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Roman Bells and Avar Pellet Bells cast in copper alloys – The materials' influence on acoustic and psychoacoustic

Římské zvony a avarské rolničky odlité ze slitin mědi – vliv materiálů na akustiku a psychoakustiku

Jörg Mühlhans / Beate Maria Pomberger

Abstract

76 Roman bells and 91 pellet bells from the Early Medieval Avar and Carolingian periods from Austria, Hungary, and Slovakia cast in various copper alloys were investigated. They were classified into archaeological types and chemical analyses were carried out to get knowledge about their alloys' compositions. Since the material, among other parameters, influences timbre and sound perception, one Roman bell and one Avar pellet bell were reproduced in six different copper alloys, to examine the influence of the materials. Additionally, six bars were cast, and five plates were forged. All objects were recorded and analysed (psycho-)acoustically for a multitude of parameters to find out which are rather influenced by material and which are mainly altered by other parameters, such as shape or weight.

Key words

Roman period, Early Middle Ages, copper alloys, acoustics, psychoacoustic, music archaeology, bells, pellet bells, idiophones

Abstrakt

V rámci studie bylo zkoumáno 76 římských zvonů a 91 rolniček z raně středověkého avarského a karolínského období z území Rakouska, Maďarska a Slovenska, odlitých z různých slitin mědi. Badatelé vypracovali archeologickou typologii těchto nálezů a podrobili je chemické analýze, aby získali informace o složení použitých slitin. Vzhledem k tomu, že jedním z faktorů ovlivňujících barvu a vnímání zvuku je právě použitý materiál, byly za účelem prozkoumání jeho vlivu vyrobeny porovnávací repliky jednoho římského zvonu a jedné avarské rolničky z šesti různých slitin mědi. Kromě toho bylo ze stejných slitin odlito i šest tyčí a vykováno pět destiček. Se všemi uvedenými předměty byl pořízen zvukový záznam, který byl následně podroben (psycho-)akustické analýze. Ta měla pomoct určit, které ze zkoumaných parametrů jsou ovlivněny spíše materiálem a které zase jinými faktory, jako je tvar nebo hmotnost předmětů.

Klíčová slova

doba římská, raný středověk, slitiny mědi, akustika, psychoakustika, archeologie hudby, zvony, rolničky, idiofony

1. Introduction and research project

The research project "Metallic Idiophones between 800 BCE and 800 AD in Central Europe", funded by the Austrian Science Fonds FWF and supported by the Natural History Museum Vienna, investigates idiophones such as bells, pellet bells, and sounding jewelry over 1600 years. It started in January 2020 and lasts until December 2023. About 500 objects are to be examined. They originate from sites in Western Slovakia, Western Hungary, Austria, Switzerland (*Pomberger – Mühlhans – Grömer 2021*).

One of our research questions concerns the materials the idiophones were made of and their influence on sound and psychoacoustic parameters. Especially in this article, we discuss their influences on bells and pellet bells. Metal bells first appeared in Central Europe with Scythians during the 1st millennium BC in the Carpathian Basin (*Bakay 1971*), but then really established during the Roman period. None caged pellet bells appeared during the 7th century CE in the Carpathians Basin during the Avar period (*Pomberger – Stadler 2018*).

2. Material

Bells and pellet bells are idiophones and sound objects. Idiophone (from ancient Greek ἴδιος ídios, German 'eigen' and φωνεῖν phōneĩn 'to sound') i.e. self-sounder is a musical Instrument. It sounds as a whole or through parts of its construction.

According to the classification of musical instruments by Eduard von Hornbostel and Curt Sachs, bells are clearly defined as percussion vessels and show the weakest vibration near the vertex. A clapper to strike the bell is attached inside the resonance corpus (system number 111.242.122) (*Hornbostel – Sachs 1914*, 564–565; *MIMO 2011*, 4–5). Pellet bells are classified as metallic vessel rattles (system number 112.13) (*Hornbostel – Sachs 1914*, 566; *MIMO 2011*, 6).

Both types vibrate in modes, but the bell's modes are stimulated by striking with a clapper on the rim, and the pellet bell's modes are stimulated via pellets bouncing against the inside of the vessel wall when shaken.

Bells discussed in this article originate from Vindobona/Vienna, Ovilava/Wels, Austria, and Savaria/Szombathely in Hungary, in total 76 objects (fig. 1). The sites are located near the Roman Danube Limes and in the backcountry of the Roman Provinces Pannonia and Noricum. The Roman bells of Vindobona/Vienna are housed in the Wien Museum and the Stadtarchäologie Wien. They were excavated in the military camp and its *canabae legionis*, which is located in the first district of Vienna, in the civil town, which is located in the third district of Vienna, and on Roman roads in the fourth and tenth district of Vienna. Some Roman bells already were published so far (*Kenner 1904*; *Donat – Sakl-Oberthaler – Sedlmayer 2005*; *Mosser 2010*; *Mosser 2016b*; *Maspoli 2014*; *Pomberger 2016*). The larger part has already been extensively studied by the authors of this article not only concerning their find-situation and provenance but also concerning their function, chemical compositions, sounds, and psychoacoustics (*Pomberger – Mühlhans – Mehofer 2022*). Ovilava/Wels was our first site, of which we examined in detail all 36 Roman bells. Ovilava was a civil town, located near the river Traun and the Noric Main Road, which connected the Danube Limes with the Adriatic Sea. The objects are kept in the Stadtmuseum of Wels and only four bells were mentioned before (*Nowotny 1894*). All bells were studied and analysed in detail within the frame of our research project and already been published (*Pomberger – Hackl – Wegner – Mühlhans 2022*). Savaria/Szomabthely is located in the county of Vas in Hungary near the ancient Amber Road. The 30 Roman bells are housed

Fig. 1. Distribution map of Roman bells (Graphic: B. M. Pomberger; map base: d-map.com)

Obr. 1. Mapa rozšíření římských zvonů (grafika: B. M. Pomberger; mapový podklad: d-map.com)

in the Savaria Museum in Szombathely. 27 of them were found within the civil town and the sanctuary district (*Borhy – Sosztarits 1998*; *Sosztarits 2003*; *Balász 2012*), two belong to a hoard, excavated in Tokorcs (*Biró-Sey – Medgyes – Torbágyi 1998*) and one was excavated in Győrvár. But the majority was not published and the authors again studied all bells extensively (*Pomberger – Santá – Mühlhans – Mozgai – Bajnóczi 2021*).

Together with Roman bells, 91 pellet bells dating to the Early Middle Ages (see distribution map of pellet bells, fig. 2) were also studied. 21 pellet bells from Vienna, Austria are kept in the collection of the Wien Museum, of which 15 pellet bells and one bell were excavated in the Avar cemetery Csokorgasse in the eleventh district of Vienna (*Streinz 1978*), but the published catalog did not contain any drawings or pictures if the objects. In 2022 all the pellet bells and bells were accurately examined and the results published (*Pomberger – Mühlhans – Mehofer 2022*). Six pellet bells were found in the Avar cemetery Carlbergergasse-Liesing in the 23rd district of Vienna (*Moßler 1948*; *Moßler 1975*) and these sound objects also were subjects to be examined within our research project by the authors (*Pomberger – Mühlhans – Mehofer 2022*).

The Avar period cemeteries in Komárno contained in total of 15 pellet bells, which are part of the archaeological collection of the Podunajské múzeum in Komárno, Slovakia. Two of them were excavated in the cemetery Komárno IV, Váradiho ul. (today Rožná ul.) (*Čilinská 1982*); one originates from Cemetery Komárno VIII Hadovská cesta (*Čilinská 1982*) and twelve were found in Komárno IX Lodenica (*Trugly 1987*; *Trugly 1993*). All these idiophones were parts to be studied in our research project and we already published our results in 2021 (*Pomberger – Mühlhans – Saunderson – Grömer 2021*). Furthermore we intensively studied pellet bells from the archaeological collection of the Slovak National Museum in Bratislava. Eleven pellet bells originate from the cemetery I of Devínska Nová Ves (*Eisner 1952*). Three pellet bells were unearthed in the cemetery of Záhorska Bystrica (*Kraskovská 1972*) and two pieces came from the cemetery in Bratislava-Rusovce (site: Pri cintoríne) (*Pichlerová – Stloukal 1978*). They all date to the Avar period. We carried out our investigations and published our results in 2022 (*Pomberger – Mühlhans – Saunderson 2022*).

The Hungarian National Museum in Budapest houses pellet bells from 15 Hungarian sites dating to the Avar Period. Each pellet bell was found in each burial from the necropolis of Cikó and Gerjen-Váradmajor (*Kiss – Somogyi 1984*). Thirteen pellet bells were excavated in the cemetery of Halimba Belátó-domb (*Török 1998*) and three originate from the site Jánoshida-Tótkérpuszta (*Erdélyi 1958*). The necropolis of Jászalsószentgyörgy contained only one pellet bell (*Madaras 1995b*). Another one belonged to a burial of the cemetery in Kiskőrös Vágóhídi-dűlő (*László 1955*). In the Kölked-Feketekapu A cemetery only one pellet bell was found (*Kiss 1996*). One pellet bell is known from the cemetery in Mosonszentjános - Kavicsbánya (*Fettich 1927*) and one from Pilismarót Öregek-dűlő (*Szabó 1975*), whereas the cemetery in Pilismarót-Basaharc contained seven pellet bells (*Fettich 1965*). Again only one pellet bell was excavated in the cemetery of Solymár near Dinnye-hegy (*Török 1994*) and three came from the cemetery I in Szebény (*Garam 1975*). At least two pellet bells belong to the cemetery in Szob Homok-dűlő (*Kovrig 1975*), one to the cemetery in Újhartyán, and the last six pellet bells the sites are unknown (*Pomberger – Mühlhans – Saunderson – Mozgai – Bajnóczi 2022*). One further pellet bell originates from the cemetery in Edelstal (Nemesvölgy) Austria (*Lobinger 2016*). All these idiophones were studied within the frame of our research project and the results were already published in 2022 (*Pomberger – Mühlhans – Saunderson – Mozgai – Bajnóczi 2022*).

