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Metallic Idiophones 800 BCE–800 CE in Central Europe: Function and Acoustic Influence – A Progress Report

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Abstract

Our project is focused on metal sound objects of the Early Iron Age (Hallstatt Culture), the Roman period, and the period of the Avar Khanate in the Carpathian Basin (Early Middle Ages). The idiophones originate from burial and settlement contexts. Our goal is to gain new information on their function, on tonal influence on ancient peoples' daily lives, and their impact on society. This interdisciplinary project combines archaeological, metallurgical, acoustical, psychoacoustical, ethnomusicological, and psychological methods supported by experimental archaeology and handcraft experience, as well as by ancient written and iconographic sources. In this article we report on the status of our current results. We present three case studies, one for each period, and an acoustic and psychoacoustic overview of all currently investigated sound objects. Analyses of textile remains adhering to pellet bells complete this paper.

Keywords

Bells – Pellet bells – Costume accessories – Acoustics – Psychoacoustics – Archaeometallurgy – Archaeological textiles

1 Introduction and the project

The research project "Metallic Idiophones between 800 BCE and 800 CE in Central Europe" will investigate metallic sound artefacts (idiophones) of different kinds, dated to three different archaeological periods. It is funded by the Austrian Sciences Funds FWF and supported by the Natural

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History Museum Vienna. The selected sites are located in the heart of Europe, from Western Switzerland, across Austria, and to Western Hungary and Western Slovakia (see Figure 1). The items date to the Early Iron Age, the Roman Period, and the Early Middle Ages.

The Hallstatt Culture (800–450/400 BCE) dominated the Early Iron Age in Central Europe. Fibulae with interlinked chains, rattling pendants and small cymbals, various combinations of ring pendants (rings interlinked), fancifully created pendants with jingles and cage-like pellet bells, and bobbles with jingles belong to women's costume accessories of this period. When beaten against each other, their jingles and pendants create sounds. This sounding jewellery has been found in burials, in both cremation and inhumation graves. The Prehistoric Department of the Natural History Museum Vienna houses a large part of the excavated objects from the famous Hallstatt necropolis in Upper Austria in its collection and still is excavating the site (Grömer and Kern 2018). Although the first author of this article already investigated a large sample of the objects (Pomberger 2016: 112–41), there still remain some items to be examined and analysed. While cage-like pellet bells and bobbles are rather rare in Hallstatt Culture, several of these artefacts were found in tumuli in western Switzerland (Drack 1966/67). They are now in the collections of the Bern History Museum (Bachmann-Geiser 2001) and the *Archäologischer Dienst des Kantons Bern* (Ramstein and Cueni 2012). An ensemble of seven cage-like bobbles and house-shaped pendants, both with jingles, originate from the Býčí skála cave, an Iron Age sacrificial site near Brno, Czech Republic, and are now part of the collection of the Natural History Museum in Vienna (Parzinger et al. 1995). A large number of bells are known from the Roman period. The bells investigated in this project come from settlements and military camps along the Roman Limes at the Danube and its vicinity in Austria: Iuvavum/Salzburg, Ovilava/Wels, Vindobona/Vienna, Carnuntum/Petronell-Carnuntum and Bad Deutsch-Altenburg, and Savaria/Szombathely in Hungary. They are housed in the archaeological collections of the Salzburg Museums, the City Museum of Wels, the "Wien Museum", the "Stadtarchäologie Wien", the Museum Carnuntinum, and the Savaria Museum. The pellet bells

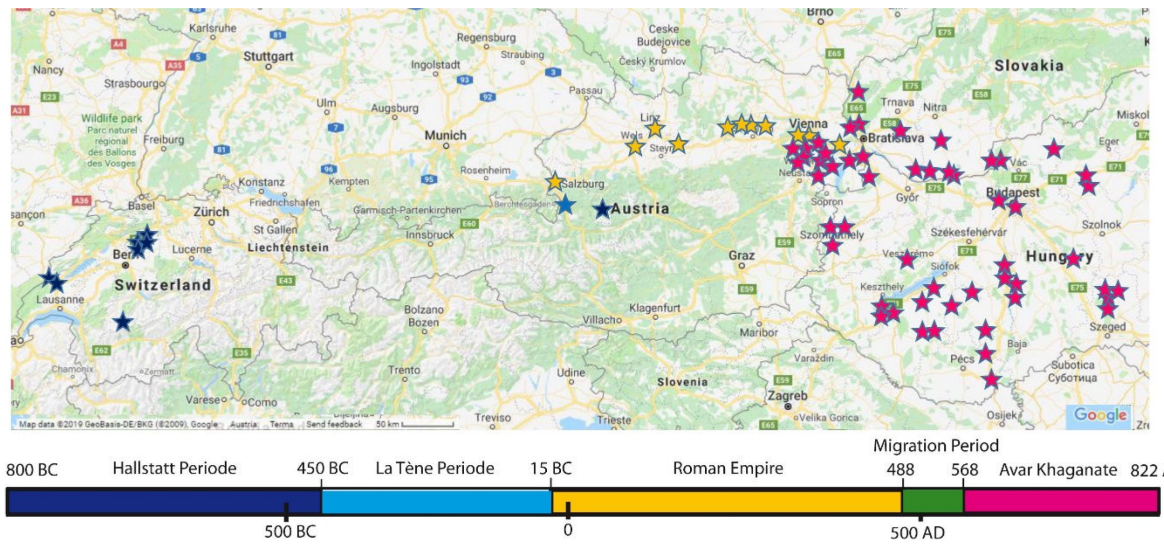

Figure 1: Map of sites with timeline. Map data: Google Earth/Google Maps; Design: B.M. Pomberger.

from the Early Middle Ages originate from the Avar period in Hungary, Slovakia, and East Austria. They are kept in the archaeological collections of the *Wien Museum*, the Slovak National Museums in Bratislava and Martin, the Danube Region Museum in Komárno, the Hungarian National Museum in Budapest, the Rippl-Rónai Museum in Kaposvár, and the Balaton Museum in Keszthely. In total there are more than 500 objects that fall under the purview of this article. We will present three case studies, one from each period, and then show an overview of all our acoustic and psychoacoustic results so far. However, it must be noted that sounds can only be studied as they can be produced and recorded today. Centuries of storage in the ground have corroded the objects. In the course of this process, the metals interact with their environment in a physicochemical way due to moisture and oxygen. Salts are deposited in the material, thus changing the chemical composition on the surface or throughout the entire body (Kaesche 1979). Although copper alloys form an oxygen-impermeable protective layer, this impairs the sound of the metal idiophones. Iron objects react so strongly that only in the rarest cases do they still sound. Corrosion not only changes the chemical composition but also the specific weight, which along with the shape of the sounding body plays an important role in the sound (Mühlhans et al. 2022; Mühlhans and Pomberger forthcoming). In addition to the above-mentioned investigations and aspects, we also examined textile residues that adhered to the sound objects in order to obtain information about their connection to the objects and the possible functions of the instruments, as well as the visual appearance (clothing) of people who carried the idiophones.

2 Research questions, methods, and terminology

When we were confronted with the plenitude of the different objects, several research questions arose, which we try to answer in our project. They can only be answered using interdisciplinary methods (see Figure 2) and we therefore created an interdisciplinary network with experts.

2.1 Research questions discussed in this paper

First, we wanted to find out what information could be obtained from the sound objects and the context of the finds that gave evidence about their function. Since we knew that we were dealing with sounds as they can be produced and recorded today, and because corrosion changes the material and thus the sounds, we needed to determine what information we could gain from the recorded sounds about frequency ranges, sound levels, and psychoacoustic parameters, as well as which metal alloys were used to produce the objects, and what their individual chemical compositions were. In addition, we investigated the influence of the materials on the produced sounds. Some pellet bells had textile residues adhered on their surfaces, so we wanted to determine their composition and the relation of this material to the pellet bells (Pomberger et al. 2021a). Finally, we investigated the possibility that the sound objects had any additional meaning.

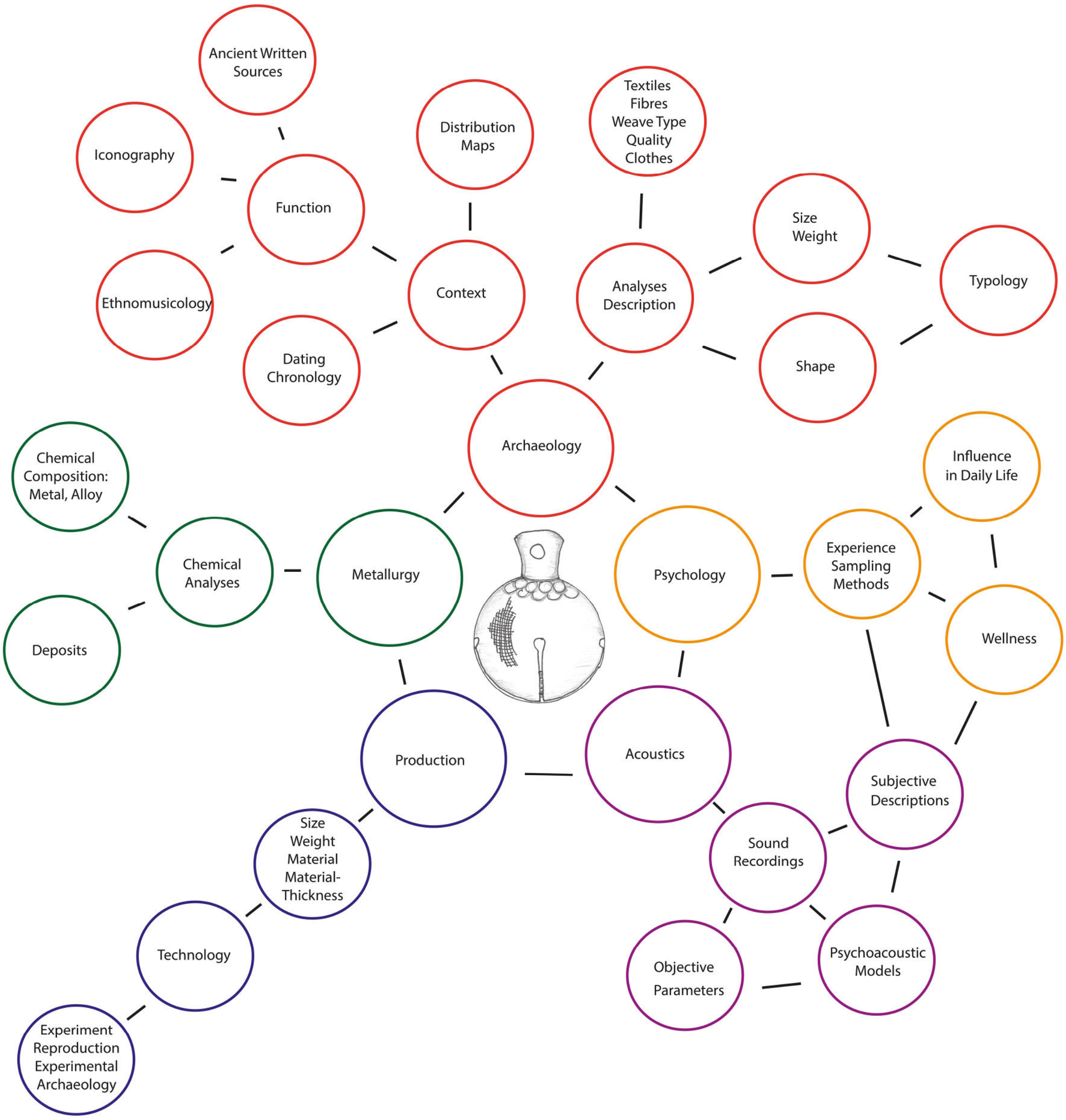

Figure 2: Model of the interdisciplinary research project. Design: B.M. Pomberger.

2.2 Methods

First, contextual analyses, measurements of the sizes and weights of the objects, classifications into types, and statistics regarding the quantitative occurrence within a site were carried out. Drawings and photos of the objects were made and extensive databases were created. Furthermore, distribution maps of the objects within the settlements and cemeteries were created and compared. In order to collect more information about the function of the idiophones in early history, ancient written and iconographic sources were studied (Pomberger et al. 2022a; Hackl and Pomberger 2022) and ethnological sources were likewise consulted. The chemical compositions of the idiophones were analysed by using X-ray fluorescence analysis and electron scanning microscopy. In order to determine the influence of metals and metal alloys on the sound, selected idiophones of the same size but made of different materials were produced and analysed (Mühlhans et al. 2022; Mühlhans and Pomberger forthcoming). Standardised analytical methods of textile archaeology comprise the analysis of weaving type, technical details about the textile qualities, and the fibre type. The sound recordings of the original idiophones were recorded in a specially designed portable recording studio with a damping of 20 mm, which was constructed for recordings in the various collections and museums. Even though the insulation cannot protect recordings from very low frequency noise, it is still quite sufficient for mid and high frequencies with a dampening effect of 21.4 dB on average (Pomberger and Mühlhans 2022). The sound recordings are analysed using Adobe Audition 2022. More complex analyses consist of a variety of audio features such as MFCCs35, which measures pitch strength[1] or impulsiveness[2], and are done using a variety of software packages within MATLAB or Python. Psychoacoustic parameters are calculated using HEAD ArtemiSuite (see also Pomberger et al. 2021b; Pomberger et al. 2020).

2.3 Terminology and definitions of acoustics and psychoacoustics

The sounds of idiophones have certain physical properties that clearly distinguish them from other types of sounds (e.g. aerophones or chordophones). Vibrating strings or air columns (e.g. in flutes, whistles, etc.) always have a fundamental and overtones or partials that are integer multiples of the fundamental, meaning from a physical point of view a harmonic oscillation or a sound. This is not the case with idiophones (formerly also often called “autophones”). In bodies that vibrate when they are excited, e.g. by striking, several partial oscillations are formed. These partial oscillations produce frequencies that are not integer multiples of a fundamental. Since the harmonic structure is missing, we speak physically of a “mixture of tones” rather than a sound. In physics/acoustics, a “tone” is only a single sinusoidal oscillation. What we describe using the language of music as a tone is – from the point of view of the physical world – a sound. The harmonic structure also plays an important role in the perception of pitch. In idiophones this is not clearly or only weakly pronounced.

Psychoacoustics is part of psychophysics and deals with the correlations between human auditory perception and the physical acoustic properties of sounds. The discipline explores which are the proportion of measurable acoustic parameters – such as fundamental frequency, partials, spectral parameters, temporal fluctuation, etc. – as well as subjective sound characteristics such as loudness, brightness, sharpness, roughness, etc. Psychoacoustic parameters are modelled by considering the properties of the human ear (e.g. critical bandwidths, see Fastl and Zwicker 2007: 149). This enables sounds and noises to be calculated by a computer and compared directly with each other.

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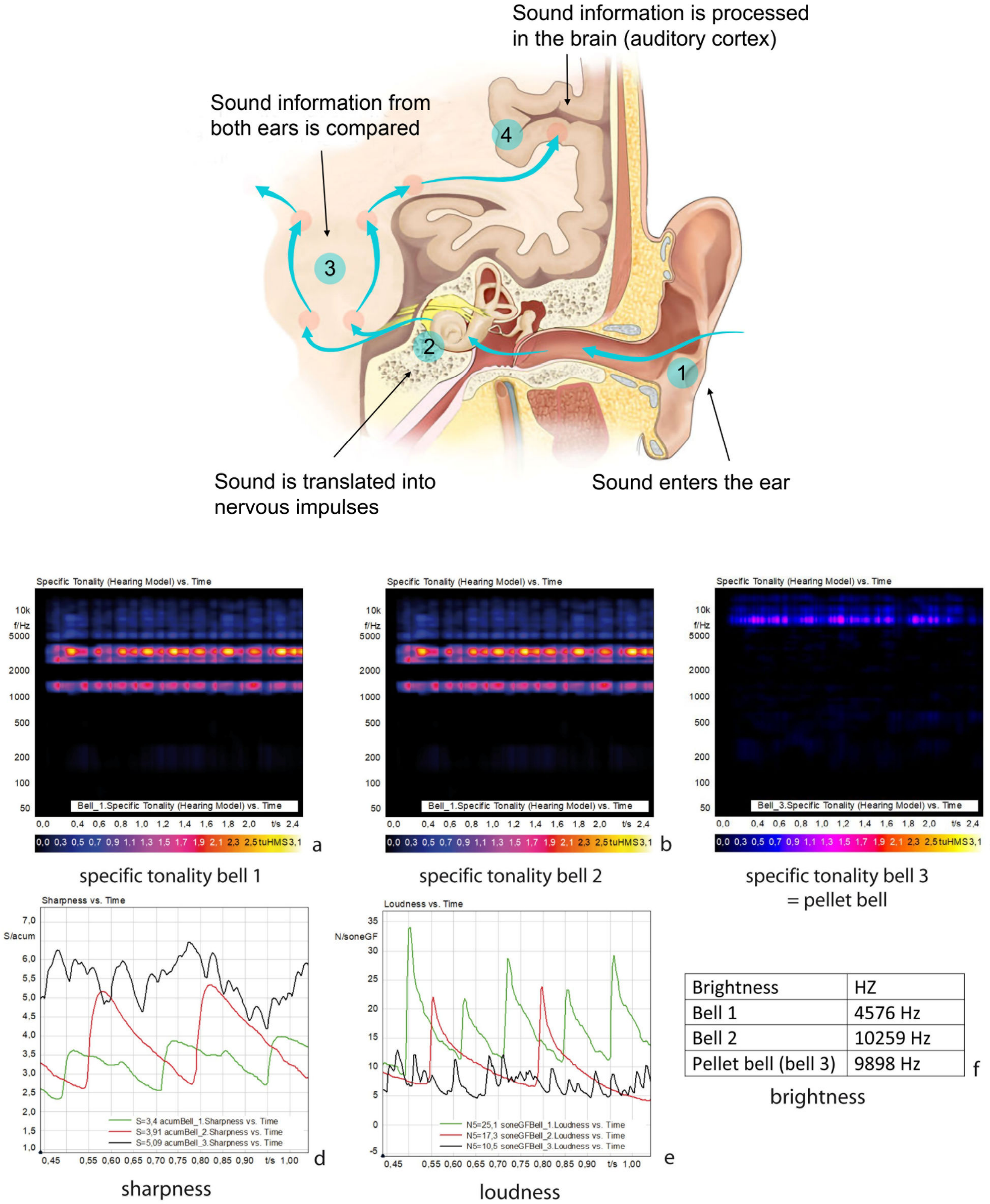
[1] MFCC stands for ‘mel frequency cepstral coefficients’ and is commonly used to calculate spectral similarities in sounds.

