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On Experimental Reconstructions of the Mammoth Ivory Flute from Geißenklösterle Cave (GK3) and Other Palaeolithic Wind Instruments from South-West Germany

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Abstract

The present paper provides a multidisciplinary approach integrating musicological, acoustical, and manufacturing aspects to the archaeological study of the mammoth ivory instrument from Geißenklösterle Cave (GK3). We present information on the archaeological background and the find history, and new insights into the playing technique of the instrument, confirming that GK3 was designed as a flute with a notch (M. Malina, S.C. Münzel). Subsequently, physical parameters causing pitch variability in general and their impact on the response of the low register of extended reconstructions are explored (G. Dalferth), before actual experiences of the *chaîne opératoire* of the GK3 ivory instrument are supplied (W. Hein). Due to its incompleteness, this Palaeolithic instrument allows for variability in reconstructing. A comparative tonal analysis of eight GK3 reconstructions in different lengths was conducted (A.F. Potengowski), offering new clues to possible musical intervals of the original instrument. Finally, the requirements for future research are considered.

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Keywords

Palaeolithic wind instruments – Reconstructions – Musical analysis – Notched flutes – Mammoth ivory – Geißenklösterle Cave – Aurignacian

1 Introduction, archaeological background, and state of the art

Susanne C. Münzel

1.1 Introduction

During the years 2020/21 the authors met in regular online meetings to prepare a workshop for the ISGMA 2021 in Berlin. The work presented here is the productive outcome of this workshop. The working group includes experts in many different fields, such as the person who refitted the ivory instrument (M. Malina); scientific museum assistants from the Urgeschichtliches Museum Blaubeuren (URMU: B. Spreer, H. Wiedmann), where some of the Palaeolithic wind instruments are housed; experimental archaeologists with a huge amount of experience in the reconstruction of Palaeolithic artefacts (W. Hein, H. Wiedmann); active flutists responsible for testing and analyzing the reconstructions[1] (A.F. Potengowski, G. Dalferth); and finally an archaeological scientist (S.C. Münzel). The joint effort of all members resulted in a workshop, held on the occasion of the ISGMA 2021, focusing on the mammoth ivory instrument from the Aurignacian layers of Geißenklösterle, a cave site near Blaubeuren in the Ach Valley, Swabian Jura, Southwestern Germany.

The first musical analyses of experimentally reconstructed instruments from the Swabian Jura were conducted in the 1990s by Wulf Hein (Hahn and Hein 1995, Hein und Hahn 1998) and Friedrich Seeberger † and were presented during the ISGMA 2000 in Michaelstein, Harz, Northern Germany (Münzel et al. 2002). Their experiments gave the first insights into the tonal diversity of the swan radius instrument from Geißenklösterle (GK1), the first artifact to be recognized as a wind instrument (Hahn and Münzel 1995). In this framework, A.F. Potengowski continued the musical analyses of these instruments in 2009, first on F. Seeberger's flute reconstruction of GK1, and later by using her own reconstructions. A comparative study of the reconstructions of four different wind instruments (GK1 and GK3 Geißenklösterle, HF1 Hohle Fels, F3α Isturitz) was presented at the ISGMA 2014 in Berlin (Potengowski and Münzel 2015; Münzel et al. 2016). Isturitz was included in the analysis, because of the completeness of the vulture-ulna instrument F3α (Lawson and d'Errico 2002).

Since the other three instruments GK1, GK3, and HF1 from the Swabian Jura are not preserved completely, there is an ongoing debate about how they originally might have been voiced. There is no final evidence whether they were flutes or another kind of a wind instrument. Thus, the question of the appropriate terminology for these instruments was also discussed at the ISGMA 2014. We will refer to the tenor of this discussion: if the blowing methods cannot be proven we use the

[1] Since none of the original instruments is fully preserved, the term 'reconstruction' here implies interpretations of the supplemented parts.

term ‘wind instruments’. If an artifact is reconstructed and voiced as a flute, we use the term ‘flute’ (Münzel et al. 2016: 226, 1.2).

One of the aims of our working group was to focus on the mammoth ivory instrument from Geißenklösterle (GK3) and on the different possibilities in reconstructing this instrument. Specifically, W. Hein experimented on reconstructing GK3 using two types of ivory, mammoth and African elephant (chapter 3.2); G. Dalferth compiled a list of parameters causing pitch variability and summarised the basic knowledge for understanding their effects on the tonal material of reconstructions (chapter 2); A.F. Potengowski tested eight GK3 reconstructions of varying length with one voicing method (straight on the notch) in an in-depth analysis (chapter 4).

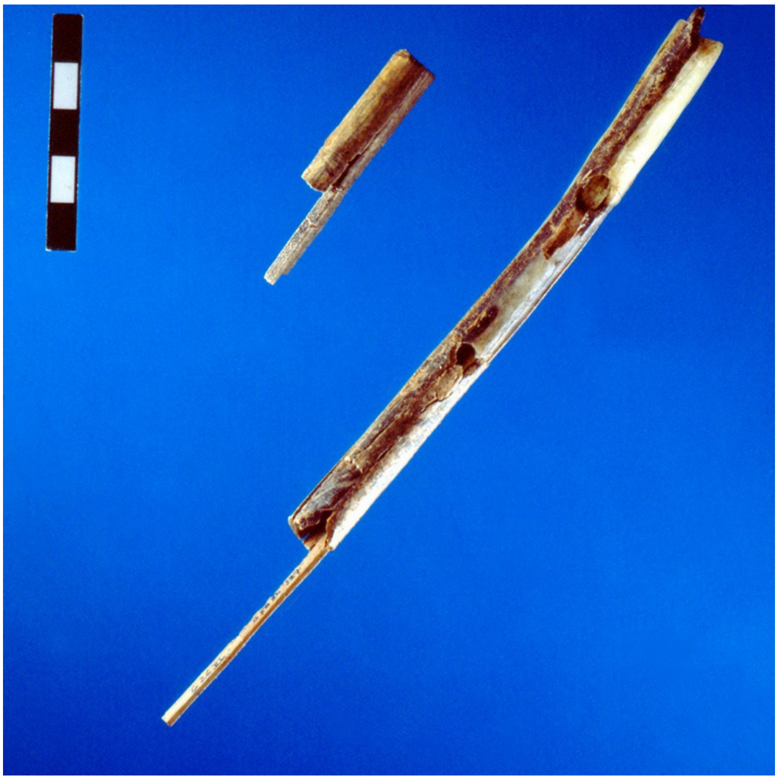

Figure 1: Mammoth ivory instrument, interpreted as notched flute, from the Aurignacian layers of Geißenklösterle, Blaubeuren (Swabian Jura, South-western Germany). Photo by H. Jensen, Tübingen University.

1.2 Archaeological background

The oldest known musical instruments are from around 40000 BP and were retrieved from three cave sites, Geißenklösterle, Hohle Fels (Ach Valley), and Vogelherd (Lone Valley), all located in the Swabian Jura (South-West Germany). Together with three other caves, Sirgenstein, Hohlenstein-Stadel, and Bockstein, they have been listed as UNESCO World Heritage since 2017 (Conard and Kind 2017). All of these sites have yielded some of the oldest examples of figurative art and personal ornaments attributable to the Aurignacian. Along with the musical instruments, they reflect the new innovative culture of modern humans (Conard et al. 2004; Conard and Malina 2006; 2008; Conard et al. 2009).

The first two wind instruments of the Swabian Jura, both made from swan radii (GK1 and GK2),[2] were discovered 22 years after their excavation in the Geißenklösterle Cave (Hahn and Münzel 1995). The pieces were identified during the study of the faunal material by S.C. Münzel.

[2] Swan radius instrument GK1 is exhibited in the *Württembergisches Landesmuseum Stuttgart*, Baden-Württemberg, and GK2 – fragments of a second swan radius instrument – are exhibited in the Urgeschichtliches Museum Blaubeuren (URMU), Baden-Württemberg, both found in the Geißenklösterle cave.

They were recognized by the fingerholes that had been characteristically scraped into the cortex of the bird bones. Nine years later, the mammoth ivory instrument (GK3)[3] was discovered. Again, this was a post-excavation find made by M. Malina during the inventory of the numerous ivory fragments from the Aurignacian layers of Geißenklösterle (Conard et al. 2004; Conard and Malina 2008). The fourth instrument, made from a vulture radius, was discovered *in situ* during excavations in the Hohle Fels Cave (HF1)[4] (Conard et al. 2009). In addition, fragments that are very likely part of ivory wind instruments were found in Hohle Fels, and bird bone and ivory fragments with significant features similar to broken wind instruments were retrieved from the back dirt of Vogelherd Cave, Lone Valley (Conard and Malina 2006; Conard et al. 2009) around 80 years after Gustav Riek's first excavation.

1.3 State of the art

The mammoth ivory instrument (GK3) raised an extensive discussion of how the instrument was played. In the first publications (Conard et al. 2004; Conard and Malina 2008) the authors followed F. Seeberger's suggestion concerning the blowing end. Through his attempts at playing the reconstructed instruments, he concluded that the distance between the notched end and the first fingerhole was too short to produce a good sound (Conard et al. 2004: 457; Conard and Malina 2008: 15). The notched end was therefore interpreted as the distal end of the instrument, while the blowing end was seen as missing and reconstructed by Seeberger with a straight cut off end (comparable to an Arabic *nay*). In the meantime, the argument of bad sound quality from blowing the notched end was disproved by several flutists (A.F. Potengowski, G. Dalferth, see also S. Schietzel in Holdermann et al. 2013). Both ends, the notched one and the formerly reconstructed straight end, have good playing properties (Potengowski and Münzel 2015; Münzel et al. 2016). Furthermore, another piece, which has not been included in the discussion of GK3 reconstructions so far, is a small ivory tube fragment with a carefully worked straight end, which could have been the missing distal end of the instrument (Figure 1; also Conard et al. 2004: fig. 13d). Because of shape, dimensions, and work traces it would be likely that it belongs to the main piece but could not be refitted so far. Another supporting argument to this hypothesis is that this piece comes from the same find concentration of GK3 in the Aurignacian layer AH II (Conard et al. 2004: fig. 4). Therefore, the total length of the mammoth ivory instrument is probably given by the sum of the lengths of the main piece (including the thin splintered distal end), which measures 18.7 cm, and that of the end part, which could have lengthened the main piece between 3.5 and 5.5 cm, depending on how it is refitted to the main piece (Figure 1).

We argue that the notched end is the actual blowing end, because the rim/edge as well as the notch were already described as being carefully worked by Conard et al. (2004: 457), and this

[3] Mammoth ivory instrument GK3 is also exhibited in the Urgeschichtliches Museum Blaubeuren (URMU), Baden-Württemberg; it was found in the Geißenklösterle cave.

[4] Vulture radius instrument HF1 is also exhibited in the Urgeschichtliches Museum Blaubeuren (URMU), Baden-Württemberg; it was found in the Hohle Fels cave.

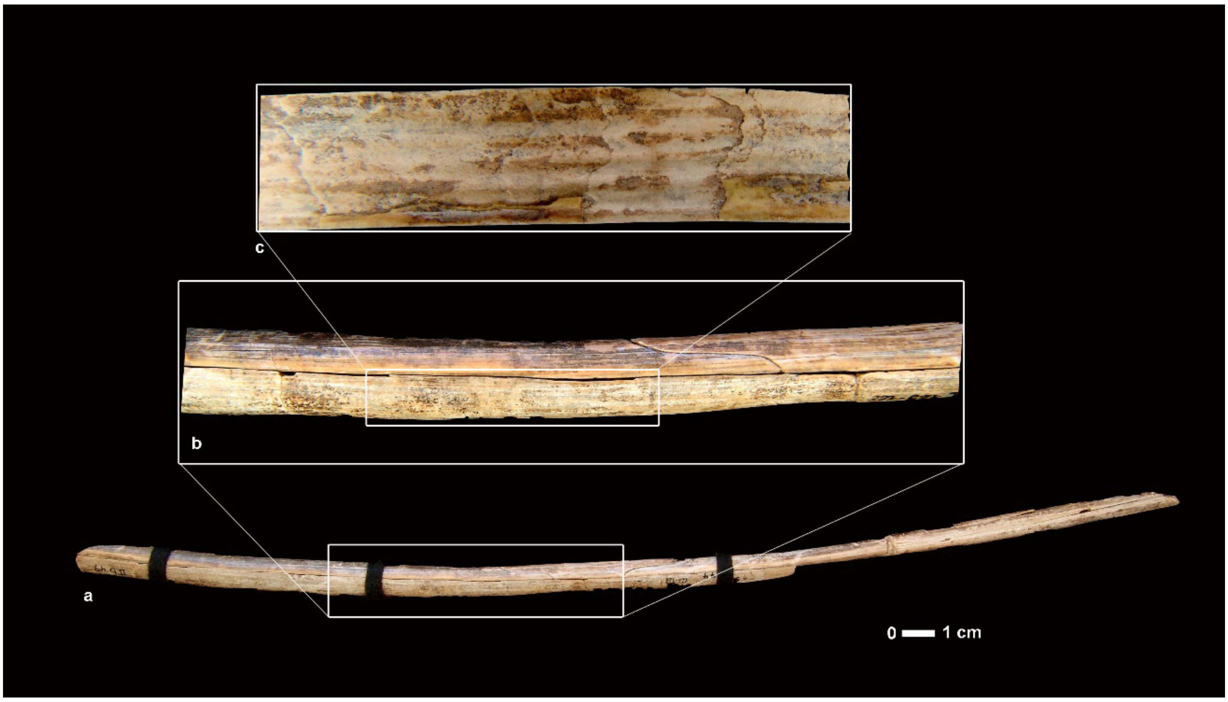

Figure 2: Ivory rod, pre-form for a flute from the Aurignacian layers AH II and III in Geißenklösterle. Photo by Ralf Ehmann.

impression is also supported by some recent close-up photos published in Ewa Dutkiewicz's dissertation (2021: 283, pl. 31). The playing properties of the notch are very good. To install a single or double reed, the shape of the notch is too short, and the angle of flattening is not appropriate.