The Savaria Museum in Szombathely keeps five pellet bells from the cemetery Vasasszonyfa Gyöp (*Kiss 1985*) and one pellet bell from the Carolingian period from Vát Telekes-dűlő (Skriba – Nyerges 2010). And again we carefully studied these objects (*Pomberger – Santá – Mühlhans – Mozgai – Bajnóczi 2021*).

47 pellet bells are known from the town Keszthely. The Balatonmuseum in Keszthely houses four pellet bells which were excavated in the Avar period cemetery Városi temető/town cemetery (*Lipp 1885*; *Hampel 1905*). The Hungarian National Museum in Budapest keeps another four objects from this cemetery. One pellet bell was excavated in the Keszthely- Dobogó cemetery and also is kept by the Hungarian National Museum in Budapest and eleven pellet bells (collection Hungarian National Museum) were found either in Keszthely-Városi temető or Keszthely-Dobogó. Their origin cannot be traced anymore because unfortunately the objects kept in the Hungarian National Museum were mixed by the time of inventorying, some were bought by the museum from Vilmos Lipp, and even in the 1880s and 1870s – when they reached the museum - they were not kept according to grave number nor site, but marked as simply "Keszthely". A few might correlate to findings mentioned by Gábor Kiss (*Kiss 1997*, 121–122). Fourteen pellet bells are known from the Avar period cemetery in Gyenesdiás. Twelve of them are housed in the collection of the Balatonmuseum. There is no knowledge about the disposition of two pellet bells (*Mül-*

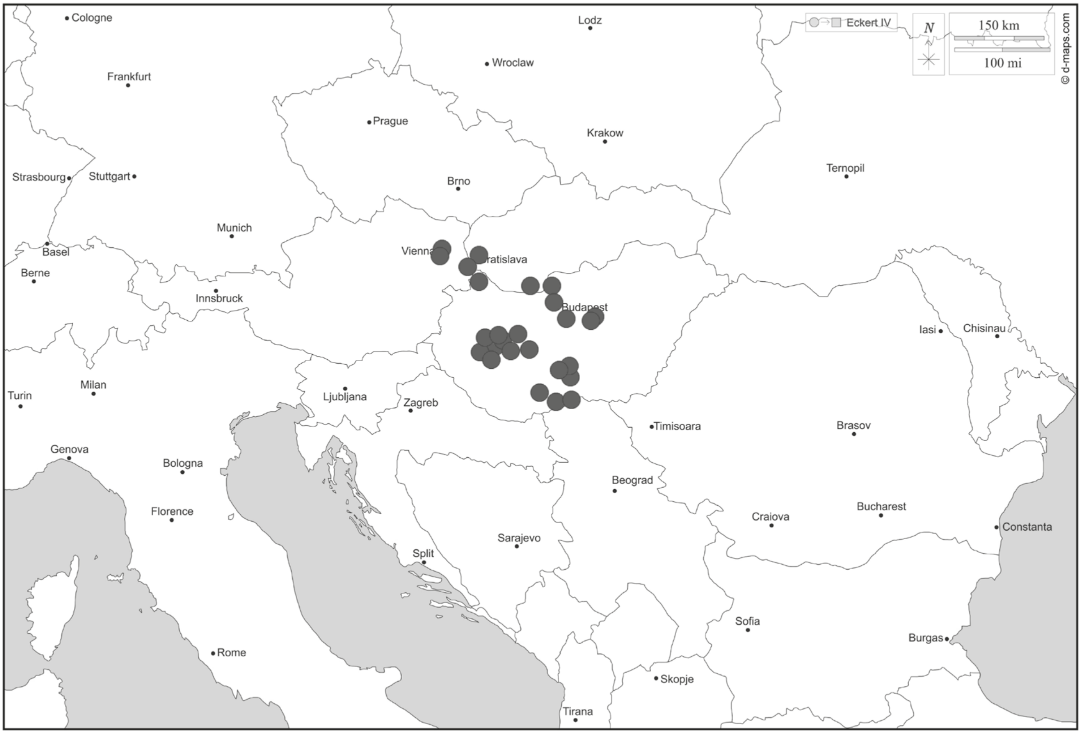

Fig. 2. Distribution map of pellet bells (Graphic: B. M. Pomberger; map base: d-map.com)

Obr. 2. Mapa rozšíření rolniček (grafika: B. M. Pomberger; mapový podklad: d-map.com)

ler without year; *Müller 2018*). Two pellet bells were found in the cemetery of Lesencetomaj B Piroskereszt, dating to the Avar period (*Müller 1992*). All these pellet bells are housed in the collection of the Balatonmuseum. But the museum also keeps objects from the Carolingian period, namely two pellet bells from Esztergályhorváthi-Alsóbárándpuszta-cemetery (*Szőke 1996*) and two further pellet bells from the cemetery on the Zalaszabar–Borjúállás-sziget in the Kiss-Balaton (*Müller 1996*; *Müller 2014*). Although four pellet bells were excavated in the cemetery IV of Keszthely-Fenékpuszta fortification south wall, only one is conserved (*Sós 1961*) and housed in the Balatonmuseum. Alle pellet bells were listed up and - if available - studied (*Pomberger – Muhlhans – Saunderson – Mozgai – Bajnoczi 2023*).

The Rippl-Rónai museum in Kaposvár also houses 38 pellet bells from the Avar age cemetery of Zamárdi-Réti földek (*Bárdos – Garam 2009*; *Bárdos – Garam 2014*).

3. Research Question and Methods

Chemical analyses carried out with scanning electron microscopy and X-ray fluorescence – both methods examining the surface of the objects – identified several alloys such as bronze, bronze with a small amount of lead and bronze with a large amount of lead, gunmetal, brass, and copper with lead. Wencke Wegner, Central Research Laboratories, Natural History Museum Vienna, Austria used scanning electron microscopy (JEOL JSM-6610LV) and analysed

21 Roman bells from Ovilava/Wels. Analyses were conducted with an energy dispersive spectrometer (Bruker) (*Pomberger – Hackl – Wegner – Mühlhans 2022*). Mathias Mehofer, archaeometallurgy laboratory of the Vienna Institute for Archaeological Science (VIAS), University of Vienna, Austria, analysed nineteen Roman bells from Vindobona and seven Avar pellet bells from the cemetery Csokorgasse and six pellet bells from Carlbergergasse-Liesing, using scanning electron microscopy (Zeiss EVO 60 XVP). The chemical composition was performed with an attached energy dispersive X-ray spectrometer (EDX) from the Oxford Instruments company (Actec) (*Pomberger – Mühlhans – Mehofer 2022*).

Bernadett Bájnoczi and Viktória Mozgai, Institute for Geological and Geochemical Research RSCAS and Research Centre for Astronomy and Earth Sciences in Budapest, Hungary, used the X-ray fluorescence method by using a handheld spectrometer (SPECTROxSORT Combi type handheld XF spectrometer) for analysing the idiophones from Hungary. They analysed 27 Roman bells from Savaria, Tokorcs, Györvár, and an unknown site (*Pomberger – Santá – Mühlhans – Mozgai – Bajnóczi 2021*) (see tab. Bells chem an). Furthermore they studied sixteen pellet bells from the Hungarian National Museum's collection (*Pomberger – Mühlhans – Saunderson – Mozgai – Bajnóczi 2022*), fifteen Avar pellet bells from the Avar age cemetery in Zamárdi-Réti földek (*Mozgai – Bajnóczi, report so far unpublished*) and nine pellet bells from the Balatonmuseum (*Pomberger – Mühlhans – Saunderson – Mozgai – Bajnóczi 2023*).

Ján Tirpák, University Konštantína Filozofa Nitra, Fakulta prírodných vied, gemologické laboratórium, used for his study also X-ray fluorescence-method by using a handheld spectrometer (X-ray fluorescence spectrometer DELTA CLASSIC+ from Olympus from the USA). He investigated 23 pellet bells from the collection of the Podunajské múzeum in Komárno (*Tirpák, unpublished report; Pomberger – Mühlhans – Saunderson – Grömer 2021*). Furthermore, he also did the chemical analyses of ten pellet bells from the collection of the Slovak National Museum in Bratislava, Slovakia (*Tirpák, unpublished report*; *Pomberger – Mühlhans – Saunderson 2022*).

49 Roman bells could be analysed and 27 bells were not available for studies. The results of the analyses bells showed up, that nine bells were cast in pure bronze, twelve had a composition of Cu-Sn and less than 5 % Pb; ten had composition of Cu-Sn and more than 5 % Pb, fifteen bells were cast in a composition of Cu-Sn-Zn-Pb, three contained Cu-Zn and a very few amounts of Pb and one bell was cast in an alloy containing Cu and Pb. Four of the bells showed a large amount of Sn, namely more than 20 % and this composition is comparable to our bell bronze (see tab. 1). Alloys composed of Cu-Sn-Zn-Pb are called "gunmetal", but we have to distinguish between red bronze, which contains more Sn than Zn and red brass, which contains more Zn than Sn. While five of the bells from Ovilava were cast in red bronze (*Pomberger – Hackl – Wegner – Mühlhans 2022*, 138–140, tab. 1), four bells from Vindobona are composed of red brass and only one in red bronze (*Pomberger – Mühlhans – Mehofer 2022*, 376, tab. 1). One bell from Savaria is cast in red bronze (*Pomberger – Santá – Mühlhans – Mozgai – Bajnóczi 2021*, 82, tab. 3). Regarding the manifold variations of alloys, we think, that during the Roman period no uniform standard for bell bronze-like today (*Weissenbäck – Pfundner 1961*, 46–48) did exist.