[2] Pitch perception is subjective but depends mainly on the harmonic structure of a sound, and thus can be predicted with pitch strength.

In 1984, Wolfgang Aures wrote in his publication that the "sensory euphony [...] is influenced by roughness, sharpness, loudness and sonority" (Aures 1984: 735). These parameters also play a central role in today's psychoacoustic research and are used for calculating the measurement of the sound objects at hand. Loudness (German: *Lautheit*) describes the subjective perception of the objectively measurable intensity of a sound event. The physical unit that measures this objective intensity is sound pressure (Pa, pascals) or sound pressure level (SPL, decibels). This measure, if given in decibels, is commonly referred to as level (German: *Pegel*). If talking about the perceived intensity, which is called loudness, the units sone (German: *Lautheit*) or phon (German: *Lautstärke-pegel*) are commonly used. The distinction in the German language does not exist in English. Both units are well defined in research resulting from various psychoacoustic experiments, and thus can be called psychoacoustic parameters. Volume (German: *Lautstärke*) and other terms often found on the knobs of audio equipment, are not clearly defined, have no scientific unit of measurement and can therefore not be used in a scientific context.

Loudness depends, among other things, on the sound pressure or sound pressure level, but must not be equated with it. Especially in the frequency range of the sound objects to be examined, for example between 2 and 5 kHz, the human ear is particularly sensitive (Gelfand 2010: 166). Therefore, the sound pressure level can lead to the subjective impression of high loudness/volume. Heinrich Barkhausen introduced the unit phon as a measure of loudness level in 1926, where 0 phon represents the human hearing threshold and 1 phon represents the smallest perceptible change in magnitude. In 1933, the curves of equal loudness levels were defined by Fletcher and Munson (Fletcher and Munson 1933: 91). In 1958, Eberhart Zwicker introduced the unit sone as a measure of loudness (Völz 1999: 51). At 1 kHz, a sound pressure level of 40 dB corresponds to a loudness level of 40 phon or a loudness of 1 sone. For the phon, an increase of 10 corresponds to a doubling (40 → 50 → 60 → 70 ...), for the sone a doubling of the number itself (1 → 2 → 4 → 8 ...). Sharpness is a parameter that depends predominantly on the spectral density and envelope, and again, the range in which the human ear is sensitive plays an essential role. The unit for sharpness is acum. A band noise with a critical bandwidth and a centre frequency of 1 kHz at 60 dB sound pressure level is defined as 1 acum. The following also applies to sharpness: doubling of the unit corresponds to a doubling of the perceived sharpness. In contrast to sharpness, which depends exclusively on spectral properties, roughness is determined exclusively by amplitude modulation (AM) – i.e. temporal fluctuation.

With a slow amplitude modulation up to about 15 Hz, the impression of a beat is created. Between 15 and 300 Hz AM, the impression of roughness is created, peaking at 70 Hz AM. From 150 Hz AM, the ear begins to perceive two separate tones. Roughness is indicated with the unit asper according to DIN (Deutsches Institut für Normung/German Institute for Standardisation) 45631 / A1. Tonal content (formerly called 'tonality') describes the perception of tonal substance in the spectrum without considering the noise components. Brightness is the psychoacoustic parameter that is most strongly correlated with an acoustic parameter, namely the spectral centroid (SC) frequency (Pomberger et al. 2020: 225–26).



Brightness	HZ
Bell 1	4576 Hz
Bell 2	10259 Hz
Pellet bell (bell 3)	9898 Hz

Figure 3: Path of the human audio perception from the outer (1), middle and inner (2) ear, over the auditory pathway (3) to the auditory cortex (4) in the brain. Single spectrograms (a-c) of three objects, sharpness over time in acum (d) and loudness over time in sone (e) for all three combined and table of brightness as the spectral centroid in Hertz (f). Design: J. Mühlhans.

3 Case studies and results

For the case studies presented in this article we chose idiophones from three sites, one dating to each period: the sounding Hallstatt Culture jewellery from the Býčí skála Cave near Brno (CZ), the bells from Roman period Vindobona/Vienna (AT), and the Avar pellet bells from Keszthely in Vas County (HU).

3.1 Sounding costume jewellery from the Býčí skála Cave, Czech Republic

The Hallstatt culture was the dominant culture in Central Europe during the Early Iron Age, being named after the famous site in Hallstatt-Hochtal in Upper Austria. This period is characterised by a great amount of various sounding bronze jewellery, such as fibulae, pectorals, multiple bracelets worn on arms and feet, belts with jingles, and even diadems with jingles (Kromer 1959; Kern et al. 2008; Grömer and Kern 2018; Urban 2000: 225–82).

The Býčí skála Cave (Bull Rock Cave) near Brno, Czech Republic, dating to 800 – 400 BCE, is one of the well-known archaeological sites in Moravia. It is located in the Moravian Karst near the village Josefov and together with the cave Rudické propadání it forms the second largest cave system of the Czech Republic. The 320-metre-long entrance area and the side entrance were used again and again in prehistory. The Czech prehistorian and speleologist Heinrich Wankel excavated the site during the second half of the nineteenth century. He excavated more than 40 human skeletons, two burnt offering sites, and a large number of precious artefacts, like the famous bronze bull sculpture, a parade carriage, weapons, animal bones, vessels, textile implements, organic fragments, tools, and bronze jewellery (Wankel 1882). The site is interpreted as a cultic or sacrificial site. The artefacts date from Ha C1 to Lt A2 (Parzinger et al. 1995).

Among the many finds, we encounter seven house-shaped pendants and seven bobbles, all jingles. They are all cast in copper alloy and, due to their equal number, might belong to a larger ornamental combination of jewellery. The house-shaped pendants are perforated vertically in a lattice-like manner and have a round eyelet at each corner. Two trapezoidal rattle sheets are hooked onto each on the two lower eyelets. The upper parts of the “houses” are decorated with three concentric circles. The pendants have a height of 10 cm in total and weigh from 26 g to 31 g. The bodies of the bobbles are composed of nine longitudinal bars that converge at the top and bottom. They are held together in the middle by a transverse bar. One round eyelet is at the top and one at the bottom. Two trapezoidal rattle sheets are interlinked in the bottom eyelet. Six bobbles have a long-oval body and one is spherical. There are no rattle bodies inside the bobbles. One bobble composition is 10.5 cm long and weighs from 27 g up to 39 g. The trapezoidal rattle sheets are decorated with small punched dots. All pendants together have a total weight of 425 g.

The cast parts are manufactured in lost wax technique. The sheets are forged by hand. Each object is unique. Local chemical EDS analysis (scanning electron microscopy) carried out in the Central Research Laboratories of the Natural History Museum Vienna, proved that the cast parts are made of high-quality bronze: they contain 70 – 95 % Cu, 7 – 24 % Sn and only little Pb, whereas the sheets contain much more Pb (Pomberger et al. 2020: 219–22).

Figure 4: The seven bobbles and seven house-shaped pendants with rattle sheets from the sacrificial site Býčí skála Cave, CZ © Naturhistorisches Museum Wien; Photo: A. Schumacher.

The pendants are classified as idiophones/indirectly struck idiophones/shaken idiophones or rattles according to the classification of musical instruments by Hornbostel and Sachs (1914: 565: system number 112.1; cf. MIMO 2011: 5).

The sounds are created by the individual rattle sheets or cast parts (depending on their arrangement) beating together. The pendants could have been worn on a belt, on a cloak, as a pectoral, or on another garment. The movement of the wearer causes the rattle objects to beat against each other and create sounds. The bobbles' rattle sheets create partials between 1.8 kHz and 20 kHz, while the bobbles beaten against each other have partials between 1.3 kHz and 16 kHz. The house-shaped pendants' sheets sound between 1.6 kHz and 19.3 kHz and the pendants have partials between 1.7 kHz and 16 kHz. A bobble and a pendant shaken together create partials from 1.4 kHz up to 11.3 kHz, and if all objects are shaken together they produce partials from 2 kHz up to 15.2 kHz. First, we have to mention that the analyses carried out show individual conditions, which can be completely different the next time they rattle, i.e. they are subject to greater fluctuations. Although, due to the similarity of the bobbles and pendants with rattle sheets, one would assume that they hardly differ in sound, clear differences are evident – especially in the brightness. The brightness of the sounds depends on the spectral distribution of partial tones and noise components, and strongly influences the perception of the timbre. Bobbles and pendants show clear differences between themselves here, but also differences in combination (Figure 5a – f).

In total, the lowest partial tones of the bobbles are just in the frequency range in which the ear is particularly sensitive. The strongest partials are found between 5 and about 12 kHz, with some specimens producing partial tones up to almost 18 kHz. However, these high components contribute little to the brightness of the sound. The pendants clearly show less tonal components.

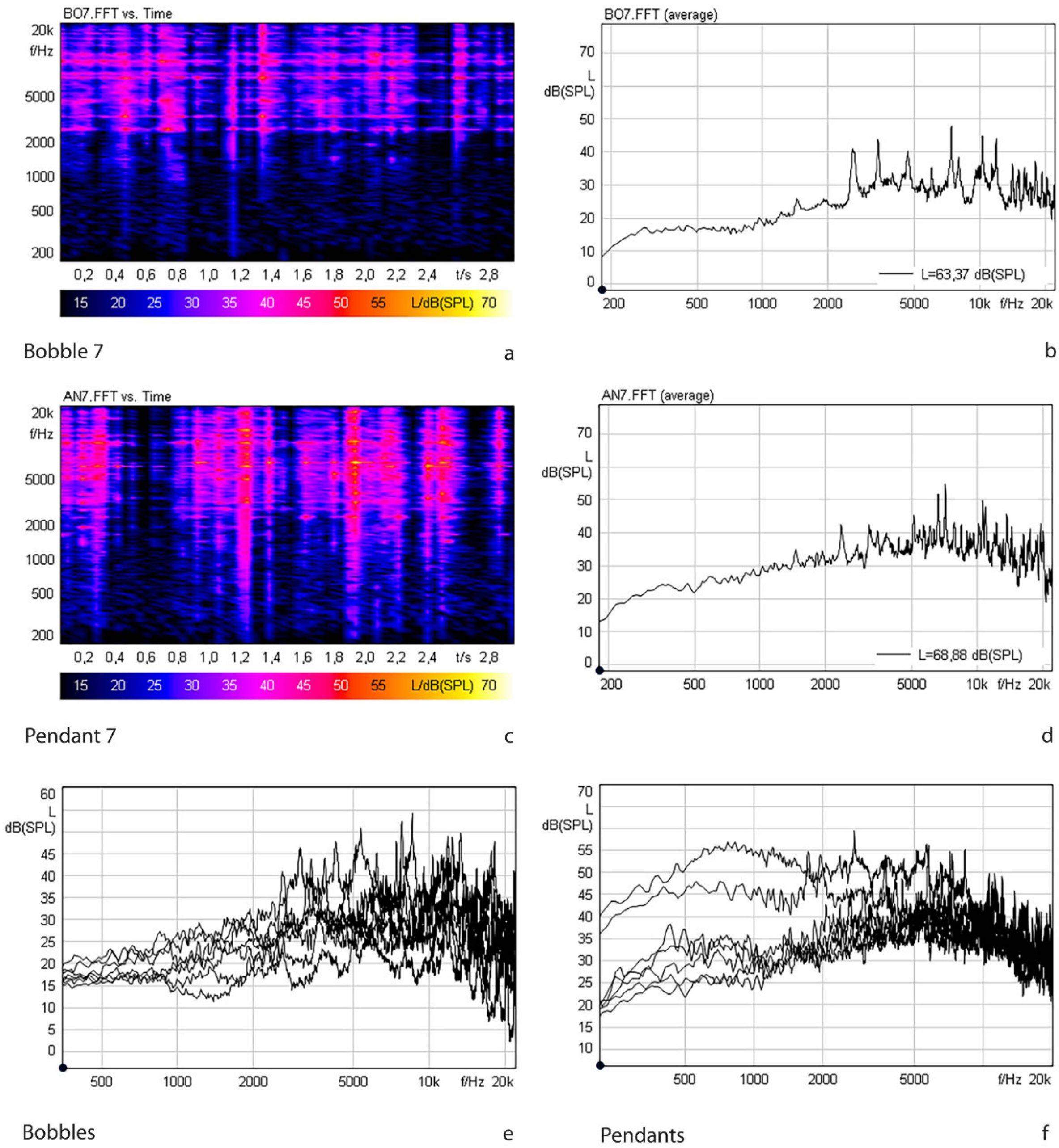


Figure 5: Acoustic analyses on bobble 7 and pendant 7 from the Býčí Skála Cave: a) and c) spectrograms, b) and d) measurements with the Fast Fourier Transformation. Energy distribution of partial tones and noise components in the spectrum: e) bobbles, f) pendants. Design: J. Mühlhans.

Noisy parts between 300 Hz and 2.5 kHz can be observed. Some pendants, however, can produce distinct partial tones. If bobbles or pendants sound at the same time, the level increases and so too does the loudness and spectral density. The decay time measured is below 1 msec.

The sound pressure level was calculated within a distance of 10 cm. The bobbles have the lowest sound pressure level with an average of 62.2 dB. If two or more bobbles are combined, the level increases to an average of 69.7 dB. A single pendant has a level of 70.2 dB on average. This increases to 73.4 dB when several are combined. Combining one bobble and one pendant together, the maximum level is 74.7 dB. Since the spectral distributions resemble one another, similar rankings can also be found in the loudness as in the level. With 10.1 / 17.1 sone (single/combined), the bobbles are the quietest. Single pendants have an average of 21.9 / 23.9 sone and together, 24.2 sone. Due to the acoustic properties of the sound objects, roughness is in all variants very low, averaging 0.06–0.09 asper. Slightly larger differences and generally higher values are reflected in sharpness. Individually, both types average 4 acum, and combined about 5 acum, which is a high value in comparison. Therefore, the sound objects may generally be considered to be sharp, but not rough. Due to the same excitation mechanisms and similar size of the objects, there are hardly any observed differences in impulsiveness. On the other hand, the bobbles are with an average of 6.6 / 8.3 dB slightly higher than the pendants with 4.2 / 5.4 dB. Sound pressure level, loudness, sharpness, and tonality increase when several sound objects are excited together. Roughness and impulsiveness are mostly the result of general sound properties and hardly change when more sound objects are added (Pomberger et al. 2020: 222–29).

Caged bobbles and pellet bells are of the same origin. The oldest known objects were found in the Iranian plateau in Tepe Giyan in grave 105, dating to the first part of the second millennium BCE (Contenau and Girsham 1935: 38). During the second half of the second millennium BCE, the objects spread over to the Caspian Sea, the Caucasus regions, and the Black Sea. They were detected mainly in burials near the hips or the neck and served as jewellery. Sometimes they were connected with a horse bridle (Castellucca and Dan 2014). Caucasian women of the Pre-Scythian period wore caged bobbles and pellet bells on their necklaces (e.g. Ateshi Gadirova 2014; Kadieva et al. 2020; Reinhold 2007). We can find caged bronzes in Greece (Kilian-Dirlmeier 1979) and the Balkan region (e.g. Bouzek 1974; Bouzek 2006; Bouzek 2012; Pomberger 2017), dating to the first millennium BCE. In the Hallstatt Culture, there are only a few known caged objects. Two of them originate from Hallstatt-Hochtal, burial 196 and burial 3/1875 (Kromer 1959: 68, pl. 22/12; Barth 2020). Both single pellet bells and bobbles, as well as combinations of two or more caged pendants, were found in Western Switzerland (Drack 1966/1967) and precious combinations of cast pectorals with pellet bells and bobbles were unearthed in eastern France, in the Jura Mountains (Wamser 1975; Ramstein and Cueni 2012; Piningre and Ganard 2004: 85–88). All these caged objects were found only in women's burials, dating from Ha C – Ha D1/800 – 600 BCE. They lay on the chest of the skeletons or were fastened on ribbons hanging from belts. Pellet bells and bobbles show the shapes of aggregate fruits like pomegranates, poppy pods, or rose hips. These fruits contain many seeds and thus symbolise fertility, abundance, magic power, love, passion, death and resurrection, and mental and spiritual fertility. They are also believed to be antidemonic (Pomberger forthcoming). Pellet bells and bobbles are rather rare finds in Hallstatt culture, which is important because rare finds can often be markers for both prestige and social status (Schumann 2015: 23–43). They were worn on the body and thus indirectly produced sounds with every movement of the wearer. The persons so adorned thus created sound fields, each with a unique profile. Clothing, costumes, personal ornaments, and sounds enabled direct non-verbal communication between people (Grömer and Pomberger 2023). We have created two videos, one describing the form, history and likely use of the original sound objects from the Býčí Skála Cave ("Bronze Pendants from the Býčí skála Cave in

Moravia")[3] and one dance video with the reconstructed jewellery ("Imagination of Dance in Hallstatt Culture").[4]

3.2 Roman bells from Vindobona/Vienna, Austria

Bells, mostly unnoticed in music archaeology and archaeology, played an important role in the Roman period. Bells are, in fact, the largest group of music archaeological finds from this period. 23 bells are known from ancient Vindobona, located near the ancient path of the river Danube. It was first founded as a military camp in the late first century CE, around which the *canabae legionis* developed. The civil town was built at the beginning of the second century CE. The Limes road along the Danube and a road to Scarbantia (Sopron), starting from the *Via Decumana*, connected Vindobona with important traffic routes of the Roman Empire. The legionary camp existed from the end of the first to the middle of the fifth century, but the civil settlement flourished with promotion to municipium only from the first to the third century CE (Kronberger and Mosser 2018). The borders of the Roman legionary camp in Vienna's inner city can still be seen today in the following streets and alleys: Tiefer Graben-Naglergasse/Graben-Rotenturmstraße/Stephansplatz and Gonzagagasse/Schwedenplatz. Like every Roman legionary camp, Vindobona was dominated by rectangular main streets, the *via principalis* and the *via decumana*. The *principia* was located at the junction of both streets. In the northern part of the camp facing the Danube were the buildings of the *tribunes*, the *thermae*, and the *valetudinarium*, in the south-western part – the *praetorium*, the barracks and the *fabricae* (Kronberger and Mosser 2018: Fig. 152). Nine bells and one clapper were found in the military camp. Two were unearthed within the area of the ancient *praetorium* at Judenplatz 7 and Parisergasse/Schulhof, and another one from the barracks at the Judenplatz, which is at the former Lazen- und Dreifaltigkeitshof (Bauernmarkt 22–24/Fleischmarkt 4 and 6). Furthermore, we know about two iron bells from this place, where a centurions' quarter may have stood (Mosser 2016; 2017). Unfortunately, they have been removed from the Wien Museum's collection. Three bells were found at the *fabricae* and barracks at 'Am Hof'. The clapper was discovered in the area of the main room ('*papilio*') of a *contubernium* of the southwestern barracks. The last bell was excavated in the area of the *intervallum* above the sewer of the *via sagularis*. The *canabae legionis* of Vindobona extends around the legionary camp to the west, south, and east, and is located within today's Ringstrasse and the Landesgerichtsstrasse. The living quarters of craftsmen, traders, businessmen, and the soldiers' families were located here. The Limes road today runs through Freyung, Herrengasse, Michaelerplatz, and Augustinerstraße, crossed by the southern road at the Michaelerplatz, which lead from the *porta decumana* of the military camp to Scarbantia/Sopron. One bell was found at the Freyung, where craftsmen carried out their work. Two bells were excavated at former metal workshops, at the Michaelerplatz, where objects were made of iron and non-ferrous metals (Donat et al. 2003; Donat et al. 2005). In the area of today's Stallburg, where in Roman times

[3] https://www.youtube.com/watch?v=tX5tDQGrSNQ.
[4] https://www.youtube.com/watch?v=PN5b1OWACPc.

