How do we perceive the sounds of both original and replica archaeological metal sound objects? An interdisciplinary study of systematic musicology, music psychology, and music archaeology

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Abstract

The history of metal idiophones dates back as far as metalworking itself. These sound objects served various purposes, such as attracting attention, displaying social status, and practical use in signalling. While once integral to everyday life, these sound objects are now rarely seen outside of museums or medieval markets. In the project "Metallic Idiophones from 800 BC – 800 CE", original and replicated metal idiophones from Central Europe were examined for their acoustic properties. Within the group of examined objects, variations in construction, shape, and alloys based on era and region can be seen. In this study, a selection of 21 original and replicated idiophones that cover most of the variations are examined for the subjective perception of their sounds. Participants in the online listening experiment (n=102, mean age = 35.6) rated sounds on pleasantness, brightness, sharpness, complexity, activation, and valence. Personality traits, musicality, preferences for sound jewellery, and beliefs in object properties were also assessed. While 75% showed low preference for sound jewellery, some associated it with high social status or metaphysical abilities. Belief in these abilities correlated with openness and preference. No age or gender effects were observed in sound ratings. Overall, sound level negatively correlated with pleasantness and positively with sharpness, activation, and valence. Sounds with higher tone-noise-ratio were perceived

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as brighter and sharper. Bell sounds were rated brighter, sharper, and higher in valence/activation than chimes, but lower in pleasantness. Though not directly applicable to the past, the study revealed effects related to human hearing rather than socio-cultural significance. Loud, bright, and sharp sounds were rated unpleasant, suggesting a shift from jewellery to signalling use.

Keywords

Music Archaeology – Psychoacoustics – Psychology of Music – Metallic Idiophones – Originals - Replicas

1 Introduction

The research project "Metallic Idiophones between 800 BCE and 800 CE in Central Europe" (FWF, Hertha Firnberg Programme, project number T 1136-G) examines archaeological contexts and the acoustic effects of metallic idiophones such as bells, pellet bells and sounding jewellery over a time span of 1600 years, including the Early Iron Age/Hallstatt culture, the Roman Period, and the Early Middle Ages/Avar period. The project aims to gather new information on the function, the social impact, and influence of metallic idiophones on the life of past societies, and on their acoustic, psychoacoustic, and psychological effects. In an interdisciplinary approach, research methods from archaeology, metallurgy, ethnomusicology, acoustics, psychoacoustics, and psychology are used, supported by experimental archaeology as well as studies of written (for the Roman period and the Early Middle Ages) and pictorial sources (Pomberger et al. 2021b; Pomberger and Mühlhans 2022; Pomberger et al. 2022b; Pomberger et al. 2020; Pomberger et al. 2021a, Pomberger et al. 2021c; Mühlhans et al. 2022; Pomberger et al. 2023b). To gain information about possible connections between (psycho-)acoustic parameters and subjective ratings from listeners, an online study by using the platform SoSciSurvey (Leiner 2023) was carried out. In this article we present the results of our online study on the originals and replicas of archaeological metal sound objects.

2 Research question

It is assumed that jewellery idiophones were historically used as status symbols, signalling devices, and ritual objects, among other purposes. The sound perception of these objects therefore plays a key role in their possible function. While the perceptions of the culture at the time of their original use can no longer be reconstructed, we may nevertheless consider how these sound objects are perceived today:

1. Are there differences in the perception between original objects and exact replicas?
2. Are there differences between the different types of idiophones (bells, pellet bells, sounding jewellery)?
3. Are there differences between materials in multiple replicas of the exact same type?

To answer these questions we chose two methods, one being the objective (psycho-)acoustical measurement of the recordings of these idiophones, and the other being an online experiment evaluating subjective perceptions of the sounds. Those two methods belong to the standard repertoire of systematic musicology, which represents the empirical branch of the research field that seeks to find evidence for causal explanations of, for instance, sound perception and cognition (Schneider 2018: 9).

3 Historical background of the idiophones

The recorded idiophones can be classified into idiophones worn on the body and those that predominantly hung on buildings, vehicles, and plants, as well as on animals.

The sound objects we used for the listening study originate from burials of the Hallstatt culture (Early Iron Age), the Avar period (Early Middle Ages) and from settlements of the Roman period. They were clothing accessories like fibulae, which functioned to keep garments together, ring pendants, which signalled a special status within a society, and pellet bells, which served as apotropaic amulets (Pomberger forthcoming).

Fibulae were used to close and fasten garments according to the principle of the safety pin. A needle pierces two pieces of fabric and holds them together – usually in the shoulder area. The bail of the needle, needle head, and needle holder provide space for artistic decoration. Fibulae thus also functioned as jewellery, status symbols, and objects of representation (Heynowski 2019: 33). They could also be bearers of symbols. Ring pendants are combinations of larger and smaller rings suspended one inside the other. In the case of ring pendants with shafts, a larger ring or a wheel-shaped ring sits at the lower end of a bar. Rattling rings and chains with jingling plates complete the ensemble. Ring pendants can be fitted with an eyelet and animal protomes, but some objects lack both. Ring pendants were used as pectorals and were evidently only worn by women. They appear in Upper Austria, Salzburg, southern Bavaria, the Upper Palatinate and very rarely in Lower Austria (Pomberger 2016: 258, 261; Glunz-Hüsken 2017: 237). Pellet bells and bobbles, which are only found in women's graves in the Hallstatt culture, symbolise fruits such as poppy capsules – opium poppies have been known in Europe since the Neolithic (Salavert 2011) – pomegranates and rose hips. Due to their large number of seeds, these fruits symbolise fertility, prosperity and eternal life (Pomberger forthcoming).

3.1 Hallstatt culture objects

The prehistoric collection of the Natural History Museum of Vienna houses a great number of objects excavated in the famous necropolis of Hallstatt Hochtal, Upper Austria, dating from 800 – ca. 400 BCE (Grömer and Kern 2017: 183). One of them, a moon shaped fibula (NHM inv. 25255, see Figure 1a) with 19 chains and 18 pairs of flat-domed cymbals attached to the chains, was found in grave 505 of Hallstatt-Hochtal (Kromer 1959: 117, plate 96/5).

Figure 1: Idiophones/jewellery from Hallstatt culture. a: original fibula, burial 505, Hallstatt; b: fibula replica; c: original ring pendant, burial 890, Hallstatt; d: ring pendant replica; e: pellet bells, burial 4, Kernenried/Oberholz; f: replicas of pellet bells. Photos: a and c: A. Schumacher; b, d and f: B.M. Pomberger, © Natural History Museum Vienna; e: B.M. Pomberger, © Archaeological Service Kanton Bern.

This grave is the cremation burial of a woman, dating to Hallstatt D1, around 600 BCE (Hodson 1990: 49, 55, 67). The fibula is cast in a copper alloy, presumably bronze. The cymbals are hammered from softer bronze sheets. The whole composition has an astonishing length of 34 cm and a weight of 234 g. The cymbals' diameter is 3.2 cm. Their frequencies range from 0.8 kHz up to 20 kHz. Fibulae work like fixing pins. They fix, for example, a peplos – a tubular garment worn by women – fastened together on the shoulders. According to their artistic design, they indicated, among other things, the social status of the wearer. Considered idiophones, they can be classified as pendulum rattles (112.121 in Hornbostel and Sachs 1914/MIMO 2011).