Nevertheless, alternative playing methods, such as the use of a reed, as a trumpet, interdental or '*nay*' embouchure as suggested by Ringot (2011; 2012), Lawson and d'Errico (2002), Garcia Benito et al. (2016), and Wyatt (2012; 2016) cannot be completely excluded.

To conclude, we interpret the notched end as the proximal blowing end, thus the mammoth ivory instrument from Geißenklösterle (GK3) can be reconstructed as a notched flute (comparable to the *quena*). The distal end was probably a straight cut end. Concerning the length of the instrument, we refer to the preform of a mammoth ivory instrument from the Aurignacian layer, which was split lengthwise into two halves, but not hollowed out (Figure 2; cf. Hahn 1988: 204–5, pl. 43,1,2; Malina and Ehmann 2009: 104).[5] Its length could have originally been around 35.1 cm (Hahn 1988: 204–5), if the thinner end had not broken off, probably during manufacturing. The remaining length of the pre-form measures ca. 25 cm and was thinned out after breakage. If we take this into account, the total length of the instrument could have reached even between 25 cm and 35.1 cm.[6]

5 The pre-form of a mammoth ivory instrument is also exhibited in the Urgeschichtliches Museum Blaubeuren (URMU), Baden-Württemberg; it was found in the Geißenklösterle cave.

6 We wondered if ivory wind instruments could have exceeded 35 cm in length, in other words if they were longer than bird bone instruments. However, in order to construct an ivory wind instrument both halves of either the cementum or the dentin must be of the same thickness and the cementum layer becomes gradually thinner towards the tip of the ivory tusk limiting the length of the ivory flutes. The broken pre-form mentioned above is probably an example of this. We should also mention here that the cementum layer of mammoth tusks is much thicker than that of African elephants (Bernhard Röck, ivory carver [Erbach, Odenwald], personal communication).

2 Basic parameters causing pitch variability in reconstructions of flutes

Gabriele Dalferth

2.1 Summary

This chapter explores the reasons behind pitch variations in reconstructions of the same Palaeolithic wind instruments from the Swabian Jura. The focus is on instruments reconstructed as flutes, although the lack of evidence regarding whether they were flutes or other types of wind instruments, for example reed instruments, justifies various types of reconstructions. In order to make this review comprehensive, my investigations are not limited to the mammoth ivory instrument (GK3), but extended to the three best preserved Swabian wind instrument findings, including the swan radius instrument (GK1) and the vulture radius instrument (HF1).

Being a flutist myself, I conducted several sound experiments which demonstrate that the pitch is significantly affected by various parameters such as length and diameter, shape, size, and position of the fingerholes, the mouthpiece, and the playing technique. Due to the incompleteness of all the instruments, these parameters cannot be fully defined. This article's purpose is to demonstrate and describe pitch changes resulting from structural modifications of the missing parts and from different playing techniques, as well as to describe related issues such as overblowing and the response of a flute in different registers, but it will not include frequency analyses of any instrument.

Figure 3: Swabian Jura wind instruments. GK1: whooper swan radius, GK3: mammoth ivory, HF1: griffon vulture radius. Photos: GK1 by H. Jensen; GK3 and HF1 by Juraj Lipták. © Tübingen University.

Additionally, the article discusses the relationship between the impressive phenomenon of a wide bending range on each tone of mainly thin bird radii instruments, interpreted as *nay* flutes, and the technique of human whistling.

2.2 Pitch variability in reconstructions

An important aspect of our group's work is the exploration of the tonal possibilities of the Swabian Jura wind instrument findings (Potengowski and Münzel 2015: 173–91). Admittedly, none of the three depicted original Swabian Jura instruments is preserved completely (Figure 3). Due to unknown parameters such as the length, the number of holes, the shape of the mouthpiece, and the diameters of lost parts, there are differences within reconstructions, due to diverse decisions on

Figure 4: Selection of reconstructions and free experimental flutes made by G. Dalferth, except flute 7 from the left, made by Rudolf Walter, with blowing end modified by G. Dalferth. Photos by G. Dalferth.

how to supplement the missing parts. Friedrich Seeberger, for example, regarded the missing end of the swan bone instrument GK1 as its blowing end and first interpreted the mouthpiece as a notch – like on a *quena* – (Seeberger 1998: 31–33) or, as he later preferred, as a beveled mouthpiece – like on a *nay* flute (Seeberger 1999: 155–57, Münzel et al. 2002: 107–18). The *quena* and *nay* hypotheses respectively lead to significant differences in the playable tones, primarily due to the different blowing techniques (see also below on thin *nay* flutes). A.F. Potengowski and I can play GK1 from either side, which also implies new pitch variations (Potengowski and Münzel 2015: 173–91).

Questions regarding the impact of structural differences in tonal possibilities repeatedly arose in our group, as well as during my own experimental making (Figure 4) and playing of numerous Palaeolithic flute reconstructions. Beside my own ones, I gathered experiences with several reconstructed Swabian Jura instruments due to personal contacts[7] with Frances Gill, Anna Friederike Potengowski, Barbara Spreer, Wulf Hein, Frank Trommer, Rudolf Walter, and Johannes Wiedmann.

7 Frances Gill, flutist and composer; Anna Friederike Potengowski, flutist; Barbara Spreer, flutist, Urgeschichtliches Museum Blaubeuren (URMU) and the archaeo-technicians Wulf Hein, Frank Trommer, Rudolf Walter, and Johannes Wiedmann, Urgeschichtliches Museum Blaubeuren (URMU).

This contribution aims to provide answers by discussing the following main questions: which parameters influence the pitches of flutes,[8] and, equally importantly, how do these parameters interact with each other?

Therefore, I focused on practical experimentation with references to common theoretical knowledge.

I approached the subject methodically by conducting experiments to discover how specific changes in the construction of the *missing parts* affect the pitch. I used instruments and tubes made both from authentic materials, like bird bones and mammoth ivory, and also from modern materials, like metal and plastic. In each experiment only one parameter of a flute was altered. Through such experiments, I gained insights regarding the physics of a flute. Although not intended as innovative from a scientific perspective, these insights form the basis for the following compact compilation of parameters, meant to facilitate access to fundamental facts of flute physics for everyone who engages in research on incomplete flutes. As not all of these researchers are flute players themselves, the parameters' impact will often be demonstrated by short videos, in order to make the sonic effects of various structural aspects more understandable and also somewhat predictable.

Acknowledging that the outcome of the investigations is applicable to flutes in general, I used the instruments from the Swabian Jura as excellent examples to transfer the results to incomplete Palaeolithic flutes. A well-preserved instrument like the Isturitz Flute F3α (Lawson and d'Errico 2002: 119–42) would not be comparably suitable for such a purpose.

Inspired by experimental playing on reconstructed flutes, I also pursued the question of why it is possible to play a wide glissando range on each fundamental tone on very thin *nay* flutes (Potengowski and Münzel 2015: 173–91). I will discuss this issue towards the end of my contribution.[9]

2.3 Basic parameters causing pitch variability

There are countless parameters that cause pitch variability. All these parameters interact with each other. Very important parameters are tube length, tube diameter, size and shape of the mouthpiece, and size and location of the fingerholes (Figure 5).

As mentioned before, none of these parameters can be defined precisely for the missing parts of the Swabian Jura wind instruments. In addition to these structural parameters, the playing technique itself has a significant impact on the pitches produced (Potengowski and Münzel 2015: 173–91).

8 Since I am a flutist, my investigations focused on these instruments interpreted as flutes rather than reed instruments. Friedrich Seeberger had suggested the possibility of attaching a reed and Jean Loup Ringot was a pioneer in reconstructing and playing them as reed instruments (Seeberger 1999: 155–57; Ringot 2011: 188–97 and 2012: 389–91).

9 During casual conversations at ISGMA 2021 in Berlin, I found that this unanswered question was a concern of many participants engaged with Palaeolithic wind instruments.

2.4 *Length of a tube*

The original length of all three instruments is unknown. The possible maximum length is limited by the length of the unmodified bird radius, which can be up to 18–20 cm for a swan radius (GK1, see Hahn and Münzel 1995: 1–12) and "roughly 34 cm" for a griffon vulture (HF1, Conard et al. 2009: 737–40); for GK3, according to an unfinished mammoth ivory pre-form, it could be a maximum of 35.1 cm (see above chapter 1.3 with note 6).

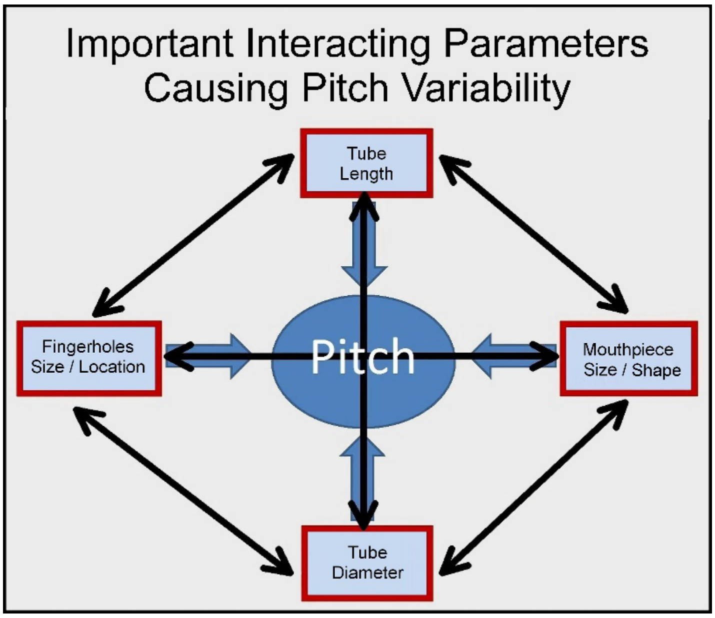

Figure 5: Interacting parameters. © G. Dalferth 2023.

When blowing over the edge of a tube, the air flow is split and the air column inside the tube starts vibrating, producing a standing wave with antinodes at open ends of a tube, and nodes at closed ends (see Halliday et al. 2019: 320 and Figure 6).
The illustration in Figure 7 shows that in open tubes the complete wave would be twice as long as the green wave section inside the tube: in tubes closed at one end the complete wave would be four times as long as the red wave section inside. Therefore, a tube closed at one end or a tube with an attached reed mouthpiece sounds an octave lower than an open tube. Tubes that are partially closed at one end sound lower the more closed they are. Figure 6 also shows that the overtone series is not identical. If a tube is closed at one end, every second overtone is missing. There is no first octave, but the fifth tone above the first octave is the first overtone, a twelfth above the fundamental.

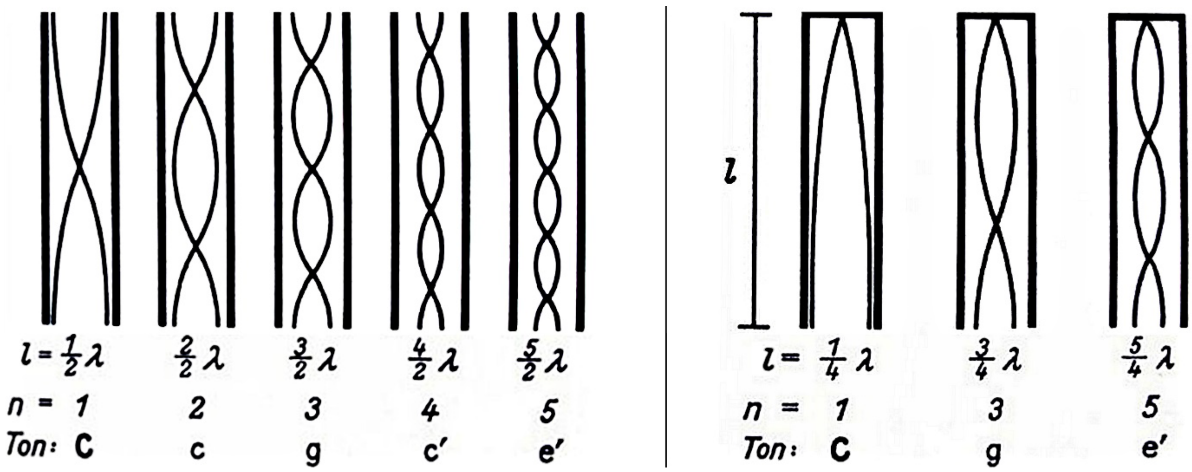

Figure 6: Position of nodes and antinodes in open pipes and pipes closed at one end. https://www.kr.perihel.ch/Material/Praktikum/Anleitungen/pfeifen.pdf [Accessed: 5 August 2023].

2.5 Diameter of a tube

Regarding the diameters of the missing parts of the three instruments, one has to consider the fact that the long pre-form of an ivory instrument mentioned above becomes thinner at one end (Hahn 1988: pl. 43; Malina and Ehmann 2009: 93–107). Swan and vulture radii are thinner at the anatomically proximal end and widen at the distal end.

It is notable that the diameter of the tube does not appear in any of the equations given in Figure 7. Since these equations are only basic approximation formulas, the question arises: does the diameter influence the frequency and thus the pitch at all?

Seeberger (1998: 33) compared two of his reconstructions of the GK1 as flutes of the same length, one made from a swan ulna with a proximal inner diameter of 6.5 mm and another one from a swan radius with a proximal inner diameter of 4.3 mm. He reports that the thinner flute produced almost the same tones as the wider one, but was more challenging to play.

