peak may blend with other peaks, making it hard to distinguish the fundamental tone of the B-tone.

The uncertainty surrounding the B-tone can be attributed to several possible causes. Corrosion of these three-thousand-year-old bells might cause fuzziness of the tones. If, however, the bells are not heavily corroded, this possibility can be dismissed. In addition, the cultivation of the B-tone might still have been in process of experimentation. Awareness of the existence of the B-tone on any bell during this period is actually doubted by a group of music historians, who believe that the awareness and practice of producing the B-tone did not emerge until the Western Zhou period, from the tenth century BCE onwards, when bird motifs appeared on the strike areas [13]. This, however, poses the question of whether bell musicians truly needed visual markers to remind them of the appropriate strike positions. An adept pianist does not need a marker to locate the C4 key and a proficient violinist does not require a label to identify the G string. Why, then, would an experienced bell player need a bird motif to guide them to the B-tone strike positions? Any marker indicating the strike position of the B-tone might

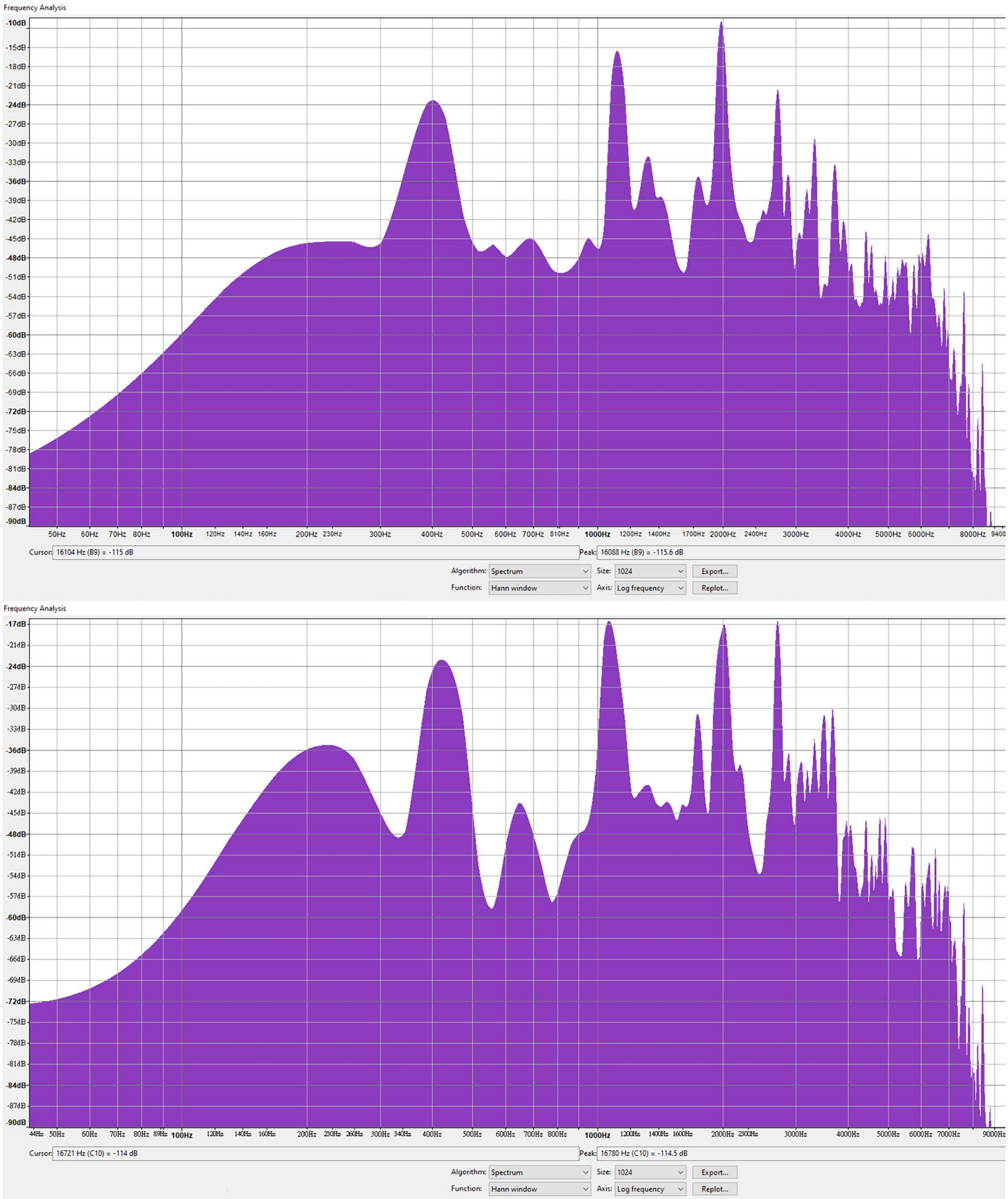


**Fig. 6** Top: frequency analysis of the A-tone of bell no. IX of the ten Shiguzhai bells (accession no. of the Changsha Museum, 1632.6), conducted via the Audacity software. The first and major peak is interpreted as its fundamental tone. Bottom: B-tone of bell no. IX