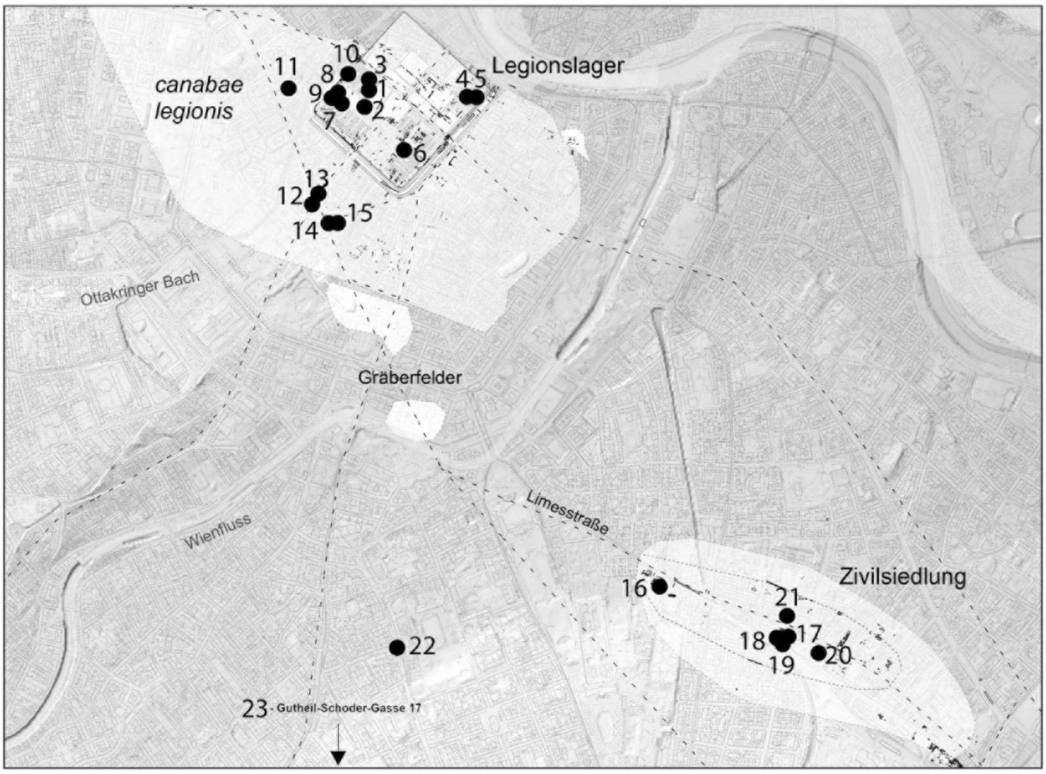


Figure 6: Distribution map of bells in Vindobona. Design: M. Mosser, Stadtarchäologie Wien © Stadtarchäologie Wien.

a small arterial road ran along the camp wall to the Limes road, two small bells were found. The civil settlement developed as early as the first century with houses along the Limes road, today the Rennweg in the third district of Vienna. Six bells from four sites are known from the settlement. One comes from the Botanischer Garten/Rennweg 14, where a building with 19 rooms was excavated. The small bell was found in a paved courtyard (Chinelli et al. 2001; Kenner 1904: 165). At Rennweg 44, where a residential, trading, and sales area was located in Roman times, three bells were found in a work pit, a storage pit, and a well (Müller et al. 2018).

One bell was discovered at Rennweg 52 in a pit backfill (Mosser 2017). Another bell from the site Rennweg 57/Schützengasse 24 comes from a residential and farm building with a courtyard and kilns.

From the junction of the Limes road into the civil settlement, a connection led to the street in the direction of Aquae (Baden). The course of this cross-connection can probably still be found today in Mayerhofgasse in the fourth district and crossed today's Favoritenstraße. Opposite today's Theresianum, a bell was found in the area of Favoritenstraße without any further known find context. Another bell was recovered at Gutheil-Schoder-Gasse 17, in the immediate vicinity of a road station (see distribution map Figure 6 and Figure 7; cf. Pomberger et al. 2022d).

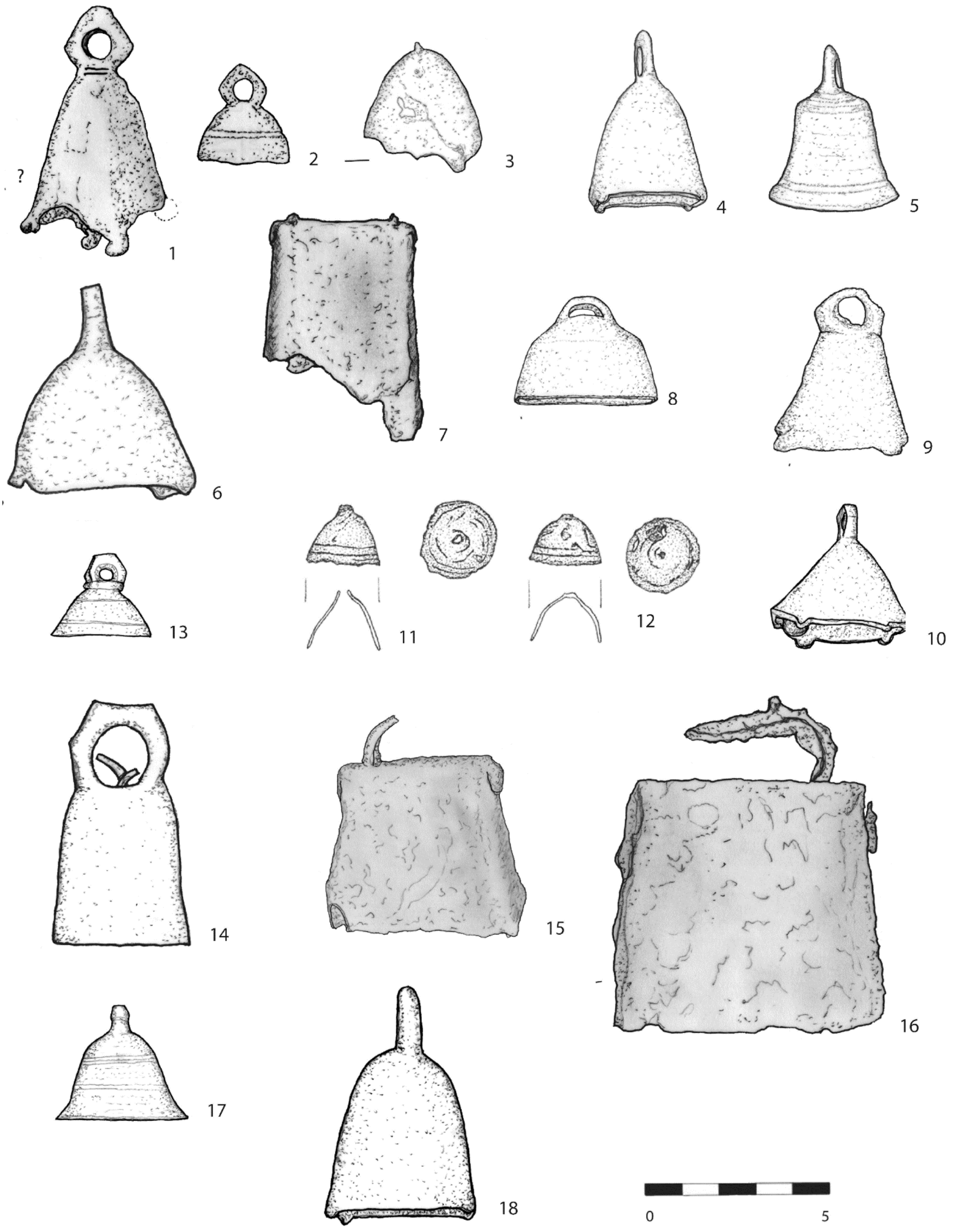


Figure 7: Bells from Vindobona. Military camp: 1 – 3/Judenplatz; 4 –5 Am Hof; 6 – 7/Bauernmarkt; *canabae legionis*: 8 – 9/Michaelerplatz; Freyung; 11 – 12/Stallburg; civil town: 13/Rennweg 14; 14 – 16/Rennweg 44; 17/Favoritenstraße; 18/Gutheil-Schodergasse 17. Design: B.M. Pomberger.

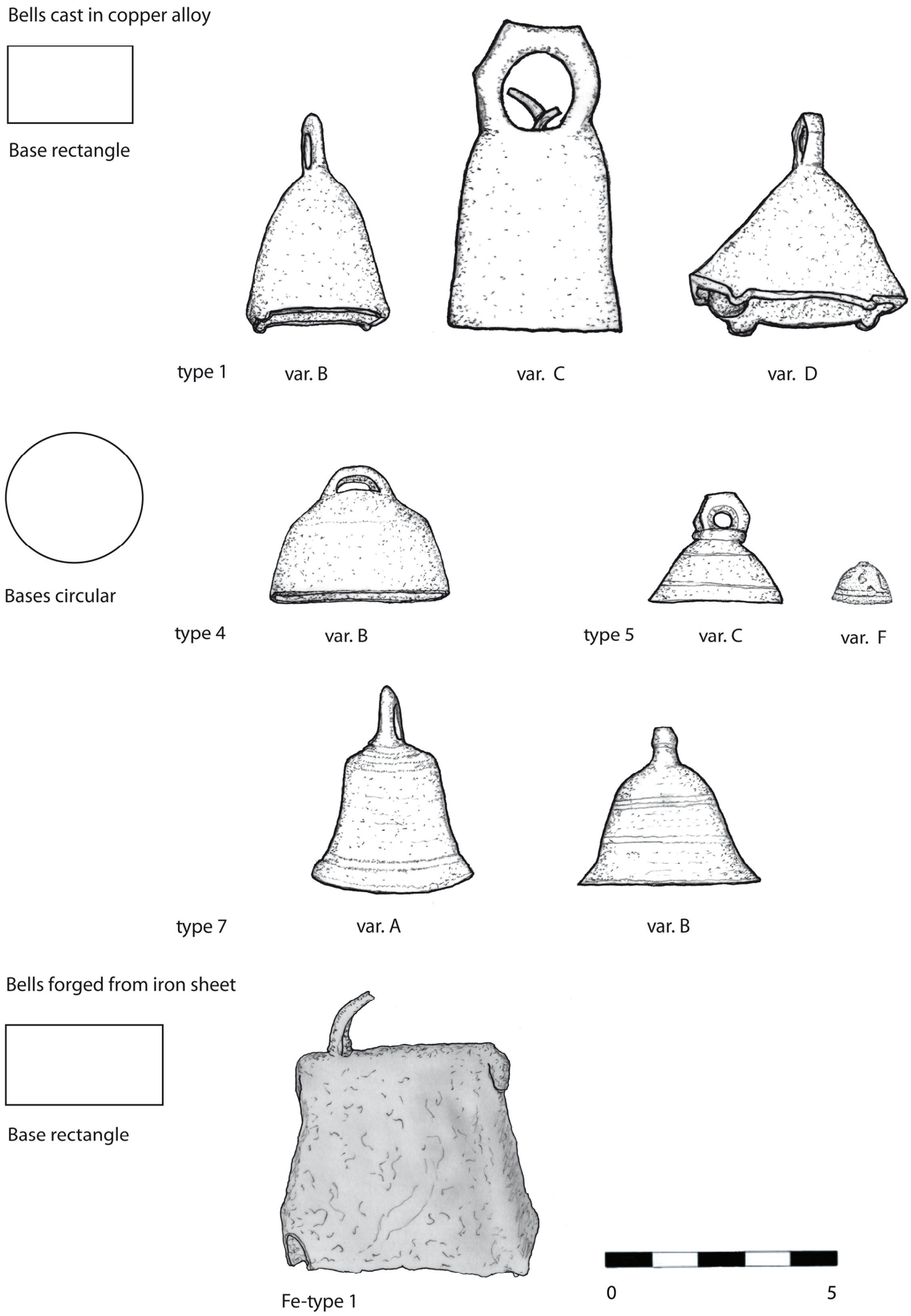


Figure 8: Types of bells from Vindobona. Design: B.M. Pomberger.

Of the Viennese bells, 18 were investigated. They have sizes between 7 mm and 91 mm and weights of 5.8 g up to 141.54 g. Three are forged from iron sheet and are classified to iron bell type 1.

site	object	Inv.Nr.	deepest partial (Hz)	highest partial (Hz)	strongest partial (Hz)
Am Hof 10/military camp	bell	MV 75/475/1	2091	20936	2091
Michaelerplatz/canabae legionis	bell	MV 25.169/1163	1981	21600	1981
Favoritenstraße	bell	MV 47.444	2706	17278	7586
Gutheil-Schodergasse 17	bell	MV 9.950/4	1593	20769	5051

Table 1: Frequency ranges from Vindobona bells.

The others are cast in various copper alloys. Eight of them have a rectangular base and are classified as Bell Type 1, Variants B, C, and D. The others have a circular base and belong to the Type 4/Variant B, Type 5/Variants C and F, and Type 7/Variants A and B (Figure 8). Compared to the bells from *Ovilava*/Wels, where 39 bells have been discovered, which can be divided into six types and several variants, the shapes of the Vindobona bells are not as varied (Pomberger et al. 2022a: 132, Figs. 4 and 5).

Ten bells were examined for their chemical composition using electron microscopy scanning by VIAS.[5] Four bells are cast in Cu-Sn-Pb bronze, (75–87 % Cu/11.6–14.3% Sn/1.2–10.7% Pb). One bell is cast in a copper-lead alloy (79% Cu/17.5% Pb) and the others are made from gunmetal (66.3–86.8 % Cu/3.7–14.3 % Sn/2.4–17% Zn/1.5–7.1% Pb) (Pomberger et al. 2022d: 375–76).

Idiophones do not have a harmonic overtone structure where all partials are integer multiples of a fundamental tone – as is the case with aerophones or chordophones. Instead, very different sound bodies produce very different partial oscillations, also called ‘modes’ (Winkler 1988: 119), which generate a multitude of partial tones, the frequency of which is not in any fixed relationship to one another.

Only four bells are intact and therefore able to have their sounds recorded today. Since the original iron clappers are corroded, we used reconstructed clappers for striking. Our analyses showed that bell Am Hof 10 has a range from 2 kHz – 20.9 kHz with a peak frequency of 2.09 Hz. The bell from the Michaelerplatz has a range from 1.98 kHz up to 21.6 kHz. The strongest partial is at 1.98 kHz. The frequencies of the bell from the Favoritenstraße range from 2.7 kHz up to 17.2 kHz with a peak frequency of 7.5 kHz and the last bell from the Gutheil-Schodergasse shows partials between 15.9 kHz and 20.7 kHz with a most developed partial at 5 kHz. Since the ear is very sensitive in the 2 kHz – 5 kHz range and can perceive even low levels, this characteristic gives the objects an average good audibility even with moderate noise (see Figure 9).

The timbre is determined primarily by the number, the spectral position, and the amplitude of partial tones. Bells have more pronounced partials, as well as less noise, therefore, they are often described as ‘clear’ or ‘pure’. This is not always the case with historical objects, as the extent of corrosion plays a significant role. Superficial corrosion only moderately dampens the vibration; however, it is not known how exactly the amount of corrosion is related to the vibration behaviour.