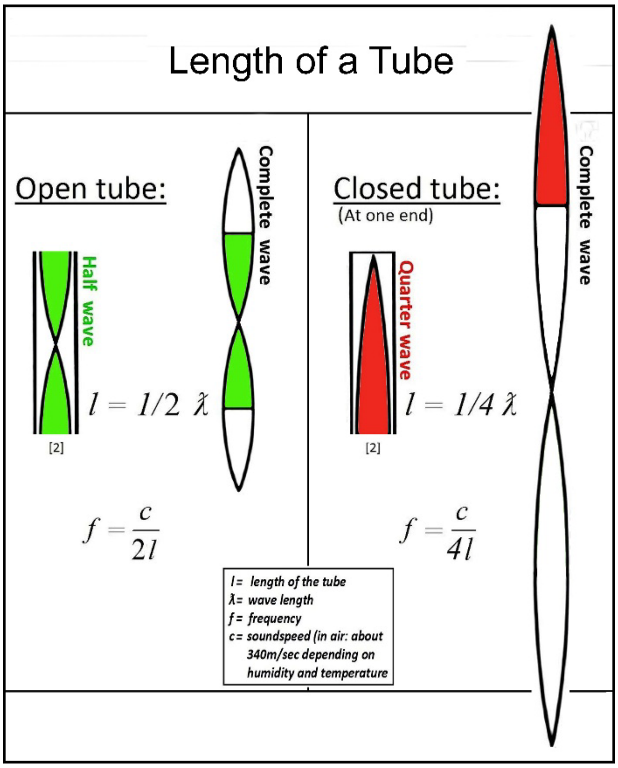

Figure 7: Wavelengths in open tubes and tubes closed at one end. © G. Dalferth 2023; equations according to Schröder 1990: 23–25.

This is noteworthy insofar as those were notched flutes, like *quenas*, and not *nay* flutes, which are the only flutes with the pronounced pitch-bending capability mentioned above, with a range of up to more than an octave, which Seeberger started reconstructing later and preferred ever since (Münzel et al. 2002: 108).

Figure 8: Wide and narrow tube, same length. © G. Dalferth 2023.

Experiment 1 (Video 1): For the investigation of the influence of the diameter, I trimmed a wide and a narrow plastic tube to exactly the same length and, in order to prevent pitch changing influences of any special mouthpiece, blew straight over the rim opposite to my lips, not oblique like on a *nay*, but in the way one would blow a pan flute to produce tones (Figure 8). I decided to use plastic tubes of a modern standardized material to make the results reliably comparable. The wider tube sounded a bit louder – as the volume increases with an increasing amplitude (Scherfgen 2006: 429). Both tubes provided a bending range of approximately one semitone. As a result, the pitch could not be determined precisely. Due to the end correction (see next subchapter), the thinner tube's range was slightly sharper than that of the wider tube, but it was still possible to produce identical tones from both tubes. Before giving an explanation as to why the pitches of both tubes did not differ, a few more issues need to be discussed in the following two chapters.

The first sound example seems to confirm a *common physical rule*: the pitch of a tube is determined by its length, meaning the longer the tube, the lower the tone. The volume is determined by the diameter: the wider the diameter, the louder the sound (see also Scherfgen 2006: 429; Halliday et al. 2019: 320).

This basic rule is – like the equations above – a useful tool for approximating the effect of the length on pitch, but is not entirely precise, as the following example will show.

2.6 End correction

If we examine the length of the vibrating air column (that determines the pitch) a little more precisely, it turns out that the sound wave reflects back into the tube as a spherical wave, causing its effective length to be slightly longer than the actual tube length, which lowers the tone. This phenomenon is called *end correction* and calculated as $k = 0.6133\,r$ for open tubes, with r being the radius.[10] That means, the wider the diameter of a tube, the stronger is the impact of k to lower the tone.

But as the diameters of all Swabian Jura instruments are very thin, the pitch lowering impact of the end correction remains very small as well, because there are some parameters influencing the pitch more than the end correction: mainly the size and shape of the mouthpiece or embouchure and the blowing technique of the player.

2.7 Mouthpiece/embouchure

A flute needs an edge/rim, or a labium, to split the airflow to produce tones. In the case of Swabian Jura instruments, this works with the preserved cut off end of GK1 (like a *nay* flute). Splitting the airflow also works with the notch of GK3 – like a *quena* or a *shakuhachi* – (see above chapter 1.3) and with a blowhole (like a transverse flute). From my own playing experience, the intentionally thoroughly scraped concave holes of all three Swabian flutes can be used as blowholes without any special processing. However, my own experience contradicts Seeberger's assumption from 1998 that the modification as a blowhole would have been an almost unachievable task for Palaeolithic people (Seeberger 1998: 31–33).

Could one imagine flutes with a constructed wind channel like recorders, fipple flutes, beck flutes, or whistles for the Aurignacian period? There is no proof for this. But there is evidence for such a construction in Magdalenian times (Figure 9, left; Luzy and Dedonder 2011: 61). The whistle or flute fragment from Abri Laraux dates back to 17000 BP (Magdalenian period) and is therefore not comparable to the three Aurignacian instruments. This does not mean that flutes with a labium could not have existed during that time as well. Technique-wise this should have been possible.

[10] As the end correction was an empirical value for a long time, there exist different but similar values. Nowadays, 0.6133 is generally accepted (Egry 2020: 4–6).

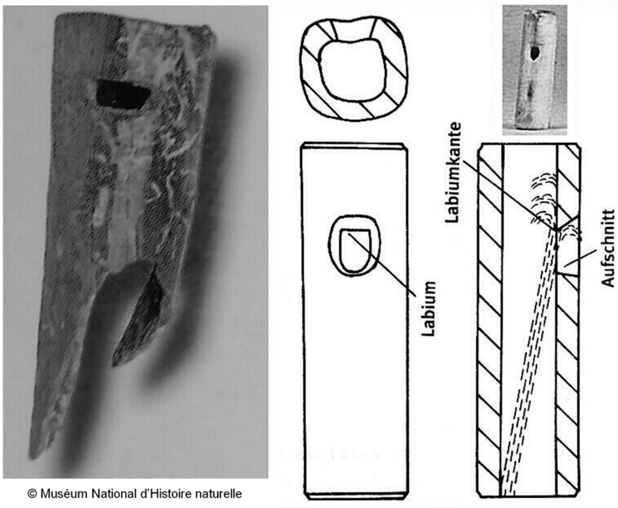

Figure 9: Photo left: Abri Laraux, bird bone. © Muséum national d'Histoire naturelle. Photo right: Gudenus cave, tubular bones. © Kunsthistorisches Museum Wien (Austria-Forum n.d.). Drawing © B.Käfer 2000, CD Booklet.

A whistle from the Gudenus cave in Austria is also thought to come from that period, but its Magdalenian age is discussed controversially (Figure 9, drawing and right photo).

So besides mainly focusing on *quena*-, *nay*-, and transverse-flute mouthpieces I also started – to a very small extent – experimenting with wind channel constructions in three different variations (Figure 10).

There are many more possibilities and variations to design a mouthpiece or some other form of a blowing device, but the following applies to all of them: the actual pitch of so called 'open flutes' with an open distal end will always be lower than what one would calculate for open tubes because the blowing end is never completely open. Thus – strictly speaking – an 'open flute' is a tube that is partially closed, because the proximal blowing end is always closed to a certain extent either by the lips of the players (see Figure 11) or due to the construction of the mouthpiece (see Figure 12).

Figure 10: Left: mute swan ulna: HF1-type mouthpiece with an applied wind channel; middle: mute swan radius with notch and 'external' wind channel; right: mute swan radius: Gudenus whistle-type wind channel. © G. Dalferth 2023.

Experiment 2 (Video 2): More covered blowholes of a transverse flute (Figure 11b) and of a *quena* (Figure 11d) produce lower pitches than the two less covered ones (Figure 11a and c).

The virtuoso flutist James Galway describes this, when he writes about tuning correction: "In some instruments, some notes are too high, and the player has to blow deeper into the blow hole; for too low notes, he blows slightly outward" (Galway 1988: 145).

Blowing more inside or more outwards means changing the angle of the airstream. Figure 11b shows the position that allows the player to blow deeper into the mouth hole, Figure 11a, the position that allows blowing more outward.

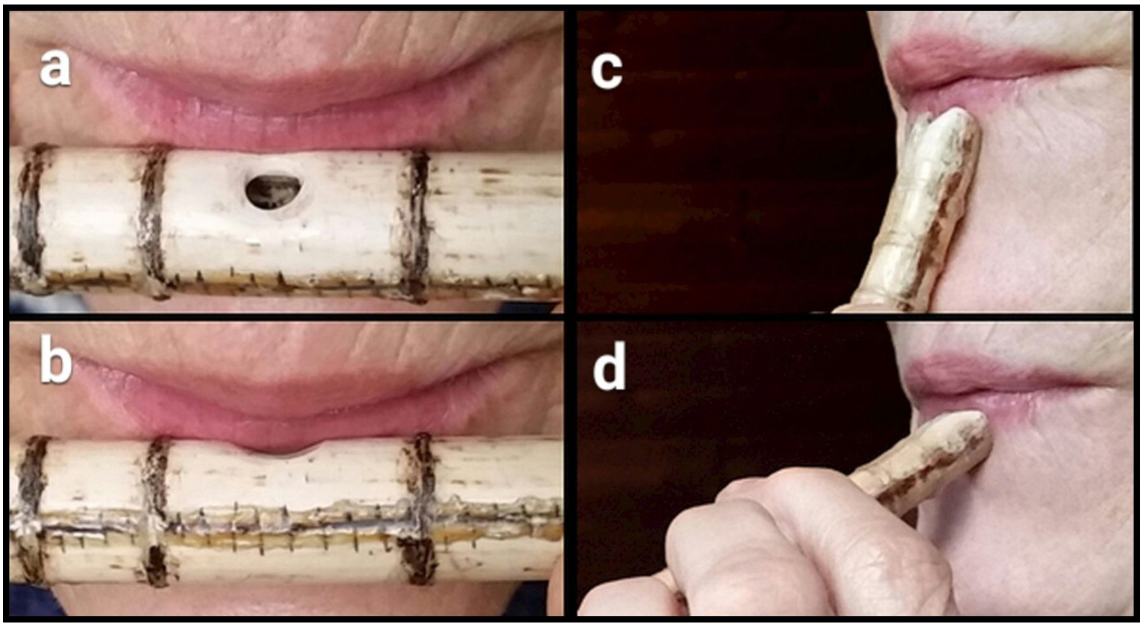

Figure 11: Coverage of the blowhole with the lips. © G. Dalferth 2023.

This also applies to Seeberger's notched GK1 reconstructions mentioned above, as well as to pan flutes. It finally gives an explanation for why his thin and wide flute, as well as the thin and the wide tube in experiment 1 (Video 1), could produce the same pitches, although, regarding the end correction phenomenon, one should have expected a lower response from the wider tube: due to its wider diameter the blowhole was less covered and thus the pitch raised by roughly the same amount as the end correction lowered it.

This also happens to *nay* flutes (end blown flutes) with significantly bigger diameters than the very thin Swabian Jura instruments. The special case of 'very thin *nay* flutes' will be discussed later.

Experiments 3 and 4 (Videos 3 and 4)**:** Again, I used modern standardized materials and instruments to demonstrate the following phenomenon: a tube with a wider notch (Figure 12, left) and a pennywhistle with a wider window (Figure 12, right) produce higher pitches than a tube of the same diameter and length with a narrower notch or the same whistle with a narrower window. In Ireland I learned that it used to be a common technique to tune flutes like recorders or whistles by reducing the size of the window, and thus of the labium as well, with wax or an adhesive pad.

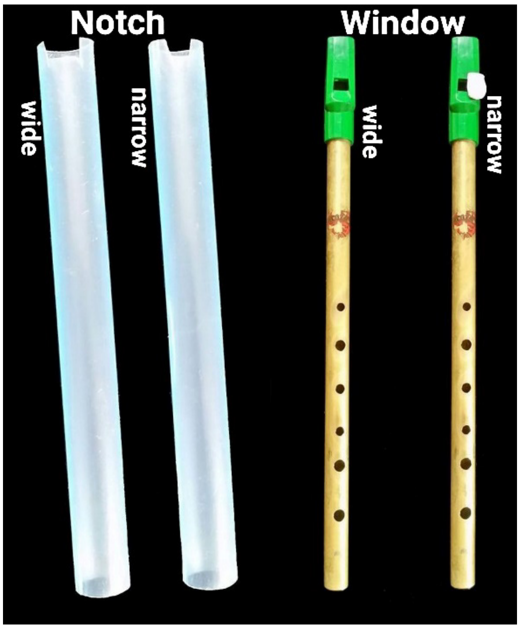

Figure 12: Coverage of the blowhole by construction, left: two tubes with a narrow and a wider notch; right: pennywhistle with a narrow and a wider window. © G. Dalferth 2023.

All these examples underline the following observations: the narrower the openings of the blowing devices, the lower the pitches. There is also an impact on volume/loudness and timbre: “A wide windway [...] makes the whistle louder, the sound becomes a bit breathy, and more air is needed; a narrow windway [...] makes the whistle quiet, the sound becomes sweet and clear, and less air is used.”[11]

We do not know if the Jura wind instruments were ever used in a musical context with other melodic instruments, such as e.g. sounding stones, or if they were adapted or tuned for such purposes. Theoretically, it is possible to build a flute with a specific lowest tone by using a tube that is initially too long for the desired frequency and gradually shortening it step by step to approach the desired tone. However, this adjustment must be done with a completed mouthpiece, as this significantly affects the pitch.