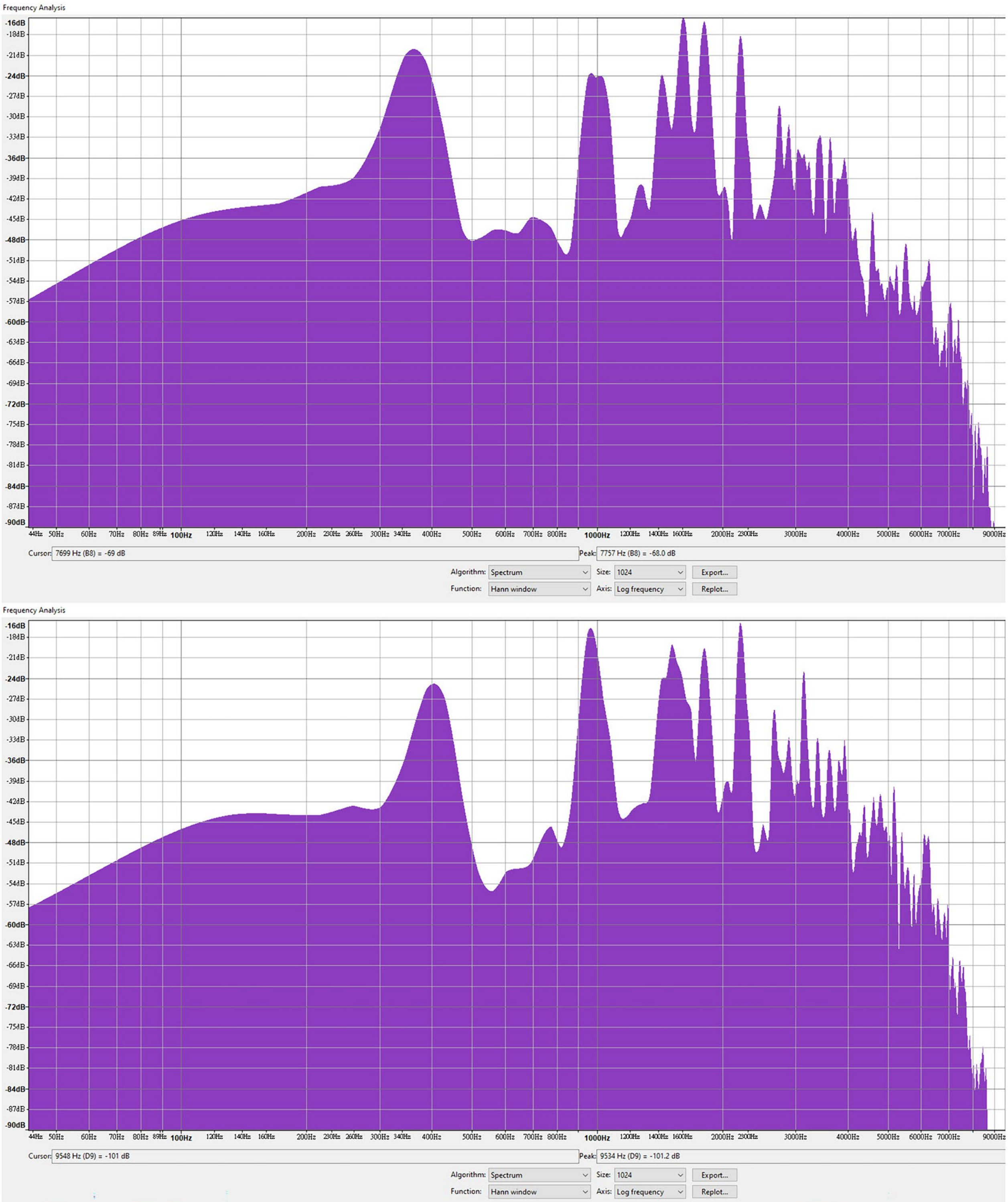


**Fig. 7** Top: frequency analysis of the A-tone of bell no. XII of the ten Shiguzhai bells (accession no. of the Changsha Museum, 1632.3). Bottom: B-tone of bell no. XII

merely have been part of a bell's decoration. Their presence could have served to inform any ordinary audience member who did not know how to play a bell.

The techniques for making a bell produce a B-tone might have been under development, resulting in a B-tone that was not as clear as the A-tone. Given the large size, thickness, and weight of these bells, it was a significant technological feat to simultaneously control both tones. In the present day, in fact, we still do not fully understand how to produce a bell with two desired tones from scratch. A bell designed to produce a desired A-tone may not necessarily yield the intended B-tone. Currently, we still rely on replicating bells with two already known tones to reproduce bells to form a bell ensemble. The twelfth century BCE casters of the Shiguzhai bells were possibly, then, experimenting with ways in which to stabilize the B-tone while maintaining the desired A-tone.

Based on the corresponding author's experience in playing the bells, each of the two tones produced by a single bell can vary slightly, even when the same player strikes the same position with the same force. The A-tone is more stable, generated as it is by striking the central, flatter part of the bell's strike area. The striking angle for the A-tone does not, therefore, alter much during striking. However, the strike positions of the B-tone are on the curved side parts of the bell, and as a result, a player's mallet may slip slightly, leading to slight variations in the striking angle and hence to varied vibrations of the bell's sounding body. Alternatively, the striking angle may simply differ because it is challenging to maintain the same angle every time. While the