5 Vienna Institute for Archaeological Science.

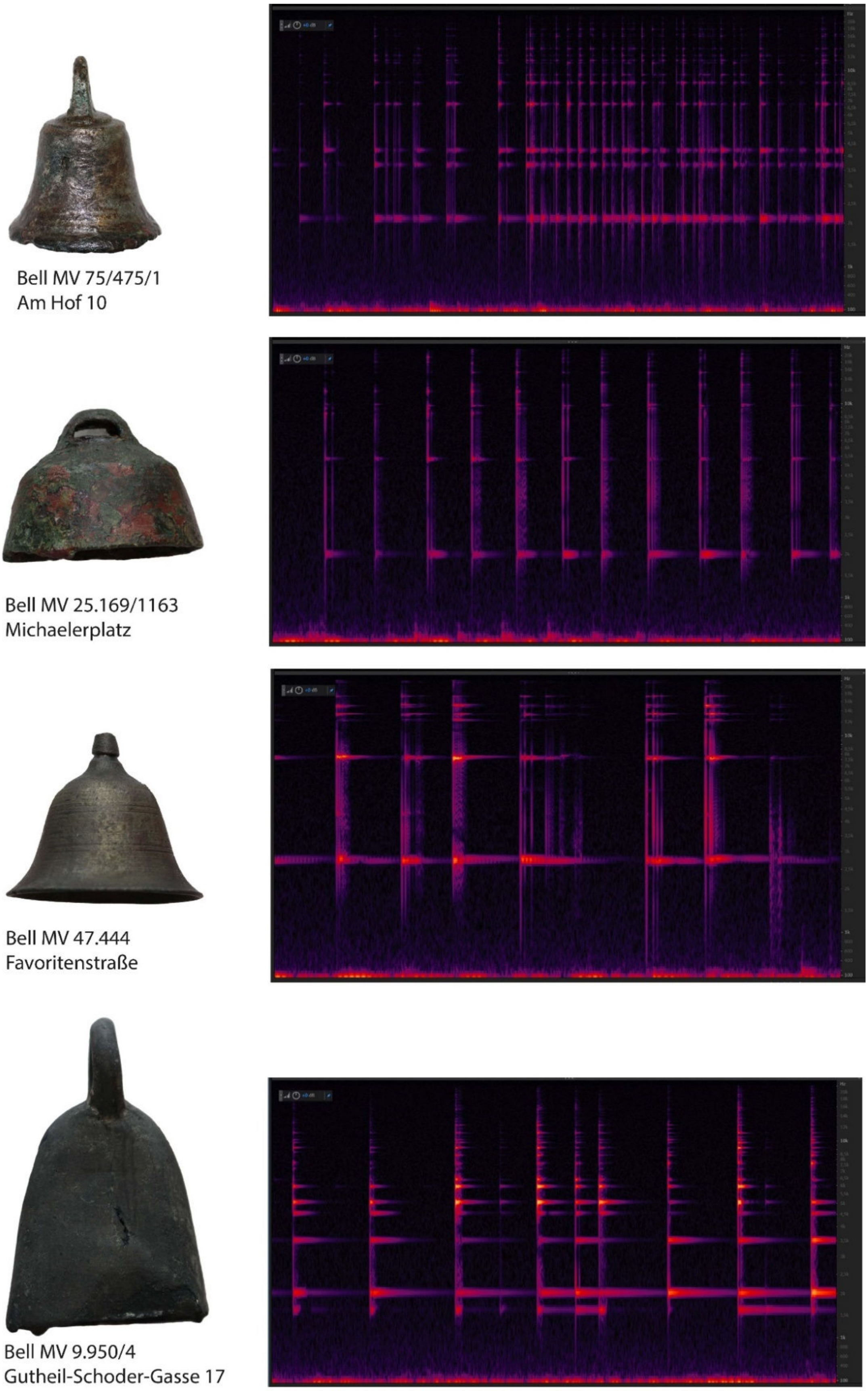


Figure 9. Sonograms of the four bells from Vindobona. Design and photos: B.M. Pomberger, © Wien Museum.

site	object	Inv.Nr.	soundpresure level	loudness	sharpness	roughness	impulsiveness	tonality (DIN45681)	brightness SC
			kalib, dB re p0	sone	acum	asper	IU	dB	Hz
Am Hof 10/military camp	bell	MV 75/475/1	63.69	13.3	3.58	0.0449	2.4	17.24	5059
Michaelerplatz/canabae legionis	bell	MV 25.169/1163	58.44	8.31	2.79	0.0321	2.48	13.67	6937
Favoritenstraße	bell	MV 47.444	72.86	16	3.87	0.0545	1.91	24.5	8034
Gutheil-Schodergasse 17	bell	MV 9.950/4	78.86	31.6	3.83	0.0514	2.65	16.97	4625

Table 2: Psychoacoustic parameters of Vindobona bells.

The four bells have a sound pressure level of 70.6 dB or a loudness of 18.1 sone. This can be attributed to their percentage of copper (average 73.1 %). Their sharpness is on average 3.51 acum, while roughness is on average 0.05 asper. This means that their sound is sharp but not rough. Impulsiveness is on average 2.3 iu (impulsiveness units, see 4.5 below) and tonality on average TNR 18.1. Both values are related to excitation. Some statistical correlations between material and tonal properties could be determined. Content of copper correlates positively with loudness and sharpness, but negatively with spectral centroid. This shows that bells with a higher copper content are louder and sharper, but lower in brightness. Peak frequency correlates negatively with the tin content. The t-test did not show any significant differences in mean values between the gunmetal and tin-lead-bronze objects (Pomberger et al. 2022d: 377–80).

Bells fulfilled various functions in ancient times. First, they were sound tools and signal instruments (Haid 2004) and thus had many functions in daily life. Their ringing announced the opening and closing times of markets and baths (Plut. *Quaest. conv.* 4.42 = 668a e.g.; Plin. *Nat*. preface 6; Mart. 14.163) and the watering times of the streets (Sext. Emp. *Math*. 8.193). Bells also tolled when fire broke out.

Their sounds served as acoustic signals for the night watchmen (Cass. Dio 54.4) and were used as acoustic weapons in acts of war (Eur. *Rhes.* 379–85; 300–10). Even when bells were mounted on shields – like in Aeschylus' *Seven against Thebes*, in which he dramatizes the mythological battle of Oedipus' sons, the brothers Eteocles and Polyneikes (Aesch. *Sept.* 380–400) – they fulfil the apotropaic role of acoustic weapons, because loud and metallic sounds create fear and terror. Weapons and objects made of metal produce overtone-rich, 'metallic' sounds when struck against each other, which are perceived as hard, powerful, energetic, sharp, and defensive. Other acoustic descriptions of the sound of metals are booms and clangs. Noise and loud, penetrating music have always been a proven means of psychological warfare and torture to generate terror (Diederichsen and Schulze 2017; Grant et al. 2015) and to manipulate targeted crowds.

Executions and punishments of adulteresses – men were allowed to commit adultery with impunity – were announced by the tolling of bells (Cass. Dio 6.24; cf. Zonaras 7.21; Niemann 1997: 20; Kramer 2016: 27; Socr. *Hist. eccl.* 5.18). Slaves were awakened by bell sounds (Lucian *Merc. Cond.* 24) and bells played a role in banquets and feasts (Petron. 47.8.5). However, bells were mostly considered apotropaic objects (Crummy 2010) and thus were used to protect home, children, and animals. Several of the bells found in houses may indicate this use (Pomberger et al. 2022a). They served to ward off evil, were supposed to bring good luck and reinforce positive qualities. In people's minds, the inherent powers and qualities attributed to them were enabling. These properties and forces are also attributed to their materials – the metals (e.g. Quast and Wolf 2010; Bächtold-Stäubli and Hoffmann-Krayer 1987a: 207–10; 1987c: 718; 1987b: 836–37; Sartori 1932). In children's graves, bells are often found attached to a bracelet or necklace (e.g. Eckardt and Williams 2018; Ruprechtsberger 1996; Ubl 1997: 300; Villing 2002).

Pets, such as dogs, sometimes wore bells on collars (Authengrüber-Thüry 2021). Pack animals, as well as mounts and pasture animals, could have bells fastened around their necks (Phaedr. 2.7.1–8; Rost and Wilbers–Rost 2010; Himmelmann 1980; Furger and Schneider 1993; Mandl 2000; Mocchi 2018; Nicolay 2007). Even chariots of emperors were decorated with bells as sounding status objects and status symbols to attract attention. A status symbol or status object is a sign which advertises someone's elevated status/belonging to a society (Duden 2001: 946).

Sixty-four bells hanging from Alexander the Great's hearse tolled when being moved through his empire (Diod. 18.27.5).

Bells hanging from temples, *villae urbanae*, and *villae rusticae* sounded to avert misfortune and announce the status of the owners (Suet. *Augustus, Caes.* 91.2.5; Casaulta 2017; Tortoli 2017). Bells tolled during cultic rituals and processions and banished demons during eclipses of the sun. But bells were also musical instruments (Isid. *Orig.* 3.22.13) and sounded to dances and at feasts – for example, at the *bacchanalia* in Sardinia (Pesce 1957).[6]

The great challenge for archaeologists is to determine the function of a bell based on its find position in settlements. For the most part, we can only theorise about its function on the basis of its size. Small bells were certainly used as apotropaic sound jewellery for humans and pets. *Tintinnabula* were composed of several bells measuring between 2 cm und 3.5 cm. Bells with sizes from 6 cm up to more than 10 cm probably hung from buildings, cult pillars, and statues. Very large bells – 20 cm and larger – were worn by herd animals. Bells were not only sound tools, signal instruments, and apotropaic objects, but they also seem to have been objects of prestige and social status.

Etymologically, both words, *status* and *prestige* derive from the Latin language, but are terms with two different meanings. The word status goes back to Latin *status*, "existence, prosperity, position, rank, situation, condition, circumstances" (Stowasser 1969: 942). In German, 'Status' means as much as situation, position within a society, state, condition (Duden 1989: 1456) – an actual state. A status symbol is a sign or object that serves to demonstrate someone's elevated status or belonging within a society (Duden 2001: 946). Prestige, on the other hand, means dazzle, magic, prestige, validity (Duden 2001: 803) and is derived from the late Latin word *praestigiae* (Duden 1989: 1178),

6 For more detailed information, see Pomberger et al. 2022a; Maria Hackl created a list of ancient literature mentioning metal idiophones and assigned them to their functions. She was able to determine the function of the idiophones in 78 citations by 46 ancient authors (Hackl and Pomberger 2022).

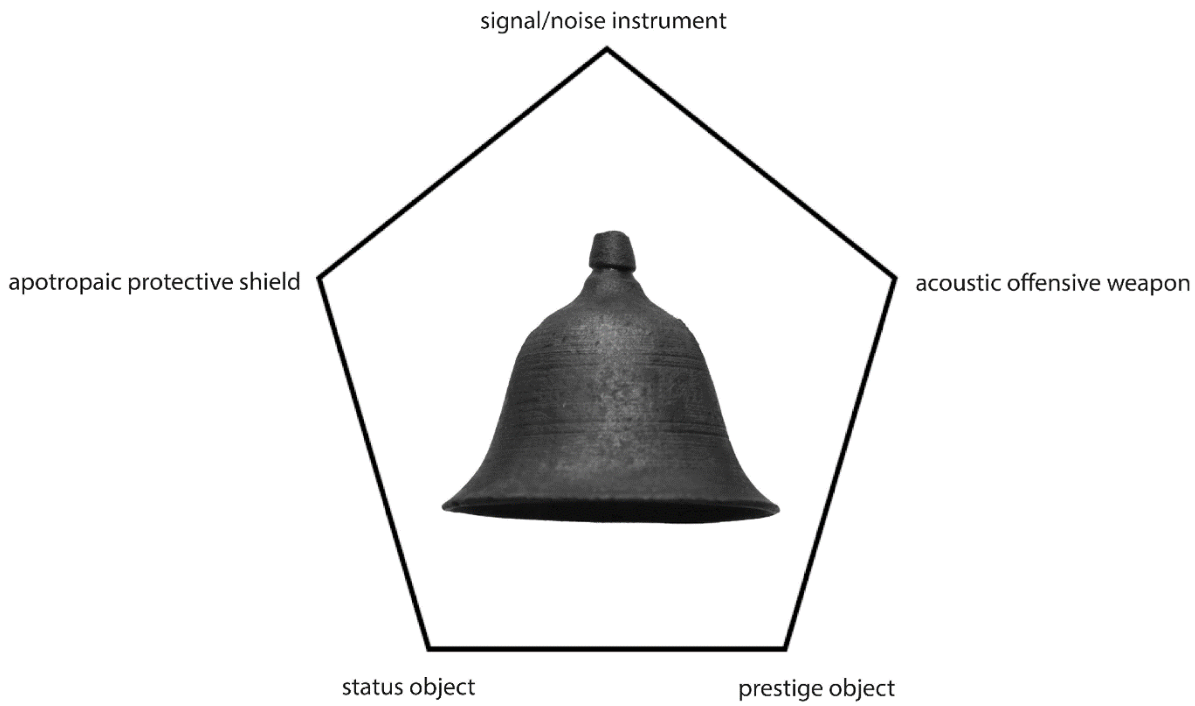


Figure 10: Diagram of bell functions. Design: B.M. Pomberger.

which in turn means dazzle and jugglery (Stowasser 1969: 796). Prestige could be described as a 'would-be state'. Prestige objects are special goods that are used to assert social prestige and to elevate oneself. They usually come from distant regions or are made of extraordinary material. Status, on the other hand, indicates a person's social origin and position within a culture, and a status symbol is an expression of power and social status (Schumann 2015: 35). In a diagram we try to show the different functions of the bells (Figure 10), however the discussion is not yet finished.

3.3 *Early Middle Ages – Avar Khaganate*

3.3.1 Avar pellet bells from the Migration Period collection of the Hungarian National Museum

Pellet bells appeared in the Avar Khaganate during the middle of the seventh century CE. They were probably imported from regions around the Black and the Caspian Sea, where they are common since the second millennium BCE (Contenau and Girsham 1935; Castellucca and Dan 2014; Ateshi Gadirova 2014; Kadieva et al. 2020; Reinhold 2007). The Hungarian National Museum houses 43 pellet bells from the Avar period originating from 17 sites – all cemeteries – in Hungary (Table 3).

The sites are Cikó, with 600 burials (Kiss and Somogyi 1984; Szentpéteri 2002; Hampl 1905) and two pellet bells, and Gerjen with 185 burials (Kiss and Somogyi 1984; Szentpéteri 2002) and one pellet bell, in the county Tolna. The necropolis of Halimba Belátó-domb, in county of Veszprém, consists of 489 burials (Török 1998; Szentpéteri 2002) and 13 pellet bells were found there. Two cemeteries with finds of pellet bells are known from the county of Jász-Nagykun-Szolnok, namely Jánoshida with 265 burials and 3 pellet bells (Erdélyi 1958) and Jászalsószentgyörgy with two burials and one pellet bell (Madaras 1995b). From the cemetery in Kiskőrös Vágóhídi-dűlő, in Bács-

Country	site	burials total	burials with idiophones	pellet bells	child	woman	man	sex?	iron	copper-alloy	gold
HU	Cikó	600	2	1		1		1		1	
AT	Edelstal = Nemesvölgy*	257	3	1	1	1	1		1	2	1
HU	Gerjen	185	1	1		1				1	
HU	Halimba Belátó domb	489	8	13	6	2			13		
HU	Janoshida	256	3	3	3				1	2	1
HU	Jászalsószentgyörgy	2	1	1						1	
HU	Kiskörös - Vágóhídi-dűlő	75	6	1	1					1	
HU	Kölked Feketekapu A	687	6	1	1				1		
HU	Mosonszentjánoss-Jánossomorja	316	1	1	1				1		
HU	Pilismarót-Öregek-dűlő	122	1	1	1				1		
HU	Pilismarót-Basaharc	197	9	7	5		1		4	3	
HU	Solymár	130	1	1	1					1	
HU	Szebény cemetery I	401	4	3	3				1	3	
HU	Szob Homokok-dűlő	140	2	2	2				2		
HU	Újhartyán (Kom. Pest)	?	1	1				1		1	
HU	unknown	?	?	6						6	

Table 3: Pellet bells from the Avar-Period/Migration-Period Collection of the Hungarian National Museum in Budapest.

Kiskun County, 75 burials are known, however only one contained a pellet bell (László 1955). The site Kölked Feketekapu A, Baranya County, consists of 687 burials, but only one pellet bell is known from this cemetery (Kiss 1996). Also, one pellet bell originates form the site Mosonszentjános Kavicsbánya, county Győr-Moson-Sopron, with 316 burials (Fettich 1927). In Pilismarót, county Komárom-Esztergom, two Avar period sites are excavated: the cemeteries Pilismarót Öregek-dűlő with 122 burials and one pellet bell (Szabó 1975) and Pilismarót Basaharc with 197 burials and seven pellet bells (Fettich 1965). One pellet bell was found in the cemetery of Solymár, Pest county, near Dinnye-hegy, Téglagyár with 130 burials (Török 1994). Two further pellet bells originate from the cemetery Szob Homokok-dűlő, Pest County, which consists of 140 burials (Kovrig 1975). The Szebény cemetery I, Baranya county, with 401 burials, contained three pellet bells (Garam 1975) and from Újhartyán, Pest County another pellet bell is known. One pellet bell from the cemetery in Edelstal 'Herrschaftsjoch' (Nemesvölgy) in Burgenland, Austria – a cemetery of 257 burials – is part of the Great Migration collection of the Hungarian National Museum (Lobinger 2016). Additionally, the collection keeps six Avar pellet bells from unknown sites. Furthermore, bells were excavated in eight of the cemeteries, but they are not the subject of this article (Pomberger et al. 2022b). The pellet bells were located near the hands, the hips and legs, and sometimes near the necks of the deceased. They were parts of the garments, served as sounding apotropaic amulets, thus influenced the appearance of the person wearing it.