There is still another influence concerning the shape of a mouthpiece: longer labial edges of a window (Figure 13, top) support the response of low tones, whereas shorter ones support the response of high tones (Figure 13, bottom). This applies to other devices like notches or blowing holes as well. The longer the windway to the labium, the better the response of low tones, whereas the shorter it is, the better the response of high tones.[12] This only works up to a certain limit. Overdoing it might lead to no response at all.


Figure 13: Long and short wind ways. © G. Dalferth 2023.

2.8 Fingerholes

If the fingerholes of a flute remain open, the vibrating air column is shortened accordingly, and the frequency becomes higher. The sound wave will not be reflected from the first opened hole directly, but again from a certain end correction distance below, which lowers the tone. The reflection point of the sound wave will be lengthened and lower the pitch even more if one or more holes are skipped due to fork fingering.

Small, opened holes lower the pitch in comparison to large holes, because with a small hole the wave extends further downwards than with a large hole. That last fact might be of interest if one should intend to build a very long GK3 mammoth ivory reconstruction with additional fingerholes on an extension below the extant part.

The holes of long flutes can be placed in such a way that they can still be reached by the fingers without spreading too much. If a hole is smaller, it can be placed a bit upwards. This method can be seen in the following example of three Irish whistles.

The deepest holes were made increasingly smaller as the instruments’ length increased (Figure 14) because it produces a lower pitch when only that particular hole remains open, compared

[11] Gonzato 2016: 7–8 on Irish whistles.
[12] Gonzato 2016: 8.

Figure 14: Location of fingerholes. © G. Dalferth 2023.

to a larger hole. Therefore, it can still be reached by the ring finger without excessive spreading. A larger hole would raise the pitch and would need to be drilled further down accordingly.[13]

2.9 Fingerhole-size/tube-diameter ratio

The hole-size/tube-diameter ratio has a significant impact on the pitch. The larger the opening of a fingerhole *in relation to the circumference* of the tube, the higher the pitch.

This is demonstrated by the following experiments with three turkey bone flutes: one narrow radius flute (Video 5) and two wide ulna flutes.

Figure 15: Three turkey bone flutes (radius and ulnae), same lengths. © G. Dalferth 2023.

Experiment 5 (Video 6): If one compares the narrow Flute 1 and the wide Flute 3 of the same length with the same hole sizes and locations, Flute 3 will sound lower on all tones with open holes.

Experiment 6 (Video 7): If one enlarges the holes of the wide flute, the result (Flute 2) is a flute with the same pitches as the thin Flute 1.

It is important to take this into account when building reconstructions because bones with exactly the same diameter as the originals are sometimes hard to find. For example, our local mute swan radii are often a bit thinner than the original GK1 whooper swan radius instrument. To avoid that pitches and intervals of this instrument differ significantly from the original, the hole sizes should be adapted to the diameter difference. It should be mentioned that this applies only (approximately!) for the preserved segments, i.e. in the case that the preserved end of GK1 is assumed to be the embouchure. More precise frequency analyses would require a method such as a 3D-printing, where the reconstruction of these segments would exhibit the same geometry as the original.

13 See also the following chapter.

Figure 16: HF1 reconstruction made by G. Dalferth. Self-made claylike material, hole sizes not yet adapted to the original. © G. Dalferth 2023.

2.10 Blowing pressure, length/diameter ratio and overblowing, cut-off frequency

The blowing pressure is an important pitch parameter. Blowing more strongly raises the blowing pressure. A higher pressure raises the pitch of all kinds of flutes while blowing more weakly lowers it. "The player's blowing pressure can alter the pitch of a note by a third of a tone, or even more."[14]

This aspect applies to all kinds of flutes, as long as no other playing techniques are used to compensate for such pitch shifts, as well as for organs: if one increases the strength of the airflow through the gap of a lip pipe of an organ, the pitch becomes higher. If one wants to amplify or weaken the volume of the organ, but avoid such pitch shifts, one has to use more or fewer pipes of the same pitch, and/or pipes with a sharper or softer timbre (Berliner 1928: 260).

The thinner a tube, the higher the blowing pressure. If the air pressure gets too high, the fundamental tone flips into the first overtone of the natural overtone series. Steadily increasing pressure will cause flipping into the following overtones. Overtone flutes (comparably thin long flutes with no fingerholes) work like this. This is a reason why not every long tube is suitable for building a flute with a low 'all-holes-closed tone' (this again is good to know if one wishes to build a very long GK3 mammoth ivory flute aiming to get considerably lower tones than with shorter flutes).

The larger the diameter, the weaker the blowing pressure. One has to blow harder to make the tone flip into an overtone. Above a certain size diameter, there is no flipping into an overtone at all. Flutes with larger fingerholes reach this limit faster. This limit is called *cut-off frequency* (Baumgartner and Messner 2010: 223–24).[15] "The cut-off frequency [...] predicts whether any hole will be able to sound the upper octave. The cut-off frequency should be at least 2 times the second octave note."[16]

Compared to its narrow diameter, the HF1 flute is very long. The deep V-shaped notch produces a very breathy sound. If one closes one hole after the other of my reconstructed instrument (Figure 16), one gets an increasingly weak or almost nonexistent response from the two lowest tones, whereas it is easy to make them flip into the overtones (Video 8). The cut-off frequencies of

[14] Gonzato 2016: 8 on Irish whistles.

[15] Explanation for cut-off frequency according to Baumgartner and Messner (2010: 223–24): "To allow the sound to emit through the tone holes, the air mass in the chimney of the tone hole must be accelerated by the sound wave in the flute within a time interval of half its period. As the frequency increases, the time interval of half the period [...] decreases. This means that from a certain frequency, which [...] is referred to as the acoustic cut-off frequency, the acoustic adaptation through the tone hole is so bad that the air column swings beyond the opening and therefore no sound emission takes place at this point."

[16] Chuck Tilbury, an American Irish whistle maker, in a personal email.

the tones could be calculated, but for most reconstruction purposes there is no need to do this. If one intends to elongate an incomplete flute and seeks to achieve good response across all tones and registers, it is helpful to examine contemporary instruments, e.g. Irish six-hole whistles. According to my own measurements from the labium to the distal end, they often have a diameter to length ratio of between 1:17 and 1:24, because then both the low and high notes respond well and sound balanced. These ratios are a good guideline for many kinds of flutes.

That does not mean that all Palaeolithic wind instruments had this ratio – as is to be seen and heard in the example of HF1. But it can help to predict whether a reconstruction as a flute is supposed to have a good response in all registers or not. It will make troubleshooting easier if one knows what kind of response can be expected based on the construction: the preserved part of the HF1 is about 21.8 cm long and has an inner diameter of about 0.8 cm. The ratio is about 27.25 : 1. In this case it would be a waste of time trying – for example – to improve the notch to get a better response from the low register. Should one decide to elongate the instrument according to the available bone length, the ratio will become larger, and so the response from the low register will get even worse, but it will boost the overtones, which could be a desired effect as well.

If an ivory flute has a weak low register response, despite the length/diameter ratio allowing for balanced tones, you might also consider whether the two halves had been fitted together tightly or whether there might be hairline cracks in the material.[17]

Nowadays the ability to sound properly in both registers is an important reason not only to change the length within a flute family when building higher or lower instruments, but also to keep the proportions steady, enlarging or diminishing the whole instrument to scale (except the small hole size and position adjustments described before, which serve to avoid an excessive spreading of the fingers on long instruments). Another reason, among others, to scale it up or down proportionally is that despite the changing of the pitch, the intervals will stay the same. If one plays melodies with exactly the same fingerings they will be the same, just transposed to another pitch.

When exploring the possibilities of any Palaeolithic wind instrument, it is undoubtedly always the best solution to adhere precisely to the known dimensions of the original. However, this turns out to be a challenge with the swan wing bone instrument GK1, which was originally made from a radius. Personally, I have not yet succeeded in finding a swan radius that matches the original in

[17] In chapter 3 of this article, W. Hein discusses the experience required for achieving a perfect glue consistency. He also talks about a flute that initially had air leakage issues and required additional bindings. The process of sealing can be particularly challenging for less experienced builders. Additionally, I encountered problems with air leakage in both a flute made by B. Spreer and one of my own ivory flutes. These flutes consistently struggled with low register response. Unfortunately, after I tried to clean Spreer's flute with water (as two of my ivory flutes respond better when humid), previously invisible hairline cracks suddenly appeared in the ivory within minutes. I experienced the same with another of my flutes, where moisture from excessive playing caused cracks. A colleague also shared a similar experience with an ivory pendant, where cracks would open and close depending on air humidity. However, it is important to note that a poor low register response can also be due to the flute's shape, in which case efforts to seal the flute would be useless.

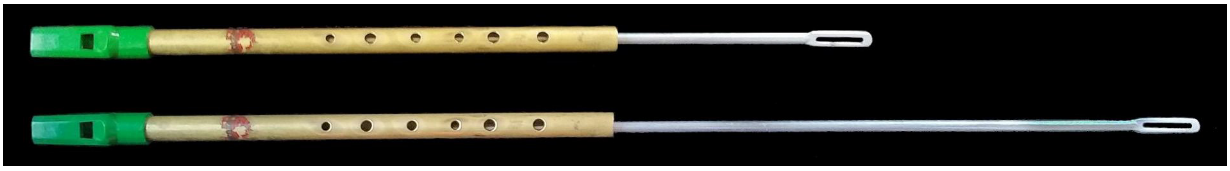

Figure 17: Whistles with a fully and a partly inserted rod. © G. Dalferth.

terms of diameter, and upon inquiry, neither have my colleagues, F. Trommer, B. Spreer, and A.F. Potengowski. The radii were at least 1 to 2 mm thinner.

So when reconstructing a Palaeolithic bone flute from a bone with a bigger or smaller diameter, one has to decide whether one wants to build the instrument to scale or whether one prefers to stick to the measurements of the original.

A scaled interpretation is an especially valuable tool if one aims at exploring its musical possibilities despite a differing diameter: the intervals will be the same and the 'overblowing behaviour' will be the same compared to an instrument of the original diameter, because the length/diameter ratio is kept. So it is possible to explore the interval structure and the range of a flute independently of its absolute pitch.

To keep the same distances between the holes and also keep the same hole sizes would mean a change of intervals and possible melodies compared to the originals. If the reconstruction is meant to produce the same frequencies and intervals, one needs to modify the hole sizes accordingly (see above chapter 2.9).

There is also another reason why working with bones that deviate strongly from the original diameter while keeping the original length and distances does not make much sense. Due to the cut-off frequencies, too thick flutes would lose higher tones, whereas too thin flutes would lose lower tones, or at least have a poorer response.

2.11 Irregular diameters

Usually the inner diameter of bone flutes varies throughout a bone. In many cases there are wider and narrower sections or, occasionally, deformations inside the tube that influence pitches and timbre.

Experiment 7 (Video 9): To diminish the air volume of a whistle, a rod is inserted fully from the distal end until it reaches the labium of the window. The pitch of the instrument does not change significantly (Figure 17, upper flute). This confirms again that the pitch is determined mainly by the length and there is nearly no impact by altering the effective diameter beneath the blowing device throughout the *complete length* of the flute.

Experiment 8 (Video 10): A rod is inserted about halfway into a whistle to diminish the air volume of the lower section of the instrument. This partly inserted rod lowers the pitch significantly in the section around the beginning of the rod, in this experiment about one semitone (Figure 17, lower flute).

The same result occurs when there are conical sections within a bone or a tube. Sections narrowing downwards lower the pitch, while sections opening downwards raise it. This effect is used for tuning open organ lip pipes. To raise the pitch, a conical tuning cone is inserted into the open end of the pipe to expand it. To lower the pitch, the open end is inserted into a conical funnel and constricted (Locher 1896: 46).

The pitch lowering effect can be useful if one intends to build a long flute with low tones. If the flute diameter narrows downwards, the flute can be built a bit shorter and so the distal holes are in easier reach for the fingers, provided one does not exceed the limit concerning the cut-off frequency described above.

2.12 Special case: very thin nay flutes

As mentioned before, transverse and *quena* flutes allow for about a semitone of pitch variability. This range may vary slightly depending on the player's technique and embouchure.

The pitch of thin end blown *nay* flutes is highly variable. The blowing device of a *nay* flute is usually just the bevelled rim of an open tube. A.F. Potengowski's analyses show: the thinner the diameter of these flutes, the higher the variability in pitch (Münzel et al. 2016: 230–33 and 242). Glissandi are possible up to well over an octave without moving any finger to open or close the holes. As different glissando ranges can be played from various tones, the range expands. So nearly every melody that is covered by this range can be played, only restricted by some challenging tones with a weak or nonexistent response right in between register changes.

Figure 18: Swan ulna (a) and radius (b). © G. Dalferth.

Videos 11 and 12 present two swan bone flutes with an enormous glissando range, but the range of the thinner radius is still significantly wider than the range of the thicker ulna (Figure 18). To ensure comparability, I closed the first fingerhole of the radius flute so that the distance between the labium and the first open hole was as similar as possible between both flutes, 7.6 cm for the radius and 7.4 cm for the ulna. I played in the fundamental register of both flutes and did not overblow.

The peculiar phenomenon that the tone can be varied so widely on very thin *nay* flutes can be explained by comparing it to human labial whistling, which works without any instrument. According to J.W. Strutt, the oral cavity acts as a Helmholtz resonator in human labial whistling. By changing the position of the tongue and the volume of the oral cavity, the pitch of the tone can be changed (Strutt 1945: 223–24).