striking force does not change the absolute pitches generated on a bell, it does alter the striking angle. Any change in striking angle therefore leads to variation in the bell's vibration, resulting in the B-tone being less stable than the A-tone. This observation can be referred to in Table 1. This phenomenon is not exclusive to the twelfth century BCE bells. While other scholars might believe that bells produced in this period were immature in their two-tone feature, it is a fact, according to the corresponding author's personal experience, that even some well-cast bells from 500 BCE found in Henan province in North China do not always produce a B-tone as steady as the A-tone.

Given these conditions, striking the B-tone positions twelve times, or occasionally more, resulted in a wider range of sound frequencies than those of the A-tone. For instance, the A-tone of bell no. I is consistently around 280 and 279 Hz, which are basically the same pitch. Its B-tone, however, varies from 269 to 283 Hz, ranging from C4 + 48 to C#4 + 36, which is a larger variation. The B-tone of bell no. III ranges even more, from 306 to 350 Hz, spanning D#4-29 to F4 + 4. As for bell no. VII, its B-tone ranges from 402–406 Hz, or from G4 + 44 to G#4-39, which can be considered almost the same. The corresponding author's approach is to record all sound frequencies generated by the bells and to make this data available to readers, enabling interested parties to determine the possible range of tones the bells could produce when tested in 2022. We also know that factors such as temperature, humidity, and possible resonance with nearby objects can also alter the sound frequencies of bells, and thus their tones. Nonetheless, the corresponding author's approach allows us to distinguish what possible pitches might have been available to the players in the twelfth century BCE, and what pitches they were likely to have preferred to produce.