Another recorded object is a ring pendant (NHM inv. 26359, see Figure 1c) from burial 890, dating to the phase Hallstatt C1, around 800 – 725 BC (Kromer 1959: 171, plate 176/15). The ring pendant was found on the chest of a deceased woman. It is a combination of a larger ring crowned with an animal protome, and four smaller rings hooked in. The object is cast in copper alloy and weighs 211.14 g. Ring pendants were worn as pectorals by only a few women and are only known from Southern Bavaria, Salzburg, Upper- and Lower Austria (Glunz-Hüsken 2017: 237; Pomberger 2016: 258–61). They probably functioned as symbols for special power, infinity, and the cycle of life (Pomberger forthcoming). The ring pendant's frequencies range between 2.8 kHz and 19 kHz. Ring pendants are classified in the same group as stick rattles and frame rattles (112.112 and 112.12 in Hornbostel and Sachs 1914/MIMO 2011; see Pomberger 2016: 259).

3.2 Pellet bells

Pellet bells are rather rare finds in Hallstatt culture and have their origins in Northern Iran (Castelluccia and Dan 2014; Contenau and Ghirshman 1935). Their walls are openwork and they remind of cages. Three pellet bells belonging to belt hangings are kept in the archaeological collection of the Archaeological Service of the Kanton Bern in Switzerland (find number 57295 for all, see Figure 1e). They were found in a woman's burial (no. 4) in Kernenried-Oberholz. The skeleton of the woman was decomposed, but the pellet bells lay near the right pair of arm rings and thus clearly hang from a belt or ribbon. The burial dates to the second half of the 8th century BCE (Ramstein and Cueni 2012). XRF analyses showed that the pellet bells were cast in bronze (Stapfer forthcoming). Their sizes vary between 3.8 and 3.9 cm and their weights between 11.72 g and 13.22 g. Pellet bells 2 and 4 are filled with pebbles, whereas pellet bell 3 contains a piece of cinder (Pomberger and Mühlhans forthcoming). Pellet bells are classified as metal vessel rattles (112.13 in Hornbostel and Sachs 1914/MIMO 2011).

3.3 The original Roman bells

Bells played an important role in everyday life during the Roman period and were used in both the profane and religious spheres (Pomberger et al. 2022a). The Roman town *Colonia Claudia Savaria* (ancient Szombathely, Hungary), located near the Amber road, was the centre of the imperial cult

Figure 2: Roman bells. a: bell R. 54.380.6; b: bell R. 54.380.1, both from Savaria (photo: B. Santá, © Savaria Museum Szombathely); c: bell MV 9.950/4, Vindobona (photo: B.M. Pomberger, © Wien Museum); d: bell AMC 13414. Photo: B.M. Pomberger, © Archäologisches Museum Carnuntinum.

bell	site	size	weight	material	frequency range
R. 54.380.1	Savaria/Szombathely	47 mm	46 g	leaded bronze	2.3 – 9.8 kHz
R. 54.380.6	Savaria/Szombathely	44 mm	38 g	bronze	3.3 kHz – 18 kHz
MV 9.950/4	Vindobona/Vienna	65 mm	78.13 g	red brass	1.5 kHz – 20.7 kHz
AMC 13914	Carnuntum/Petronell Carnuntum-Bad Deutsch-Altenburg	48 mm	50.02 g	copper alloy	2 kHz – 20.8 kHz

Table 1: Roman bells, their materials, measures and frequency ranges.

of the Roman province Pannonia Superior and was famous for its cult districts. 37 Roman bells are known so far from Savaria. The sounds of two bells, dating to the 2^{nd} – 4^{th} century CE, are parts of our online-study. The bells' find contexts are unknown. While bell R. 54.380.1 is cast in leaded bronze, bell R. 54.380.6 consists of nearly pure bronze. The analyses were carried out by using the XRF-method. Both have rectangle bases and their iron clappers are not conserved. Their sizes are

Figure 3: Avar pellet bells. a: burial 86, Komárno IX (Lodenica), SK; b: burial 92, Holiare, SK; c: burial 1689, Zamárdi-Rétiföldek, HU; d: burial 104, Gyenesdiás, HU; e: replicas of a pellet bell from burial 110, Komárno IX (Lodenica) in different sheet metals, from left to right: copper – bronze – iron. Photos: B.M. Pomberger, a: © Podunajské Múzeum v Komárne; b: © Institute of Archaeology, Slovak Academy of Sciences Nitra; c: © Rippl-Rónai Múzeum Kaposvár; d: © Balaton Múzeum Keszthely; e: © L. Kerbler.

less than 50 mm and the frequencies range between 2.3 kHz – 18 kHz. The bells are kept in the Savaria Museum in Szombathely, Hungary (Pomberger et al. 2021c). One bell, cast in red brass, is housed in the Wien Museum in Vienna (MV 9.950/4). It was found on the ancient trail from the military camp *Vindobona* (Vienna) via Inzersdorf – now part of the 23rd district of Vienna, Austria – to *Aquae* (Baden, Austria) and *Scarbantia* (Sopron, Hungary). The bell with a rectangle base probably belonged to a draft or pack animal and is dated between the 1st and 5th century CE (Pomberger et al. 2022d). The last bell we used for our research work originates from Carnuntum's Roman military camp (Figure 2; Table 1).

3.4 Avar period

Pellet bells were not very common in the Avar Khanate. They appeared during the middle of the 7th century and mostly were found in children's burials, in some women's and a few men's graves (Pomberger and Stadler 2018). Pellet bells probably served as amulets. They were fastened on belts and perhaps also on sleeves, and were worn on bracelets and necklaces. In the author's opinion, pellet bells imitate vascular shaped fruits and thus are symbols for fertility, abundance, and eternal life, and as a result protect against evil forces (Grömer and Pomberger 2024; Pomberger forthcoming).

They are cast in different copper alloys or forged from metal sheets. Our chemical analyses of original sound objects were carried out by using scanning electron microscopy and XRF-analyses

replicas	material	weight	frequency range
pellet bell burial 110, Komárno IX	bronze	18.45 g	1.6 kHz – 20 kHz
pellet bell burial 110, Komárno IX	copper	14.27 g	1.2 kHz – 20 kHz
pellet bell burial 110, Komárno IX	iron	15.13 g	2.0 kHz – 20 kHz
ring pendant burial 890, Hallstatt-Hochtal	bronze	357.1 g	0.6 kHz – 20 kHz
fibula with cymbals, burial 505, Hallstatt-Hochtal	tombac	444.5 g	0.68 kHz – 20 kHz
pellet bell 2, burial 4, Kernenried/Oberholz	bronze	23.3 g	7.3 kHz – 20 kHz
pellet bell 3, burial 4, Kernenried/Oberholz	bronze	24.1 g	7.7 kHz – 20 kHz
pellet bell 4, burial 4, Kernenried/Oberholz	bronze	26.4 g	6.8 kHz – 20 kHz

Table 2: Replicas, their material, weight and frequency-ranges.

(Pomberger et al. 2021a; Pomberger et al. 2021c; Pomberger et al. 2022a; Pomberger et al. 2022b; Pomberger et al. 2022c; Pomberger et al. 2022d; Pomberger et al. 2023).