The clappers of the bells usually were forged from iron and mostly were corroded. The forms of the bells discussed in this article can be classified into seven types. The majority of the bells show a rectangular base and belong to type 1. Among this group of type 1, six variants can

site	country	bells	Cu-alloy	Cu-Sn	Cu-Sn (Pb>5%)	Cu-Sn (Pb<5%)	Cu-Sn-Zn-Pb	Cu-Zn (Pb)	Cu-Pb	high amount of Sn
Vienna/Vindobona	AT	19	9		4		5		1	
Wels/Ovilava	AT	30	11	7			9	3		
Szombathely/Savaria	HU	24	5	2	6	10	1			4
Tokorcs	HU	1			1					
Györvár	HU	1	1							
unknown site	HU	1	1		1					
total		**76**	**27**	**9**	**12**	**10**	**15**	**3**	**1**	**4**

Tab. 1. The Roman bells chemical composition (compilation: B. M. Pomberger)

Tab. 1. Chemické složení římských zvonů (sestavila: B. M. Pomberger)

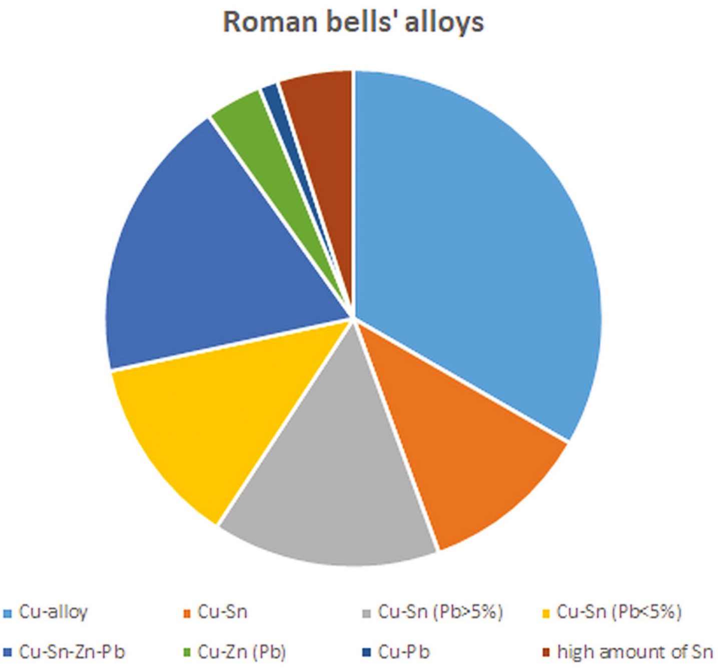

Fig. 3. Distribution of alloys within the investigated Roman bells (Graphic: B. M. Pomberger)

Obr. 3. Podíl jednotlivých slitin v rámci zkoumaného souboru římských zvonů (graf: B. M. Pomberger)

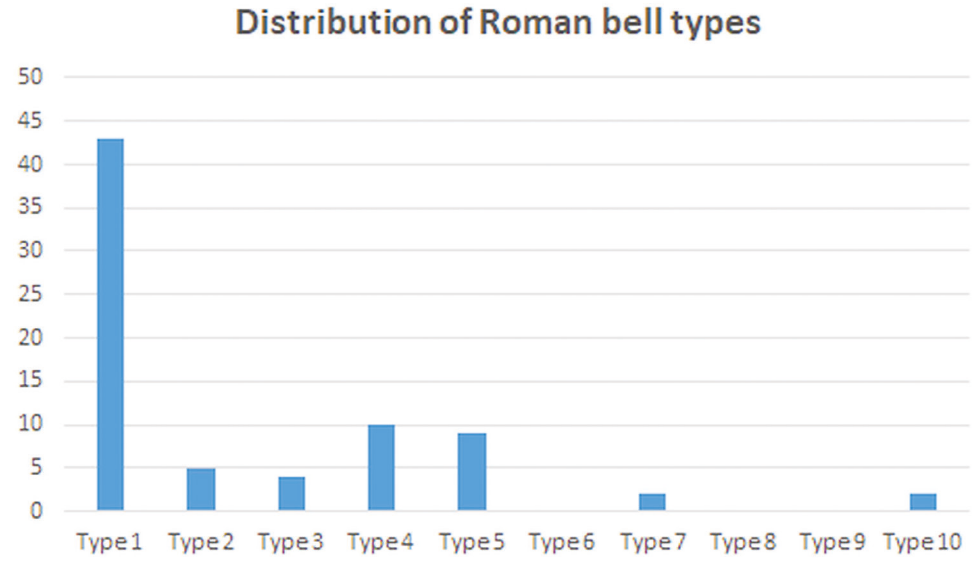

Fig. 4. Distribution of Roman bell types (Graphic: B. M: Pomberger)

Obr. 4. Rozdělení četností jednotlivých typů římských zvonů (grafika: B. M: Pomberger)

be distinguished. The other bells are classified into the types 2, 3, 4, 5, 7, and 10 (*Pomberger 2018*; *Pomberger – Santá – Mühlhans – Mozgai – Bajnóczi 2021*; *Pomberger – Hackl – Wegner – Mühlhans 2022*; *Pomberger – Mühlhans – Mehofer 2022*) (fig. 4) The surface is usually smooth and polished. Circular-based bells are returned on the lath and sometimes have two circular lines on the lower part. Their sizes are between 0.7 cm and to 9.7 cm and their weight is from 1 g up to 130 g.

36 Early Middle Age pellet bells could be analysed concerning their chemical compositions and from 45 pieces we only know, that they are cast in copper alloy. Five pellet bells are cast in Cu-Sn- bronze, four pellet bells contain of Cu-Sn and less than 5 % Pb. 25 pellet bells show a composition of Cu-Sn and more than 5 % Pb. Eight are cast in red bronze. They originate from the sites Csokorgasse, AT (*Pomberger – Mühlhans – Mehofer 2022*, 376, tab. 1), Gyenesdiás and Esztergályhorváthi-Alsóbárándpuszta, (*Pomberger – Mühlhans – Saunderson – Mozgai – Bajnóczi 2023*), Szebény, HU (*Pomberger – Mühlhans – Saunderson – Mozgai – Bajnóczi 2022*, 66, tab. 1) and two from Zamárdi-Réti földek, HU (*Mozgai – Bajnóczi, report so far unpublished*). One has a composition of Cu-Zn-Pb and three show a composition of Cu-Pb. Four pellet bells are gilded (see tab. 2, fig. 5). Riita Rainio investigated a large amount of pellet bells from Iron Age Finland and found out, that one group of the pellet bells was composed of copper and lead, another cluster of copper, tin and lead (*Rainio 2008*). The investigated pellet bells of Central Europe show a larger variety of chemical compositions.

The pellet bells can be classified into eleven different shapes (*Pomberger 2020*; *Pomberger – Santá – Mühlhans – Mozgai – Bajnóczi 2021*; *Pomberger – Mühlhans – Saunderson – Mozgai – Bajnóczi 2022*; *Pomberger – Mühlhans – Mehofer 2022*). Shape I and shape II are the most common ones, followed by shape IV and shape V

site	country	pellet bells total	Cu-alloy	Cu-Sn	Cu-Sn (Pb>5%)	Cu-Sn-Pb(<5%)	Cu-Sn-Zn-Pb	Cu-Zn-Pb	Cu-Pb	bronze gilded
Devinska Nová Ves	SK	11	6		2	3				
Bratislava Záhorska Bystrica	SK	3				3				
Bratislava Rusovce	SK	2				2				
Komárno-Lodenica	SK	7		4	2	1				2
Komárno-J. Váradiho ul.	SK	1	1							
Csokorgasse, 1110 Wien	AT	7	2			3	2			
Carlbergergasse 40-42, 1230 Wien	AT	6				6				
Edelstal = Nemesvölgy	AT	1	1							1
Keszthely-Városi temető	HU	5	5							
Keszthely-Fenékpuszta fortification south wall; cemetery IV	HU	4	4							
Gyenesdiás	HU	6	2			2	2			
Cikó	HU	1							1	
Janoshida	HU	1	1							
Pilismarót-Basaharc	HU	1	1							
Solymár	HU	1							1	
Szebény	HU	2				1	1			
Újhartyán (Kom. Pest)	HU	1				1				
Esztergályhorváthi-Alsóbárándpuszta	HU	3				1	1		1	
Zalaszabar - Borjúállás	HU	2		1				1		1
Vasasszonyfa, Güöp cemetery	HU	1	1							
Szombathely, Kőszegi ut.	HU	1	1							
Zamárdi-Réti földek	HU	19	15			2	2			
Vát, Telekes-dűlő	HU	1	1							
unknown	HU	4	4							
total		**91**	**45**	**5**	**4**	**25**	**8**	**1**	**3**	

Tab. 2. The pellet bells' chemical compositions

Tab. 2. Chemické složení rolniček

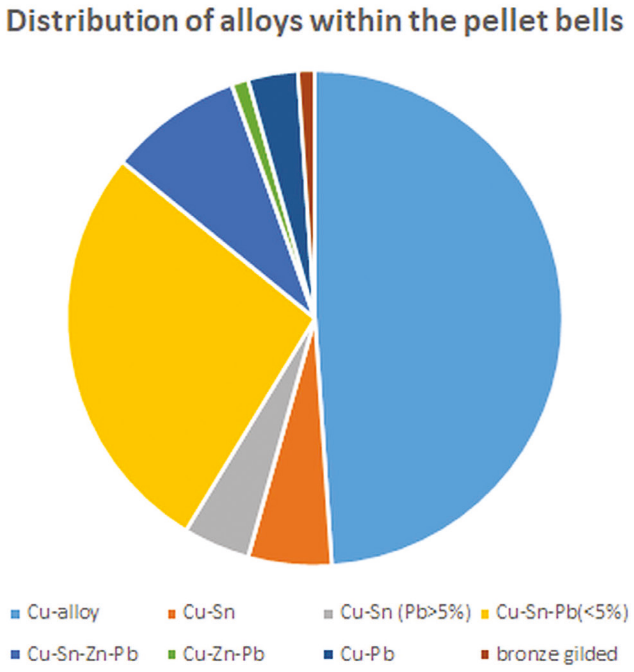

Fig. 5. Distribution of alloys within the pellet bells (Graphic: B. M. Pomberger)

Obr. 5. Podíl jednotlivých slitin v rámci zkoumaného souboru rolniček (graf: B. M. Pomberger)

(fig. 6). Mostly the surface is smooth, but some pellet bells are decorated. The decorations are vertical, radial, and sloped grooves, bands of vertical and horizontal lines, impressions, spirals like a mustache, scale patterns, circular grooves, circumferential bands, grid patterns, herring bone patterns, fluted lower parts, and men's faces. The sound slots are shaped simple or cruciform, only one is three-parted. Two to four sound holes are at the ends of the sound slots. They also can be arranged like a pair of eyes or arranged opposite on the upper part. Some pellet bells have one to two sound holes on the vertex or rectangular-shaped sound holes near the sound slot. The sizes vary between 2.5 cm and 5 cm with diameters between 1.8 × 2.1 cm and 3.4 × 3.4 cm and weights from 1.89 g up to 33.66 g.