It may be hypothesized that the ancient casters were experimenting with developing the two-tone feature, although they may have occasionally failed in their task. In this context, the musical notes recorded for the B-tone in Table 1 should be interpreted as ranges rather than as precise notes. For example, the B-tone of bell no. I is recorded as C#4 + 36, but we can conceptually allow for the fluctuation of this note and acknowledge that its B-tone can produce a range of pitches ranging from C4 to C#4, plus and minus a certain number of musical cents, or even reaching as far as B3 or D4. Realizing the possible range of the B-tone or the A-tone that a bell could produce, rather than pursuing a single, precise musical note such as the one heard when pressing a key on a modern grand piano, will help to provide a better understanding of what possible pitches were available to the ancient casters and musicians. Given the related technical difficulties, a twelfth century BCE bell player would have had to carefully control their mallets in order to maintain a stable striking angle. While more experienced players may well have known how to produce the two desired, high-quality tones from each bell, they did not pass this knowledge directly onto us.

The clear distinctions and stable intervals between A-tones and B-tones on the ten bells (I to X), as presented in Table 1, suggest awareness and deliberate practice on the part of their casters. The intervals of the two tones on any of the bells were not spaced to the same intervals as those deemed to be harmonious by modern music historians, nor were they familiar to historians of later generation bells whose two-tone intervals were major thirds or minor thirds. For some bells, even, the B-tone is almost the same as the A-tone. The fact that cannot, however, be disregarded is that these bells exhibit a tendency towards gradual changes in pitch. Table 2 presents the spectrum of possible sound frequencies produced by the ten bells, with the exclusion of those that are repetitive. It can be seen that this spectrum ranges from C4 to A4. Although the twelfth century BCE bell players might not have used

**Table 2** Pitch distribution of the ten Shiguzhai bells found in June 1993

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | C4+48 | C#4+18<br>C#4+36 | D4+14 | D#4+10<br>D#4-29<br>D#4+10<br>D#4-1 | E4-19<br>E4-24 | F4+4<br>F4+28 | F#4-28<br>F#4+32<br>F#4-19<br>F#4-38<br>F#4+42 | G4+44<br>G4+48<br>G4+44 | G#4-39<br>G#4-26<br>G#4+32<br>G#4-22<br>G#4-10 | A4-12 | | |
| Octave / Pitch | C | C# | D | D# | E | F | F# | G | G# | A | A# | B |

all of the pitches listed in Table 2, the available spectrum still yields valuable clues.

Given the expected variation and fluctuations in bell pitches, Table 2 shows that the pitch range extends from C4 to A4, with virtually no gap between these two pitches within the same octave. Specifically, ten of the twelve consecutive semi-tones can be found within the same octave. Robert Bagley inferred from the 1997 test report published by the Changsha Museum that the ten bells can yield nine consecutive semi-tones within the same octave: C#4, D4, D#4, E4, F4, F#4, G4, G#4, A4. He further posits that this evidence strongly suggests the first ever discovery of the chromatic scale in world history [4]. C4 can now potentially be included in this scale, although it is subject to further testing and discussion due to the allowance made for the pitch range and variation. Regardless of whether the ten bells can yield nine or ten consecutive tones, they are capable of generating a series of progressive pitches in the form of consecutive semi-tones within the same octave. The likelihood of this being mere coincidence is extremely low, and indicates that the ten bells could indeed form a musical set.