Their sound slots have simple or cruciform shapes and some even are without sound-slots. The number of sound holes varies between none and four. The pellet bells' surfaces are smooth or decorated with grooves and some show face-like features with eyes. Small pebbles, bronze balls, or cinders serve as pellets. The sounds of four original pellet bells cast in copper alloy and three replicas in three different sheet metals – replicas of one original metal sheet pellet bell – are parts of the online-study (see Figure 3). The originals originate from the cemeteries of Komárno IX (Lodenica) and Holiare, Slovakia, and from the Hungarian sites Zamárdi-Rétiföldek and Gyenesdiás. The pellet bell from burial 86, Komárno IX (Lodenica), a child's grave, was found between the pelvis and the right arm. It is cast in bronze,[1] is 28 mm high and weighs 18 g. Its frequency spectrum ranges from 2 kHz up to 20 kHz with peaks at 4.5 kHz (Pomberger et al. 2021a). A child's corroded pellet bell was found in grave 110, lying near the right leg (Trugly 1993: 198; Pomberger et al. 2021a). Another bronze pellet bell originates from an adult/senile woman's burial, grave 92, in the Slavic-Avar cemetery of Holiare in Slovakia (Točík 1968: 25). It has a height of 3.6 cm and is decorated with vertical grooves. Frequencies range from 1.7 kHz up to 21 kHz. In the grave of a juvenile individual in the cemetery in Zamárdi-Rétiföldek, burial 1689, a completely conserved pellet bell cast in bronze with zigzag lines on its surface was detected (Bárdos and Garam 2014: 40). Its height is 3.9 cm. A small bronze ball serves as a pellet. The pellet bell shows frequencies between 0.9 kHz and 22 kHz. The last original pellet bell to be mentioned was found in an infant's burial (grave 104), in the cemetery of Gyenesdiás, Hungary showing a height of 3.45 cm and a weight of 22.24 g. Its frequency range is from 2.1 kHz up to 16.5 kHz (Pomberger et al. 2023a; cf. Figure 3a – d).

3.5 The replicas

We are aware that the original metal objects no longer have the same sounds as they had when they were made and used. When the objects are buried in the ground for centuries and are exposed

[1] See Pomberger et al. 2021a.

to air and moisture, the metals oxidize and the material properties change greatly, which also affects the sound properties. The amount of metal in the object decreases dramatically, while the amount of metal salts increases greatly. The objects thus lose density, while at the same time the wall thickness increases. This leads to damping, so that the porous originals hardly sound at all. This has a major impact on the partial tones, their prominence and also the overall loudness or sound pressure level. Metallurgical examination can provide good information about the alloy that was used. Using this knowledge to produce replicas, the original sound can be reconstructed within a relatively small margin of variation, which is what makes it possible to evaluate the original sounds today.

Replicas were made of the fibula from burial 505 and the ring pendant from burial 890, both Hallstatt-Hochtal, the three pellet bells from burial 4, Kernenried/Oberholz and the pellet bell from burial 110, Komárno IX. A copper alloy (bronze) consisting of 90 % Cu and 10 % Sn was used for the ring pendant and the three pellet bells from Kernenried/Oberholz.[2] The fibula was produced from tombac, which is a kind of brass with more than 70 % Cu.[3] The Avar period pellet bell – the original is forged from iron sheet – from burial 110, Komárno IX Lodenice, served as a model for three replicas in different sheet metals, which were forged in copper, bronze and iron sheet. Each is filled with a small pebble (Figure 3e; cf. Mühlhans et al. 2022). Non-astonishingly, they show different weights (Table 2). Bells were replicated, but since the bells had many casting defects (Mühlhans and Pomberger 2023), we decided not to use their recordings.

4 Methods

4.1 Method 1: (Psycho-)acoustic measurements

The sound recording forms the basis of the objective analysis. Any given sound has temporal features, such as the excitations per time period or the decay time of a sound, and also spectral features, such as the frequency range, amplitudes of partial frequencies, the spectral peak frequency and many more. These acoustic parameters can be extracted using audio analysis software, and represent the sound on what is called a “low level” in acoustics, meaning that each single parameter only gives very limited information about the sound itself, but a number of parameters can be combined to represent sound on a higher level.

Sounds of the original objects were recorded on-site at museums and archaeological collections using a portable recording chamber (Pomberger and Mühlhans 2022). The setup consisted of a Laptop with Adobe Audition (Adobe Inc. 2023) and a PreSonus audioBox iOne interface with the PRM 1 measurement microphone. The replicas were recorded in studio of the MediaLab, Faculty

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2 Replicas cast by Michael Konrad, Schrattental, Austria.

3 Replica made by Stefan Jaroschinski, Frankenberg, Germany. The precise composition of the alloy is the artisan’s secret.

of Philological and Cultural Studies of the University of Vienna, also using Adobe Audition, a Presonu Studio 24c interface and the Earthworks M30 measurement microphone.[4]

4.1.1 *Acoustic parameters*

The sound of an idiophone is emitted by the entire object oscillating after excitation, which is caused by the physical impact of an external or internal object or part of the instrument itself. The partial oscillations inside of the object are called ‘modes’ and they create the partial frequencies that form the sound. Sound is created either by simply shaking the objects, which causes a small encapsulated pellet to hit the inner walls of the object, and single parts like rings and plates to hit against each other, or by hitting the object with a separate clapper, as was the case for many bells.

Basically, the sound of constant excitation of an idiophone is not one single sound, like the sustained note played on a flute, but a quite dense ‘cluster’ of single impulsive sounds (Benade 1976: 10) that occur roughly 5–10 times per second for external excitation with a clapper, and up to 20–30 times per second for the internal excitation with a small stone or lump of metal inside of a pellet bell. The single hits can be identified from either the waveform (Figure 4a) or the spectrogram (Figure 4b – c) of the sound. In the figures, stimulus 14 was used as a typical example for an original Roman bell and stimulus 20 for an original Avar pellet bell. Visualisations of other stimuli in the same category are rather similar.

Another acoustic property common to all idiophones is the non-harmonic structure of the partials. Unlike aerophones and chordophones, this type of instrument does not have a fundamental frequency whose integer multiples make up the harmonics, but rather several partial ‘modes’ of oscillation, which produce a series of non-harmonic partial frequencies (or simply ‘partials’). For this reason, the perception of pitch is weaker in idiophones than in the other two types. As a result of their shape and mode of excitation, bells create more pronounced partials, and thus clearer pitch perception, than pellet bells (Figure 4), because they oscillate more freely with less dampening. Narrow high peaks in the spectrum indicate clear partials (tonal components), broader flat peaks indicate a higher proportion of noise. This property also affects subjective perception of some psychoacoustic parameters, like tonality, harmonicity, brightness and some more.

4.1.2 *Psychoacoustic parameters*

Psychoacoustics is a sub-field of psychophysics that seeks to understand the relation between physical parameters and human perception of sound (Roederer 1973: 6–10). Human perception cannot be calculated directly, because it varies between subjects, but can be estimated using algorithms designed with the findings from listening experiments. The human perception of sound, sound quality, and timbre is highly dependent on acoustic parameters, but is still subjective to a

[4] The choice of software and interface has no impact on the recordings. While there may be slight differences between microphones, measurement microphones are designed to have nearly identical frequency responses. In fact, the microphones used in this research were tested against one another, revealing only minimal variations in measurement parameters – well beyond the threshold of human auditory perception.