When all graves of the cemeteries listed here are added together, there are a sum total of 3856 burials, but pellet bells were discovered in only 27 graves, a surprisingly small percentage at 0.7%. This fact shows that pellet bells were not at all common, but rather extremely uncommon in Avar

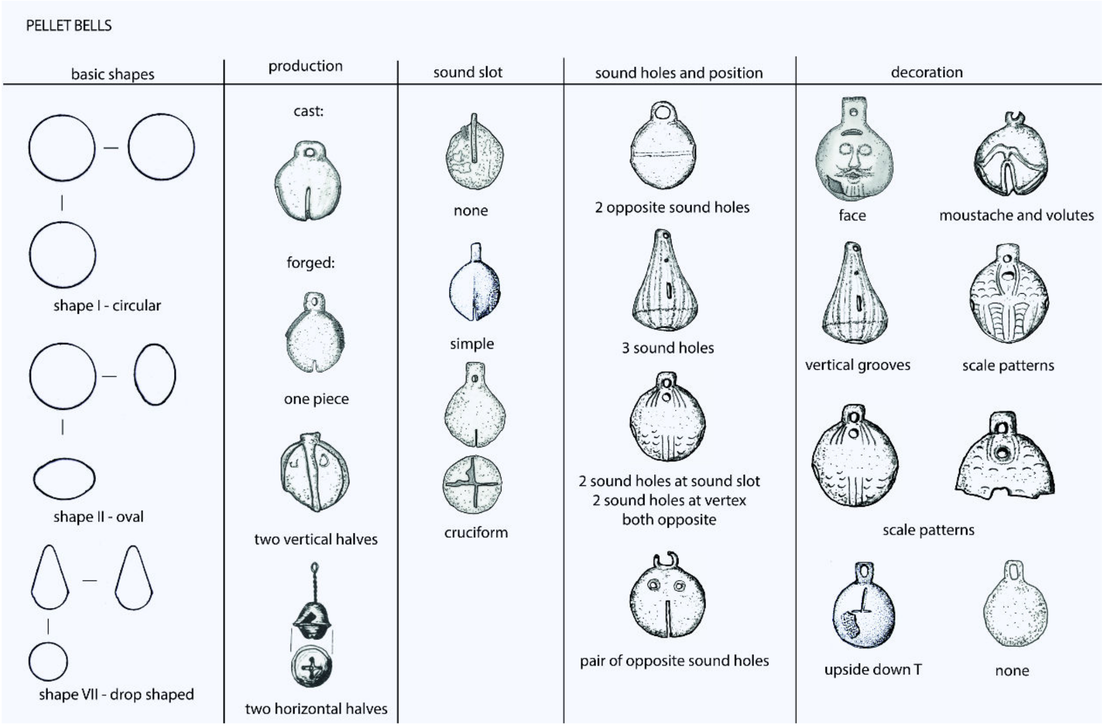


Figure 11: Shapes and decorations of Avar pellet bells form Hungary. Design: B.M. Pomberger.

communities. We are also not sure if they were imported products or were made in local workshops. 22 pellet bells are made from copper alloys and 25 are forged from iron sheet. The following copper alloys could be detected: Cu-Sn, Cu-Sn-Pb, Cu-Sn-Zn-Pb, Cu-Zn-Pb, and Cu-Pb. Some alloys show an astonishingly large amount of lead. Riita Rainio also mentions a large variety of copper alloys in her study on Finnish Iron Age pellet bells (Rainio 2008).

Two of the Hungarian sheet metal pellet bells are gilded (Pomberger et al. 2022b: 65, tab. 1). The sizes vary from 27 mm up to 46 mm with handle and the preserved weights from 5 g up to 37 g. Small pebbles, lumps of cinder, and bronze balls serve as pellets. Figure 11 shows the variety of shapes and decoration of these pellet bells. Furthermore, we must also mention that in the early Avar period burial bells were found. They are similar to Roman bell types and most probably from the Roman period.

The frequencies of the pellet bells are between 1.1 kHz and 20 kHz and range from 3–28 sone. Depending on background noise levels, the pellet bells can be heard from a distance of 1 m to a maximum of 12–15 metres. Noise content has more effect in lower frequencies, therefore pellet bells are usually lower in brightness (3.5–5 kHz). They have values between 0.02 and 0.1 asper as well as 2.5 and 4.5 acum and can be described as not at all rough, but instead quite sharp. With 4–8 dB they have barely more tonal than noise components (Pomberger et al. 2022b). Some original pellet bell sounds are published in our video "Pellet bells and bells from the Avar Period in the Hungarian National Museum in Budapest".[7]

[7] https://www.youtube.com/watch?v=nrMvHKKIjAM.

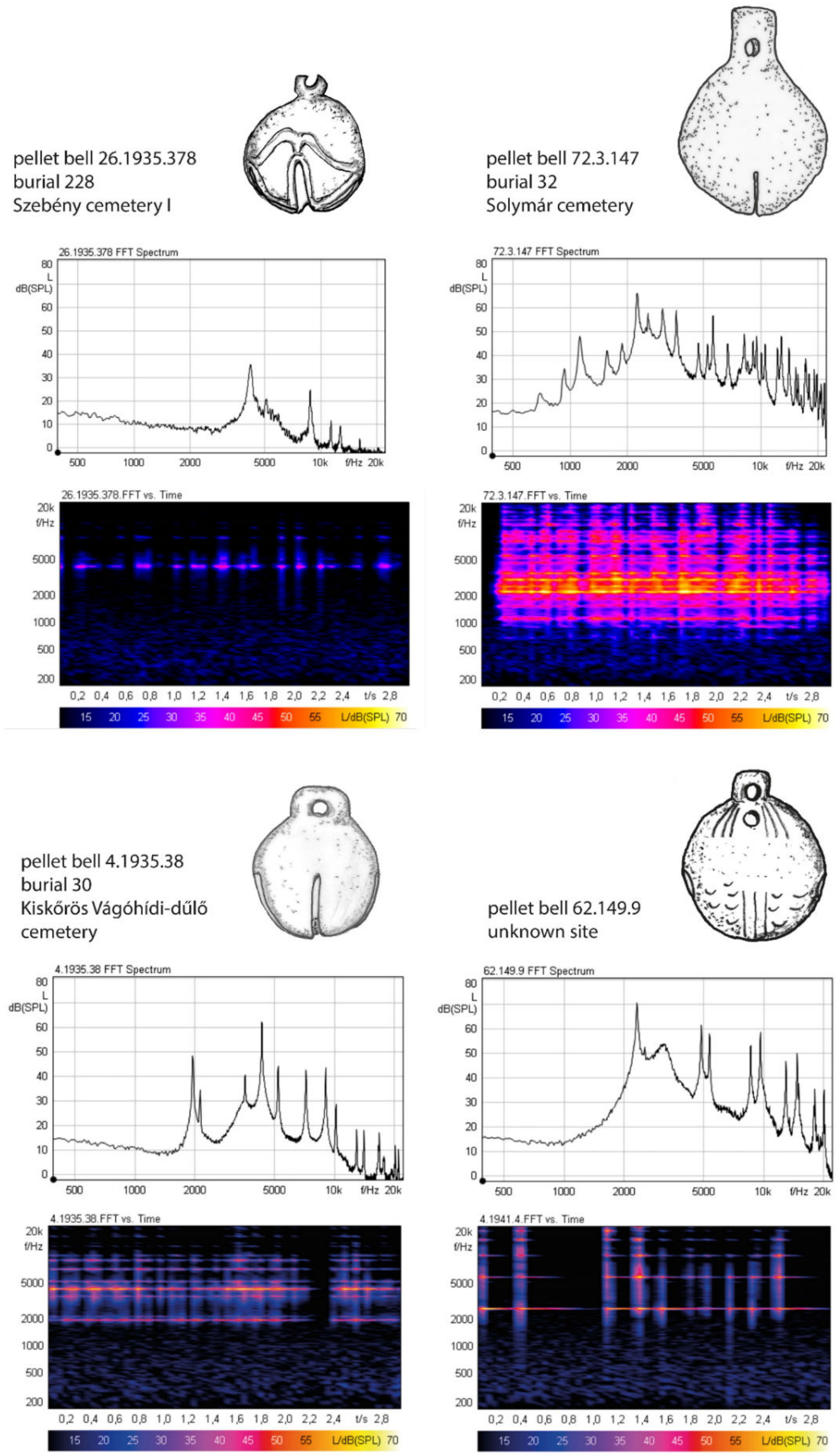


Figure 12: Sonograms and spectrograms of the pellet bells MNM 26.1935.378/burial 228/Szebény I; MNM 72.3.147/Burial 32/Solymár; MNM 4.1935/Kiskőrös Vágóhídi-dűlő and MNM 62.149.9/unknown site. 4096 window size, 85% overlap Hanning. Design: J. Mühlhans and B.M. Pomberger.

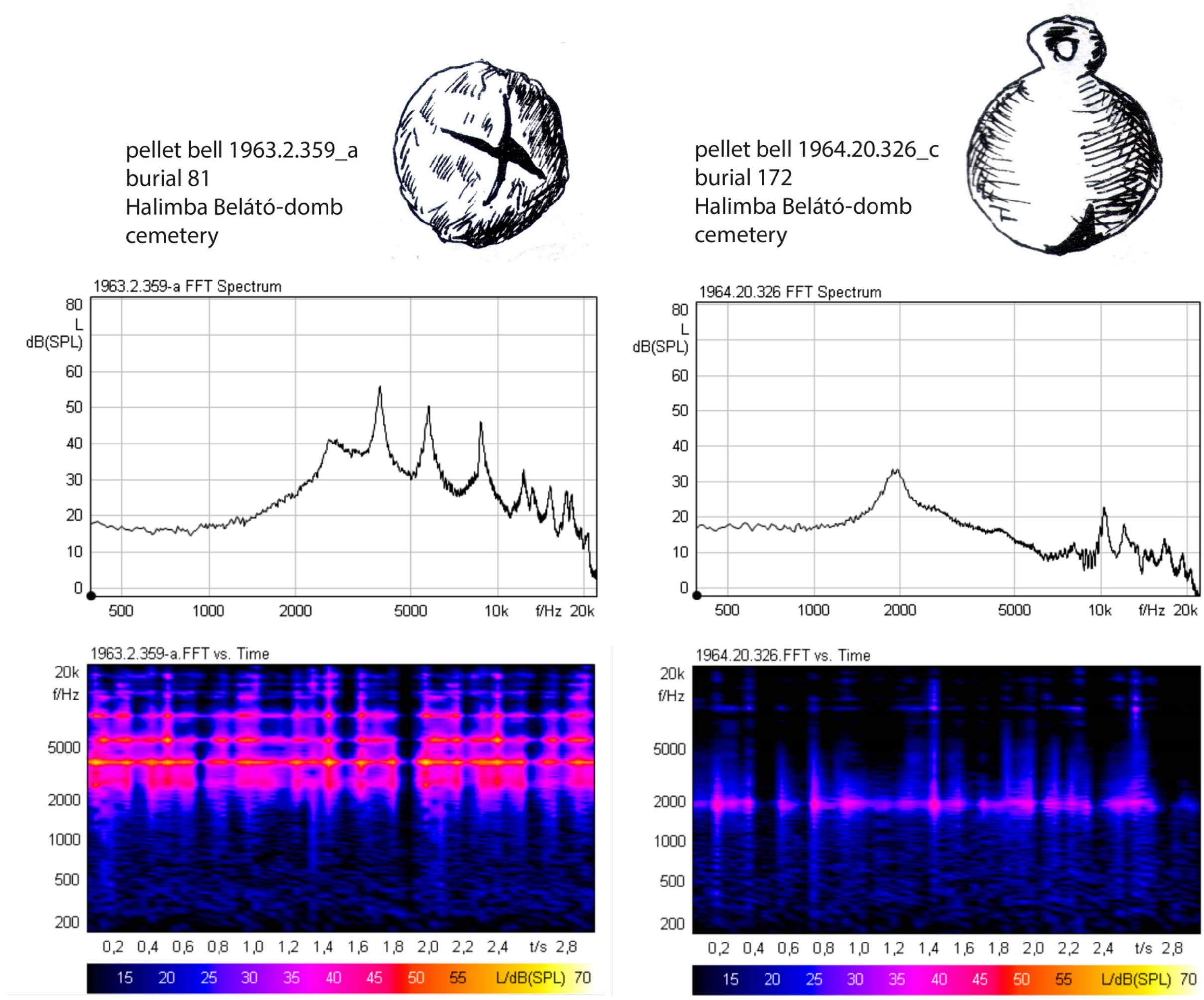


Figure 13: Sonograms and spectrograms of the pellet bells MNM 1963.2.359a/burial 81/Halimba Belátó-domb; MNM 1964.20.326c/burial 172/Halimba Belátó-domb. 4096 window size, 85% overlap Hanning. Design: J. Mühlhans and B.M. Pomberger.

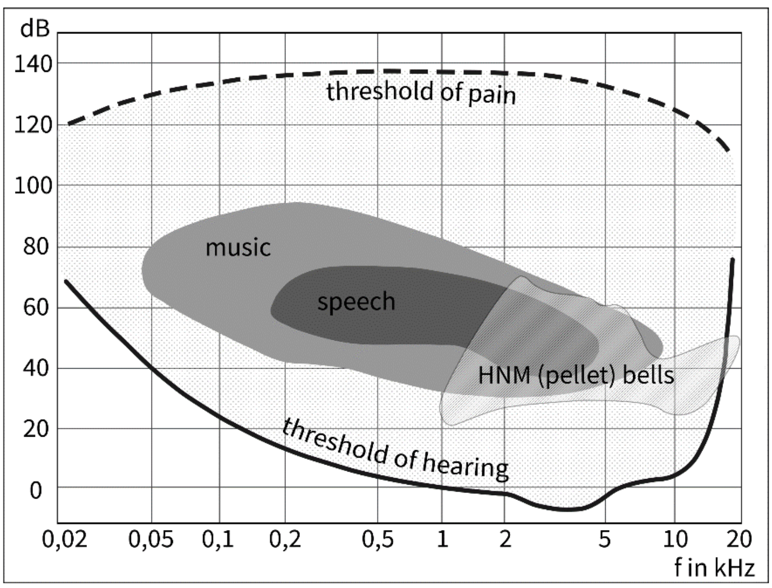


Figure 14: Human auditory thresholds and pellet bells from Hungarian sites. Design: J. Mühlhans.

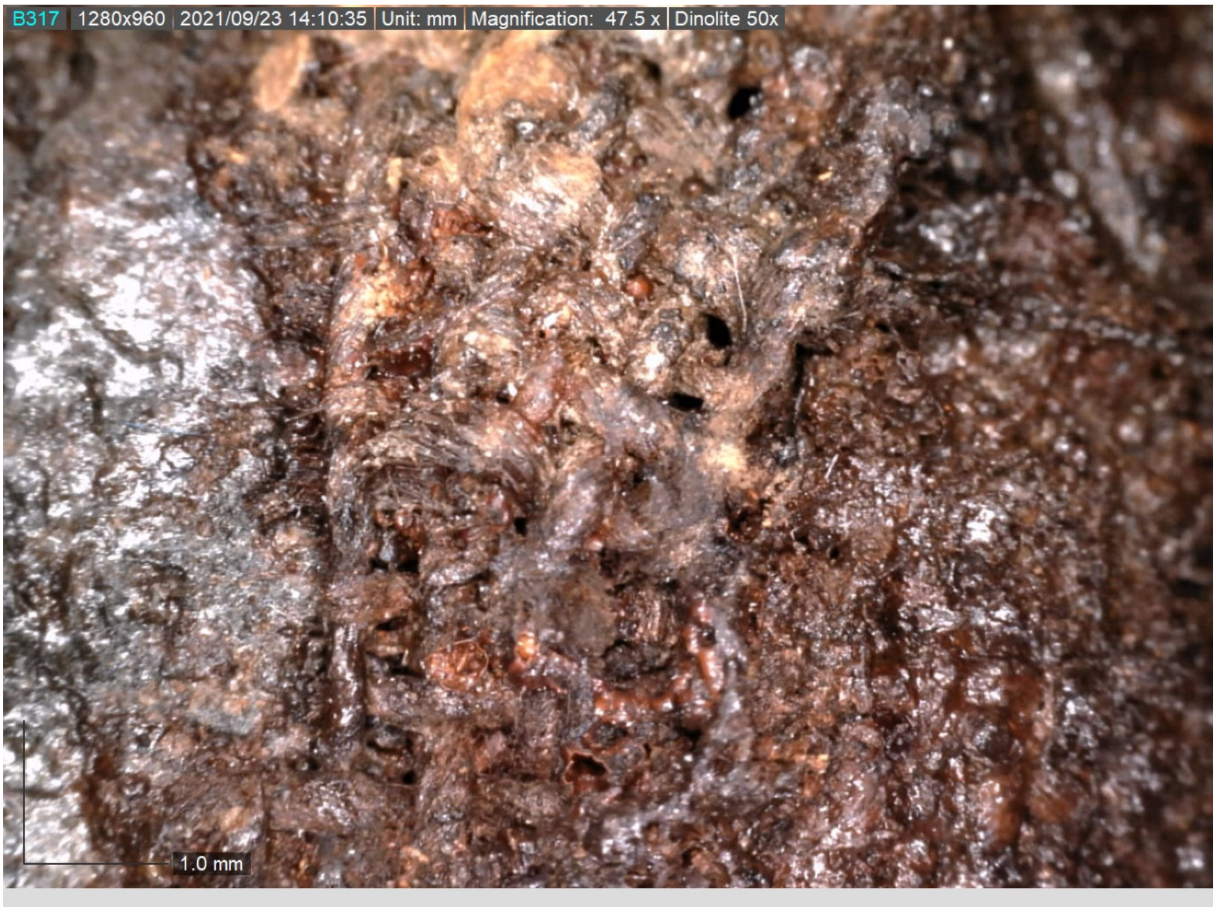


Figure 15: Textile fragments on an iron pellet bell from burial 17, Halimba-Belátó-domb, DinoLite_50x-Taxtile A_6. Photo: K. Saunderson.

3.3.2 *Textiles on Avar pellet bells*

Pellet bells were worn as parts of clothing, either on a necklace, on a bracelet on the wrist, or on a long hanging strap such as a ribbon or chain. They influenced not only the acoustic profile but also the visual appearance of the wearer.

Textiles found on the bells and pellet bells in question are therefore considered in the project, since they can offer further information on their function. These textiles were identified during their primary typological analysis and then analysed using a DinoLite digital microscope, measureing the thread diameters, densities, and twist angles, as well as identifying spin directions, weave types, layers, and special features.

These small fragments of textiles remained as mineralised pseudomorphs. Those analysed – from Devínska Nová Ves and Komárno (Slovakia); Gyenes/Gyenesdiás, Halimba-Belátó-domb, Jánoshida, Keszthely, Kölked-Feketekapu, Pilismarot-Öregek-dűlő, and Szob (Hungary); and Zillingtal (Austria) – fit well into the known spectrum of textiles from the Avar period (Hundt 1984; Dolejšová 1987; Scharrer-Liška and Klatz 2010; Grömer 2015; Grömer and Rapan Papeša 2015), mainly consisting of plant fibres (probably flax), and tabby-woven, z-spun, or single-ply yarn with most thread diameters being 0.3 – 0.4 mm. The function of the textile remains on pellet bells is difficult to determine. Fine, creased fabrics might derive from clothing, such as the fragments on an iron pellet bell from burial 17, Halimba-Belátó-domb (Figure 15), which lay in the area of the woman's knee, perhaps belonging to a loosely cut and gathered dress.