The inclusion of additional bells from the Shiguzhai finds reduces even further any likelihood of coincidence. The upper section of Table 3, shown in normal font, is a simplified version of Table 2. Meanwhile, the lower section, shown in *italics*, represents the pitches generated from two additional bells that have so far been tested—the Ningxiang-Shiguzhai-Feng2 bell from the August 1993 find, and the Ningxiang-Shiguzhai-elephant1 bell from the 1959 find. It is known from the *Daxi* that the two tones of the Ningxiang-Shiguzhai-elephant1 bell are G#3–45 and A#3–23. The corresponding author of this article struck the Ningxing-Shiguzhai-Feng2 bell in the large window case where it is displayed, and recorded its two tones as A#3–31 and B3-29. Although the testing condition was not ideal, since resonance within the window case may have directly altered the bell's two tones, this is currently the best reliable result available. We see that the range of pitches produced by the ten bells from the June 1993 find is supplemented by the pitches yielded by these two additional bells. A series of thirteen almost consecutive semi-tones, with only the A3 pitch missing, spanning two neighboring octaves from G#3 to A4, can be identified across the twelve bells. Combined with Bagley's observations, this finding significantly reduces the possibility of coincidence even further. All the available pitches have formed a series of progressive, consecutive pitches, thus making the twelve bells a viable musical ensemble.

## Bells with gradually changing sizes as a set

The overall height of each of the ten bells from the June 1993 find has been used as a critical point of contention regarding whether or not the bells could form a set, because they do not display incremental height changes (Table 1). This issue can however be addressed

**Table 3** Distribution of the currently known pitches of the Shiguzhai bells

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | C4 | C#4 | D4 | D#4 | E4 | F4 | F#4 | G4 | G#4 | A4 | | |
| 3 | | | | | | | | | *G#3* | | *A#3* | *B3* |
| Octave / Pitch | C | C# | D | D# | E | F | F# | G | G# | A | A# | B |

by focusing on other measurements of the bells. Each bell consists of a long shank and a sounding body. Considering that a bell only supported by its shank could easily fall, it was likely that the shank was inserted into something else to stabilize the entire bell so that it could be struck [1, 26, p. 35]. In this scenario, the overall height of a bell would not have been visible when it was being played and struck. Instead, only the main sounding body would have been revealed to the audience, and only the main sounding body contributed to the vibration. When the focus is on the size of the sounding body, the data shows a different picture.

The side length, spine length, and girth of the lip-mid-hip (LMH) of the ten bells shown in Table 1, along with those of the two additional bells, show some gradual, steady changes, despite that they are not perfect and we do not have the relevant measurement data of the Ningxiang-Shiguzhai-Feng2 bell. Through incorporation of the data of the *xianjian* and *gujian* of the cavity that is the space enclosed by the bell walls, and the *wuxiu* and *wuguang* of the cavity, we can see steady incremental changes across the ten bells. These range from larger bells with lower pitches to smaller bells with higher pitches, which nicely align with the acoustic properties of objects. Girth and cavity should therefore become the new points of focus for future bell measurements.

## Conclusion

A list of arguments we have so far made can be summarized as follows:

1. Similar designs might not be that important in forming a musical bell set; however, different criteria should be reconsidered for this case;
2. Progressive pitches and gradually changing sizes are critical factors in identifying a musical bell set;
3. Additional bells that fit these two factors might be considered when identifying a bell set.

By shifting the focus from the general size of the bells to other factors such as their two tones, valuable insights may be gained into musical developments in the twelfth century BCE. It is highly probable that intentional musical, acoustic, and casting experiments were being conducted during this time, which led to a host of innovations. Bell casters in that era dedicated tremendous effort into exploring the relationship between the size and tones of bells, even although they experienced failures. At times, they produced larger bells that yielded higher pitches, and at other times, smaller bells with lower pitches. They chose not to melt down these bells that were anomalous to the intended set because the bells still provided some of their desired pitches. They were experimenting in how to control the size and the two tones of the bells, and through these investigations, they may well have discovered the chromatic scale, as evidenced by the nine (Bagley's version), ten, or even thirteen (corresponding author's version) consecutive semi-tones that can be sounded on the bells. The bells that can provide all these compatible, progressive pitches could indeed form a musical set. Considering the progressive changes in the size of their sounding bodies, it is hard to deny that it was indeed their casters' intention to create a set of bells for both performance and display.