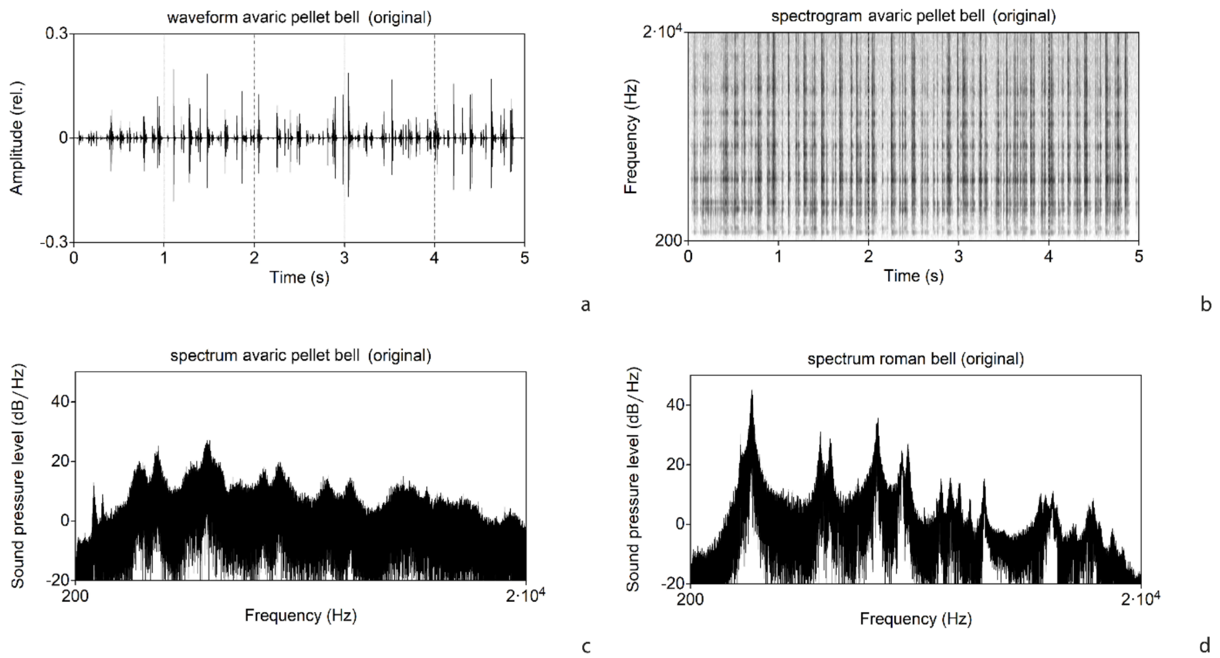

Figure 4: Side-by-side comparison of the acoustic parameters of stimulus 20 (left side, original Avar pellet bell) and stimulus 14 (right side, original Roman bell) in the waveform (a), spectrogram (b) and the spectrum (c–d). Graphic and ©: J. Mühlhans.

certain extent. Among those are the perception of qualities like the loudness, brightness, or sharpness of a sound. Some can be predicted directly from one single acoustic parameter, others are constructed from a variety of so-called 'audio features' with different weighting and highly complicated algorithms of computation. Below are the objectified psychoacoustic parameters:

Loudness is the subjective perception of the intensity of sound. The objective parameter that can be measured is the sound pressure level. They are correlated but do not match exactly, because the ear is rather insensitive to very low and very high frequencies but quite sensitive to the frequency range around 2–5 kHz. Human perception of loudness is estimated using "phon" or "sone", which scale differently but are basically just different methods of calculating. At 1 kHz a sound pressure level of 40 dB equals 40 phon or 1 sone (Fastl and Zwicker 2007: 203). In the phon scale, 10 phon more represent a sound twice as loud to the human ear, in the sone scale it simply represents a doubling of the value. 40 phon and 1 sone is the same loudness level, a sound twice as loud would be described as 50 phon or 2 sone (and so on).

Sharpness is an addition to the sensation of unpleasantness of a sound and depends on the spectral shape, density, and especially the tonal content of a sound in the frequency range where the ear is particularly sensitive. The unit for that parameter is 'acum', which scales the same way that sone does (Fastl and Zwicker 2007: 239).

Roughness is produced by the fluctuation in amplitude and also adds to the sensation of unpleasantness of sounds. It is calculated in 'asper' as a value between 0 and 1, with 1 being the highest possible roughness sensation, as experiments showed (Fastl and Zwicker 2007: 257).

Brightness of sounds is basically what is being expressed in verbal descriptions like "bright", "high", "brilliant" and their counterparts "dark", "low" and "dim". However, there is a physical measurement that is correlated to that sensation, namely the spectral centroid (SC) or spectral centre of gravity. It is a simple measure that divides the spectrum (or rather the spectral energy) in two equal halves and gives the dividing frequency in Hz. The higher the SC, the higher, brighter or more brilliant a sound is perceived (Marozeau and Cheveigné 2007: 383).

Tonality, also known as tone-noise-ratio (TNR), is a measure that separates the tonal component (partial frequencies) from the noise part of a sound and gives a value in decibels. Negative values indicate more noise than tonal components, positive values indicate more tonal components than noise (Becker et al. 2019: 5820).

Impulsiveness of sound is determined by high energy that is usually caused by an impact – as is mostly the case in idiophones (Blommer et al. 1995: 2302).

4.2 Method 2: Empirical online survey with an audio experiment

Despite the fact that the psychology of music has been a completely independent scientific discipline since the mid-20th century, it is also an important part of systematic musicology because of its empirical methods (Thaut 2009: 552). While music psychology is primarily concerned with researching the perception and cognition of entire pieces of music, psychoacoustics is more concerned with the same questions about individual sounds and noises. However, both disciplines count listening tests and associated questionnaires on the subjective perception of the stimuli presented as their most important tools.

The perception and evaluation of music highly depends on the cultural background of the listener (Becker 2001: 136). The perception of sound and noise in the psychoacoustic understanding is on the other hand closely related to the physical properties of the sound itself and the non-linear behaviour of the human ear (Fastl and Zwicker 2007: 11). We are fully aware that subjective ratings of sound perception from today's audience cannot be directly transferred to an audience in the timespan between 800 BCE and 800 CE. However, since the evolution of the human (like any mammalian) hearing is a very slow process, and studies have shown that land mammals have quite common frequency responses (Kanders et al. 2017), it can be assumed, that the properties of the human ear have not changed significantly over probably even millions of years. Perceptions that highly depend on the behaviour of the human hearing thus might not have changed much over the decades. Using psychophysics, in this case psychoacoustics, as a method to find correlations between a physical stimulus and psychological response is most likely the best approach to the questions at hand.