A Helmholtz resonator consists of a larger air space that is connected to a narrower neck of the resonator. The inert mass of the neck of the resonator is related to the elasticity of the entire volume of air in the connected air space. Such a so-called 'mass-spring system' has a defined natural frequency (Egry 2020: 4–6).[18]

Toshiro Shigetomi and Mikio Morio researched whistling through experiments and expanded Strutt's findings: "We demonstrated that the principle of resonance in human whistling includes not only the Helmholtz resonance but also an air-column resonance [...]. The findings of this study are expected to be useful for engineers because the principles of sound production in wind instruments (including human whistling) are not yet completely known" (Shigetomi and Morio 2016: 86).

Through experimental playing while observing my lip and mouth activities I tried to explore the question of why increasing the diameter of *nay* flutes causes the possible glissando range to decrease more and more. Some parallels to human labial whistling were found: the lips work as a labium in human whistling. When playing a *nay* flute, the blowing edge of the flute replaces the lips. But the blowing technique feels much the same. So I conclude that in the case of a very small diameter, the flute volume is dominated by the bigger volume of the oral cavity and – as when whistling – the pitch of the tone can be changed by changing the position of the tongue and the volume of the oral cavity. In the case of a wide diameter, the flute volume approaches or exceeds the mouth cavity volume. As the proportion of the instrument's own resonance increases in comparison to the Helmholtz resonance of the oral cavity, it causes a reduction in the glissando range.

It should be emphasized that this playing technique is by no means to be understood as mere *human whistling*. Depending on the size or volume of the flute, different frequency results are obtained, indicating that the instrument itself plays a role in generating these frequencies, especially regarding the characteristic break during register changes. This break can, according to Potengowski, clearly be attributed to a specific frequency and cannot be manipulated by the oral cavity volume (Potengowski et al. 2015: 232).

Although it does not concern any of the narrow instruments of the Swabian Jura, it should be mentioned that also a wider *nay* flute can produce a considerable glissando range, if fingerholes are located very close to the blowing end and kept open, because then the volume of the vibrating air column inside the flute is very small as well and the volume of the oral cavity can approach or exceed it.

2.13 Conclusions

If one tries to find answers to the question of frequencies of the Swabian Jura wind instruments by reconstructing them as flutes, one has to keep in mind that every small modification of all

[18] Wolfram Language and System Documentation Center n.d.

previously described interacting parameters will cause pitch changes – and that there are still many more parameters influencing the pitch beside these basic ones.

Such modifications significantly contribute to pitch variability in reconstructions since none of the original instruments is entirely preserved. That incompleteness prevents an exact definition of all pitch relevant parameters necessary for achieving exactly the same results.

Trying to define frequencies related to missing sections of the original instruments must necessarily remain speculative. Nevertheless, reconstructions of original instruments with missing sections can provide valuable data on pitches related to the preserved parts and offer insights into the potential frequency ranges of instruments that might have originally been longer.

However, as the analyses of different GK3 reconstructions conducted by A.F. Potengowski show (see chapter 4 below), there are many similarities in terms of frequencies and intervals among the instruments, if one adheres closely to the measurements of the preserved parts of the original instrument (see below), and assuming that one uses the notched end as the embouchure end, as it was indicated in chapter 1.3 (p. 62 above).

On the other hand, as long as reconstructions are handmade from mammoth ivory that occasionally warps visibly when exposed to humidity[19] and from naturally slightly deviating bones, it is to be expected that the reconstructions will not be entirely accurate concerning the frequencies, compared to the originals, even within their preserved sections.

The wide field of digital 3D-printing (see chapter 5, below p. 98) could nowadays be an additional way to reconstruct the instruments from the Swabian Jura because one could adhere to the original dimensions, thus achieving better pitch accuracy and rendering considerations (see above) of proportionally scaled instruments based on deviating bone sizes obsolete. But still, the original materials for reconstructions remain essential and irreplaceable in all cases where one aims to experimentally explore their properties and to discover various processing techniques.

3 Reconstructing the mammoth ivory wind instrument from the Geißenklösterle Cave: A progress report

Wulf Hein

3.1 Summary

Since the discovery of the wind instruments from the Aurignacian layers of the caves in the Swabian Alb, interpreted as flutes, the author has been engaged in reconstructing these so far oldest musical instruments in the world. The following report describes the experiences gained during the work, using the example of the latest replication of the mammoth ivory instrument from the Geißenklösterle cave.

[19] I encountered flattening of the initially round diameter of one of my mammoth ivory flute reconstructions and becoming oval-shaped.

"… little more than a tube with a few holes …"

These words attributed to the French composer André Jolivet (1905–1974) describe the flute as a "[…] musical instrument par excellence […] which allows the player to express his deepest feelings with the simplest means." Apparently, the people of the Ice Age were aware of this; it is not without reason that the oldest certain evidence of melodic-musical instruments in the world to date is an assembly of wind instruments and wind instrument fragments, which come from karst caves in the Swabian Jura (Conard et al. 2009) and can be reconstructed and played as flutes.

Interesting in Jolivet's quote are the two incidental words "little more" because indeed all extant Palaeolithic wind instrument findings in the archaeological record are made of bones, mainly the wing bones of large birds. These bones are natural 'ready-made' pipes with human modifications such as fingerholes made by drilling or scraping into the bone (Buisson 1990; Hahn and Münzel 1995; Käfer 1998; Conard et al. 2009; Ringot 2012). The exception to the rule, however, is a mammoth ivory instrument, interpreted as flute, recovered from archaeological horizon (AH) IIb belonging to the Aurignacian technocomplex, from the cave site of Geißenklösterle in the Ach Valley near Blaubeuren (Conard et al. 2004). Concerning this object, a "little more" work was undoubtedly spent!

Tusks of woolly mammoths are hollow in the proximal part, which sits in the alveoli of the upper jaw (*maxilla*). This cavity is funnel-shaped, because "figuratively speaking, the tusk consists of numerous dentin cones pushed into each other" (Banerjee et al. 2011: 3), rather like a stack of tightly-packed ice cream cones. It is not as easy to make a flute from this material as it is from a bird bone, where diameter and wall-thickness measurements along the entire length of the bone are approximately uniform. Nevertheless, the Aurignacian occupants of Geißenklösterle chose to undertake a task which was not only extremely time-consuming, but also difficult work.

The question of "why bother to go to so much trouble" (Lawson 2020) might be answered by the fact that even the wing bones of the largest birds of prey and water birds such as vultures, eagles, or swans, limit the maximum length of a wind instrument made from them; typical ulnae and radii measurements are rarely longer than about 26 cm.[20] Making a longer flute therefore requires an artificially-designed tube in some shape or form. The tusk of a mammoth is an ideal material for this; ivory is very hard and elastic at the same time and can be easily worked with stone tools. The ivory instrument find GK3 measures 187 mm. Despite the preserved state of the instrument (Figure 1), some of its extant features are fragmentary; the original length cannot be determined with absolute certainty. Together with other ivory finds in context from Geißenklösterle, including a 35 cm long ivory-stave artefact, it is assumed that it was possible to produce roundish cylindrical bars or rods of worked ivory up to one metre in length (Hahn 1988: 204–5, but consider footnote 6).

20 But see Wyatt (2012: 393), who joins two goose bones together with beeswax to make one tube.

3.2 *Previous attempts at reconstruction*

In an archaeological experiment, M. Malina and R. Ehmann demonstrate how an ivory rod is split and hollowed out (Malina and Ehmann 2009). In addition, they re-examined ivory fragments from the archaeological context and were able to determine that the 35 cm ivory stave from AH IIb and III of Geißenklösterle (mentioned above) was worked in this way (ibid., 104). For this purpose, first a stave is taken from the outer layer of the tusk, scraped into a cylindrical round form (Figure 19.1) and a groove is made on each lateral side along its entire length (Figure 19.2). This is followed by using a flint knife to incise many small notches down each side of the rod, perpendicular to the conjunction between the cementum and dentin; in preparation for gluing the two longitudinal halves back together after subsequent splitting (Figure 19.3). Most probably, these notches served to enlarge the gluing surface, a procedure understood to be the case for the production of projectile points in the Palaeolithic (Stodiek 1993: 167). Next, the rod is split by means of small wedges, which is only possible at the exact boundary point between the very outer tooth cementum and the dentin below (Malina and Ehmann 2009: 102, fig. 16). Finally, both halves are scraped out with a small flint scraper and reassembled. Malina and Ehmann refrained from further reconstruction at that time because the length of the original instrument could not be determined.

Friedrich Seeberger (1938–2007), who studied the Ach Valley wind instruments and their playing techniques like no other (Seeberger 1998; 1999) and knew how to make his reconstructions sound masterfully, first made a reconstruction from elder wood after the discovery of the mammoth ivory instrument (Conard et al. 2004: 458; Seeberger, personal communication), and later reconstructed another from ivory (Malina and Ehmann 2009: 94).[21]

In 2013, a team associated with the Urgeschichtliches Museum Blaubeuren (URMU) traced and described the process of making an ivory flute reconstruction for the first time (Holdermann et al. 2013). The context in which this research was performed postdates an experiment in 2012 by some members of the same team together with Frances Gill, using material coming from the same mammoth-ivory tusk from which the first reconstruction following the length of the 35 cm ivory rod was constructed (full results in Gill forthcoming; Gill 2012: 60; 74–5; Gill 2014b; Atema 2014: 30).

3.3 *Current attempts to reconstruct the flute GK3*

I have been engaged in the construction of these unique finds since the discovery of the first wind instruments in the Ach Valley, during which time, together with the excavator of the Geißenklösterle, Joachim Hahn (1942–1997), I also made the first reconstruction attempts (Hahn and Hein 1995; Hein and Hahn 1998). Numerous replications of ivory finds followed during the course of my work, including the Lion Man statuette from the Hohlenstein-Stadel cave (Hein and Wehrberger 2010) and the Venus and animal figures from the Swabian Alb (Hein 2018), many of

[21] Unfortunately, F. Seeberger was unable to publish his specific contribution to the research about GK3, but see Gill forthcoming for an appraisal and analysis of his valuable work concerning GK3 from other available sources.

them found with authentic tools. Extensive experience was gained in the handling of mammoth tusk material, including the reconstruction of seven GK 3 type flute to date, some of which have already been the subject of music archaeological investigations (Potengowski and Münzel 2015; Münzel et al. 2016).

Here I can present the results of my most recent experiments (Figure 23; Table 1: Instruments (e), (f), (g)) correlating them with some discussion points that were raised by my colleagues in Blaubeuren. First, I did not encounter the same degree of difficulty as the Holdermann team (2013: 65) in evenly hollowing out the two halves of the stave (Figure 19.4) all the way to each end. This is likely due to the fact that I have accumulated extensive experience working with ivory through many hundreds of hours of work and practice. F. Gill recalls in a poster presentation for ISGMA in Berlin (2014a) in connection with an interview that I had given that "I heard the scraping of ivory in my dreams" during the time period in which I was carving the Lion Man. Ultimately, then, it is also a matter of patience and practice in which precision is finally achieved through tacit knowledge (e.g. Polanyi 1966).

Provided that a fresh mammoth tusk has (approximately) the same properties as fresh recent ivory, I can answer questions posed by the Blaubeureners (Holdermann et al. 2013: 63) regarding workability as follows: the African elephant tusk from which I made the Lion Man was just as hard and difficult to work as the fossil mammoth ivory that I used for other replications coming from the same source as used in their experiment. However, this need not be true for every fossil material; an incident during my workshop at the British Museum in London (2013) demonstrated that ivory from different parts of the same fossil tusk can have very different properties (Hein 2018: 442). However, it is questionable whether such material is then suitable for the production of a flute, for which one would rather select the best quality, because the wall thickness of the artificially created tube is very thin at only 1.5 mm, and it is above all the stability and accuracy of fit of the edges that is important when both halves are put together.

Unlike the Blaubeuren team, I did not bevel the edges, but merely ground a small chamfer on the outside. Also, I did not put the halves together, fix them, and then apply the glue, but first applied the glue to both halves (Figure 19.5), heated them evenly over a grease lamp, and then joined the two parts together (Figure 19.6). I also used birch pitch for gluing, which was made by the double-pot method and therefore turned out very fine. It is unclear whether such a quality could be produced aceramically in the Aurignacian, but in principle the adhesive can be obtained from birch bark without pots (Palmer 2007; Schmidt et al. 2019). When thickening the extracted tar into pitch, the duration of the process allows the viscosity to be adjusted relatively accurately after mastering the process. When bonding ivory or other materials, great care must be taken to ensure that the pitch is not too soft, or it will melt at low temperatures and smear instead of stick. But it also must not be too hard, or it will become brittle and crumble back out of the glue joint.

On my own GK3 flute reconstructions, which I made in 2012, 11 years ago, and which I have since carried, shown, and (with my very modest skills as a flutist) played at countless events and trips, the glue joints are still completely intact. With the last three flutes reconstructions which I

Figure 19: Manufacturing of an ivory flute reconstruction: 1. Round scraping of the released stave; 2. Applying the splitting groove with a narrow burin; 3. Cutting the notches above the adhesive joint with a blade; 4. Hollowing out the halves with a scraper; 5. Applying the adhesive birch pitch to the glued surfaces; 6. Joining the two halves together and carefully heating them; 7. Scraping off the excess glue with a burin; 8. Wrapping the body of the flute with wet animal sinew; 9. Scraping the fingerholes with a burin; 10. Attaching the labium by grinding on a fine sandstone. Photos by W. Hein.