Generally, burial shrouds, wrappings, and burial linings can be suggested for many finds. Especially for a textile with extraordinarily thick threads (up to 1.6 cm) from burial A-342 of Kölked-Feketekapu, we must consider that the small child interred there might have been wrapped in a blanket together with the pellet bell (Pomberger et al. 2022b). A more secure finding derives from a textile on a pellet bell from burial 63 of Gyenes/Gyenesdiás, near Lake Balaton, which strongly suggests that the object was placed in a small bag or wrapped in a piece of fabric, which can be seen by the orientation of the threads, which are preserved all around the pellet bell (Pomberger et al. 2023). This emphasises the symbolic meaning of the pellet bell, at least in the context of a burial, since the sounding of the instrument would have been quite restricted when wrapped in fabric. It must be noted, though, that the wrapping of burial goods seems to be a general custom in this period.

Unfortunately, little is known about the clothing of the Avars, as no complete garments have been found due to the preservation conditions for textiles. Some literary evidence derives from (pseudo-)Maurikios' sixth/seventh-century Byzantine *Strategikon*, where Avar clothing is mentioned as wide-fitting tunics with wide sleeves of linen, goat's fur, or coarse fabric, which covered the knees while on horseback (Dennis and Gamillscheg 1981: 81). Although it must be noted that the author is describing clothing in military contexts, the description partially corresponds with the pictorial and textile archaeological evidence, though these are also sparse. For textile clothing, an antler object from Nosza (Serbia, seventh to ninth century) (Bugarski 2016: 86–88; Vida 2017: 93, Fig. 67.3) is most interesting, as it seems to depict two people with horses wearing a caftan, which covers most of the legs. As described above, archaeological textile finds also indicate a popular use of plant fibres (linen), though it is not always possible to determine if the fabric derives from clothing, and the frequently occurring folds could point to loosely fitting garments. Nevertheless, the information on the textiles and clothing (including the other accessories) can be used for visualisations and acoustic demonstrations of how the pellet bells might have been worn in reconstructions, which is useful for public communication of the research. Still, it must always be stressed that due to the lack of direct evidence, such reconstructions are speculative and involve a lot of interpretation. Three costumed dolls were recreated in order to physically visualise how the pellet bells might have been worn. The cuts of the clothing were based on the complete finds from the Moshchevaja Balka burials in the North Caucasus (Ierusalimskaja 1996: 33–58; 143–60; 307–16). These date to the eighth to ninth century and although they are associated with the Alanic period, they serve as a useful comparison for Avar textiles, as caftans – depicted on the Avar object from Nosza, as mentioned – were also worn by men and also because linen and tabby weaves were quite common. The other clothing components were based on typical Avar period finds: decorated men's belts, more simple women's belts, and bead necklaces. For the man and the woman, the pellet bells were hung from a string on the belt. The young child wears the bell on a band on its wrist. Figure

Figure 16: Avar costumes with pellet bells. Reconstruction: K. Saunderson. Photo: B.M. Pomberger.

16 shows dolls in Avar clothing that has been reconstructed based on the best evidence currently available, and wearing pellet bells.

4 Acoustics of metallic Idiophones

The spectral and temporal sound properties of (pellet) bells and other similar objects mainly depends on shape, size, material/alloy, wall thickness, and mode of excitation. In bells, a clapper hits the inner surface at the mouth/lip, creating approximately 5 to 12 single impulses per second when rung constantly. Inside the pellet bells an encapsulated stone or metal ball bounces against the inner surface, also creating single impulses, up to 50 per second. Bells produce a higher number and more pronounced partial frequencies, are louder and have a longer decay time than pellet bells, which gives the typical sound more tonal components and a clearer pitch, while pellet bells contain less partials, more noise components and hardly evoke any pitch perception. Neither sound is harmonic, however, multiple so-called *natural modes* (oscillations) create a variety of partial frequencies (Hall 1980: 158–62).

To gain an overview of all currently investigated idiophones, recordings of the following items were analysed: 14 pendants from the site Býčí skála cave, seven bells from Vindobona, 15 bells from

Ovilava, ten bells and two pellet bells from Savaria, six Avar pellet bells and two Roman-Avar bells from the Hungarian National Museum, Great Migration collection, eight Avar pellet bells and five Roman bells from the Slovak National Museum Bratislava, seven Avar pellet bells from the Danube Region Museum in Komárno and seven Avar pellet bells and seven Roman-Avar bells from the Wien Museum, in total 83 idiophones and 83 recordings.

4.1 Analysis of the sample

In this study, 83 recordings of metallic idiophones have been compared, consisting of bells (39), pellet bells (30), and other rattling pendants (14). All recordings were made inside of a mobile noise absorbing chamber, which was constructed for this project (Pomberger and Mühlhans 2022). For further low frequency noise reduction, a 500 Hz lowpass filter (Bessel, 5th order) was applied prior to analyses.

Sounds can be described physically and objectively, using acoustic parameters such as sound pressure level, amplitudes of partials, spectral shape/energy and the like, which were calculated using Audition and Praat for this study. Subjective descriptions mostly use contrasting pairs of adjectives like bright/dark, sharp/dull, simple/complex and the like. Psychoacoustics, being a part of psychophysics, seeks to find the connection between subjective impressions of a stimulus and its physical properties in order to model prediction parameters such as loudness, sharpness, roughness, tonality, brightness, and harmonicity (Fastl and Zwicker 2007), which were calculated using HEAD ArtemiS SUITE (HEAD acoustics GmbH 2022). JASP was used for statistical analyses of all known parameters.

4.2 Spectral and temporal features

In general, the objects from this sample produce partials roughly between 2 and 20 kHz, with only few exceptions reaching as low as 1 kHz. Figure 17a shows the spectra of all 39 bells, which are exclusively from the Roman period, Figure 17b shows the spectra of 30 pellet bells, almost exclusively from the Avar period. The bells clearly show more pronounced partials and higher amplitudes, but particularly more spectral energy in the frequency range above 5 kHz, rendering them brighter in perception. Both share a certain amount of spectral energy in the 2–4 kHz range, where the human ear is particularly sensitive, so they can be heard even at very low levels.

Figure 17a shows the temporal structure of an average Roman bell from the sample (Vindobona Cat. 23), with a decay time of about 300 ms, compared to Figure 17b with that of an average Avar pellet bell (Vindobona Cat. 35) at about 35 ms.[8]

[8] Pomberger 2022.

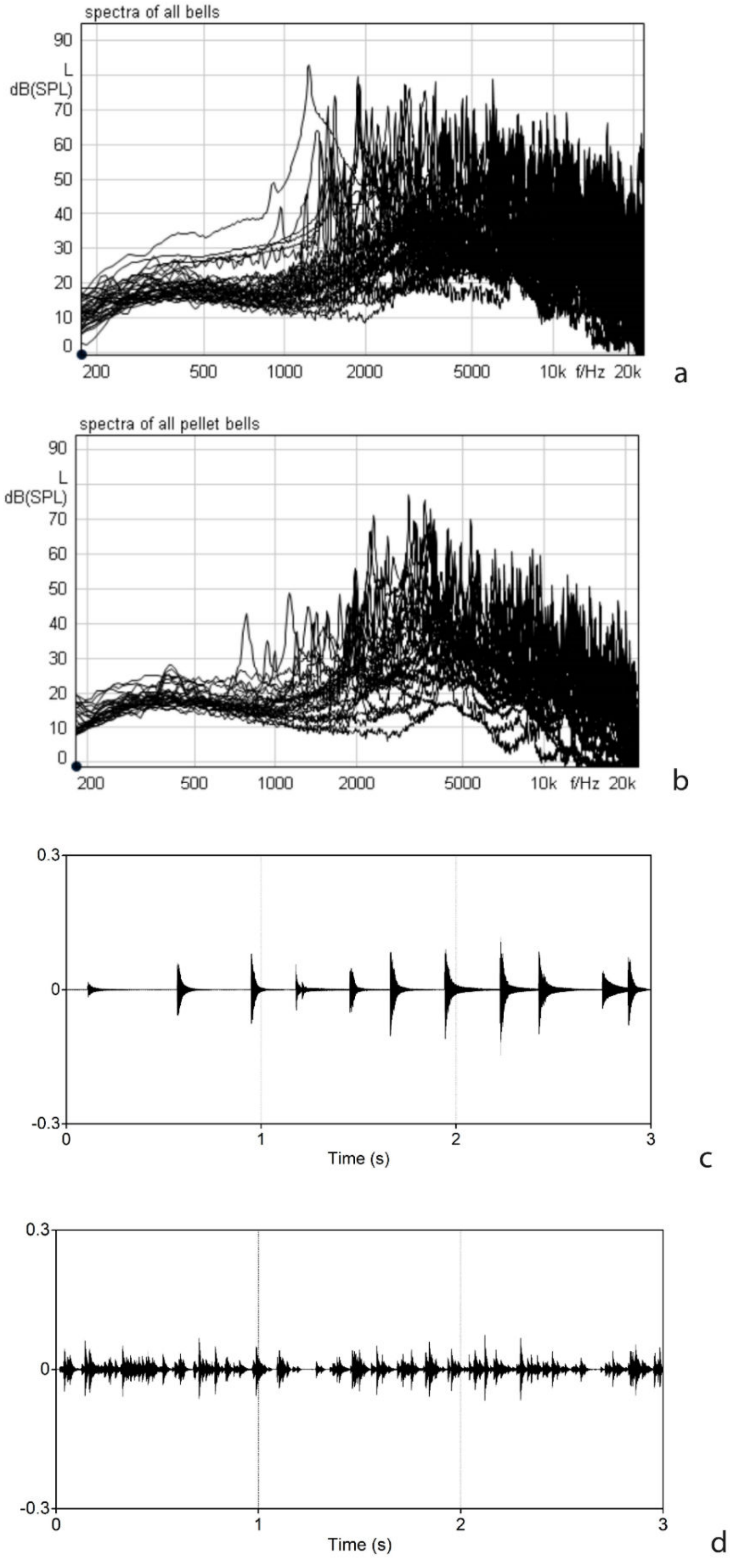


Figure 17: a: Spectra (4096, 85%, HAN) of all 39 bells from the sample;
b: Spectra (4096, 85%, HAN) of all 30 pellet bells from the sample;
c: Waveform of an average Roman bell (Vindobona Cat. 25);
d: Waveform of an average Avar pellet bell (Vindobona Cat. 35). Design: J. Mühlhans.

4.3 Sound pressure level and loudness

Loudness, measured in phon or sone (Fastl and Zwicker 2007: 203–5), is not to be confused with the level given in dB re p_0,[9] but instead depends on it, thus a correlation of r=0.95*** can be observed.[10] On average, bells are louder (73.5 dB, 23.5 sone, 83.5 phon) than pellet bells (69.1 dB, 18.8 sone, 80.5 phon), but with only a medium effect size[11] of about d=0.4*. Unsurprisingly, heavier/larger objects are also louder, with a correlation between weight and level of r=0.67***. Also, the amount of copper in the alloy (known for 45 objects) correlates with level/loudness at r=0.39**, which could also be observed in prior measurements, but with a too small sample.

4.4 Sharpness, brightness, and roughness

Sharpness is influenced by spectral shape and density and is inversely related to pleasantness (Fastl and Zwicker 2007: 239–40). Brightness is highly correlated with the spectral centroid (Schubert and Wolfe 2006). Roughness is a sensation evoked by the modulation of tonal components (Sottek 2009). All three parameters show large effects in a t-test between Roman bells and Avar pellet bells, with the former showing higher mean values for brightness (d=0.86***), but lower values for sharpness (d=-0.81***) and roughness (d=-0.75**). However, while both types can be classified as bright and sharp sounds, despite the group differences, they are not rough at all. Again, the amount of copper is highly correlated with sharpness (r=0.47***), but not at all with the remaining two parameters. Sharpness is also weakly correlated with level (r=0.47***) and loudness (r=0.37**).

4.5 Impulsiveness and tonality

Impulsiveness depends on the energy of the onsets in a sound which adds to the dynamic sensation in a stimulus (Sottek et al. 1995) and is calculated in the ArtemiS software in *impulsiveness units* (iu) using the Sottek Hearing Model. Tonality is calculated as the simple ratio between tonal and noise components in the signal in dB. The Roman bells are slightly more tonal (d=0.55*) with a mean value of 18.6 dB compared to 15.0 in the Avar pellet bells. In terms of impulsiveness, no difference between the groups can be seen, since more impulses per time unit also create less energy, which evens out the parameter between the types. Nevertheless, tonality is negatively correlated with impulsiveness itself at r=-0.52***. In this calculation, only a minor trend could be found for the amount of copper in the alloy for tonality r=0.23, p<.067.[12] Tonality is negatively correlated with roughness (r=-0.62***) and positively with impulsiveness (r=0.81***).

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[9] p_0 = 20 µPa (Micropascals) is the commonly used reference sound pressure.

[10] Here *r* describes the correlation coefficient that can range from 0 (no correlation at all) to positive 1 (strict linear correlation) or negative 1 (inverse linear correlation). The level of significance, which depends on the sample size, is often marked with asterisks, * for a p<.05, ** for p<.01 and *** for p<.001. The more asterisks, the higher the significance.

[11] The effect size between two means is expressed as *Cohen's d*, 0.2 = small, 0.5 = medium, and 0.8 = large effects.

[12] If a p-value is close to significance (in this case p<.05), it is sometimes referred to as a *trend* or *tendency* that could undergo further examination.

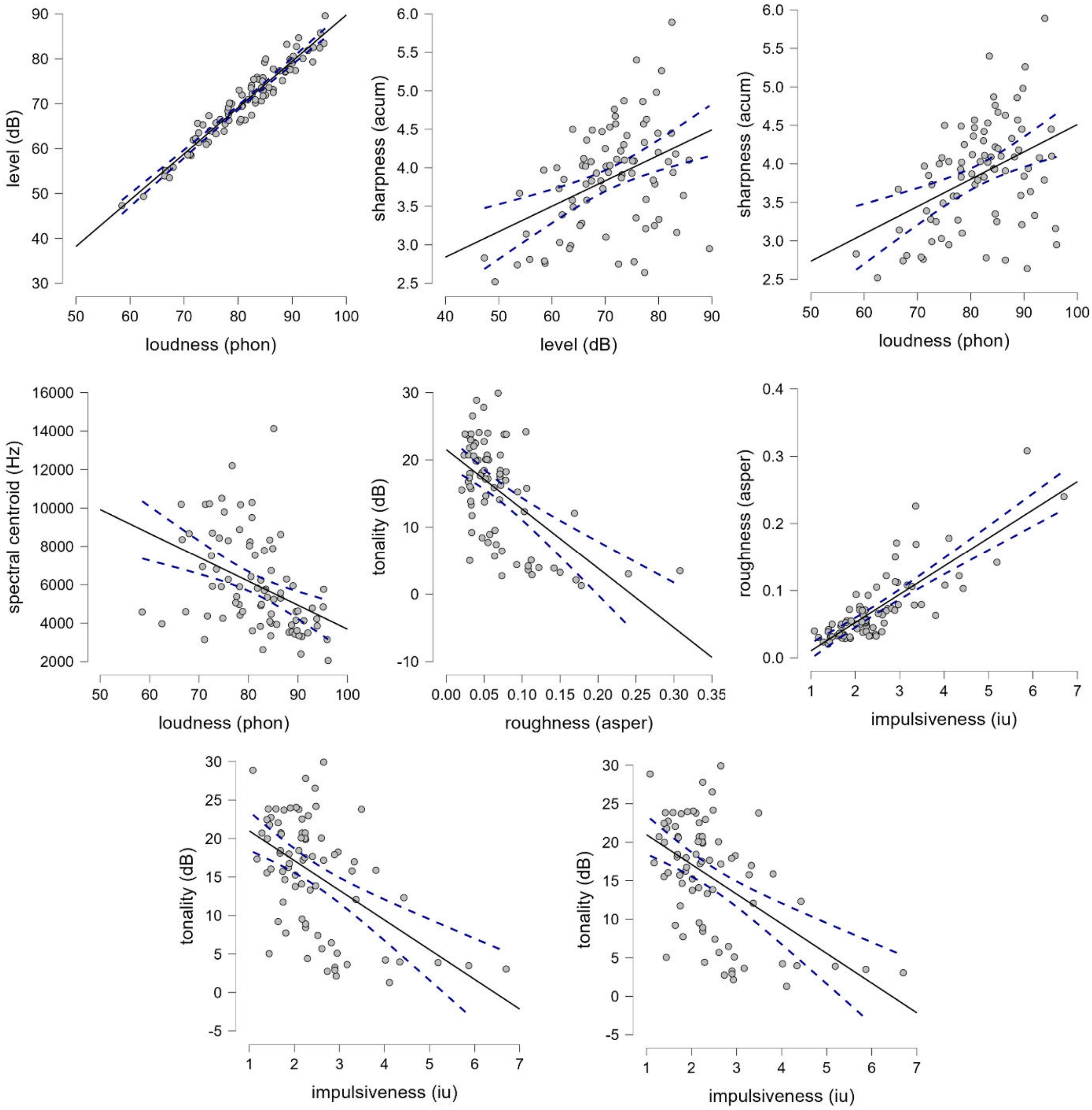

Figure 18: Scatterplots for the eight highly significant correlations between two parameters (p<.001) with 95% confidence interval (dashed blue line). Design: J. Mühlhans.

4.6 *Peak frequency and lowest partial*

The peak frequency is the strongest partial in amplitude over the measurement and is likely to influence pitch perception, which is not obvious from the spectral components (Benade 1976: 56). The lowest partial or *fundamental* in bells depends on thickness and diameter and is a result of the axial mode [2,0] (Fletcher and Rossing 1991: 578). Peak frequency is correlated with brightness (r=0.72***), but the lowest partial only shows very weak negative effects with loudness (r=-0.26*).