An audio experiment requires two essential things, one being well prepared and controlled audio stimuli, and the other being carefully selected 'items' for a questionnaire.

name	object	type	category	period
stimulus01	ring pendant 26359, Hallstatt burial 890	ring pendant	original	Hallstatt Culture/Early Iron Age
stimulus02	replica of stimulus01	ring pendant	replica	Hallstatt Culture/Early Iron Age
stimulus03	fibula, Hallstatt burial 505	fibula	original	Hallstatt Culture/Early Iron Age
stimulus04	replica of stimulus03	fibula	replica	Hallstatt Culture/Early Iron Age
stimulus05	Kernenried pellet bell 2	pellet bell	original	Hallstatt Culture/Early Iron Age
stimulus06	replica of stimulus05	pellet bell	replica	Hallstatt Culture/Early Iron Age
stimulus07	Kernenried pellet bell 3	pellet bell	original	Hallstatt Culture/Early Iron Age
stimulus08	replica of stimulus07	pellet bell	replica	Hallstatt Culture/Early Iron Age
stimulus09	Kernenried pellet bell 4	pellet bell	original	Hallstatt Culture/Early Iron Age
stimulus10	replica of stimulus09	pellet bell	replica	Hallstatt Culture/Early Iron Age
stimulus11	replica pellet bell, Komárno IX/burial 110: copper	pellet bell	replica	Avar/Early Middle Age
stimulus12	replica pellet bell, Komárno IX/burial 110: bronze	pellet bell	replica	Avar/Early Middle Age
stimulus13	replica pellet bell, Komárno IX/burial 110: iron	pellet bell	replica	Avar/Early Middle Age
stimulus14	bell Savaria 54.380.1	bell	original	Roman Period
stimulus15	bell Savaria 54.380.6	bell	original	Roman Period
stimulus16	bell Vindobona MV9.950–4	bell	original	Roman Period
stimulus17	bell Carnuntum 13914	bell	original	Roman Period
stimulus18	pellet bell, Komárno IX/burial 86 (A_5683)	pellet bell	original	Avar/Early Middle Age
stimulus19	pellet bell, Gyenesdiás/burial 104, FNR_104–1	pellet bell	original	Avar/Early Middle Age
stimulus20	pellet bell, Zamárdi-Rétiföldek/burial 1689, inv. 247.1.1689.1	pellet bell	original	Avar/Early Middle Age
stimulus21	pellet bell, Holiare/burial 92, inv. 92 2760	pellet bell	original	Avar/Early Middle Age

Table 3: Table of stimuli and periods.

4.2.1 *Stimuli for the experiment*

A set of 21 stimuli, covering a range of various objects from different eras, and both original and replicated sounds, has been selected for the experiment (see Table 3). To avoid the effects of stimulus duration, every sound has been limited to 5 seconds of constant excitation with a 100 ms fade in/out in the beginning and end of the stimulus. Amplitudes were maintained to keep the original loudness of the items, since this parameter influences others, like pleasantness, sharpness, or valence, as well as arousal ratings. Low frequency ambient noise was quite low in the recording itself, but was still removed using a 500 Hz high pass filter. A separate test sound was created that included multiple sounds similar to, but not exactly matching the stimuli, for the participants to set up the volume on their speakers or headphones. This sound was not evaluated nor analysed.

4.2.2 Sample

In this exploratory within-subjects study design, an ad hoc sample of 102 participants was recruited for an online study using the platform SoSciSurvey (Leiner 2023). The age of the sample varied between 18 and 65 years (age_{mean}=37; SD=13.78) and consisted of 66 female (age_{mean}=35.61; SD=13.27) and 36 male (age_{mean}=39.56; SD=13.96) participants. In this sample 73.53% of participants reported an academic degree, 24.51% a high school diploma, 0.98% compulsory education and 0.98% a master craftsman as highest education.

Before the actual listening trial, participants were asked to self-assess the Big Five personality traits with the German version of the BFI-10 (Rammstedt and John 2007) on a five-point Likert-scale. The Big Five personality traits are a set of five broad dimensions of personality that are used to describe human personality. The five traits are neuroticism, extraversion, openness, conscientiousness, and agreeableness. To assess musical preferences participants were asked to complete six items from the German revised Music Preference Questionnaire (MPQ-R; see Nater et al. 2005) which is a self-assessment on how much music and which music genres participants listen to, as well as in which situations they listen to music. A transcript of the questionnaire (original language German) can be found in the appendix. The list of the raw data is available on the repository of the Natural History Museum (Foramitti 2024).

In order to further investigate the metaphysical and apotropaic beliefs in metallic idiophones (Pomberger forthcoming), another eight items were used to determine the extent to which participants consider bells to be toys, status symbols, or even utilitarian objects. Three of these were specifically aimed at evaluating beliefs in supernatural abilities, such as driving away evil spirits or bringing good luck. Also, participants were asked for their preference for sounding jewellery.

In the main part of the experiment, the 21 stimuli were presented in a random sequence to avoid effects of order. Along with each stimulus, participants were asked to rate the sound using a slider on a bipolar scale for six parameters: pleasantness (unpleasant/pleasant), brightness (dark/bright), sharpness (dull/sharp), complexity (simple/complex), arousal (calming/activating) and valence (sad/happy). Participants could listen to the stimuli as often as preferred during ratings.

Valence (negative/positive or sad/happy) and arousal (low/high or calming/exciting) especially are items often used in studies to evaluate emotional perception of music or sounds using the circumplex model of affect (Russell 1980).

For the statistical comparisons with the subjective ratings, acoustic and psychoacoustic parameters were measured using ArtemiSuite (HEAD 2023) and Praat (Boersma and Weenink 2023). Statistical calculations were done using JASP (JASP Team 2023).

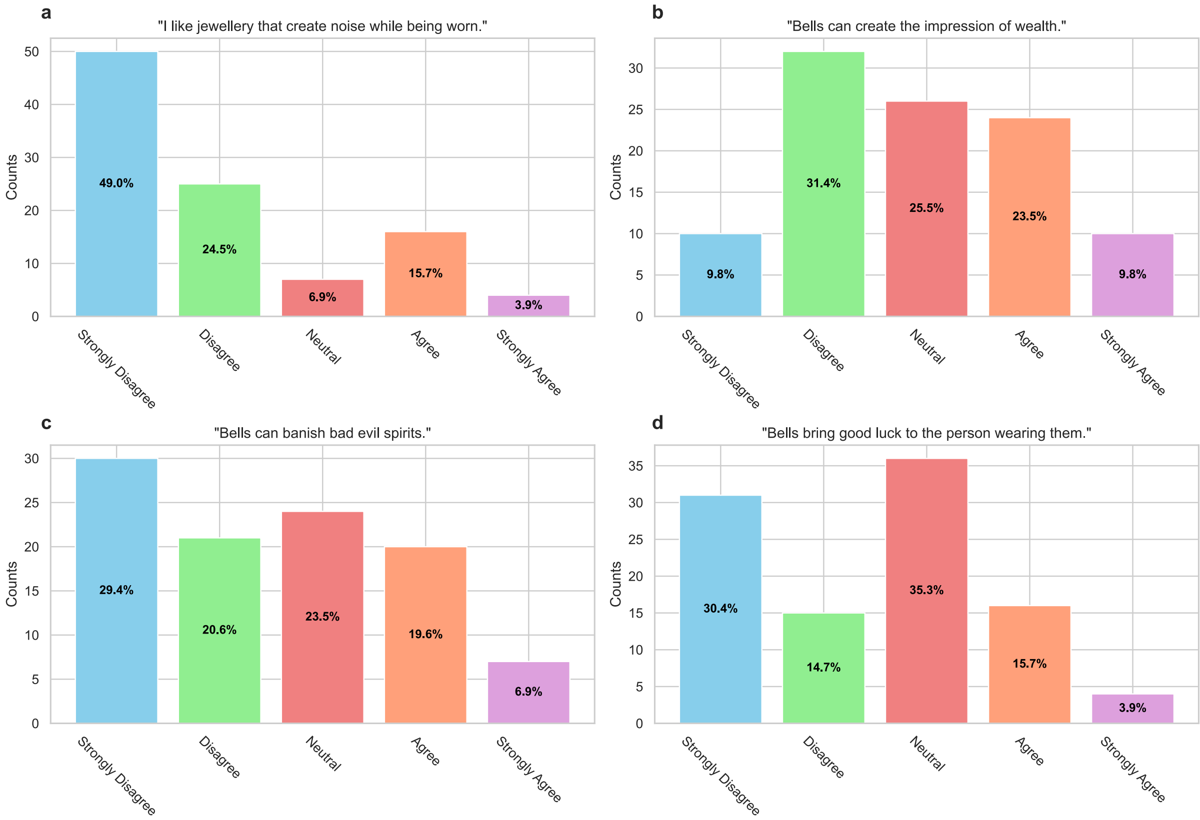

Figure 5: a, b: distribution plot for preference and status symbol; c, d: distribution plots in belief 'metaphysical powers' banish spirits concerning (pellet) bells. Graphic and ©: M. Foramitti.