The results of the chemical analyses showed a great variety of alloys. The sounds of idiophones depend on the metallurgic composition, shape, and specific weight. We wanted to find out, which influence the different alloys had on the sound. Therefore, we decided to cast idiophones in six alloys and analyse their sounds, namely bells, pellet bells, and bars. Furthermore, five plates were forged from five alloys.

The Roman bell Nr. 89 from Ovilava (Wels) and the Avar pellet bell from the grave 30, Kiskőrös- Vágóhídi-dűlő served as models for the replicas of all six alloys. Furthermore, bars with a length of 10 cm and a diameter of 5 mm were cast. The bronze Bell Nr. 89 from Ovilava/Wels, is part of a hoard excavated during the construction of the railway in Wels-Thalham near a

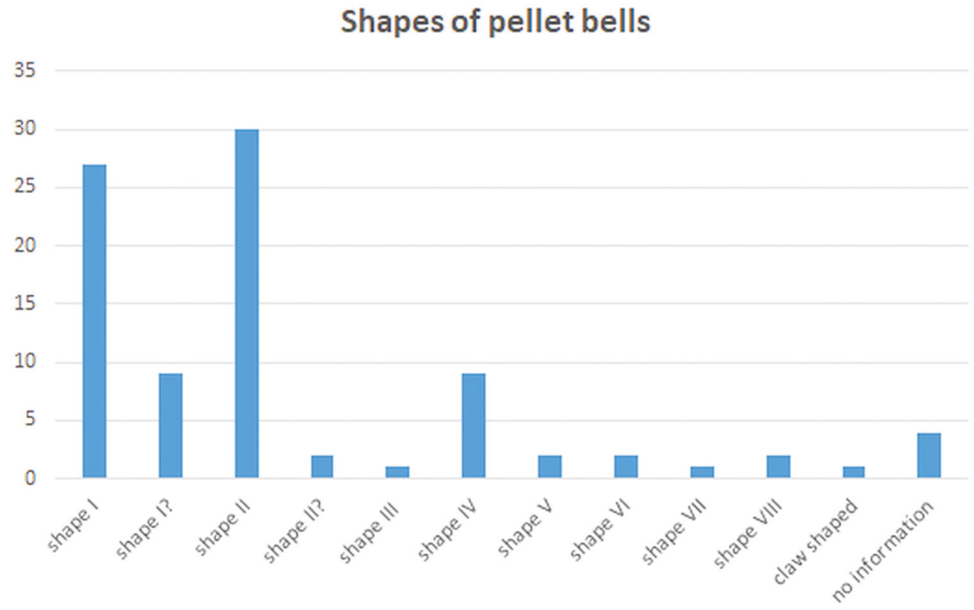

Fig. 6. Distribution of pellet bells shapes (Graphic: B. M. Pomberger)
Obr. 6. Rozdělení četností jednotlivých tvarů rolniček (graf: B. M. Pomberger)

Roman water pipe. Its base measures 4.8 cm × 4.3 cm, its height is 7.1 cm, and its weight 84 g. The clapper is lost (*Pomberger – Hackl – Wegner – Mühlhans 2022*). The pellet bell MNM 4.135.38 was found in the late Avar burial of a child in the cemetery Kiskőrös – Vágóhídi-dűlő, laying on the right side of the skeleton. The diameter is 2.7 × 2.6 cm, the height including the eyelet is 3.2 cm, the wall thickness is 1 mm, and the weight is 24 g. It has a cruciform-shaped sound slot and contains a small pebble (*Pomberger – Mühlhans – Saunderson – Mozgai – Bajnóczi 2022*, 83). So, although the mother molds for casting the replicas are similar, the single-casting molds could differ a little bit. Clappers were not preserved in the bells. The pellet bells each contain one pebble.

Michel Konrad, the experimental archaeologist, cast the objects. He prepared six alloys: Alloy I: bronze with 90% copper and 10% tin, alloy II: bell bronze with 76% copper and 24% tin, alloy III: leaded bronze with 80% copper, 10% tin, and 10% lead, alloy IV: leaded bronze with 70% copper, 10% tin, and 20% lead. Furthermore, red bronze (alloy V) with a proportion of 70% copper, 10% tin, 10% zinc, and 10% lead, and brass (alloy VI) with 58% copper, 39% zinc, and 3% lead (see tab. 3). The authors have repeatedly urged the colleague who cast the objects to write up the experiment - as originally discussed - but unfortunately, we never received an answer or a text. However, it would be a great pity not to publish our extremely important research results. Therefore, we have decided to complete the article without the production process.

The objects were not cast exactly as the originals, because the caster performed the casting of bells and pellet bells for the first time. The replicated objects exhibit holes, the handles are

Alloy	
Bronze -	> 90% Cu/10% Sn
Bronze with a large amount of tin	> 76% Cu/ 24% Sn
Bronze with lead	> 80% Cu/ 10% Sn / 10% Pb
Bronze with lead	> 70% Cu/ 10% Sn / 20% Pb
Red bronze ("gunmetal")	> 70% Cu/ 10% Sn/ 10% Zn / 10% Pb
Brass	> 58% Cu/ 39% Zn/ 3% Pb (Standardbrass MS58)

Tab. 3. Six selected alloys for casting our idiophones (compilation: B. M. Pomberger)

Tab. 3. Šest vybraných slitin pro odlévání zkoumaných idiofonů (sestavila: B. M. Pomberger)

Alloy Nr.		weight bell	weight pellet bell	weight bar
I	Cu 90 / Sn 10	194.87 g	50.32 g	26.25 g
II	Cu 76 / Sn 24	165.63 g	40.5 g	26.31 g
III	Cu 80 / Sn 10 / Pb 10	136.91 g	38.45 g	30.18 g
IV	Cu 70 / Sn 10 / Pb 20	179.86 g	36.45 g	30.65 g
V	Cu 70 / Sn 10 / Zn 10 / Pb 10	163.58 g	42.42 g	27.49 g
VI	Cu 58 / Zn 39 / Pb 3	138.7 g	28.88 g	25.12 g

Tab. 4. Weights: Weight of the objects cast in different alloys. (compilation: B. M. Pomberger)

Tab. 4. Hmotnost předmětů odlitých z různých slitin (sestavila: B. M. Pomberger)

not complete or formed, and the surfaces are polished roughly. It requires a lot of experience to cast the liquid metal mass into the mold at the right time so precisely that all cavities are filled (see Figs. 7 and 8).

Furthermore, bars with a length of 10 cm and diameters of 5 mm were cast in all six alloys (see fig. fig. 9a). Here the casting succeeded completely, and no holes were in the objects.

With these, we could best investigate the effects of the different alloys on the sound. Plates of alloys I, III, IV, V, and VI measuring 7 cm × 3.2 cm × 2 mm were forged (fig. 9b). Alloy II (bell bronze) was too hard for forging due to the high content of tin (24 %).

4. Acoustics and psychoacoustics

The sound/timbre of idiophones is quite complex since – unlike with aero-/chordophones – it is not composed of integer multiples of one single fundamental frequency (f_0) but rather a complex pattern of natural modes (*Hall 1980*, 158). If the material of a guitar string is changed, the frequencies of overtones remain the same[1] but the amplitudes vary. If the material/alloy of an idiophone is altered, the frequency spectrum looks entirely different. Identifiable patterns occur at similar shapes but might be shifted up or down in frequency. The sound of idiophones is known to depend on size, mass, material/alloy, wall thickness, and excitation of the object, but the exact influence of every single parameter on the sound is difficult to measure.

Fig. 7. The original Roman Bell Nr. 89 from Ovilava and its replicas. A – Roman bell Nr. 89, Ovilava/Wels, bronze; B – alloy I (bronze); C – alloy II (bell bronze); D – alloy III (leaded bronze); e - alloy IV (leaded bronze); F – alloy V (red bronze); G – alloy VI (brass). (Photos: J. Mühlhans, B. M. Pomberger)

Obr. 7. Původní římský zvon č. 89 z Ovilavy a jeho repliky. A – římský zvon č. 89, Ovilava/Wels, bronz; B – slitina I (bronz); C – slitina II (zvonový bronz); D – slitina III (olovnatý bronz); E – slitina IV (olovnatý bronz); F – slitina V (červený bronz); G – slitina VI (mosaz). (Foto: J. Mühlhans, B. M. Pomberger)