Variable		level (dB)	loudness (phon)	sharpness (acum)	roughness (asper)	tonality (dB)	impulsive-ness (iu)	spectral centroid (Hz)	peak fre-quency (Hz)	lowest partial (Hz)	Cu
2. loudness (phon)	n	83	—								
	r	0.964 ***	—								
	p	< .001	—								
3. sharpness (acum)	n	83	83	—							
	r	0.420 ***	0.421 ***	—							
	p	< .001	< .001	—							
4. roughness (asper)	n	83	83	83	—						
	r	0.095	0.097	-0.115	—						
	p	0.394	0.384	0.301	—						
5. tonality (dB)	n	79	79	79	79	—					
	r	0.355 **	0.313 **	0.277 *	-0.578 ***	—					
	p	0.001	0.005	0.013	< .001	—					
6. impulsiveness (iu)	n	83	83	83	83	79	—				
	r	0.256 *	0.236 *	-0.252 *	0.815 ***	-0.521 ***	—				
	p	0.019	0.032	0.021	< .001	< .001	—				
7. spectral centroid (Hz)	n	83	83	83	83	79	83	—			
	r	-0.341 **	-0.411 ***	0.021	-0.331 **	-0.039	-0.214	—			
	p	0.002	< .001	0.852	0.002	0.733	0.053	—			
8. peak frequency (Hz)	n	83	83	83	83	79	83	83	—		
	r	-0.159	-0.276 *	0.144	-0.233 *	0.042	-0.194	0.761 ***	—		
	p	0.151	0.012	0.193	0.034	0.715	0.078	< .001	—		
9. lowest partial (Hz)	n	82	82	82	82	78	82	82	82	—	
	r	-0.159	-0.265 *	0.210	-0.016	-0.020	-0.184	0.073	0.150	—	
	p	0.153	0.016	0.059	0.884	0.859	0.099	0.515	0.177	—	
10. Cu	n	45	45	45	45	43	45	45	45	45	—
	r	0.388 **	0.458 **	0.466 **	-0.179	0.233	-0.113	-0.045	0.049	-0.317 *	—
	p	0.009	0.002	0.001	0.239	0.133	0.459	0.771	0.747	0.034	—

Table 4: Pearson's correlations for all calculated parameters with sample size (n), correlation coefficient (r) and significance (p). * $p < .05$, ** $p < .01$, *** $p < .001$.

The statistical calculations above are mainly a result of comparing only 69 objects from the sample for a direct comparison of Roman bells and (mostly) Avar pellet bells. Some statistical values change slightly when the 14 remaining objects from the Iron Age are considered, e.g., r-value from weight-loudness changes from 0.67*** to 0.62*** and roughness-impulsiveness from 0.81*** to 0.82***. Table 4 gives an overview of the correlations between all parameters for the entirety of the sample.

5 Conclusion/Discussion

Investigating metallic idiophones over a time span of 1600 years demonstrates their various uses and functions, their diversity of material and chemical compositions, and their influence on their

	impulsiveness (iu)	loudness (phon)	Cu	weight (grams)	level (dB)	sharpness (acum)	roughness (asper)	tonality (dB)	spectral centroid (Hz)	peak frequency (Hz)	lowest partial (Hz)
impulsiveness (iu)		0.236	-0.113	0.405	0.256	-0.252	0.815	-0.521	-0.214	-0.194	-0.184
loudness (phon)	0.236		0.458	0.597	0.964	0.421	0.097	0.313	-0.411	-0.276	-0.265
Cu	-0.113	0.458		-0.087	0.388	0.466	-0.179	0.233	-0.045	0.049	-0.317
weight (grams)	0.405	0.597	-0.087		0.629	-0.072	0.154	0.05	-0.187	-0.12	-0.256
level (dB)	0.256	0.964	0.388	0.629		0.42	0.095	0.355	-0.341	-0.159	-0.159
sharpness (acum)	-0.252	0.421	0.466	-0.072	0.42		-0.115	0.277	0.021	0.144	0.21
roughness (asper)	0.815	0.097	-0.179	0.154	0.095	-0.115		-0.578	-0.331	-0.233	-0.016
tonality (dB)	-0.521	0.313	0.233	0.05	0.355	0.277	-0.578		-0.039	0.042	-0.02
spectral centroid (Hz)	-0.214	-0.411	-0.045	-0.187	-0.341	0.021	-0.331	-0.039		0.761	0.073
peak frequency (Hz)	-0.194	-0.276	0.049	-0.12	-0.159	0.144	-0.233	0.042	0.761		0.15
lowest partial (Hz)	-0.184	-0.265	-0.317	-0.256	-0.159	0.21	-0.016	-0.02	0.073	0.15	

Table 5: Heatmap with Pearson's correlations of all calculated parameters, coefficients (r) shown as numbers, negative correlations marked in red, positive ones in blue. Design: J. Mühlhans.

acoustic surroundings. The fourteen pendants from the Býčí skála Cave, Hallstatt culture, very probably were sacrificial offerings of a woman. Cage shaped pendants (here the bobbles) have their origin in the regions of the Black Sea and the Caspian Sea. Bobbles and pellet bells imitating pomegranates or poppy seeds can be interpreted as symbols and amulets for fertility, luck, and abundance. Their material is bronze with some amounts of lead. The sounding jewellery is quite heavy and produces sounds/noises with frequencies between 1.3 kHz and 20 kHz. They are quite sharp, but not rough or loud and can be described as pleasant.

The Roman bells of Vindobona were cast from three different copper alloys and forged from iron sheets. The materials, types, and average sizes are very common in the Roman imperial period. Their analysed sounds are in the upper human auditory range, show more tonal components than noise character, and would be perceived as sharp but not rough. Bells are multifunctional sound objects that could serve many purposes. Their basic functions were as noise and signal objects, acoustically-perceived offensive weapons, perceived apotropaic protective sound shields, and, furthermore, objects of status and prestige. Ancient authors inform us about their use in daily life, revealing uses both profane and sacral. Given the range of uses, precise statements about a given bell's function is thus highly dependent on the context in which it was found. This means that bells in specific find contexts, for example, in graves, in connection with animal skeletons, or attached to chariots, allow for more precise statements than bells discovered in buildings, roads, or ditches.

During the Early Middle Ages (Avar period), bells seem to lose their important role. Only a few (of Roman origin) were found in burials. Pellet bells appear in the Carpathian base again in the middle of the seventh century and are similarly excavated in burials, mainly of children. They probably spread from the Black Sea region and the Caspian Sea back to Central Europe. Each object is unique and of different metallurgic quality. Shapes and ornaments are manifold. Pebbles, bronze balls, and lumps of cinder serve as rattle bodies. Textile fragments of various quality as well as their find positions in the graves demonstrate that they could have been worn on the body or placed in a small bag or wrapping. Some horse bridles might have been decorated with pellet bells. They are made from various copper alloys and iron. Their sounds are rather high, with partials located between 1 kHz and 20 kHz. They would thus be perceived as sharp but not rough. We do not know for certain if the Avar people really believed that pellet bells served an apotropaic purpose, as has been suggested in many publications, or whether other imaginations and ideas lay behind their inclusion in burial contexts. In any case, it is strange that they appear in such conspicuously small numbers.

This article examined a total of 83 objects (83 recordings) for a variety of (psycho-)acoustic parameters. 39 bells stemming exclusively from the Roman period were compared to 30 pellet bells mainly from the Avar period. These two groups showed the greatest differences in the acoustic parameters. 14 Iron Age objects consisting of other types of metallic idiophones were also calculated in to provide context for the overall correlations. The results were as follows: Roman bells consistently ranked higher in weight, level/loudness, tonality, brightness, and peak frequency. The Avar pellet bells ranked higher in the amount of copper in the alloy, sharpness, and roughness. Other parameters, such as impulsiveness and lowest partial frequency, were approximately similar between the two groups. In statistically precise terms, large effect sizes could be observed between the groups in terms of weight, sharpness, roughness, and brightness, with a Cohen's $d>0.75$. Medium and therefore less significant effects could be seen in level and tonality with a Cohen's $d>0.5$. Other differences were either small in effect size or not significant in the t-test. Since the corpus of parameters in the project grew larger with time, an exploratory factor analysis was done to determine if the complexity of data could be reduced. The results were positive but mixed. If only bells and pellet bells are calculated, reducing the single parameters to two factors can cumulatively explain about 55% of the variance. Adding a third factor explains up to 67%. This is still not satisfying, and indicates that many parameters have a high value in uniqueness and thus are needed for a detailed understanding of the differences among the tested metallic idiophones.

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Primary Sources

Aeschylus, *Septem contra Thebas* (ed. M.L. West), Stuttgart: Teubner 1992.

Cassius Dio, *Historiarum Romanarum quae supersunt* (ed. U.P. Boissevain), Berlin: Weidmann 1895–1931.

Diodorus Siculus, *Bibliotheca historica*, (ed. C. de Boor, R. Büttner-Wobst, U.Ph. Boissevain), Berlin: Teubner 1903–1906.

Euripides, *Rhesus* (ed. G. Zanetto), Berlin: Teubner 1993.

Isidorus Hispalensis, *Etymologiae/Origines* (ed. W.M. Lindsay), Oxford: Clarendon 1985.

Lucianus Samosatensis, *De mercede conductis* (ed. M.D. Macleod), Oxford: Clarendon 1972–1987.

Marcus Valerius Martialis, *Epigrammata* (ed. D.R. Shackleton Bailey), Berlin: Teubner 1990.

Gaius Petronius Arbiter, *Satyrica* (ed. K. Müller), Berlin: Teubner ^{5}2003.

Gaius Plinius Secundus, *Naturalis Historia* (ed. K. Mayhoff), Berlin: Teubner 1892–1909.

Lucius Mestrius Plutarchus, *Questiones convivales* (ed. C. Hubert et. al.), Leipzig: Teubner 1929–1978.

Sextus Empiricus, *Adversus Mathematicos* (ed. H. Mutschmann, J. Mau), Berlin: Teubner 1: 1958; 2: 1914; 3: 1954; 4: 1962.

Suetonius Tranquillus, *De vita Caesarum: Augustus* (ed. M. Ihm), Berlin: Teubner 1908.

Bibliography

Aures, W. (1984). Der Wohlklang: eine Funktion von Schärfe, Rauhigkeit, Klanghaftigkeit und Lautheit. *Fortschritte der Akustik DAGA'* 84, 735–38.

Autengruber-Thüry, H. (2021). *Hunde in der römischen Antike: Rassen/Typen - Zucht - Haltung und Verwendung*. Oxford: Archaeopress.

Ateshi Gadirova, N. (2014). Zur Identifizierung von bewaffneten Frauen in den Gräbern des 2. bis 1. Jahrtausends v. Chr. in Aserbaidschan auf Basis der archäologischen Funde. *Archäologische Informationen* 37, 239–56.

Bachmann-Geiser, B. and Aeschbacher, W. (2001). *Europäische Musikinstrumente im Bernischen Historischen Museum: die Sammlung als Spiegel bernischer Musikkultur*. Bern: Bernisches Historisches Museum.

Bächtold-Stäubli, H. and Hoffmann-Krayer, E. (1987a). *Handwörterbuch des deutschen Aberglaubens*. Band 2. Berlin – New York: Walter de Gruyter. DOI: 10.1515/9783110855371.1.

Bächtold-Stäubli, H. and Hoffmann-Krayer, E. (1987b). *Handwörterbuch des deutschen Aberglaubens*. 5. Berlin – New York: Walter de Gruyter.

Bächtold-Stäubli, H. and Hoffmann-Krayer, E. (1987c). *Handwörterbuch des deutschen Aberglaubens*. 6. Berlin – New York: Walter de Gruyter. DOI: 10.1515/9783110840100.

Barth, F.E. (2020). Die vergessenen Toten von Hallstatt. *Mitteilungen der Anthropologischen Gesellschaft in Wien (MAGW)* 150, 243–66.

Benade, A. (1976). *Fundamentals on Musical Acoustics*. New York – London: Oxford University Press.

Biró-Sey, K., Medgyes, M., and Torbágyi, M. (1998). *Der spätrömische Schatzfund von Tokorcs*. Budapest: Ungarisches Nationalmuseum.

Bouzek, J. (1974). Macedonian Bronzes. Their origin, distribution and relation to other cultural groups of the Early Iron Age. *Památky archeologické ročník* 45.2, 278–41.

Bouzek, J. (2006). Macedonian Bronzes – 30 Years Later. *Folia archaeologica Balkanica* 1, 97–109.

Bouzek, J. (2012). Central Europe and Caucasus in the Early Iron Age. In: W. Blajer (ed.), *Peregrinationes archaeologicae in Asia et Europa Joanni Chochorowski dedicatae*, Kraków: Wydawnictwo Profil-Archeo, 537–47.

Bugarski, I. (2016). Carved antler tools from Nosa and Manđelos reassessed: a glimpse into the Avar pictorial evidence. In: S. Vitezović (ed.), *Close to the bone: current studies in bone technologies*. Belgrade: Belgrade Institute of Archaeology, 86–97.

Casaulta, M. (2017). Die Funde aus dem römischen Wohn- und Wirtschaftsgebäude von Erschwil. Archäologie. *Archäologie und Denkmalpflege im Kanton Solothurn* 22, 19–34.

Chinelli, R., Mader, I., Sakl-Oberthaler, S., and Sedlmayer, H. (2001). Die Grabungen im botanischen Garten der Universität Wien. *Fundort Wien. Berichte zur Archäologie* 4, 294–305.

Dennis, G.T. and Gamillscheg, E. (1981). *Das Strategikon des Maurikios*. Vienna: Austrian Academy of Sciences.

Diederichsen, D. and Schulze, H. (2017). *Krieg singen.* Berlin: Matthes & Seitz.

Dolejšová, J. (1987). Funde von Textilresten in Komárno – Schiffswerft. *Slovenská archeológia* 35.2, 385–90.

Donat, P., Sakl-Oberthaler, S., and Sedlmayer, H. (2003). Die Werkstätten der canabae legionis von Vindobona. Befunde und Funde der Grabungen Wien 1, Michaelerplatz. Fundort Wien. *Berichte zur Archäologie* 6, 4–57.

Donat, P., Sakl-Oberthaler, S., and Sedlmayer, H. (2005). Die Wohnbereiche der canabae legionis von Vindobona. Befunde und Funde der Grabungen Wien 1, Michaelerplatz (1990/1991) – Teil 2. *Fundort Wien. Berichte zur Archäologie* 8, 24–90.

Drack, W. (1966/67). Anhängeschmuck der Hallstattzeit aus dem schweizerischem Mittelland und Jura. *Jahrbuch der Schweizerischen Gesellschaft für Ur- und Frühgeschichte* 53, 29–70.

Duden 1989: *Deutsches Universalwörterbuch A – Z*. Mannheim: Dudenverlag.

Duden 2001: *Duden, Das Fremdwörterbuch.* Mannheim-Leipzig-Wien-Zürich: Dudenverlag.

Eckardt, H. and Williams, S. (2018). The sound of magic? Bells in roman Britain. *Britannia* 49, 179–210. DOI: 10.1017/S0068113X18000028.

Erdélyi, I. (1958). *A jánoshidai avarkori temető*. Régészeti Füzetek II/1. Budapest: Magyar Nemzeti Múzeum-Történeti Múzeum.

Fastl, H. and Zwicker, E. (2007). *Psychoacoustics – Facts and Models*. Berlin - Heidelberg: Springer.

Fettich, N. (1927). Újabb fegyvertörténeti adatok a koraközépkori lovasnomádok magyarföldi hagyatékából. *Az Országos Magyar Régészeti Társulat* Évkönyve, 166–71.

Fettich, N. (1965). *Das awarenzeitliche Gräberfeld von Pilismarót-Basaharc*. Budapest: Akadémiai Kiadó.

Fletcher, N.H. and Rossing, T.D. (1991). *The Physics of Musical Instruments* (Springer Study Edition). New York: Springer, 577–605.

Fletcher, H. and Munson, W.A. (1933). Loudness, its definition, measurement and calculation. *Journal of the American Society of Acoustics* 5, 82–108.

Furger, A.R. and Schneider, Ch. (1993). Die Bronzeglocke aus der Exedra des Tempelareals Sichelen 1. *Jahresberichte aus Augst und Kaiseraugst* 14, 159–72.

Garám, É. (1975). The Szebény I-III cemetery. In: É. Garam, I. Kovrig, J.G. Szabó, and Gy. Török, (eds), *Avar Finds in the Hungarian National Museum. Cemeteries of the Avar Period (567 – 829) in Hungary,* Vol. 1., Budapest: Akadémiai Kiadó, 49–120.

Gelfand, S. (2010). *Hearing: An Introduction to Psychological and Physiological Acoustics.* London: Routledge, Taylor & Francis Group.

Grant, M., Papaeti, A., and Leder, S. (2015). Die zersungene Seele: Musik als Instrument der Folter. In: G. Bernatzky, G. Kreutz, (eds), *Musik und Medizin*. Vienna: Springer. DOI: 10.1007/978–3–7091–1599–2_27.

Grömer, K. (2015). Awarische Textilien aus den Gräbern von Zwölfaxing II (Burstyn-Kaserne). In: S. Müller (ed.), *Das awarische Gräberfeld in Zwölfaxing, Burstyn-Kaserne* (Archäologische Forschungen in Niederösterreich 14), St. Pölten: Verlag NÖ Institut für Landeskunde, 192–207.

Grömer, K. and Rapan Papeša, A. (2015). Jednostavne tkanine i žigosana koža: organski nalazi s avarodobnog groblja u Nuštru (istočna Hrvatska) / Simple cloth and stamped leather: organic finds from the Avar graveyard in Nuštar (Eastern Croatia), *Vjesnik Arheološkog muzeja u Zagrebu* 3.48, 51–83.

Grömer, K. and Kern, A. (2018). *Artifacts: Treasures of the Millennia* (A Guide through the Prehistoric Collections). Wien: Naturhistorisches Museum Wien.

Grömer, K., Saunderson, K., and Pomberger, B.M. (2021). Metallic idiophones 800 BCE and 800 CE in Central Europe. Their function and acoustic influence in daily life. *Archaeological Textile Review* 63. 24–28.

Grömer, K. and Pomberger, B.M. (2023). Soft clothes and sounding jewellery – sound fields of rich women in Eastern Hallstatt culture. In: A. Gouy, (ed.), *Textiles in Motion. Dress for Dance in Ancient World* (Ancient Textiles Series 41), Oxford – Philadelphia: Oxbow Books, 96–105.