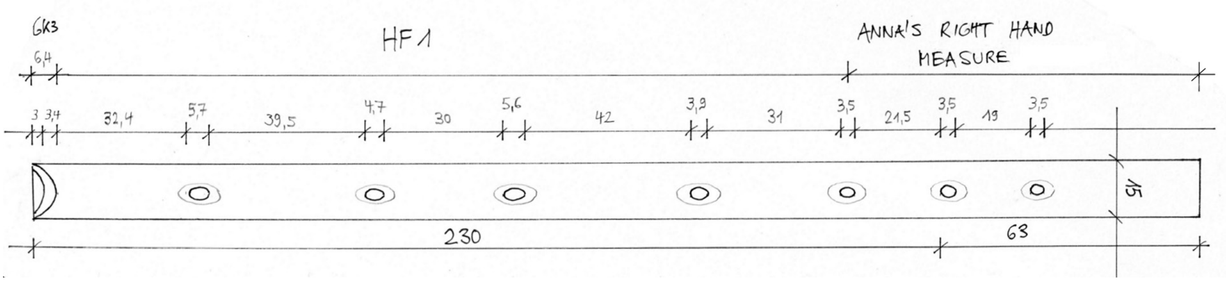

Figure 20: Construction sketch for the Haskell flute reconstruction. © W. Hein.

made from African elephant ivory in 2021, I secured the connection with additional sinew wrappings as a precaution. They are also still working well, one of which is a recent commission by F. Gill who has played it frequently, even outside in colder temperatures (personal communication). If birch-pitch beads form in the tube when the halves are joined, the interior can be warmed slightly, and the beads can be carefully smoothed out with a bone or wooden stick that has also been warmed. Excessive protruding beads would affect the airflow and thus the playability. Finally, the excess pitch on the surface is carefully scraped off with a burin (Figure 19.7).

One thing is certain: without glue, an airtight connection of both halves, without which the flute would be unplayable, is impossible to achieve. However, it is still unclear what material was actually used for this purpose on the GK3 artefact (Conard et al. 2004: 456). Frank Trommer, a member of the Blaubeuren experimental team, has successfully used a mixture of resin and wax – and in some cases even oil – for new replicas (personal communication). The use of such a mixture or individual components in the Palaeolithic has been a source of speculation (Stodiek 1993: 151), whilst it has been proven elsewhere in context (Thieme et al. 2014: 68; Baales et al. 2017: 1160).
Finally, the flute tube must be secured by means of binding (Figure 19.8). Both A. Holdermann's team (Holdermann et al. 2013) and I used animal sinew for this, in my case reindeer leg tendons. These are beaten between two pebbles (if dried, soaked in water, otherwise in fresh condition) and subsequently divided into very fine threads. Then they are laid individually and wet in several layers around the flute, the loose end – as thin as possible – is pulled once or twice under the last winding so that it cannot come off again. During drying, the winding contracts very strongly, and at the same time the individual fibres stick together, so that a stable and durable connection guarantees cohesion between the two halves of the flute. Of course, other materials such as plant fibres, for example, the bast of willow, or nettle fibres, and possibly even thin strips of leather or rawhide are possible, but we have had the best results with sinew so far. In addition, a binding with this material wears very little, which is an advantage when playing the flute, because it is easier to grip. It is still unclear whether an adhesive was also used (Conard et al. 2004: 456); it could be hide glue, which has now been proven at least for the Neolithic (Bleicher et al. 2015). This would indeed further improve the adhesion of a (tendon) binding.

Whether the fingerholes were made before the halves were put together or only afterwards cannot be determined, but in any case, this happened only after at least one half was hollowed out, according to M. Malina (personal communication). The Blaubeuren team scraped fingerholes prior

Figure 21: The completed ivory flute reconstruction. Photo by W. Hein.

to gluing, whereas I prefer to do this after the two halves are assembled and glued (Figure 19.9). Then the tube is more stable again and easier to handle. As I learned when working on the Lion Man, it is always easier 'to go with the grain' when scraping, i.e. from the surface of the flute down into the fingerhole. If you work the other way around and against the grain, the stone tool starts to rattle and leaves small unsightly heels. I do not understand the remark in A. Holdermann's report that the edges of the fingerholes must be sharp in order to break the air flow. After all, the flute tone is produced exclusively at the mouthpiece, at whose labium the air stream must be divided. If this were not the case, modern recorders or the flute reconstruction from the Austrian site Grubgraben (Einwögerer and Käfer 1998) with drilled holes would not work at all. Finally, the blowing notch is made, which I do by applying the rim to various grinding stones that have varying degrees of surface fineness (Figure 19.10).

In spring 2020, David Haskell of the University of the South, Sewanee, Tennessee, USA, asked me to make a reconstruction of the mammoth ivory instrument GK3 (Figure 23; Table 1, Instrument (g)). The remit was that it should not necessarily be an exact replica of GK3, but primarily demonstrate the technical skills of the Ice-Age hunter-gatherers. Since I had at my disposal a mammoth ivory stick of 35 cm, I suggested that I should make a replica of GK3 but also extend it to this size. At the same time I contacted Anna Friederike Potengowski, a flutist, and music-archaeological researcher and performer on Palaeolithic flute reconstructions; this was a unique additional chance for us to incorporate her perspectives into the design right at the start of the experimental work

(Figure 20). The design that we decided on can be described as follows: dimensions and positions of the fingerholes and labium follow: the mammoth ivory instrument (GK3) for the labium; the wind instrument from Hohle Fels (HF1) for the five holes running from the proximal end; and the dimensions of A.F. Potengowski's hand for two holes at the distal end. The proposition was acceptable to D. Haskell, and so another Aurignacian ivory flute was constructed from mammoth tusk (Figure 21).

The gluing of the two halves was handled invisibly with a modern two-component glue for reasons of better durability; I considered that the flute could manage without an additional winding directly at the blowing end. However, I was quickly proven wrong, because of how ivory actually 'works', i.e. it warps, as Malina and Ehmann had already noted:

> "During the experiment care had to be taken not to let the two halves lie independently of each other for too long. Only when tightly laced to each other, they could remain fitted." (Malina and Ehmann 2009: 107; translation by the author)

After A.F. Potengowski had played the flute reconstruction for a few days, the halves became detached from each other at the end with the notch. Two additional windings remedied this, however, and since then the two halves have remained tightly in position and have not changed.

4 Comparison of eight different reconstructions of the mammoth ivory instrument from Geißenklösterle Cave. Constants and differences in playability and resulting tonal material

Anna Friederike Potengowski

4.1 Summary

This chapter deals with the comparison of the tonal material of 8 different reconstructions of the mammoth ivory instrument from Geißenklösterle (GK3). We here provide a detailed description of the reconstructions and of the practice process that precedes the collection of usable musical data. As a result, not only expected differences between the various reconstructions are recorded, but also obvious similarities, which specify the range of possible tonal material producible by the original instruments. Our research also offers new insights regarding the playability of reconstructions that are longer than the original.

4.2 Introduction

The incompleteness of the Palaeolithic musical instruments from the Swabian Jura led to a long series of questions, including what frequencies, what intervals and what tonalities were played on these instruments 40 000 years ago. Our work attempts to answer these questions through a systematic comparative study of the tonal results produced on the different reconstructions.

A previous study of four different Palaeolithic wind instrument reconstructions from Geißenklösterle, Hohle Fels, SW-Germany, and Isturitz, France (Potengowski et al. 2015; Münzel et al. 2016) yielded considerable insights into voicing methods, offering suggestions for defining basic

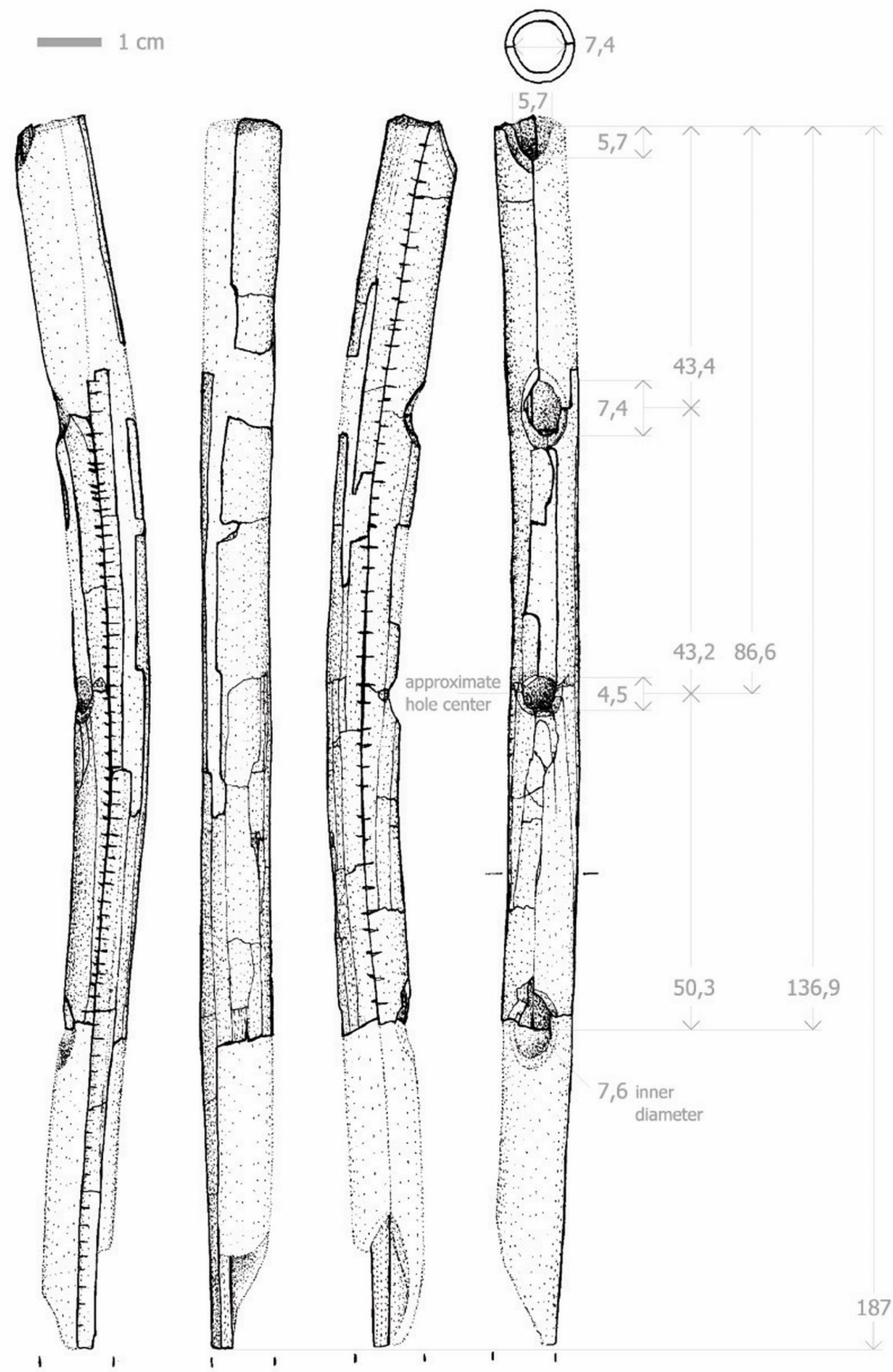

Figure 22: Measurements of the original find GK3 in mm.
Drawing by R. Ehmann, supplemented by Stephan Hahn, measurements from Conard and Malina 2004; 2006.

Figure 23: Eight reconstructions of GK3 (cf. Table 1).
Photos a, b, c, e, f, g: A.F. Potengowski; d: G. Dalferth; h: M.C. Thumm. Design H. Wiedmann.

notes and for building a richer tonal material than that previously described by F. Seeberger (1998; 1999; cf. Münzel et al. 2002). This was done by considering the possibilities of the glissando effect, i.e. a substantial gliding pitch change obtained by altering the embouchure. This is both a curse and a blessing. On one hand it enriches the possibilities of artistic expression, on the other it makes the search for specific musical material from Palaeolithic times more difficult.

The following study attempts to reduce the frame of possibilities by focusing on one find – the mammoth ivory instrument GK3 (Figure 1). Since the method of playing on the notch compared to the method of oblique playing on the edge reduces the possibilities of the glissando effect to zero, the tonal material of this instrument is more limited, compared to the other Palaeolithic aerophones, which were purportedly voiced obliquely on the edge. Reconstruction of the possible tonal framework of the original instrument is achieved by searching for similarities in tonal results despite changing parameters, such as length and number of fingerholes.

An open door may tempt a saint: during the last years the present author was given the task to record audio examples of several GK3 reconstructions made by different constructors with different intentions. This unique opportunity allowed the collection of scientific data – measurements, tonal material, as well as musical and technical playing experiences including audio examples.

4.3 Measurements of wind instrument finds and their reconstructions

The measurements of the original find (Figure 22) taken by F. Seeberger (a former engineer and experimental archaeologist) differs from the way A.F. Potengowski measured the reconstructions. Depending on which content is to be discussed, one focuses on different distances. Seeberger's intention in collecting the data is unfortunately not documented. Presumably, he surveyed from an engineer's point of view. He focused for instance on the distance between the rim of the notched end of the instrument and the centre of the following hole. In contrast, Potengowski as a flutist focused on measurements that influence the pitches of the respective instrument. For example, the distance between the lower edge of the notch and the upper edge of the following hole, since this distance essentially determines the pitch (see chapter 2 above). Thinking ahead, if the first fingerhole is closed, then the distance between the lower edge of the notch and the upper edge of the second fingerhole is relevant.

4.4 Description of the studied GK3 reconstructions

Before going into detail on the musical analysis, a careful description of the eight different handmade reconstructions is called for (Figure 23). Deviations from the original mammoth ivory instrument GK3 depend on the constructors' respective skills, on the raw material properties, on use of stone tools during construction, and on the different aims of the instrument makers (Figure 23; Table 1).

