Calculating Auloi – The Louvre Aulos Scale

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ZUSAMMENFASSUNG

Kann man aus den Funden antiker Auloi den für die einzelnen Instrumente intendierten Tonvorrat ermitteln? Sowohl der experimentelle Ansatz als auch die bisher verwendeten rechnerischen Methoden stoßen hier auf Probleme. Einen großen Schritt weiter kommt man mit speziell entwickelter Software, die es erlaubt, im Rahmen der verfügbaren Parameter die Bandweite der unbekannten Werte, speziell der effizienten Rohrlänge zu erkunden und so zu Lösungen zu gelangen, die im Rahmen der antiken Musik und Skalenlehre sinnvoll sind. Beispielhaft ausgewertet wird das besterhaltene Gesamtinstrument: der Louvre-Aulos.

Was war aber die übliche Spielpraxis auf dem gedoppelten Instrument? Die Interpretation antiker Textpassagen stellt den Aulos in den Zusammenhang einer intervallisch-heterophonen Musikkultur, wie sie auch für den alten Orient bezeugt ist, und die auch in Griechenland mit hoher Wahrscheinlichkeit schon vor die klassische Zeit datiert.

Auloi come in pairs. This at least is obvious to anyone who has seen some of the countless iconographical representations of this major woodwind instrument of antiquity. Weird as it seems to the Western musician of today, throughout antiquity the Greeks have not abandoned the custom of playing two double-reed pipes at once instead of exploiting the advantages of the extended range of and control over a single pipe; nor have other peoples in their neighbourhood. To such an extent the pair of pipes was felt as a unity, that the instrument was more often than not called by the singular "pipe", *aulós*. The type of instrument familiar to us was not unknown, but it was perceived as a deviation and was referred to by the explicit notion of a "single pipe", *mónaulos*. We will come to this instrument later.

As interest in ancient music increased during the last decades, the aulos gained particular importance as a promising source of information on early scales. While literary testimonies on this subject are notoriously late and to be treated with suspicion – not to mention the problems of transmission errors –, and while the tuning of stringed instruments has left no archaeological traces, woodwind instruments could be hoped to preserve the scales they were intended to play within the arrangement of their finger holes. Nevertheless we are facing the paradoxical situation that, in spite of the fact that numerous fragments of auloi and even complete pipes have been unearthed, these findings have shed no light on ancient musical practice. There is no theory that inserts the archaeological evidence into our picture of ancient Greek music, and all attempts to interpret single instruments are far from satisfactory.

This obvious failure has sometimes led to a pessimistic view[1]: on reed-driven woodwind instruments, the player can vary the pitch quite easily by means of embouchure. An accurate tuning is by no means guaranteed by the proper arrangement of finger holes (and this was well known in antiquity[2]). So we can never know which scales were played on extant instruments. However, this is true only in principle, as we learn from comparison with modern instruments as oboes or clarinets. Certainly skilled players are able to play scales on these for which they are not designed, mainly by adjusting the pitch of the reed by different lip pressure. But to do so, they have to play "against" the instrument. The same is true for ancient auloi, for which we have evidence that they were designed in order to give a certain scale no less than modern instruments. First of all, aulos finger holes are not spaced equally, nor in a way that fits the player's hand best, but differently on different instruments. And secondly, there are also traces of fine-tuning by undercutting the rims of the holes, a procedure that makes sense only if the player did not intend to fine-tune each tone just on playing.

1 Most prominently Landels 1981; Mathiesen 1999, 193. Cf. also Becker 1966, 98–100.

2 Aristoxenus, Harm. 2.41–42, p. 52.9–21 Da Rios.

So it is clear that the reed-control problem is not fatal to our primary assumption that aulos finger holes may be guides to aulos scales. But unfortunately, it is indeed fatal to the evaluation of these scales by playing replicas[3]. It seems that we would need a skilled aulos player with a good original aulos reed to achieve an embouchure steady enough for meaningful measurements. Modern players are not only not familiar with the instrument; they are also subject to the danger of unconsciously adjusting their embouchure to "correct" the scale according to modern customs. And even if the instrument would no doubt support the player who knows the intended pitches, those who don't are at a loss, and end up with the impression (not unfounded, as we have seen) that they could play anything.

And still this is only the minor problem with the practical approach. More serious is the fact that in the majority of cases the upper end of the pipe is missing, and even if we possess the instrument in its whole length we do not *a priori* know the effective length of the reed (nor its acoustical properties). Practical experiments with the continuum of possible lengths are hardly possible; so in most cases one has to start from a theory of a scale to check it in experiment, facing at last the obstacles described above.

This leads us to the second approach, the mathematical one. Woodwind instruments follow the laws of physics, so it is in principle possible to predict their behaviour without building replicas. J. G. Landels was the first to propose a simple procedure for finding the approximate pitches of an instrument with unknown effective length[4]: One needs

1. to find two finger holes which are likely to give a certain concordant interval, preferably a fourth, because this is the basic interval of ancient Greek scales,
2. to calculate the effective length of the pipe from the distance between these finger holes and the ratio implied by that interval, e.g. the ratio 4 : 3 for a fourth,
3. to calculate the pitches for the rest of the finger holes from their positions, using the effective length obtained in step 2.