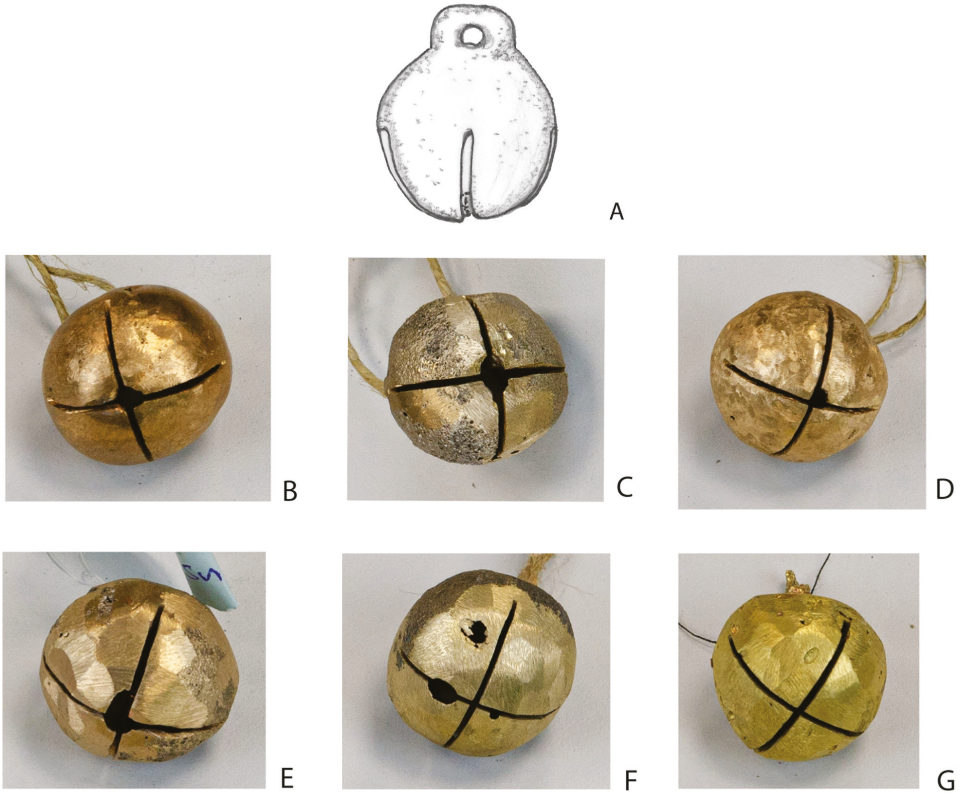

Fig. 8. The pellet bell from Kiskőrös – Vágóhídi-dűlő, grave 30 (34) and its replicas. A – Pellet bell MNM MNM 4.135.38 from grave 30, Kiskőrös – Vágóhídi-dűlő, bronze; B – alloy I (bronze); C – alloy II (bell bronze); D – alloy III (leaded bronze); E – alloy IV (leaded bronze); F – alloy V (red bronze); G – alloy VI (brass) (Photos: J. Mühlhans, B. M. Pomberger)

Obr. 8. Rolnička z Kiskőrös – Vágóhídi-dűlő, hrob 30 (34) a její repliky. A – rolnička MNM 4.135.38 z hrobu 30, Kiskőrös – Vágóhídi-dűlő, bronz; B – slitina I (bronz); C – slitina II (zvonový bronz); D – slitina III (olovnatý bronz); E – slitina IV (olovnatý bronz); F – slitina V (červený bronz); G – slitina VI (mosaz) (Foto: J. Mühlhans, B. M. Pomberger)

4.1 Comparison of the objects and variance of physical parameters

Casting objects of the same shape and size allows for control of the influence of the material/alloy with some limitations: If size and shape remain similar with altering alloys, the weight still varies. Lead is heavier than the other elements, rendering objects with a higher content heavier (see tab. 5).

Weight variations are lowest in the bars (avg=27.7g, sd=2.3g), followed by the plates (avg=47.2g, sd=4.4g). The pellet bells vary to some extent (avg=39.5g, sd=7.1g), the bells even more so, which is explained by irregularities in lip/mouth and crown, as well as the gaps on the surface (avg=163.3g, sd=22.7g) (fig. 10).

With the least variation in size, the bars are almost identical in weight and shape, and the pellet bells are quite similar as well. In plates,

Fig. 9. Bars and plates: alloys from left to right: a – I, II, III, IV, V, VI; b – I, III, IV, V, VI. (Photos: B. M. Pomberger)

Obr. 9. Tyče a destičky: slitiny zleva doprava: a – I, II, III, IV, V, VI; b – I, III, IV, V, VI. (Foto: B. M. Pomberger)

Element	Densitiy
Cu	8.933 g/cm^3
Sn	7.287 g/cm^3
Zn	7.134 g/cm^3
Pb	11.342 g/cm^3

Tab. 5. Elements used in the casting/forging process (Data derived from https://pubchem.ncbi.nlm.nih.gov/periodic-table/)

Tab. 5. Prvky používané v procesu odlévání/kování (údaje převzaty z https://pubchem.ncbi.nlm.nih.gov/periodic-table/)

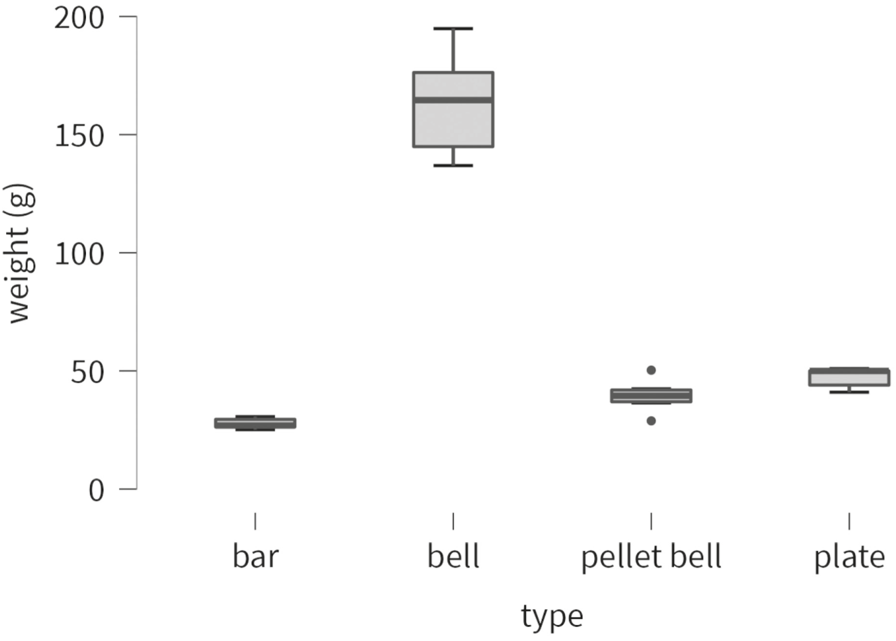

Fig. 10. Boxplots for the weight distribution of the four shapes (Graphic: J. Mühlhans)

Obr. 10. Krabicový graf rozdělení hmotností čtyř zastoupených tvarů předmětů (graf: J. Mühlhans)

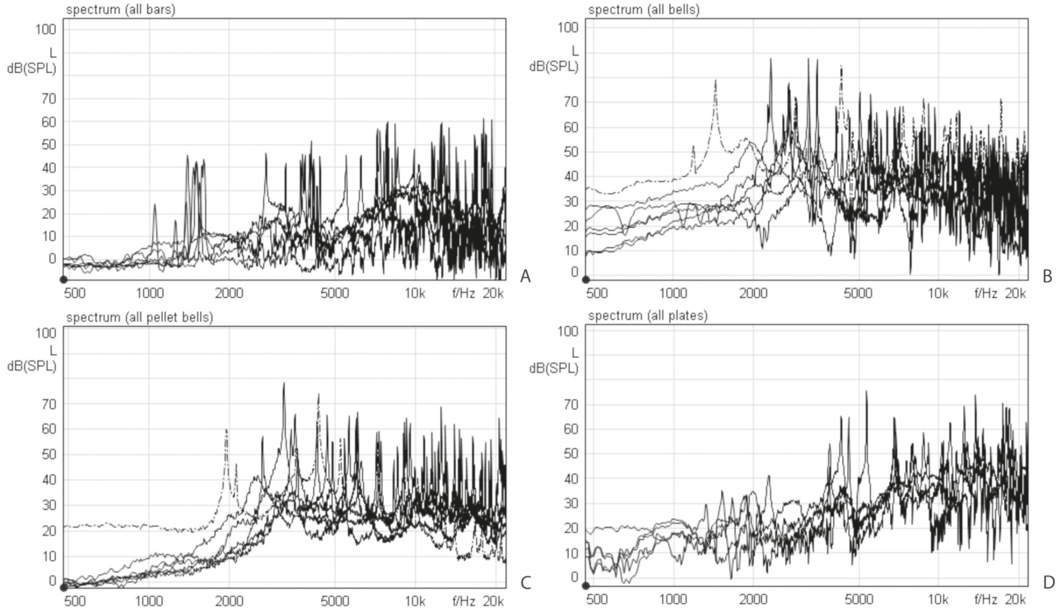

Fig. 11. A – Spectra of all bars; B – Spectra of all bells including original); C – Spectra of all pellet bells (including original); D – Spectra of all plates (Graphic: J. Mühlhans)

Obr. 11. A – Spektra všech tyčí; B – Spektra všech zvonů (včetně originálu); C – Spektra všech rolniček (včetně originálu); D – Spektra všech destiček (graf: J. Mühlhans)

the thickness and shape vary to a certain extent, still, they can be used to compare modes of oscillation with reduced complexity compared to (pellet) bells because they are more two-dimensional.

4.2 Influence of physical parameters on the (psycho-)acoustic domain

For the statistical calculations, physical (shape, alloy, weight), acoustical (lowest partial and peak frequency, sound pressure level, decay time) and psychoacoustic parameters (loudness, brightness, sharpness, roughness, tonality, impulsiveness) were measured using Adobe Audition (*Adobe Inc., 2023*), Praat (*Boersma – Weenink, 2023*) and HEAD ArtemiSuite (*HEAD, 2023*). Two types of calculations were performed, for metric parameters correlation analyses were calculated, and for the comparison of variances within the nominal groups (shape, alloy) ANOVAS were calculated (JASP Team, 2023). Additionally, descriptives and boxplots were created for the alloy groups to visualize the distributions.

The first insight is that hardly any sound property depends on a single physical parameter. This can be shown by the inconsistency of results between the groups. Alloys that score high on a parameter in one shape, mostly score low on the same parameter in a different shape. This shows that the influence of the alloy accounts for the sounds, but in a different way, depending on the shape.