The influence of deviations in measurements on the pitches was not on focus for all constructors. With one exception, Instrument (a), none of the instruments was especially made to be compared to other reconstructions.

	Name	Tem-plate	Finger-holes	Length (mm)	Material	Designer/Constructor	Owner
(a)	GK3_2H_SwU_Pot	GK3	2	129.5	Ulna, mute swan	A.F. Potengowski	A.F. Potengowski
(b)	GK3_3H_SwU_Pot/Spreer	GK3	3	183	Ulna, mute swan	B. Spreer A.F. Potengowski	A.F. Potengowski
(c)	Gk3_3H_MI_Hein	GK3	3	185	Mammoth ivory	W. Hein	A.F. Potengowski
(d)	GK3_5H_MI_Dalferth	GK3	3	187.8	Mammoth ivory	G. Dalferth	G. Dalferth
(e)	GK3_4H_AI_Hein	GK3	4	242.5	African elephant ivory	W. Hein	W. Hein
(f)	GK3_4H-AI_Pot	GK3	4	255.5	African elephant ivory	A.F. Potengowski	A.F. Potengowski
(g)	GK3/HF1_7H_MI_Hein/Pot	GK3, HF1	7	296[22]	Mammoth ivory	A.F. Potengowski (idea) W. Hein (idea and con-struction)	D. Haskell (USA)
(h)	GK3_5H-MI_Trommer	GK3, HF1	5	305	Mammoth ivory	F. Trommer, A. Holdermann, H. Wiedmann	F. Trommer

Table 1: Key parameters of eight different GK3 reconstructions.
The name contains the following information: scientific name of the find, number of holes, material, producer. SwU – swan ulna, MI – mammoth ivory, AI – African elephant ivory.[23]

Instrument (a) was especially made for comparative use, to gauge similarities independently of length. The inner diameter of swan ulnae is very similar to the inner diameter of the original GK3. For comparison, the inner diameter of the notched end of instrument (a) is 7.5 mm, that of the original 7.4 (measured by Malina and Seeberger). Swan ulna was used here to avoid waste of rare material and high costs of using mammoth ivory. The size of the notch and holes was defined by measurements taken from the cast of the original artefact GK3.

Instrument (b), an earlier version of this instrument, was originally made for the Urgeschichtliches Museum Blaubeuren as part of a group of instruments for demonstrating different playing methods in the exhibition area (idea of B. Spreer). A.F. Potengowski, who was involved in the production of audio examples for the museum, came up with the idea of building similar reconstructions herself for demonstrative, analytical, and comparative purposes. The natural diameter of the ulna shaft is very close to that of GK3. The reconstruction has the same length as the original, as measured between the two ends including the thin sliver at the distal end. The notch and holes were made according to measurements taken from the original instrument. The third hole was reconstructed by mirroring the preserved half (idea of B. Spreer).

Instrument (c), of mammoth ivory, was commissioned by A.F. Potengowski as a concert instrument with the request that it should be reconstructed true to the original. Its diameter is determined by the natural conditions of the ivory segment out of which it is made. As with Instrument (b), the notch, holes, and length were made to measure like those of the original instrument.

22 Deviation in measurements from Figure 24 and Figure 25 are due to problems with data transfer. Correct measurements are reported in Table 1.
23 CITES certified material. We participate in the critical ethical discourse on the necessity of using original animal materials for the construction of reconstructions and have carefully weighed the use of this material.

Instrument (d), also of mammoth ivory, was designed and made by G. Dalferth, after the original measurements. Because weathering by taphonomic processes is believed to have modified the extent of the notch on the original instrument, G. Dalferth made the notch of this reconstruction slightly smaller than that of the original. Her idea was to produce a good playable instrument for demonstration purposes. The length was limited by the properties of the material available for reconstruction.

Instrument (e), of African elephant ivory, arose from a cooperation between W. Hein and A.F. Potengowski with the financial support of the Deutsche Musikrat 'Neustart Kultur'. The Research objective was to test the tightness and playability of fresh ivory as opposed to fossil ivory (A.F. Potengowski). The reconstruction is based on the original instrument but is extended in length according to the maximum length of the available raw material. A fourth hole was added, positioned according to a comfortable position of the right-hand fourth finger of A.F. Potengowski (see chapter 3 above).

Instrument (f), also of African elephant ivory, was designed and produced by A.F. Potengowski parallel to Instrument (e) and for the same purposes as the latter, but also with the intention of gaining first-hand experience in the processing of ivory flutes. The total length of the reconstruction differs from that of the original instrument and was determined by the conditions of the available material. A fourth hole was added, positioned according to a comfortable position of the right-hand fourth finger of A.F. Potengowski.

Instrument (g) was commissioned by D.G. Haskell (University of the South, Tennessee, USA) in the context of his studies for the book *Sounds Wild and Broken* (Melbourne, VIC: Black 2022). The length of the instrument was given by the proportions of the available material. The griffon vulture instrument from Hohle Fels (HF1) was chosen as a template for the spacing and size of the first 5 fingerholes. The position of holes 6 and 7 was chosen according to a comfortable position of the third and fourth fingers of A.F. Potengowski (see chapter 3 above).

Instrument (h), of mammoth ivory, was designed and produced by F. Trommer, A. Holdermann, and H. Wiedmann (Holdermann et al. 2013). Its length was inspired by the existence of longer instruments like HF1, as well as the ivory rod find from Geißenklösterle (Figure 2) and determined by the dimensions of the material available for reconstruction. The spacing of the first three fingerholes follows GK3 measurements. Holes 4 and 5 repeat these measurements.

4.5 Development of playing skills – preparation steps for the musical analysis

To gain comparable musical data it was first and foremost necessary to carefully develop the basic playing skills. Since we assume that the notched end of the original instrument was used for tone production – it was necessary to develop the embouchure, the individual position of lips, tongue, oral cavity, to direct the air flow with an optimal tonal result on the notch. Attention was paid to identifying the most effective fingering, in other words, to understanding which finger serves which hole the best.

The acquisition of playing skills like overblowing to reach the overtones of the instrument required considerable time and practice, especially because of physical differences between the reconstructions that affected the way of blowing. From my experience it takes years to get familiar with instruments like these and it is an ongoing process. After 12 years of performing on reconstructions of Palaeolithic wind instruments I am still improving my playing skills and developing new techniques. Therefore, it is useful from time to time to take pauses in the learning process in order to describe and consolidate the results. At the bare minimum, I would practice for 3 weeks to explore the musical possibilities, playing an individual reconstruction at least 1 hour a day with maximum 3 days off. The next step was to describe the musical potential of the respective instrument 3 times with a few days break to record the results over separate time periods in order to avoid biases depending on physical conditions of the player. Frequency measurements were taken with the Tuner T1 App Version 4.15 (JSplashApps). Tone pitch was also noted down in modern music notation.

4.6 How to image the tonal material for comparison

Modern stave notation evolved simultaneously to the development of our instruments, playing skills and musical preferences, and is adjusted to contemporary musical traditions. However, no notation system has been handed down to us from Palaeolithic times. There is no knowledge about the playing skills of Palaeolithic humans, their musical traditions, or their musical perception. Were people familiar with the whole tonal spectrum of their instruments as we know them from our modern reconstructions? Did they consider microtonal possibilities? Did they know and prefer intervals resulting from physical factors like the overtone scale? These are all questions to which no certain answer can be given.

Tonal results from the reconstructions are not comparable with the currently used tuning systems of either pure or tempered musical intervals. Distances between tones might sound wider or smaller than the musical intervals to which we are familiar. Therefore, the imaging of the musical potential of these reconstructions should be handled and perceived with care to avoid an uncritical application of our modern musical tradition and experience to the past. Hence the choice of representing the results on one hand through frequency values (Figure 24 and Figure 25), which despite their accuracy are hard for the reader to visualise, and on the other hand through transcription of the results in the modern five stave notation system (Figure 26), which due to intrinsic limitations cannot describe the results accurately.

A third way of describing the tonal material of the reconstructions is to notate the resulting musical Intervals. Again, this method generates inaccurate descriptions of the relationship between the resulting tones and carries the risk of inappropriately applying modern musical categories to the past.

Figure 24: Four reconstructions – measurements and frequency numbers. Design by Matthias Kraus.

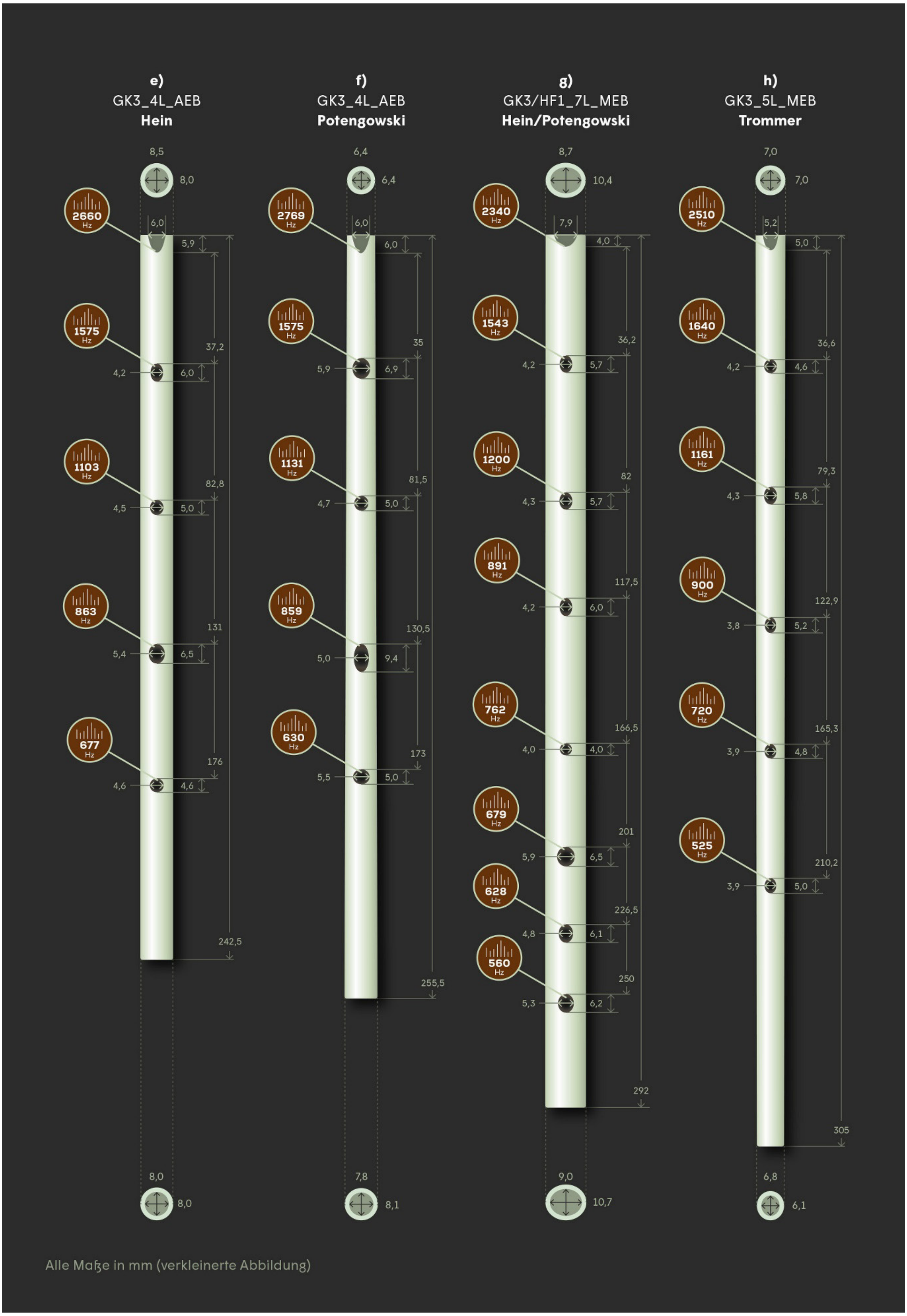

Figure 25: Four more reconstructions – measurements and frequency numbers. Design by Matthias Kraus.

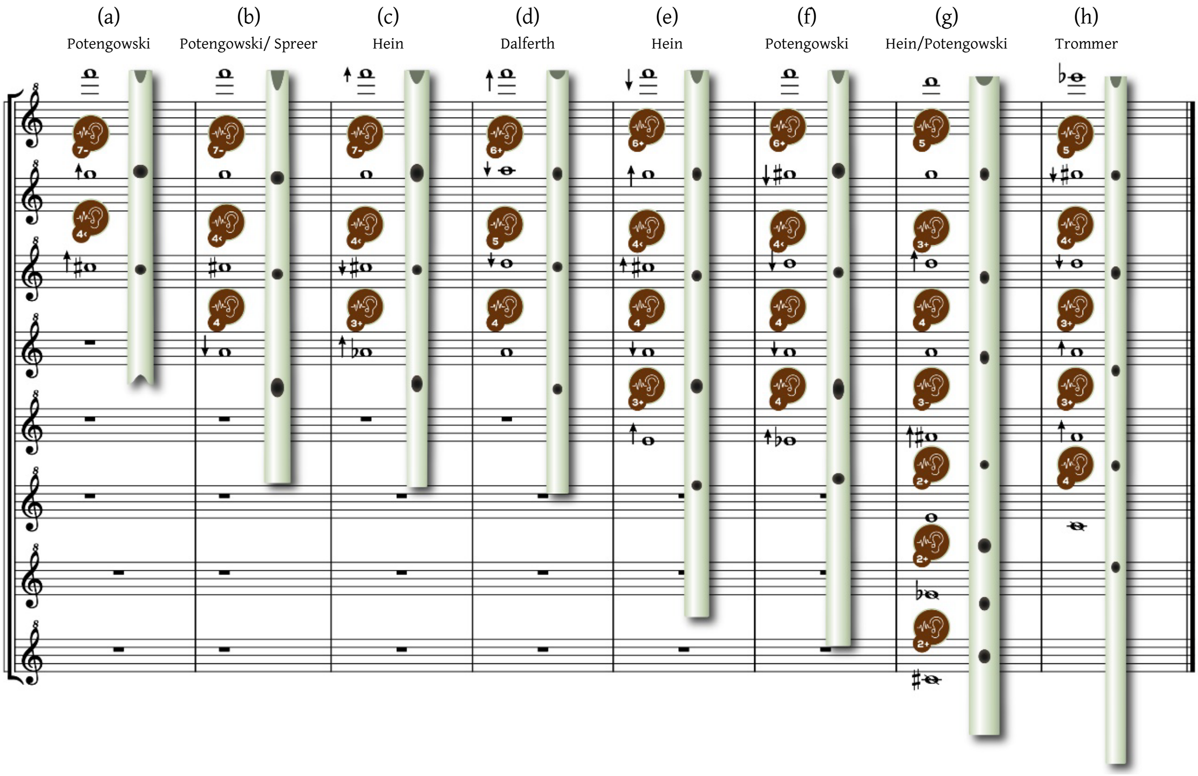

Figure 26: Tonal analyses of eight reconstructions of GK3 (cf. Audio Examples a–h). Design by Matthias Kraus.