If we focus on the designs of the bells to determine whether they could form a design set, then only the nine bells from the June 1993 finds fit the criteria. Following this logic would, however, require that many more bells with highly similar designs be included in this set. This would then necessitate the testing of the two tones of all these bells. As many bells unearthed from South China have not yet been tested, our understanding of the full scope of the development of bell cultures in ancient South China remains incomplete.

If we focus on the geographical context of the bells to determine if they could form a set, then all seventeen bells found on Shiguzhai hill must be tested. It is possible that this approach may lead to more exciting discoveries as Table 3 could be populated with more data. Nonetheless, as it stands, the data shown in Table 3 already presents a convincing piece of evidence for the formation of a playable set of musical bells that were produced through application of an experimental approach by casters with an innovative production mindset.

**Acknowledgements**

The authors extend a debt of gratitude to Josh Yiu of the Art Museum, The Chinese University of Hong Kong, who kindly permitted the team to examine the bell collection of the museum. Sincere appreciation is also expressed to all curators and staff at the museums and archaeological institutes referenced in this article, and David Tsang and Venus Ng for their tremendous help in data input. Furthermore, the invaluable insights provided by Robert Bagley and the anonymous reviewers have significantly enriched this study. Their efforts are deeply acknowledged and appreciated. All remaining errors belong to the corresponding author.

**Author contributions**

KSSL is the corresponding author who designed the framework of the project, acquired most of the data, interpreted the data, drafted the first version of the manuscript, prepared all of the images, figures, and tables, and is responsible for all other tasks not mentioned here, and the errors that are found herein are his alone. YL provided access to the Changsha Museum and helped acquired most of the data. GCM, KIL, and KPN contributed to the revision of the manuscript. HWL, KW, and QF provided the team with access to the research materials and technical assistance in their institutes. XQC, KSL, and THC were the technical supporting staff to help draft the tables. JMP and XQ provided advice from a musical historian's perspective to the team. HRJ assisted in collecting research materials. They all reviewed the manuscript.

**Funding**
The work described in this paper was partially supported by grants from the Research Grants Council of the Hong Kong Special Administrative Region (HKSAR), People's Republic of China (Project No. HKBU 12618422 and 22601019), and Quality Education Fund E-Learning Ancillary Facilities Programme (2021/0257) awarded to the corresponding author.