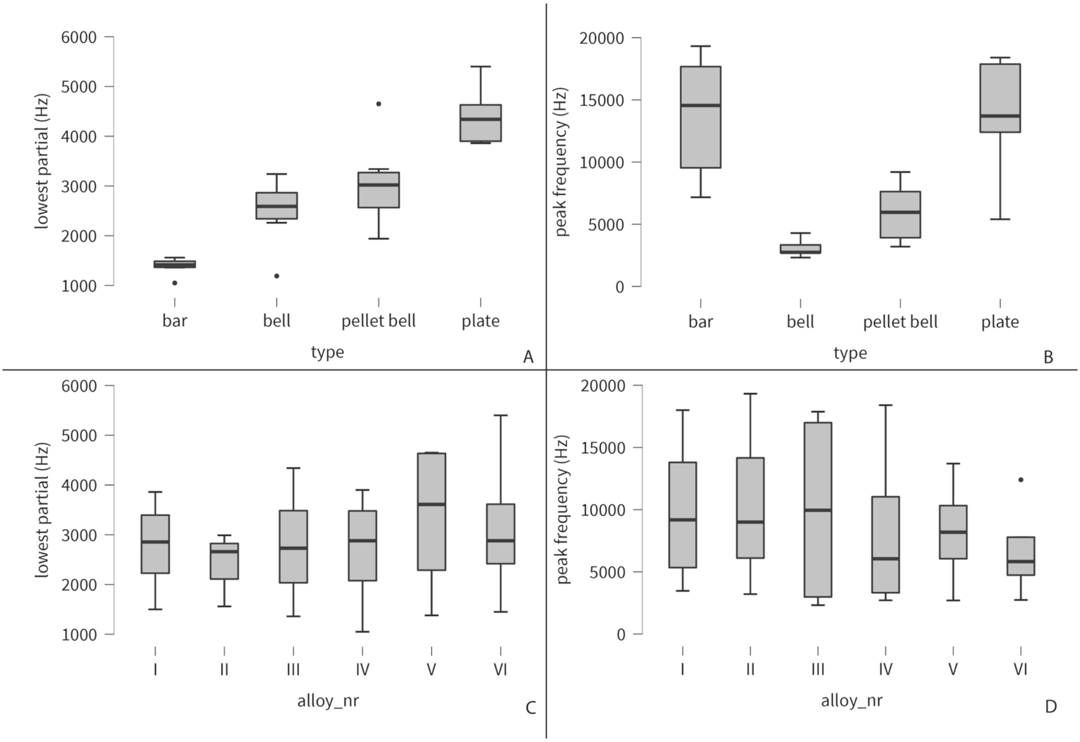

Fig. 12. Distribution of partials. A – Lowest partial distribution in shapes; B – Peak frequency distribution in shapes; C – Lowest partial distribution in alloys; D – Peak frequency distribution in alloys (Graphic: J. Mühlhans)

Obr. 12. Rozdělení sinusových složek. A – Rozdělení základní frekvence u jednotlivých tvarů; B – Rozdělení nejvyšší frekvence u jednotlivých tvarů; C – Rozdělení základní frekvence u slitin; D – Rozdělení nejvyšší frekvence u slitin (graf: J. Mühlhans)

4.3 Spectral distribution of partials, lowest- and peak-frequency, decay time

Figures 11/A – D show the spectra of all objects within one group in a graph. In Figures 11B and 11C, the original object is included as a reference (dashed line). Only the spectra of the six bars create a visible pattern of somewhat clustered partials.

The lowest partials of the original objects - both bells and pellet bells - lie significantly lower than those of all replicas. This impacts pitch perception greatly; the original is perceived roughly one musical octave lower than the replicas. This is likely an effect of corrosion, which turns metal into oxides or chlorides, rendering the object less dense – which causes a weight reduction – but also less flexible, thus reducing its ability to oscillate (*Pomberger – Hackl – Wegner – Mühlhans 2022*).

Figures 12/A and 12/B show the distribution of the lowest partial and peak frequencies for the different shapes. Interestingly, the bars are quite similar in the lowest frequencies but have a high variance in peak frequencies, unlike the bells that have more variation in the lowest frequency.

Pellet bells vary consistently in both parameters, and the plates mainly vary in peak

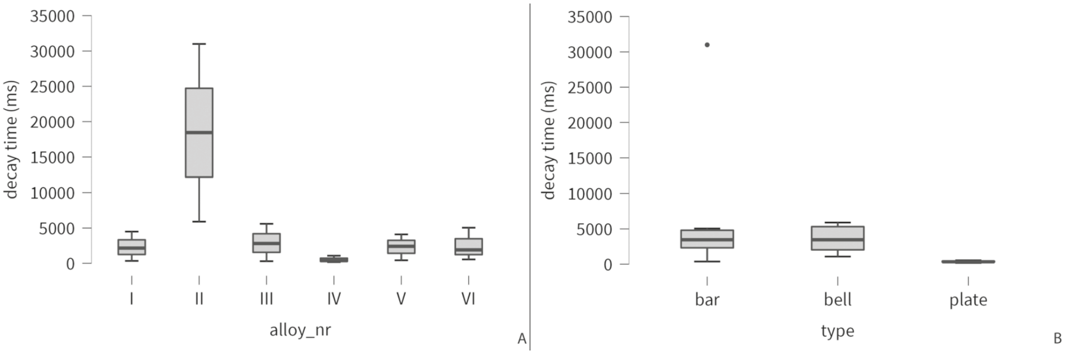

Fig. 13. Decay time distribution. A – Decay time distribution in alloys; B – Decay time distribution in shapes (Graphic: J. Mühlhans)

Obr. 13. Rozdělení doby dozvuku. A – Rozdělení doby dozvuku u slitin; B – Rozdělení doby dozvuku u jednotlivých tvarů (graf: J. Mühlhans)

frequency. Weight is significantly correlated to peak frequency (r=-0.57, p=.003) but not to lowest frequency, which depends more on the shape of the objects. ANOVAs showed no significant results for the alloys, likely due to high variance within each group and the low number of objects.

Figures 12/C – D clearly show that the influence of shape is greater and much more consistent than the influence of the alloy on the given parameters.

The decay time is measured from the moment of impact in a single impulsive excitation of the object to the moment when the sound pressure level reaches that of background noise. In other words, how long an object rings after a single excitation (impulse). This parameter is rather significant for bells, but not so much for pellet bells, which are excited constantly. Small bells also ring constantly while being worn as a pendant or mounted onto belts, but are also not dampened after a single hit, like the pellet bells are by the ball/lump inside, resting against the inner wall. The decay time shows quite interesting results within alloys, less within shapes (fig. 13).

Plates – probably because of the material thickness – did not ring at all – the average decay time was approximately 360 ms. Except one outlier at 35 seconds(!), bells and bars averaged around roughly 3 seconds, which is a common value for the given size and weight (see Fig. 13/B).

However, while the remaining four alloys were quite consistent in decay time, alloy II produced exceptionally long-ringing objects, while the ones from alloy IV hardly rang at all (500 ms on average), no matter what shape. It seems obvious that alloys with a very high lead content make the objects so soft that a long reverberation is not possible at all due to too high damping.

4.4 Audibility of the objects – level and loudness

Sound pressure level (SPL) is the physical measure of how much sound is emitted into the air, given in decibels (dB) at a reference sound pressure p_0. of 20 a (*Maling 2014*, 1006). A doubling of the sound pressure is reflected in an increase of SPL by 6 dB. This is a common source of error, as the logarithmic decibel scale is often misinterpreted as linear. 96 dB SPL is

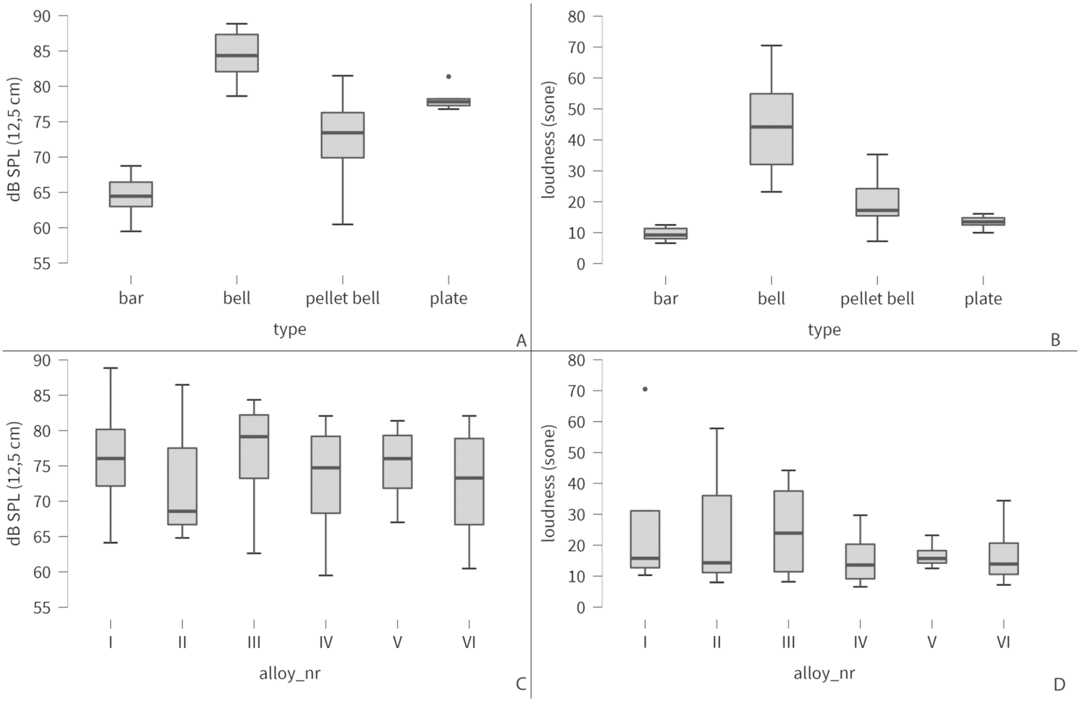

Fig. 14. Distributions of sound pressure level and loudness. A – SPL distribution in shapes; B – Loudness distribution in shapes; C – SPL distribution in alloys; D – Loudness distribution in alloys (Graphic: J. Mühlhans)

Obr. 14. Rozdělení hladiny akustického tlaku a hlasitosti. A – rozdělení hladiny akustického tlaku u jednotlivých tvarů; B – Rozdělení hlasitosti u jednotlivých tvarů; C – Rozdělení hladiny akustického tlaku u slitin; D – Rozdělení hlasitosti u slitin (graf: J. Mühlhans)

twice as intense as 90 dB. Plus/minus 6 dB is an important value to remember because the sound pressure level is also halved when the distance to the sound source is doubled – which also corresponds to minus 6 dB. It is the other way around if the distance is halved, through which the sound pressure is doubled (*Attenborough 2007*, 115).