5 Results

5.1 General findings

Even though the sample scores relatively high in the personality trait 'openness', preference for the objects is rather low, only about 20% of the participants stated they like or very much like ringing jewellery (Figure 5a). Still, about 33% agree or strongly agree that (pellet) bells can create the impression of wealth (Figure 5b).

20–25% agreement with the supposed metaphysical abilities of bells (Figure 5c – d) seems a lot, as it is generally assumed that such a belief decreases with the level of education. However, studies show that this is not the case (Lindeman and Aarnio 2007). This finding is relevant when it comes to assessing the development of belief in metaphysical properties in the population, especially those in the supposed apotropaic effect of such decorative idiophones (Pomberger and Stadler 2018b; Pomberger et al. 2021b). Although such findings are not simply transferable to historical societies, they can at least help to provide some evidence for very relevant questions, such as the possible use or application of such objects in earlier eras.

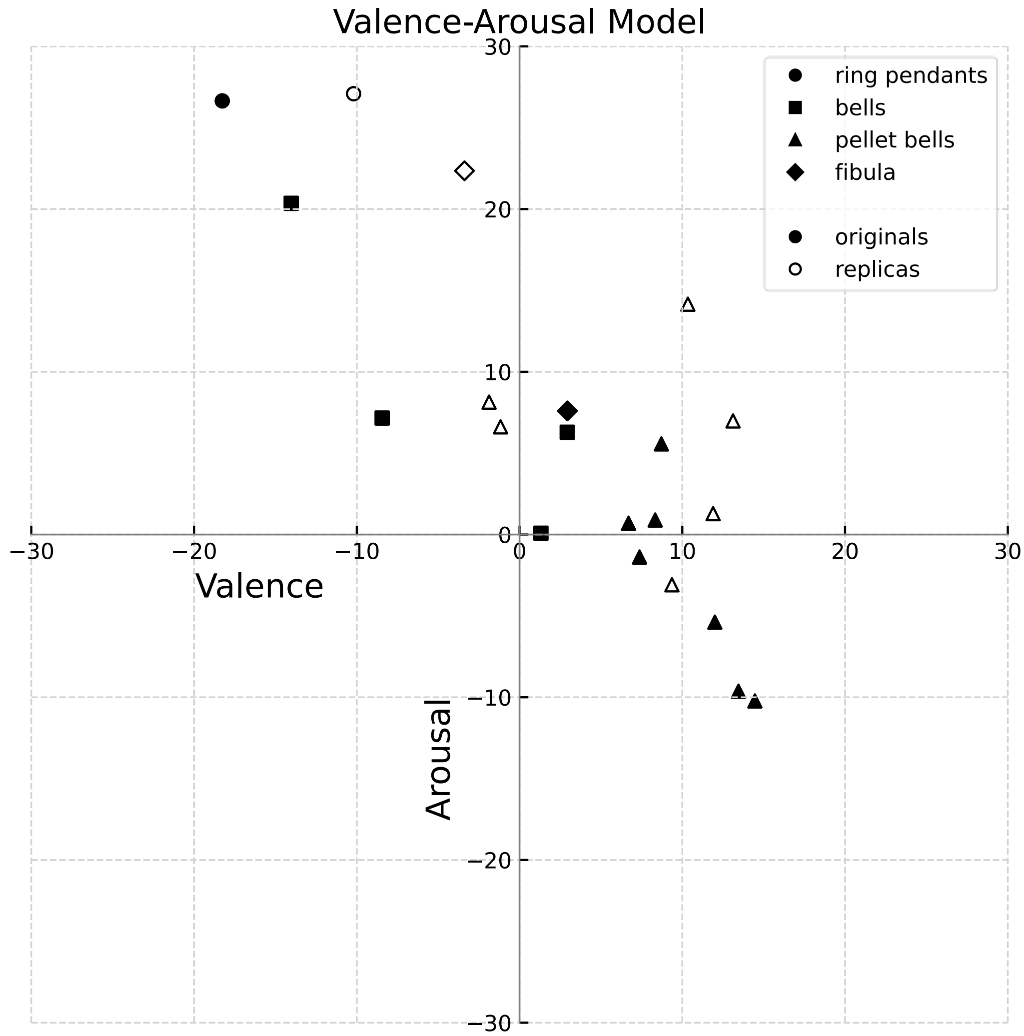

Figure 6: Valence-Arousal-Graph for all 21 stimuli, coded by type and originals/replicas. © J. Mühlhans/M. Foramitti.

On average, the six subjective ratings of the sounds were rather neutral, with only brightness ratings being higher in most cases, because the frequency range is high compared to most other known music instruments or sound objects. No correlation between personality traits and any of the ratings could be found. The combined valence-arousal-graph (Figure 6) shows that pellet bells score higher in valence than bells, and other types of objects score higher in arousal (most likely because they are much louder).

Many correlations could be found both within (psycho-)acoustic parameters and subjective rating as well as between them. Most notably, loudness or level-related parameters and sharpness are highly correlated to most ratings (see Figure 7).

Loud and sharp sounds are considered less pleasant, but higher in arousal and in valence. Interestingly, among the two parameters that were measured (psychoacoustic model) and rated, only sharpness is correlated, while brightness is not. For further investigation, stimuli have been divided into groups by their category or type.