**Data availability**
No datasets were generated or analysed during the current study.

## Declarations

**Competing interests**
The authors declare no competing interests.

Received: 11 February 2024 Accepted: 16 July 2024
Published online: 30 July 2024

**References**

1. Gao ZX. A comprehensive discussion of Shang-Zhou period bronze *nao*-bells found in South China **中國南方出土商周銅鐃概論**. In Hunan Provincial Institute of Relics and Archaeology (Ed.), Anthologies of Hunan archaeology, vol. 2 **湖南考古輯刊第二集**. Yuelu Press; 1984. pp. 128–35 (**in Chinese**).
2. Castelluccia M, Dan R. Caucasian, Iranian and Urartian bronze bells. Ancient Civ Scythia Siberia. 2014;20:67–104. https://doi.org/10.1163/15700577-12341261.
3. Ma CY. Two-tone bronze bells of the Shang-Zhou period **商周青銅雙音鐘**. Acta Archaeol Sin **考古學報**. 1981;1:131–46 (**in Chinese**).
4. Bagley R. Prehistory of Chinese music theory. Proc Br Acad. 2005;131:41–90.
5. Bagley, R. Percussion. In: So JF (Ed.), Music in the age of Confucius. Smithsonian Institution; 2000. pp. 35–63. https://doi.org/10.5479/sil.850012.39088016680316.
6. Jing M. A theoretical study of the vibration and acoustics of ancient Chinese bells. J Acoustic Soc Am. 2003;114(3):1622–28. https://doi.org/10.1121/1.1600727.
7. Morrison AC, Rossing TD. Percussion musical instruments. In: Bader R, editor, Springer handbook of systematic musicology. Springer; 2018. p. 157–70. https://doi.org/10.1007/978-3-662-55004-5_9.
8. Debut V, et al. The sound of bronze: Virtual resurrection of a broken medieval bell. J Cult Herit. 2016;19:544–54. https://doi.org/10.1016/j.culher.2015.09.007.
9. Debut V, et al. Reverse engineering techniques for investigating the vibro-acoustics of historical bells. In: Tahar F, et al. editors, International conference on acoustics and vibration ICAV 2018: Advances in acoustics and vibration II. Springer; 2018. p. 218–26. https://doi.org/10.1007/978-3-319-94616-0_22.
10. Mercuriali G. Computation imagination and digital art history. Int J Digit Art Hist. 2018;3:140–51. https://doi.org/10.11588/dah.2018.3.47287.
11. Cekus D, et al. Quality assessment of a manufactured bell using a 3D scanning process. Sensors. 2020. https://doi.org/10.3390/s20247057.
12. Parfenov V, et al. Use of 3D laser scanning and additive technologies for reconstruction of damaged and destroyed cultural heritage objects. Quant Beam Sci. 2022. https://doi.org/10.3390/qubs6010011.
13. Huang XP. Known materials of music artifacts of the Neolithic and Bronze Age and problems of the history of development of musical scales in China **新石器和青銅時代已知音響資料與我國音階發展史問題**. Part 1, in: Editorial Team of Discussions of Music (Ed.), Discussions of music **音樂論叢**. 1978;1:184–206. Part 2, in: Discussions of music. 1980;3:126–61. People's Music Press (**in Chinese**).
14. Wu S. Refining technopoiesis: Measures and measuring thinking in ancient China. Philos Technol. 2023;36(22):1–41. https://doi.org/10.1007/s13347-023-00623-w.
15. Kunej D, Turk I. New perspectives on the beginnings of music: Archaeological and musicological analysis of a middle Paleolithic bone "flute." In: Wallin NL, Merker B, Brown S, editors, The origins of music. MIT Press; 2000. p. 235–68. https://doi.org/10.7551/mitpress/5190.003.0020.
16. Shelach G. The Qiang and the question of human sacrifice in the late Shang period. Asian Perspect. 1996;35(1):1–26.
17. Keightley, D. The ancestral landscape: Time, space, and community in late Shang China, ca. 1200–1045 BC. Institute of East Asian Studies, University of California, Berkeley, Center for Chinese Studies; 2000.
18. Chen Z. From exclusive Xia to inclusive Zhu-Xia: The conceptualisation of Chinese identity in early China. J R Asiat Soc. 2004;14(3):185–205. https://doi.org/10.1017/S135618630400389X.
19. McNeal, R. Erligang contacts south of the Yangzi River: The expansion of interaction networks in early Bronze Age Hunan. In: Steinke K, Ching D, editors, Art and archaeology of the Erligang civilization. P.Y. and Kinmay W. Tang Center for East Asian Art, Department of Art and Archaeology, Princeton University; 2014. p. 173–90. https://www.academia.edu/37623870/Erligang_Contacts_South_of_the_Yangzi_River_The_Expansion.