Loudness, on the other hand, is a psychoacoustical parameter that takes human hearing into consideration and models/objectifies subjective human loudness perception in either the sone or phon scale (*Fastl – Zwicker 2007*, 203–206). Level and loudness are not equal, but are highly correlated (r=0.79, p<.001). Loudness (and level) is also correlated positively to weight (r=0.83, p<.001) and negatively to peak frequency (r=-0.61, p=.002) and brightness (r=-0.72, p<.001). Bells are the loudest objects on average (83.7 dB at 12.5 cm; 43.3 sone), and pellet bells are four times less intense (71.7 dB, 18.1 sone).

When categorizing by alloy, the results are again inconsistent. Levels vary from 72.2–76.3 dB and loudness from 15.8–28 sone but variations within the alloys (at only 3–4 observations) are quite large. Again, an alloy that seems to make a loud bell (II) makes a rather silent pellet bell but also the other way around (IV). To get statistically significant results, a much larger number of objects from each alloy is necessary.

For the intensity parameters of sound there were also no significant results in the ANOVAs for shapes and figures 14/A – B and 15/A – B show that the influence of the shape is again more consistent and greater than that of the alloy.

4.5 Psychoacoustic differences – sharpness, roughness, tonality, brightness, and impulsiveness

As with loudness, other psychoacoustic parameters also model human subjective perception for comparison. Brightness is one of the most solid parameters and can be quantified simply with the spectral centroid, given in Hz (*Schubert – Wolfe – Tarnopolsky 2004*, 656).

Sharpness depends on the spectral shape and energy – especially in the 2–4 kHz band, where the human ear is particularly sensitive. The value is given in a linear scale in "acum" (*Fastl – Zwicker 2007*, 241). Roughness depends on the amplitude modulation and often occurs when partials are quite close to each other. The sensation is rather unpleasant and reaches its maximum at an amplitude modulation of about 70 Hz, which corresponds to one "asper" (*Fastl – Zwicker 2007*, 257–261).

Tonality is represented as the ratio between tonal (partials) and noise components (*DIN45681*), given in dB. Positive values indicate more tonal components and negative more noise components, 0 dB is a 1:1 ratio. Since the moment of impact in idiophones creates large amounts of noise and pellet bells have much more single impacts when the pellet is bouncing against the inner walls, they score lower in tonality than bells. This number of single impacts also influences impulsiveness, another psychoacoustic parameter (*Sottek – Genuit 2005*), given in a linear scale of impulsiveness units.

Sharpness and roughness averages are more similar between shapes than between alloys, given that the objects can overall be considered rather sharp but not rough at all. Brightness averages are similar to sharpness within alloys but not within shapes.

Both sharpness and brightness score the lowest average value in the high lead alloy IV, while at the same time, it has the highest roughness. Fig. 15/E also shows quite consistent data in bars and bells, less in plates, and least in pellet bells for brightness. Sharpness and roughness are not correlated to any parameters (see Fig. 15).

Tonality and impulsiveness show some interesting results within both alloys and shapes and are correlated negatively to one another ($r=-0.57$, $p=.003$) (see fig. 16). This correlation is even higher in bars and plates only, but disappears in bells and pellet bells, where values are distributed more evenly. Once again alloys II and IV stand out, II having the highest values in tonality and lowest in impulsiveness and the exact opposite being true for alloy IV.

4.6 Influence of the elements and their percentages in the alloy

The percentages of elements in the alloy affect certain physical properties such as density or hardness, thus influencing the timbre of sounds. Copper is the only element present in every alloy, but from a statistical point of view, there is no significant correlation between the copper content and (psycho) acoustical parameters. Tin – being present in at least five of the alloys – is the only element correlated with other parameters, namely decay time ($r=0.75$, $p=.002$) and tonality ($r=0.58$, $p=.01$) (fig. 16).

Lead shows no correlation with other parameters, despite the obvious effect on the oscillation characteristics at a high content.

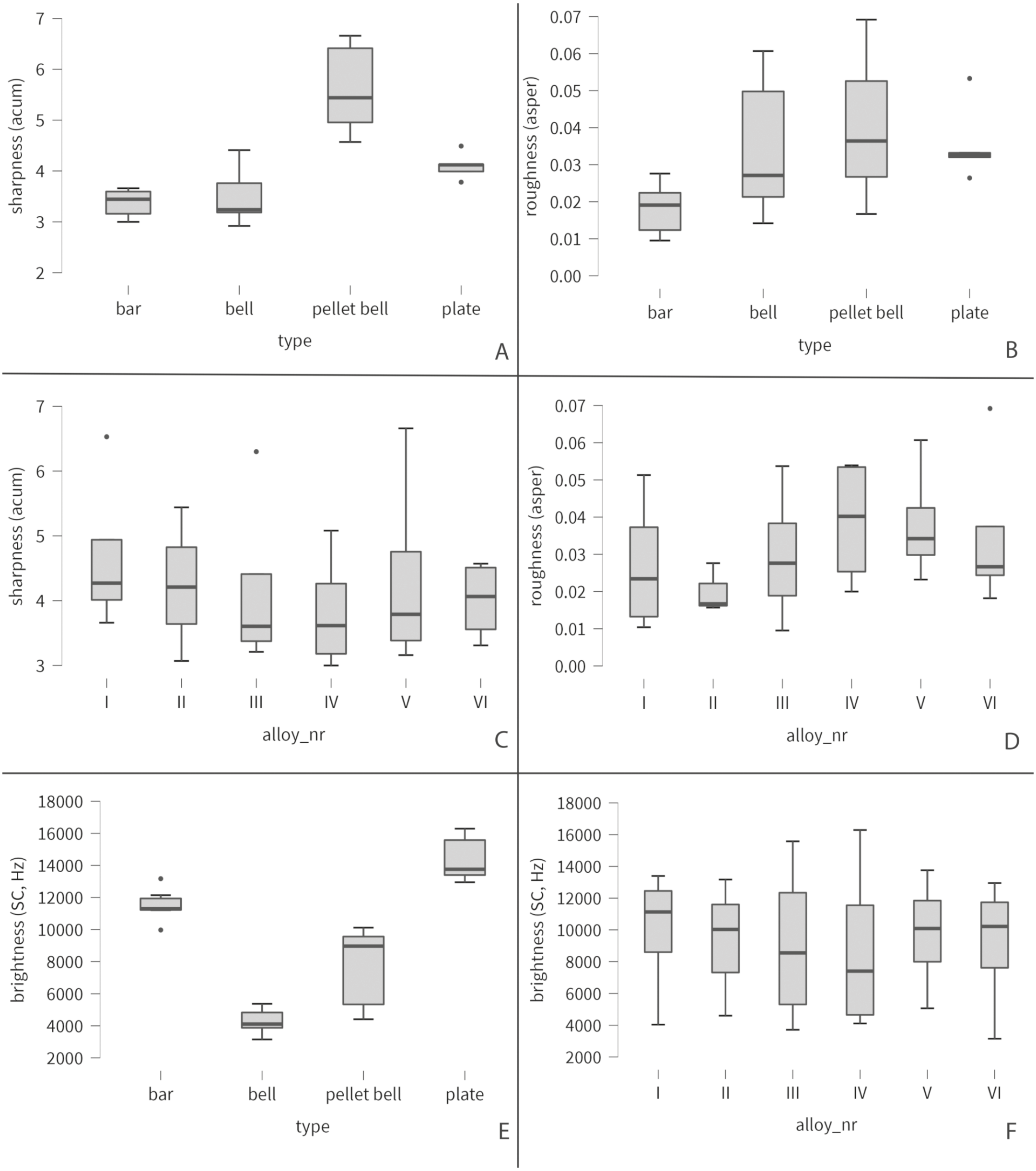

Fig. 15. Distribution of sharpness, roughness, and brightness. A – Sharpness distribution in shapes; B – Roughness distribution in shapes; C – Sharpness distribution in alloys; D – Roughness distribution in alloys; E – Brightness distribution in shapes; F – Brightness distribution in alloys (Graphic: J. Mühlhans)

Obr. 15. Rozdělení ostrosti, drsnosti a jasu. A – Rozdělení ostrosti u jednotlivých tvarů; B – Rozdělení drsnosti u jednotlivých tvarů; C – Rozdělení ostrosti u slitin; D – Rozdělení drsnosti u slitin; E – Rozdělení jasu u jednotlivých tvarů; F – Rozdělení jasu u slitin (graf: J. Mühlhans)

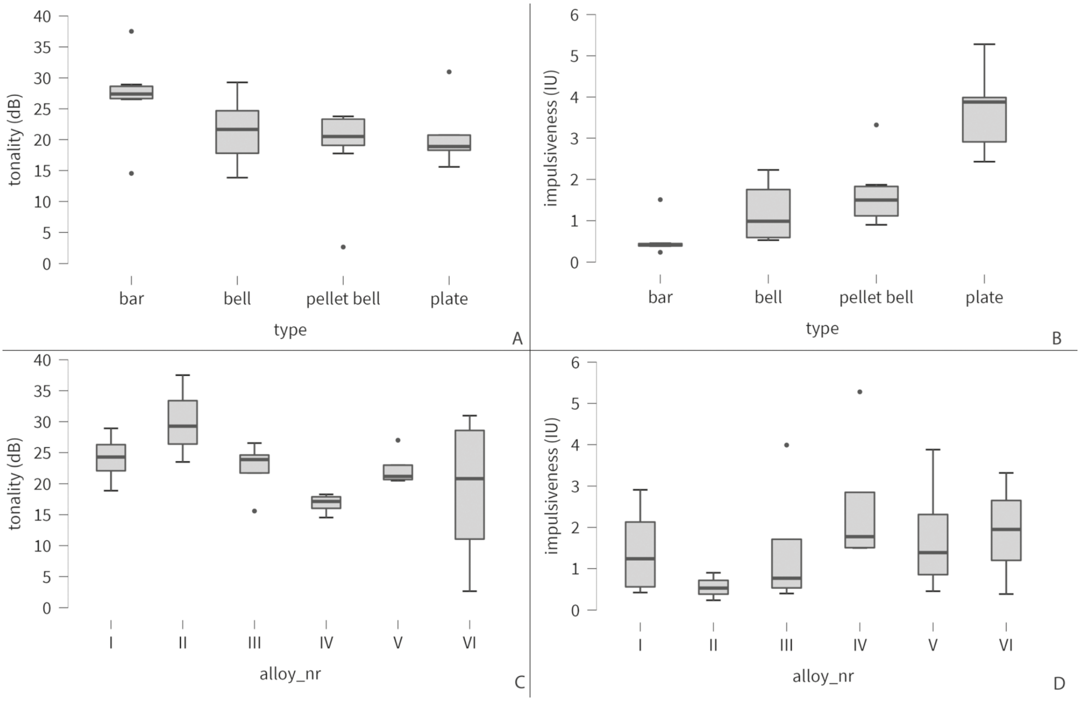

Fig. 16. Distribution of tonality and impulsiveness. A – Tonality distribution in shapes; B – Impulsiveness distribution in shapes; C – Tonality distribution in alloys; D – Impulsiveness distribution in alloys (Graphic: J. Mühlhans)

Obr. 16. Rozdělení tonality a impulzivnosti. A – Rozdělení tonality u jednotlivých tvarů; B – Rozdělení impulzivnosti u jednotlivých tvarů; C – Rozdělení tonality u slitin; D – Rozdělení impulzivnosti u slitin (graf: J. Mühlhans)

Most likely there is simply no linear effect and smaller amounts of lead are even beneficial e.g. decay time, while higher amounts are detrimental, which has already been demonstrated in experimental bell casting 50 years ago (*Schad – Warlimont 1973*).