4.7 *Explanation of the graph*

The results of the comparative analyses of the 8 different GK3 reconstructions are shown in Figure 26, which is a simplified representation of the resulting tonal material. The reconstructions are labelled at the top with their name, followed by the name of their maker. Pitches are abstracted in noteheads representing the results of the frequency meter Tuner T1. The reference pitch used is 440 Hz. The arrows beside the noteheads indicate a strong deviation from the note mean. Scaled down sketches of the reconstructions are included. Each hole is flanked by its corresponding notehead in the five-line staff representation to mark clearly where the intervals occur. Only simple fingering is applied. Accordingly, the graph must be read from top to bottom. The noteheads beside the notches in the first stave represent the pitches produced when no holes are closed. The second stave represents the case when the first hole is closed. Similarly, the third and fourth stave represent, respectively, the cases when the first and second holes and the first, second, and third holes are closed and so on. Intervals were analysed by ear by taking as reference values those of a modern recorder flute (440 Hz). These are visually represented by red ear icons with interval numbers between the related noteheads and should be read vertically.

Attention must be given to the fact that the distances between the notes differ from time to time from the ear-analysed intervals. An example of this is the following: Instrument (e) produces a C♯ when the first two holes are covered and an A when the third hole is also covered – normally this is described as an interval of a major third, but the analysed interval is represented in the graph as a fourth. In fact, as the arrows show, the C♯ is particularly high, and the A is low. The distance between both tones is therefore wider than that representable by the note system. The resulting interval sounds to the human ear like a fourth.

4.8 Description and discussion of the results

Differences in the resulting tonal material of the individual reconstructions, are attributable to a variety of components (see chapter 2 above). These include not only the length of the instrument but also differences in notch design, hole size and shape, and the distance between the blowing edge and the next open hole. The diameter of the tube mainly influences the volume of the instrument, but also the pitch to a small extent through the phenomenon of end correction (see chapter 2 above). The influence of the other parameters is much stronger, so that the influence of the diameter on the difference in pitches of the reconstructions with respect to a given tone hole can be neglected in this analysis. Regarding the playability of low notes, the diameter must be taken into account, as will be explained in the following.

For the sake of clarity, I will discuss the results of the analysis by using tone and interval names. Subtle variations in pitch or pitch spacing are represented in Figure 26 (see frequency numbers and compare the Audio Examples). Alternatively, in the text they are described in the musical sense as 'different shades'.

On the first stave, with no closed holes, the note F_7 is clearly dominant. Only Instruments (g) and (h) deviate from this pattern. In line two, with the first hole closed, everything seems to revolve around shades of the tone G_6. Five of the eight reconstructions play a G_6 and two a $G\sharp_6$. Instrument (d) shows the greatest difference with a pitch equivalent to A_6. Pitch shadings around the notes $C\sharp_6$ on (a), (b), (c), (e) and D_6 on (d), (f), (g), (h) are predominant in line three when 2 holes are closed. When 3 fingerholes are covered, seven reconstructions play an A_5 while one plays an $A\flat_5$. With 4 closed holes, line 5, differences in pitch become greater, and they are hardly comparable with each other when 5 holes are covered. This is both due to the small sample of the reconstructions, there being only 2 instruments with corresponding length and number of holes, and also to the playability of the notes, which is made more difficult due to the relation between the increasing length of the vibrating air column and the narrow diameter of the tube (see again chapter 2). It is not possible to voice the lowest notes of Instruments (g) and (f) properly. This is an important result of the comparative analysis. In fact, it proves that elongating the instrument while maintaining the same diameter, with the intention of achieving lower tones, is not effective (see chapter 2.4 above). This part of the analysis deals primarily with the fundamental tones of the instruments. The intention behind longer instruments (Figure 2) with the same diameter could still have been the extension of the tonal range, but only in the overblown, higher register. Overblowing of the tones is possible (see chapter 2 above) up to all closed holes. However, to keep the graph clear, overblown tones are not represented in Figure 26.

Summing up, there are clear similarities between the tones produced by the reconstructions when the first 3 holes are progressively covered. Differences between the various reconstructions concerning the pitch of the same hole are never larger than a whole tone. It is therefore possible, when searching for the tones of the original instrument, to limit the range of possible pitches belonging to a certain hole to the range within a whole tone.

In musical practice, when stringing together tones to form scales and melodies, pitch differences even within this range have a nature-changing effect on the music. We all know the crucial difference that even a semitone can make in the reception of our modern major-minor system. For this reason, we should look at differences and similarities in the resulting intervals for the respective fingerings.

The tone spacing between all holes open, and first hole closed, corresponds to a minor seventh on Instruments (a), (b), and (c), a major sixth on Instruments (d), (e), and (f), and a fifth on Instruments (g) and (h). Here, no apparent constancy can be detected. On the other hand, the interval of the augmented fourth (tritone) is clearly predominant between holes 1 and 2, despite differences in length between the reconstructed instruments (Audio Example i). Only Instruments (d) and (g) deviate from this pattern. It is very likely that a 'shading' of this interval could also have been played on the original instrument. The most frequent musical interval between holes 2 and 3 is the fourth. The intervals produced on Instruments (b), (d), (e), (f), and (g) correspond to fourth, while the same fingering generates a major third on Instruments (c) and (h).

The intervals between holes 3 and 4 can be compared only between reconstructions (e) to (h), albeit with reservations, since the fingerholes of (g) and (h) are placed at very different distances. Three instruments, (e), (g), and (h), produce a third, specifically two major thirds and a minor third, and one instrument, (f), produces a fourth. With 5 closed holes, Instrument (h) already reaches its fundamental tone, in contrast to the 7-hole-instrument (g), which does not. This explains the large interval differences between holes 4 and 5. The comparability for the intervals between hole 5 and 6 and hole 6 and 7 is not given. The respective tones are nearly unplayable and comparable reconstructions are missing.

4.9 Conclusions

In this study we have compared the various reconstructions of GK3 to detect similarities, differences, musical possibilities, and also limitations in the reconstruction of the original tonal material of GK3. Even if the original length of GK3 remains unknown, our study shows that several tonal materials can be excluded, and the possible range of the original tone material can be narrowed down. The analyses of the reconstructions of the mammoth ivory instrument GK3 indicates that increasing instrument-length without adapting the diameter causes problems in the voicing of the lower fundamental notes even though overblown tones still remain playable. Thus, elongating the mammoth ivory instrument in the attempt of reaching the lower fundamental tones is not effective, whereas the aim of extending the tone range with new tones can be achieved by overblowing.

Regardless of instrument-length, clear similarities emerge in the results obtained for the upper 3 fingerholes. Therefore, the original interval between hole 1 and 2 might have corresponded to an augmented fourth, and between hole 2 and 3 to an interval around a fourth or major third. We conclude that the comparative analyses of the different reconstructions of GK3 may be regarded as a reasonable method to gain knowledge on the original tonal material of the instrument.

5 Future research

Even though the variability in the reconstructed instruments allows for the exploration of different musical possibilities, it also poses a limitation to the study of GK3. Therefore, our next step will be to compare our results with those produced on 3D-printed reconstructions in order to exclude biases generated by differences between the reconstructions and the original instrument. Additionally, the replicability of the results will be tested by other players so as to exclude errors derived from the subjective interpretation of a single player. Future work will additionally include the creation of spectral analyses in order to present more exact data. The development of a more neutral representation system is also called for. In this way we can avoid an uncritical application of our modern understanding of music to 40000-year-old instruments. A standardised system for analysing and representing the tonal material of different reconstructions might become a useful tool in the study of other instrument findings, such as those from the Ach and Lone Valleys. Analyses concerning the influence of embouchure morphology on the tonal material of the reconstructions as well as the different effects of fresh and fossil ivory on the sound properties of reconstructions are in progress.

Acknowledgements

Foremost we would like to thank the excavators of the oldest wind instruments, the professors Joachim Hahn † (Urgeschichtliches Institut, Universität Tübingen) and Nicholas Conard (Department of Early Prehistory and Quaternary Ecology, Universität Tübingen), whose instrument finds opened up new horizons in music archaeology and appreciation. Fritz Seeberger † we thank *posthum* for his pioneering work in experimental musical analysis of the wind instruments from the Swabian Jura. And we should not forget to express our gratitude to Frances Gill, who always is a very supportive person when it comes to discussing results. Last but not least we would like to thank Giulia Toniato, who handled our earlier version of this manuscript and transferred it into readable English.

Video Examples

1: Wide and narrow tube, same length. © G. Dalferth 2023.
https://youtu.be/ikIFVY1jue0

2: Coverage of the blowhole with the lips. © G. Dalferth 2023.
https://youtu.be/71JLQByPoYc

3: Two tubes with a narrow and a wider notch. © G. Dalferth 2023.
https://youtu.be/jzhH_s02AiU

4: Pennywhistle with a narrow and a wider window. © G. Dalferth 2023.
https://youtu.be/bDW4Lv9ZbTs

5: Flute 1: Narrow turkey radius flute, small fingerholes. © G. Dalferth 2023.
https://youtu.be/r9-H9bXzJ-U

6: Comparison between Flute 3 and Flute 1, Flute 3 being a wide turkey ulna flute with same finger hole sizes as the narrow radius flute. © G. Dalferth 2023.
https://youtu.be/rMOUxJzyk7Q

7: Comparison between Flute 2 and Flute 1, Flute 2 being a wide turkey ulna flute with larger fingerholes compared to the flutes in Videos 5 and 6. © G. Dalferth 2023.
https://youtu.be/J7TfYcbHJmo

8: Reconstructed HF1 flute, response from the low and from the overblown register. © G. Dalferth 2023.
https://youtu.be/hFy_I7XI8SU

9: Whistle with fully inserted rod. © G. Dalferth 2023.
https://youtu.be/17NqyK7kgp4

10: Whistle with partly inserted rod. © G. Dalferth 2023.
https://youtu.be/zzlOAILb_Gk

11: Swan ulna, glissando range (low register only). © G. Dalferth 2023.
https://youtu.be/w6GB7OGhzs0

12: Swan radius, glissando range (low register only). © G. Dalferth 2023.
https://youtu.be/3xmiMl4o2IYv

Audio Examples

a) GK3: basic notes from no hole closed to all hole closed from instrument (a). © A.F. Potengowski 2023
https://soundcloud.com/friederikepotengowski/a-gk3-2h-swu-potengowski/s-1UOddO9b5MN

b) GK3: basic notes from no hole closed to all hole closed from instrument (b). © A.F. Potengowski 2023
https://soundcloud.com/friederikepotengowski/bgk3-3h-swu-potengowski-spreer/s-pHQGdza3Mzu

c) GK3: basic notes from no hole closed to all hole closed from instrument (c). © A.F. Potengowski 2023
https://soundcloud.com/friederikepotengowski/c-gk3-3h-mi-hein/s-ngD5322yabM

d) GK3: basic notes from no hole closed to all hole closed from instrument (d). © G. Dalferth 2023
https://soundcloud.com/friederikepotengowski/d-gk3-3h-mi-dalferth/s-P3RIhaHWSOC

e) GK3: basic notes from no hole closed to all hole closed from instrument (e). © A.F. Potengowski 2023
https://soundcloud.com/friederikepotengowski/e-gk3-4l-ai-hein/s-Elde1eJ7rvV

f) GK3: basic notes from no hole closed to all hole closed from instrument (f). © A.F. Potengowski 2023
https://soundcloud.com/friederikepotengowski/f-gk3-5l-ai-potengowski/s-lUegFY7Z9q1

g) GK3: basic notes from no hole closed to all hole closed from instrument (g). © A.F. Potengowski 2023
https://soundcloud.com/friederikepotengowski/g-gk3-7l-mi-hein/s-RXH2C9aAEvE

h) GK3: basic notes from no hole closed to all hole closed from instrument (h). © A.F. Potengowski 2023
https://soundcloud.com/friederikepotengowski/h-gk3-5h-mi-trommer/s-C9CmvujibCj

i) GK3: Reconstructions (a) to (h) from 2 holes closed to 1 hole closed. © A.F. Potengowski 2023
https://soundcloud.com/friederikepotengowski/8-reco-comparison-example/s-DDlMdZUtI6O

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