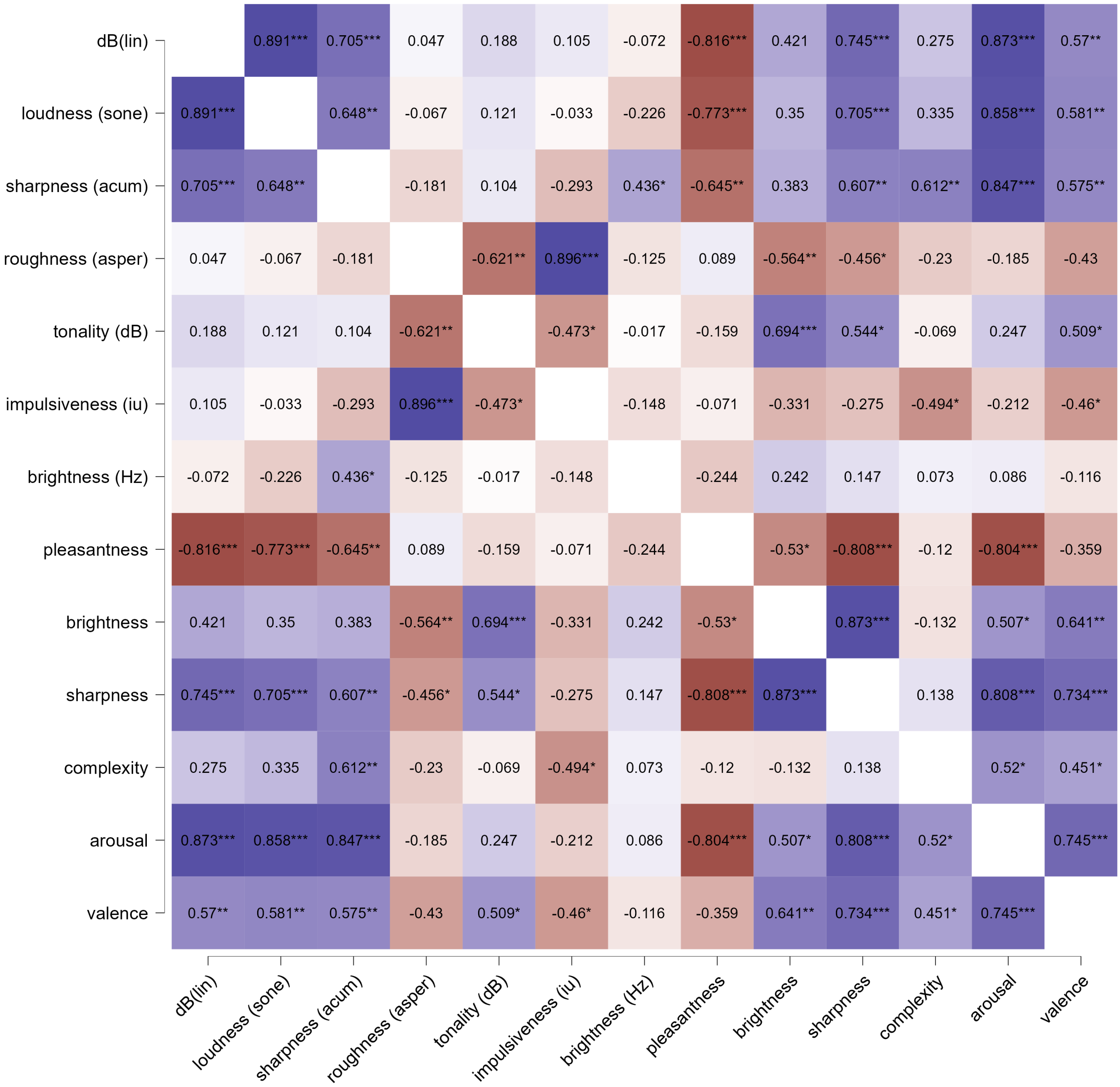

Figure 7: Pearson's Heatmap of correlations between all acoustic parameters and subjective ratings for all stimuli. Parameters with units in brackets are objective measures, parameters without units are ratings from participants. R-values in the fields indicate the correlation coefficient (blue equals positive correlations, brown indicates negative ones), stars the level of significance (*p<.05, **p<.01, ***p<.001). Graphic and ©: J. Mühlhans.

5.2 *Original vs. replicated objects*

Firstly, original idiophones (n=5) were compared to their replicated counterparts' (n=5) subjective ratings. Since the Shapiro-Wilk test of normality indicates a deviation from normal distribution in the data, this comparison was conducted with the non-parametric Mann-Whitney-U test. It showed that subjects evaluated the stimuli of the originals as being significantly more pleasant (p<.001, r=.307) and significantly darker (p<.001, r=.554) than their replicated counterparts. The replicates have been rated significantly higher in sharpness (p<.001, r=.539), arousal (p<.001, r=.531) and valence (p<.001, r=.374) than the originals.

This might be explained by the higher average sound pressure level of the replicas (81.3 dB) in comparison to the originals (69.9 dB). Measured sharpness is indeed higher in replicas on average as well (6.7 acum) than in originals (4.8 acum). The brightness ratings also reflect the measured brightness values of the items (11.7 kHz vs. 8.4 kHz; see Figure 8a).

5.3 Bells vs pellet bells

Secondly, original bells (n=4) were compared to original pellet bells (n=4) in their ratings, using the Mann-Whitney-U test. The sounds of the bells were rated as being significantly brighter (p<.001, r=.738), sharper (p<.001, r=.738), more arousing (p<.001, r=.321) and higher in valence (p=.001, r=.307) than the pellet bells. Yet, the sounds of the bells were rated as being significantly less pleasant (p<.001, r=-.501) as well as less complex (p=.01, r=-.209) than the pellet bells.

Bells are louder (43.8 sone) than pellet bells (27.0 sone), but almost equal in sharpness (4.3 and 4.6 acum). Bells are also more tonal (20.4 dB TNR) than pellet bells (11.8 dB) but not as bright in terms of spectral centroid (4.6 kHz vs. 5.6 kHz), with brightness ratings reflected by the acoustic data (Figure 8b).

5.4 Identical replicas with different materials

The three replicas of pellet bell 110, Komárno IX Lodenice in different materials (bronze, copper, iron) were also compared separately (n=3), to see whether the large differences in acoustic parameters are also reflected in subjective ratings. This was done using preliminary Kruskal-Wallis tests, followed by post-hoc Dunn's tests with a sequential Bonferroni-Holm correction, to reduce the likelihood of false positives. The comparison shows significant differences between the objects in the rating of darkness (p<.001, η^2=.087), sharpness (p<.001, η^2=.062) and arousal (p<.001, η^2=.059). The post-hoc tests show that the copper pellet bell has been rated as significantly darker than the bronze pellet bell (p<.001, d=.36) and the iron pellet bell (p<.001, d=.75). The copper pellet bell has also been rated as being significantly less sharp than the iron pellet bell (p<.001, d=.626). Finally, the iron pellet bell has been rated as being significantly more arousing than the copper pellet bell (p<.001, d=.609) and the bronze pellet bell (p=.03, d=.339). There are no significant differences between the pellet bells of different materials in their ratings of pleasantness, complexity and valence.

With n=3 objects, correlations between averages of ratings and measured parameters hardly reach a satisfying significance level, however, there are several very high correlation coefficients (r>.95). Loudness, sharpness, and tonality, showing the most results, are positively correlated with perceived brightness, sharpness, and arousal, and a tendency to correlate with valence, but not at all with pleasantness and complexity, however, exactly those two parameters are correlated with impulsiveness (Figure 8c. p-values for the higher r-values range between .006 and .1).