20. Campbell R. Violence, kinship and the early Chinese state: The Shang and their world. Cambridge University Press; 2018. https://doi.org/10.1017/9781108178563.
21. Ma J, et al. Metal trade and national integration: Bronze technology and metal resources of Yue style bronzes from Hunan (8–5 c. BCE). Herit Sci. 2023;11(128):1–12. https://doi.org/10.1186/s40494-023-00973-w.
22. Rawson J. Western Zhou ritual bronzes from the Arthur M. Sackler Collections (2 parts). Arthur M. Sackler Foundation and the Arthur M. Sackler Museum, Harvard University; 1990.
23. Falkenhausen LV. Chinese society in the age of Confucius (1000–250 BC): The archaeological evidence. Cotsen Institute of Archaeology, University of California, Los Angeles; 2006. https://doi.org/10.2307/j.ctvdmwwt6.
24. Cao B, Chen B. Ritual changes and social transition in the Western Zhou period (c.a. 1050–771 BCE). Archaeol Res Asia. 2019;19(100107):1–9. https://doi.org/10.1016/j.ara.2018.04.002.
25. Li F. Landscape and power in early China: The crisis and fall of the Western Zhou, 1045–771 BC. Cambridge University Press; 2006. https://doi.org/10.1017/CBO9780511489655.
26. (Daxi) Editorial team of Chinese music artifacts (Ed.). Chinese music artifacts **中國音樂文物大系**. Series II, Hunan volume **湖南卷**. No vol. no. Daxiang Press; 1999–2007 (**in Chinese**).
27. Changsha Museum. Bronze *nao*-bell set unearthed at Laoliangcang, Ningxiang Hunan **湖南寧鄉老糧倉出土商代銅編鐃**. Cult Relics **文物**. 1997;12:16–27 (**in Chinese**).
28. Lehr A. Campanology textbook: The musical and technical aspects of swinging bells and carillons. Originally published in Dutch, translated to English by Kimberly Schafer. The Guild of Carillonneurs in North America; 2005.
29. Jin X, Wang X, Pu H, et al. Nondestructive testing technologies of cultural relics by using audible sound and ultrasonic wave. In: Osman A, et al. editors, Advanced nondestructive and structural techniques for diagnosis, redesign and health monitoring for the preservation of cultural heritage. Springer; 2024. pp. 41–51. https://doi.org/10.1007/978-3-031-42239-3_4.
30. Jin X, Wang X, Cao X, et al. Construction and recognition of acoustic ID of ancient coins based on deep learning of artificial intelligence for audio signals. Herit Sci. 2023;11(46):1–7. https://doi.org/10.1186/s40494-023-00891-x.
31. Jin X, Wang X, Xue C. Nondestructive characterization and artificial intelligence recognition of acoustic identifiers of ancient ceramics. Herit Sci. 2023;11(144):1–10. https://doi.org/10.1186/s40494-023-00990-9.
32. Audacity Team. Audacity®: Free Audio Editor and Recorder [Computer application]. Version 3.1.3. Accessed on August 9, 2021. Audacity® software is copyright © 1999–2021 Audacity Team. It is free software distributed under the terms of the GNU General Public License. The name Audacity® is a registered trademark. 2021. Website: https://audacityteam.org/.
33. Li KS, et al. Decorated model, replication, and assembly line of the bronze industrial production in 500 BCE China. Early China. 2021;44:109–42. https://doi.org/10.1017/eac.2021.9.
34. Peng P. Between piece molds and lost wax: The casting of a diatrete ornamentation in early China rethought. Hum Soc Sci Commun. 2023;10(456):1–12. https://doi.org/10.1057/s41599-023-01984-5.
35. Chen QY. Doubts about the bronze *nao*-bell set unearthed at Laoliangcang Ningxiang **寧鄉老糧倉出土銅編鐃質疑**. Cult Relics. 2001;8:43–45 (**in Chinese**).

36. Cho GJ. The discovery of musical equal temperament in China and Europe in the sixteenth century. Edwin Mellen Press; 2003.
37. Scott C. Technology in a new key: Toward a reexamination of musical theory and practice in the Zeng Hou Yi bells. T'oung Pao. 2020;106:219–65. https://doi.org/10.1163/15685322-10634P01.
38. Bagley R. Ancient Chinese bells and the origin of the chromatic scale. In: Center for the Study of Art and Archaeology, Zhejiang University (Ed.), Zhejiang University Journal of Art and Archaeology, vol. 2. Zhejiang University Press; 2015. pp. 56–102.

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