Haid, G. (2004). *Lärminstrumente*. https://www.musiklexikon.ac.at/ml/musik_L/Laerminstrumente.xml [Accessed 13 May 2023].

Hackl, M. and Pomberger, B.M. (2022). References to metallic idiophones in ancient literature between 600 BC and 800 AD. https://www.academia.edu/92935781/References_to_metallic_idiophones_in_ancient_literature_between_600_BC_and_800_AD_Table_by_Maria_Hackl_and_Beate_Maria_Pomberger.

Hampel, J. (1905). *Alterthümer des Frühen Mittelalters in Ungarn*. Band 2. Braunschweig: F. Vieweg und Sohn.

HEAD acoustics GmbH (2022). ArtemiS SUITE [Computer program]. Version 9.3. Available at: https://www.head-acoustics.com/products/analysis-software/artemis-suite.

Himmelmann, N. (1980). Über Hirten-Genre in der antiken Kunst. *Abhandlungen der rheinisch-westfälischen Akademie der* Wissenschaften 65, Opladen: Westdeutscher Verlag.

Hornbostel, E.M. and Sachs, C. (1914). Systematik der Musikinstrumente. Ein Versuch. *Zeitschrift für Ethnologie / Journal of Social and Cultural Anthropology* 46.4/5, 553–90.

Hundt, H.-J. (1984). Textilfunde aus Grab 86 des awarischen Friedhofs von Sommerein am Leithagebirge, Niederösterreich. In: F. Daim and A. Lippert (eds), *Das awarische Gräberfeld von Sommerein am Leithagebirge, NÖ.* (Studien zur Archäologie der Awaren 1. Studien zur Ur- und Frühgeschichte des Donau- und Ostalpenraumes 2. Denkschriften/Österreichische Akademie der Wissenschaften, Philosophisch-Historische Klasse 170). Vienna: Verlag der Österreichischen Akademie der Wissenschaften. 181–82.

Ierusalimskaja, A.A. (1996). *Die Gräber der Moščevaja Balka: frühmittelalterliche Funde an der nordkaukasischen Seidenstrasse*. Munich: Ed. Maris.

Kadieva, A.A., Demidenko, S.W., and Emkyzhev A.A. (2020). Burial of the Pre-Scythian time with a bronze chest cloth from the burial grave of Zayukovo-3. *Кавказология / Caucasology* 2, 50–67.

Kaesche, H. (1979). *Die Korrosion der Metalle – Physikalisch-chemische Prinzipien und aktuelle Probleme*. Berlin – Heidelberg – New York: Springer Verlag.

Kiss, A. (1996). *Das awarenzeitlich-gepidische Gräberfeld von Kölked-Feketekapu A.* Innsbruck: Wagner.

Kiss, G. and Somogyi, P. (1984). *Tolna megyei avar temetők: Bonyhádvarasd, Cikó, Gerjen, Regöly, Závod, Tolna megyei szórványok. / Awarische Gräberfelder im Komitat Tolna.* (Dissertationes Pannonicae Series III, Vol. 2), Budapest: Múzsák.

Kenner, F. von (1904). Römische Funde in Wien aus den Jahren 1901 bis 1903. *Jahrbuch der K.K. Zentralkommission für Erforschung und Erhaltung der Kunst- und Historischen Denkmale* 2.1, 103–69.

Kern, A., Kowarik, K., Rausch, A.W., and Reschreiter, H. (2008). *Salz – Reich. 7000 Jahre Hallstatt* (Veröffentlichungen der Prähistorischen Abteilung). Wien: Naturhistorisches Museum Wien.

Kovrig, I. (1975). The Szob Cemetery. In: É. Garam, I. Kovrig, J.G. Szabó, and Gy. Török, (eds), *Avar Finds in the Hungarian National Museum. Cemeteries of the Avar Period (567 – 829) in Hungary,* Vol. 1., Budapest: Akadémiai Kiadó,157–208.

Kramer, K. (2016). *Die Glocke: Eine Kulturgeschichte*. Kevelaer: Verlagsgemeinschaft Topos plus.

Kromer, K. (1959). *Das Gräberfeld von Hallstatt*. Firenze: Sansoni.

Kronberger, M. and Mosser, M. (2018). Wien – Vindobona. In: V. Gassner and A. Pülzl (eds), *Der römische Limes in Österreich. Führer zu den archäologischen Denkmälern*. Wien: Verlag der Österreichischen Akademie der Wissenschaften, 242–67.

László, Gy. (1955). *Études archéologiques sur l'histoire de la société des Avars* (Archaeologia Hungarica 34). Budapest: Akadémiai Kiadó.

Lobinger, Ch. (2016). *Das awarenzeitliche Gräberfeld von Edelstal (Nemesvölgy) im Burgenland. Die Ausgrabung Ágost Sötérs von 1884 bis 1887* (Universitätsforschungen zur Prähistorischen Archäologie 288). Bonn: Dr. Rudolf Habelt GmbH.

Madaras, L. (1995). Avarkori lelőhelyek Jász-Nagykun-Szolnok megyében. In: Z. Ujváry, (ed.), *Tanulmányok és közlemények*, Debrecen – Szolnok: Ethnica, 81–107.

Mandl, F. (2000). Weideglocken und Schellen aus der Dachstein- Salzkammergutregion. *Mitteilungen der ANISA 21.*1/2, 74–84.

MIMO (2011). *Revision of the Hornbostel-Sachs Classification of Musical Instruments by the MIMO Consortium,* 1–26. http://www.mimo-international.com/documents/Hornbostel%20Sachs.pdf [Accessed: 8 August 2023].

Mocchi, G. (2018). Tintinnabula: Il Suono Ritrovato. *Amoenissimis... Aedificiis. Lo scavo di Piazza Marconi a Cremona* 1/2, 1–33.

Mosser, M. (2016). Befunde im Legionslager Vindobona. Teil VIII: Der Legionslagerplan – Grundrissrekonstruktion und Chronologie. *Fundort Wien. Berichte zur Archäologie* 19, 24–45.

Mosser, M. (2017). Vorbericht zu den Grabungen in Wien 3, Rennweg 52. *Fundort Wien. Berichte zur Archäologie* 20, 162–70.

Mühlhans, J., Kerbler, L., and Pomberger, B.M. (2022). Avar pellet bells from different sheet metals: Finds, experimental forging and acoustics. *Studia Archaeologica Brunensia* 27. 1, 119–41.

Mühlhans, J. and Pomberger, B.M. (2020). Imagination of Dance in Hallstatt Culture. https://www.youtube.com/watch?v=PN5b1OWACPc.

Mühlhans, J. and Pomberger, B.M. (forthcoming), Roman bells and Avar pellet bells cast in copper alloys – the materials' influence on acoustic and psychoacoustic. *Studia Archaeologica Brunensia*.

Müller, M., Chinelli, R., Demsbki, G., et al. (2018). *Ein Wohn-, Handwerks- und Verkaufsbereich in der römischen Zivilsiedlung von Vindobona. Die Ausgrabungen in Wien 3, Rennweg 44* (Monografien der Stadtarchäologie Wien 11).

J. Nicolay, J. (2007). *Armed Batavians. Use and significance of weaponry and horse gear from non-military contexts in the Rhine Delta (50 BC to AD 450)* (Amsterdam Archaeological Studies 2). Amsterdam: Amsterdam University Press.

Niemann, H. (1997). Das Liturgische Läuten: Seine Geschichte und die Rechtsgrundlagen. In: K. Kramer (ed.), *Glocken in Geschichte und Gegenwart* (Beiträge zur Glockenkunde Band 2), Karlsruhe: Badenia, 18–30.

Parzinger, H., Nekvasil, J., and Barth, F.E. (1995). *Die Býči-Skala-Höhle. Ein hallstattzeitlicher Höhlenopferplatz in Mähren* (Deutsches Archäologisches Institut, Römisch-Germanische Kommission 54). Mainz: von Zabern.

Pease, A.S. (1904). Notes on some uses of bells among the Greeks and Romans. *Harvard Studies in Classical Philology* 15, 29–59.

Pesce, G. (1957). *Sarcofagi Romani di Sardegna*. Roma: L'Erma di Bretschneider.

Piningre, J.-F. and Ganard, V. (2004). *Les Nécropoles protohistoriques des Moidons et le site princier du Camp du Château à Salins (Jura)*. Paris: Librairie Archéologique.

Pomberger, B.M. (2016). *Wiederentdeckte Klänge. Musikinstrumente und Klangobjekte vom Neolithikum bis zur römischen Kaiserzeit im mittleren Donauraum* (Universitätsforschungen zur Prähistorischen Archäologie 280). Bonn: Dr. Rudolf Habelt GmbH.

Pomberger, B.M. (2017). Bronzebommeln und Schellen – eine klangliche Errungenschaft aus der Spätbronze- und frühen Eisenzeit. *Studia Archaeologica Brunensia* 22.2, 15–34.

Pomberger, B.M. (2022): Tabelle römischer Glocken und awarischer Schellen aus Wien. https://www.academia.edu/76217324/Tabelle_r%C3%B6mischer_Glocken_und_awarischer_Schellen_aus_Wien_%C3%96sterreich_BMPomberger.

Pomberger, B.M. and Mühlhans, J. (2020). Bronze Pendants from the Býčí skála Cave in Moravia. https://www.youtube.com/watch?v=tX5tDQGrSNQ.

Pomberger, B.M. and Stadler, P. (2018a). Der Klang der Schellen. Schellenfunde aus dem awarischen Gräberfeld von Vösendorf-Laxenburgerstraße, Österreich. *Študijné zvesti Archeologického Ústavu Slovenskej Akadémie Vied SAV* 63, 125–46.

Pomberger, B.M. and Stadler, P. (2018b). Sicher vor Dämonen? Musikarchäologische Forschungen zu Glocken in awarischen Gräbern. *Archaeologia Austriaca* 102, 227–49. DOI:10.1553/archaeologia102s227.

Pomberger, B.M., Grömer, K., Mühlhans, J., and Topa, D. (2020). Schlitzbommeln und Anhänger – Klingender Trachtschmuck aus der Býčí skála-Höhle bei Brünn. *Mitteilungen der Anthropologischen Gesellschaft in Wien (MAGW)* 150, 215–42.

Pomberger, B.M. and Mühlhans, J. (2021). A komárom-hajógyári temető 107. sírjának csörgői. *Iuxta Danubium* 17, 148–57.

Pomberger, B.M., Mühlhans, J., Saunderson, K., and Grömer, K. (2021a). Pellet Bells from the Avarian Cemeteries of Komárno. *Slovenská archeológia* 69.1, 99–131.

Pomberger, B.M., Mühlhans, J., and Grömer, K. (2021b). The project “Metallic idiophones between 800 BC and 800 AD in Central Europe – their function and acoustic influence in daily life” (First reports). In: K. László, D. Băcueț-Crișan, I. Stanciu, F. Mărginean (eds), *Exploring Dwellings and Manufacturing Spaces in Medieval Context (7th–14th Centuries)* (Orbis Mediaevalis III), Cluj-Napoca: Editura Mega, 9–29.

Pomberger, B.M., Sánta, B., Mühlhans, J., Mozgai, V., and Bajnóczi, B. (2021c). Roman bells from Savaria and the Great Migration period pellet bells from Vas County. *Savaria* 43, 73–120.

Pomberger, B.M. and Mühlhans, J. (2022). A portable noise-absorbing recording chamber for sound recordings of archaeological idiophones. *Annalen des Naturhistorischen Museums Wien,* Serie A 123, 65–79.

Pomberger, B.M., Hackl, M., Wegner, W., and Mühlhans, J. (2022a). Ancient bells from Ovilava/Wels – first studies. *Römisches Österreich* 45, 127–91.

Pomberger, B.M., Mühlhans, J., Saunderson, K., Mozgai, V., and Bajnóczi, B. (2022b). Pellet bells and bells from the Avar Period in the Hungarian National Museum. *Archeometriai Műhely* 19.1, 57–90.

Pomberger B.M., Mühlhans, J., and Saunderson, K. (2022c). Metallic idiophones of the Early History Period from the archaeological collection of the Slovakian National Museum in Bratislava. *Zborník Slovenského Národného Múzea – Archeológica* 32, 355–78.

Pomberger, B.M., Mühlhans, J., and Mehofer, M. (2022d). Von römischen Glocken und awarischen Schellen – frühgeschichtliche Idiophone aus Wien. *Študijné zvesti Archeologického Ústavu Slovenskej Akadémie Vied* 69.2, 355–406.

Pomberger, B.M., Mühlhans, J., Saunderson, K., Mozgai, V., and Bajnóczi, B. (2023). Pellet bells from the Avar and the Carolingian period in the Keszthely region. *Archeometriai Műhely* 20.1, 37–64.

Pomberger, B.M. and Grömer, K. (forthcoming). Dance in Hallstatt Culture: from iconography to choreography – an experiment. *Telestes*.

Pomberger, B.M. (forthcoming): Approaching the symbolism of pellet bells, bobbles and ring pendants in Hallstatt Culture*. Ethnoreligion Series*.

Ramstein, M. and Cueni, A. (2012). Kernenried, Oberholz. Gräber der Hallstattzeit. *Archäologie Bern*, 95–134.

Rainio, R. (2008). Classifying iron age bells, pellet bells and bell pendants. *Studien zur Musikarchäologie* (*Orient-Archäologie*) *6* (22). Rahden: Leidorf, 509–35.

Reinhold, S. (2007). *Die Spätbronze- und frühe Eisenzeit im Kaukasus. Materielle Kultur, Chronologie und überregionale Beziehungen* (Universitätsforschungen zur Prähistorischen Archäologie 144). Bonn: R. Habelt.

Rost, A. and Wilbers-Rost, S. (2010). Weapons at the battlefield of Kalkriese / Armas en el campo de batalla de Kalkriese, Gladius. *Estudios sobre armas antiguas, arte militar y vida cultural en oriente y occidente* 30, 117–36.

Ruprechtsberger, M. (1996). *Ein spätantikes Säuglingsgrab mit reichen Beigaben aus Lentia/Linz* (Linzer archäologische Forschungen 24). Linz: Stadtmuseum Linz.

Sartori, P. (1932). *Das Buch von deutschen Glocken*. Berlin – Leipzig: De Gruyter.

Saunderson, K. (unpublished, 2022): Textilien auf awarenzeitlichen Schellen von Keszthely. Unpublished report. Natural History Museum Vienna.

Scharrer-Liška, G. and Klatz, A-K. (2010). Awarenzeitliche Textil- und Lederfragmente am Beispiel von Grab 298 des awarischen Gräberfeldes von Frohsdorf, NÖ. Zum archäologischen Kontext, Befund und der Interpretation. In: J. Cemper-Kiesslich (ed.), *Primus Conventus Austriacus Archaeometriae*. Salzburg: Eigenverlag Universität Salzburg, 134–38.

Schubert, E. and Wolfe, J. (2006). Does timbral brightness scale with frequency and spectral centroid? *Acta Acustica united with Acustica* 92.5, 820–25.

Schumann, R. (2015). *Status und Prestige in der Hallstattkultur. Aspekte sozialer Distinktion in der ältereisenzeitlichen Regionalgruppe zwischen Altmühl und Save* (Münchner Archäologische Forschungen 3). Rahden/Westfalen: Leidorf.

Seidl, B., Pomberger, B.M., and Mühlhans, J. (2021). Pellet bells and bells from the Avar Period in the Hungarian National Museum in Budapest. https://www.youtube.com/watch?v=nrMvHKKIjAM.

Sottek, R. (2009). Modeling Engine Roughness. *SAE International Journal of Engines* 2.1, 1891–99.

Sottek, R., Vranken, P., and Busch, G. (1995). Ein Modell zur Berechnung der Impulshaltigkeit. *Forschritte der Akustik* 21.2, 791–94.

Stowasser, J.M. (1969): *Lateinische-deutsches Schulwörterbuch*. Wien: Hölder-Pichler-Tempsky.

Szabó, J.G. (1975). The Pilismarót Cemetery. In: É. Garam, I. Kovrig, J.G. Szabó, and Gy. Török, (eds), *Avar Finds in the Hungarian National Museum. Cemeteries of the Avar Period (567–829) in Hungary,* Vol. 1., Budapest: Akadémiai Kiadó, 243–81.

Szentpéteri, J. (2002): *Archäologische Denkmäler der Awarenzeit in Mitteleuropa* (Varia Archaeologica Hungarica 13). Budapest: Archäologisches Institut der Ungarischen Akademie der Wissenschaften.

Tortoli, F. (2017): Ein römisches Wohn- und Wirtschaftsgebäude in Erschwil. *Archäologie und Denkmalpflege im Kanton Solothurn* 22, 11–18.

Török, G. (1994). *Das awarenzeitliche Gräberfeld von Solymár* (Das awarische Corpus Beihefte 1). Debrecen–Budapest: Kapitalis.

Török, G. (1998). *Das awarenzeitliche Gräberfeld von Halimba* (Das awarische Corpus Beihefte 5). Debrecen–Budapest: Kapitalis.

Ubl, H.J. (1997). *Katalog zur Schausammlung „Römerzeit" des Museums Lauriacum.* (Forschungen in Lauriacum 1.2). Enns – Wien: Museum Lariacum.

Urban, O.H. (2000). *Der lange Weg zur Geschichte. Die Urgeschichte Österreichs* (Österreichische Geschichte bis 15. V. Chr). Wien: Überreuter.

Vida, T. (2017). *Die frühbyzantinische Messingkanne mit Jagdszenen von Budakalász (Ungarn)*. Budapest: Hungarian Academy of Sciences, Institute of Archaeology.

Villing, A. (2002). For whom did the bell toll in ancient Greece? Archaic and Classical Greek bells at Sparta and beyond. *Annual of the British School at Athens* 97, 223–95. DOI: 10.1017/S0068245400017408.

Völz, H. (1999). *Das Mensch-Technik-System*. Renningen-Malmsheim: Expert / Wien: Linde.

Wamser, G. (1975). Zur Hallstattkultur in Ostfrankreich. Die Fundgruppen in Jura und Burgund. *Bericht der Römisch-Germanischen Kommission* 56, 1–178.

Wankel, H. (1882). *Bilder aus der Mährischen Schweiz und ihrer Vergangenheit*. Wien: Holzhausen.