Overall, the high tin bronze alloy II (being quite close to the modern "bell bronze" in composition) scored high on average in parameters that are desirable for (pellet) bells in terms of the pleasantness of sound, while the high lead bronze did not.

5. Summary

Compared to the originals, the replicas show how much the timbre changes due to corrosion, the originals sound much lower and darker. By analyzing only the recordings of excavated objects, the original sound at the time when they were forged or cast cannot be estimated. Therefore, replicas are a necessary tool for sound analysis.

The peak frequency depends essentially on the mass, while the lowest frequency depends more on the shape and alloy.

Not only is the influence of the alloy greatest on the decay time, but from an acoustic point of view there are more "ideal" alloys, especially for bells, so that the objects can oscillate freely all. Bells are much louder than pellet bells, but in both cases, the influence of the alloy is also very large.

In the psychoacoustic parameters of sharpness and brightness, the influence of the alloy is significantly higher in the case of pellet bells, in tonality and impulsiveness it is exactly the opposite, and in roughness, both types have similar influence due to the material.

Since certain alloys were preferentially used in different ages and geographical regions, it can be assumed from these findings that the perception of such idiophones must also have been different. This will be investigated in further experiments with the collected sounds of originals and replicas.

6. Discussion

The sound of idiophones is complex and multivariate. It depends on several parameters whose exact influence is difficult to control. The study was a first attempt to make these parameters for bells, pellet bells, and additional control objects (bars, plates) largely controllable by replicas of the same shape/form in different materials/alloys and thus to be able to better assess them.

In the manufacturing process, especially the bells proved to be difficult, which led to some irregularities in the shape, which in turn was reflected in the weight distribution of the objects. However, these do not seem to have too great an influence on the acoustic parameters, since the range of variation compared to the much more evenly manufactured pellet bells was similar on average.

Through (psycho-)acoustic analyses and descriptive statistics, it was possible to show which parameters or properties of the objects were more influenced by the shape or the alloy. However, since the data was collected with a small number of individual objects per alloy, it is suggested to replicate this process or add more different alloys in future studies. This could further narrow down the precise influence of individual parameters.

7. Conclusion

Our study investigated 76 Roman bells and 91 pellet bells from the Early Medieval Avar and Carolingian periods. The objects originate from Austria, Hungary, and Slovakia. Bells were found in settlements, in hoards, on roads, and in military camps. Although they have previously not received much attention in archaeological research, they played an important role in the lives of people of the time, both in ritual and profane settings. Their bases are rectangular, quadrangular, round, and oval, but their shapes are manifold. So far, ten different types with many variants can be distinguished. Bells with a round base were turned on a lathe and decorated with lines all around. Pellet bells were found in burials. The deceased persons wore them around the neck and fastened on belts or around the arm joint. Only a few horses were decorated with pellet bells on their bridles. Pellet bells can be classified into eleven types/shapes. Chemical analyses carried out on the surfaces with scanning electron microscopy and X-ray fluorescence spectrometry showed a large variety of copper alloys. Besides shapes and sizes, the material influences the sound and the psychoacoustic parameters of idiophones. Six copper alloys were produced: alloy I – bronze (Cu 90/Sn 10), alloy II – bell bronze (Cu 76/Sn 24), alloy III – leaded bronze (Cu 80/Sn 10/Pb 10), alloy IV – leaded bronze (Cu 70/Sn 10/Zn 10/Pb 10), alloy V – red bronze (Cu 70/Sn 10/Zn 10/Pb 10), and alloy VI – brass (Cu 58/Zn 39/Pb 3). A reconstructed bell shape (original: Roman bell FNr. 89, Ovilava) and pellet bell shape (original: pellet bell, burial 30 (34), Kiskőrös – Vágóhídi-dűlő) as well as a bar were cast in these six alloys. Furthermore, five plates were forged (alloys I, III, IV, V, VI). All objects were weighed and compared. Sound recordings and sound level measurements were carried out at the sound recording studio of the MediaLab, University of Vienna, and analysed. Additionally, descriptives and boxplots were created for the alloy groups to visualise the distributions. The influence of shape and alloy on the sound of cast objects was examined in this study. Shape proved to be the more prominent factor with fewer variations in each group (n=6) than the alloy (n=4) that delivered less consistent values even though it was the smaller group. For the group differences, ANOVAs were calculated but delivered no significant results, most likely because of the small number of objects in each group. Still, the distribution plots show which parameters are likely driven by the shape or the alloy of the object. Overall spectral shape, distribution of partials, thus lowest partial and peak frequency, as well as sound pressure level, loudness, and brightness are rather driven by the shape of the object. Tonality and Impulsiveness seem to be equally affected by shape and alloy. Decay time, however, seems to be influenced by the alloy or the composition of elements much more than by the shape.

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1) Irregularities or deviations can always occur, as partial tone series are not mathematically perfect. Due to bending stiffness, especially very high partials are usually inharmonic (*Winkler 1988*, 86).

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Římské zvony a avarské rolničky odlité ze slitin mědi – vliv materiálů na akustiku a psychoakustiku

V rámci naší studie jsme zkoumali 76 římských zvonů a 91 rolniček z raně středověkého avarského a karolínského období z území Rakouska, Maďarska a Slovenska. Zvony byly nalezeny na sídlištích, v depotech, v místech cest a ve vojenských táborech z doby římské. Přestože se jim dříve při archeologických výzkumech nevěnovala velká pozornost, hrály důležitou roli v životech tehdejších lidí, kteří je využívali jak pro rituální, tak profánní účely. Ústí zvonů bývají obdélníková, čtyřúhelníková, kruhová i oválná, ale celkové tvary jsou rozmanité. Zatím je možné rozlišit deset různých typů s mnoha variantami. Zvony s kruhovým ústím byly vyráběny na soustruhu a zdobeny oběžnými liniemi. Nálezy rolniček pocházejí z hrobových kontextů. Zemřelí je měli zavěšené kolem krku a připevněné na opasku nebo kolem paže. Jako ozdoba koňské uzdy byly rolničky nalezeny jen v několika málo případech. Rolničky můžeme rozdělit do jedenácti typů/tvarů. Chemické analýzy povrchu rolniček za použití rastrovací elektronové mikroskopie (SEM) a rentgen-fluorescenční spektrometrie (XRF) ukázaly širokou škálu slitin mědi. Kromě tvaru a velikosti ovlivňuje zvuk a psychoakustické parametry idiofonů také použitý materiál. Pro účely výzkumu bylo vyrobeno šest slitin mědi: slitina I – bronz (Cu 90/Sn 10), slitina II – zvonový bronz (Cu 76/Sn 24), slitina III – olovnatý bronz (Cu 80/Sn 10/Pb 10), slitina IV – olovnatý bronz (Cu 70/Sn 10/Zn 10/Pb 10), slitina V – červený bronz (Cu 70/Sn 10/Zn 10/Pb 10) a slitina VI – mosaz (Cu 58/Zn 39/Pb 3). Z těchto šesti slitin byly odlity repliky zvonu (originál: římský zvon, nález č. 89, Ovilava) a rolničky (originál: rolnička, hrob 30 (34), Kiskőrös – Vágóhídi-dűlő) a také šest tyčí. Kromě toho z nich bylo vykováno i pět destiček (slitiny I, III, IV, V, VI). Všechny předměty byly zváženy a porovnány. Zvukové záznamy a měření hladiny zvuku byly provedeny a analyzovány ve zvukovém nahrávacím studiu MediaLab na Vídeňské univerzitě. Kromě toho byly pro skupiny slitin vytvořeny popisy a krabicové grafy pro vizualizaci rozdělení četností. V rámci této studie byl zkoumán vliv tvaru a použité slitiny na zvuk litých předmětů. Tvar se ukázal jako významnější faktor s menšími odchylkami v každé skupině (n=6) než slitina (n=4), která poskytla méně konzistentní hodnoty, i když tvořila menší skupinu. Pro určení rozdílů mezi skupinami byly vypočteny hodnoty ANOVA, ale nepřinesly žádné významné výsledky, s největší pravděpodobností kvůli malému počtu předmětů v každé skupině. Grafy rozdělení četností přesto ukazují, které parametry jsou pravděpodobně ovlivněny spíše tvarem daného předmětu a které spíše slitinou použitou na jeho výrobu. Celkový tvar spektra, rozdělení sinusových složek, tedy základní a nejvyšší frekvence, stejně jako hladina akustického tlaku, hlasitost a jas jsou spíše dané tvarem objektu. Zdá se, že tonalita a impulzivnost jsou ovlivněny tvarem a slitinou ve stejné míře. Doba dozvuku je však evidentně ovlivněna slitinou nebo prvkovým složením mnohem více než tvarem.

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