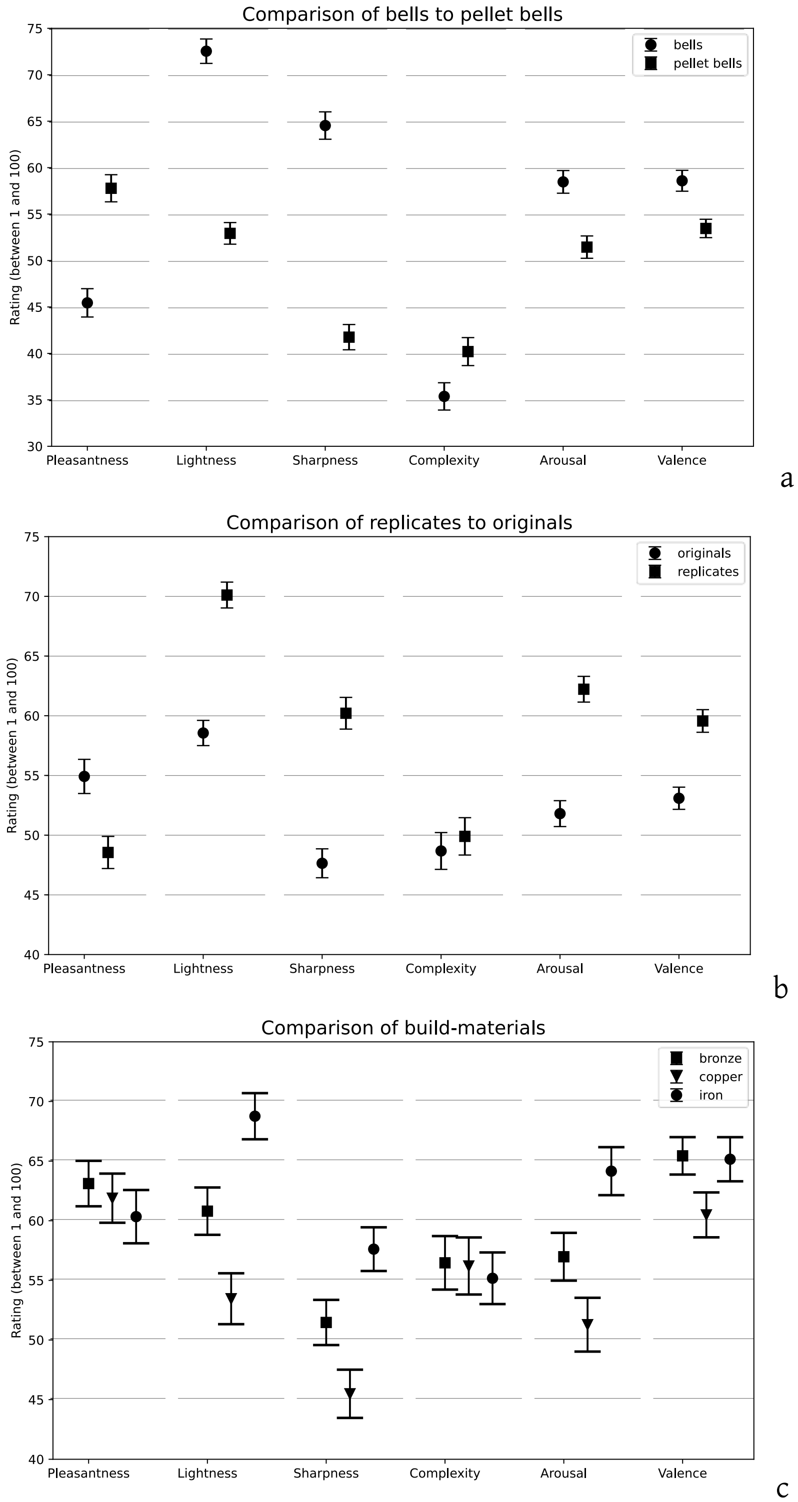

Figure 8: Graphic of Results. a: comparison of the originals and replicates according to their assessment in pleasantness, brightness, sharpness, complexity, arousal, and valence (whiskers represent the standard error); b: comparison of bells and pellet bells replicas according to their assessment in pleasantness, brightness, sharpness, complexity, arousal, and valence (whiskers represent the standard error); c: comparison of build-materials according to their assessment in pleasantness, brightness, sharpness, complexity, arousal, and valence (whiskers represent the standard error). Graphic and ©: M. Foramitti.

No gender effects[5] could be found in the ratings of sounds nor in preference for sounding jewellery or the belief in what might be called 'spiritual power' thereof. The only significant finding being male participants were more likely to consider (pellet) bells to be decorative objects rather than jewellery (p=.018, F=5.8).

6 Conclusion/Discussion

The aim of this study was to find out more about the actual subjective perception of sounding jewellery from a contemporary perspective, in order to come closer to an assessment of its possible uses in the age of its creation. In particular, we also wanted to know how the different types of sound jewellery differ in terms of perception beyond the measurement data, how originals and replicated objects are perceived differently, and what influence the material has on the sound and its perception. Through the acoustic measurements, we were able to isolate some parameters that are strongly related to the different perceptions.

In general, we were able to show that loud (dB SPL, sone), bright, and sharp objects of all categories have an activating effect but are also perceived as unpleasant. This can be explained by the fact that they contain a relatively large amount of sound energy in a range to which the human ear is very sensitive. This supports both the hypothesis that the objects could have been worn to attract attention in the social environment and to send out signals in general.

The belief in metaphysical properties (driving away ghosts, bringing good luck) is present in about 20–25% of the test subjects today, while at the same time the preference for sounding jewellery is rather low. However, over 30% of the test subjects ascribe status to these objects. This naturally raises the question of what this distribution might have looked like in society in different eras and regions.

We would like to point out once again that we are well aware that such results cannot be directly transferred to the perception of a population living at the time from the Hallstatt period to the Avar period. Nevertheless, we believe that this method is useful for estimating the possible perception of sound features, especially those that depend more on the physical characteristics of the ear than on cultural socialisation.

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[5] "No gender effects" is the standard phrase to indicate that there have been no differences between the sexes/gender affiliations.

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Appendix: Transcript of the questionnaire

The questionnaire started with an explanation about the experiment and some basic instructions about handling the rating scales. Participants were asked to take their time and do the experiment in a quiet surrounding, if possible with headphones or a loudspeaker system (no laptop speakers). A test-sound was presented for the participants to adjust the volume of their system to a clear and loud but not unpleasant volume.

Stimulus ratings

Items and rating scales were the same for every single stimulus during the experiment, they were presented randomized to avoid effects of order. For every sound, six bi-polar scales with descriptions at the extremes were used. Participants rated every item using a slider:

Q: Please use the slider to evaluate how you would describe the sound with the given adjectives. Please answer intuitively.

A1: Unpleasant – Pleasant

A2: Dark – Bright

A3: Dull – Sharp

A4: Simple – Complex

A5: Calming – Activating

A6: Sad – Happy

Sociodemographic data

Q: What gender do you identify with?

A: Male, Female, Divers, No Answer

Q: How old are you?

A: I am [   ] years old.

Q: What is your highest education?

A: Elementary School, Compulsory School, High School, Collage, University, Craftsmanship Apprentice, Craftsmanship Master

Musicality

For the evaluation of musicality, the MPQ-R-6 (Nater et al., 2005) was used with 4 selected items.

Personality traits ("Big Five")

For the evaluation of personality traits, the German version of the BFI-10 (Rammsted and John, 2010) was used with all ten items.

Other single item questions:

Q: To what extent do you agree with the following statement?
S1: I like jewellery (necklaces, bracelets...) that create noise while being worn.
S2: (Pellet) Bells can create the impression of wealth.
S3: (Pellet) Bells can banish bad evil spirits.
S4: (Pellet) Bells are jewellery.
S5: (Pellet) Bells can chase away wild animals.
S6: (Pellet) Bells are rather children's toys.
S7: (Pellet) Bells are rather decorative objects.
S8: (Pellet) Bells bring good luck to the person wearing them.
S9: (Pellet) Bells can reduce stress.
A(all): Not at all – Fully agree (5 point scale)