This procedure has since been applied to a number of early aulos fragments, however without convincing results[5]. To find its possible weak points, it is important to make explicit the assumptions that lie behind these calculations:

1. It is likely to encounter concordant intervals on one pipe of an aulos.

This may seem obvious at first glance, just because there is no doubt that concordant intervals played a vital role in Greek music. Yet it is not so clear that we find them necessarily on each pipe of a double-pipe instrument, nor even that we find them on any of both: the pitches that form the concords might have been distributed between the pipes. This touches the highly disputed matter of ancient heterophony, and we will postpone the question for the moment, to examine the second assumption:

2. The pitch relations of woodwind finger holes are the same as the relation of their distance from the top of the instrument

This is true only in a first approximation. The statement may not be extended to the pipe with all holes closed[6]; but this is not problematic with early auloi, which usually have a vent hole to sound the lowest note. Because wall thickness as well as hole diameters remain constant over the length of an aulos, the intervals that one obtains between individual finger holes will not be so far off. Nevertheless there are mathematical means to go well beyond the level of accuracy that is available by this simple procedure, means which allow also gauging not only the pitch relations but the actual pitches. The extended calculations inherent in the application of these more accurate formulae can be done easily by the help of the computer, and I will show below how this is most efficiently done.

First we have to consider the question of concordant intervals, which depends on how the two pipes of the aulos played together. The different views taken by scholars on this topic need not be recapitulated here in full, nor need the arguments in favour of each of them[7]. Currently the older view, that there was a "melody" and an "accompaniment"[8], seems to be gaining territory again, after a period during which it was more fashionable to believe in strict unison, both between the pipes and, if lyres or auloi accompanied vocal music, between instruments and voices. The latter view is, however, still held by Landels in his recent book. Interestingly enough, it is not shifting evidence that has caused the changes in the scholars' opinions; it seems rather to be a question of on which type of sources one is inclined to rely most. Landels, for instance, makes it explicit, that for him[9]

> "the first, and by far the most valuable, is the pictorial evidence from vase-paintings. … the

3 Cf. Landels 1999, 272.
4 Landels 1963; Landels 1968; Landels 1999, 271–275.
5 Cf. Letters 1969; West 1992, 97–101.
6 As done by West 1992, 100 f. Given the relation of the diameter of the bore to that of the finger holes, West's calculations for the intervals from finger holes to the whole pipes are off by more than a quartertone.
7 An excellent overview is given by Landels 1992, 41–46.
8 In 1928, Winnington-Ingram could speak about "the orthodox theory of polyphony" (8).
9 Landels 1992, 42.

> literary evidence is much less satisfactory; in fact, there is no explicit statement about the piping techniques of the Classical period."

We will have to concern ourselves with the question of literary testimonies later. Let us first consider for a moment the possible value of pictorial evidence for playing techniques. Evidence about the pipes sounding different notes could be gained from two possible features: either if different fingering is clearly shown, and if it can be made plausible that the painter has done so deliberately, or if the hands are depicted at different locations on both pipes, and again if this may not be accounted for by purely artistic motifs. Landels argues that none of the criteria is met on any painting, even if he admits that different hand positions are clearly depicted on at least one example. Interestingly enough, an analysis of the same pictorial evidence can also come to the opposite conclusion[10], which proves at least that extensive statistical data based on clear criteria are needed in support of any statement on this issue.

On the other hand, I would argue that any pictorial evidence must be treated with the highest degree of suspicion *a priori*. On the basis of vase paintings it has even been argued that the bore of the aulos widened gradually from the mouthpiece to the main part, although a glance on the extant fragments tells us for sure that the pipes had a continuously cylindrical bore[11]. The vase painters strove for elegance, and to maintain a "realistic" impression within the limits of their technique, they would have had to dispose of photographic ideals, even if they could be assumed to have possessed them (which they can not). Furthermore, when a musician is depicted in actually playing his instrument, we cannot tacitly assume that a snapshot is given of his gestures at any given moment. Instead, we have to expect traditional typical positions: just as in images of lyre players we find the left hand usually in a typical "playing" position, with four fingers stretched out, or in a "holding" position, with fingers relaxed and bent: almost nothing of the more complex movements which we expect during playing. In aulos playing, more often than not it is hard to tell if the painter intended to depict any fingering at all. And if he did, and both hands show the same fingering, this need not mean more than that he has indicated that both pipes are being fingered. To infer unison playing from iconography almost implies that the painters wanted to transmit information that would become relevant only for future musicologists. If we look at it from the artist's view: the task is to paint two times the item "hand fingering aulos". If in the painters mind there exists a template with index finger raised, why not apply it twice? If, on the other hand, different fingering is shown, this need not necessarily imply heterophonic playing. Yet it is much more likely to have been done deliberately, and thus a much stronger hint to non-unison playing than equal fingering is to unison playing.

Literary evidence, on the other hand, has to fear none of these objections. Especially in music-theoretical sources, we obtain information not just by incidence: it is in the authors' interest to make things clear to their recipients. Often enough, it must be admitted, matters remain dark to us, because we do no longer know of things which the original readers were familiar with; but this will annoy, not deceive us. Only sometimes is it possible that the theories brought forth are biased by ideology. But this is true almost exclusively for Pythagorean sources; Aristoxenus (and his followers) did not need to search for conformity with presupposed dogmatic views.

A. Barker, in an admirably clear account of the available literary sources, has dealt with the question of "*heterophonia*" in ancient Greek music; that is, with the difference between the notes sounded by the melody and the accompaniment[12]. On the basis of overwhelming evidence, he concludes that already in early time music was performed in which a quite independent accompaniment played a substantial role, not at last to support the perception of the rhythm. Though in detail many uncertainties remain, I think we can take Barker's main conclusions for granted. To me, the most puzzling problem seems to be: how could the very existence of ancient heterophony[13] be denied in modern scholarship, facing the evidence cited by Barker? Curiously enough, this blind spot seems to be connected with the most celebrated source for our knowledge of *heterophonia*, from Plato's Laws, which I would like to quote in full. It forms part of a discussion about how and to which extent music shall be taught to the young:

> Τούτων τοίνυν δεῖ χάριν τοῖς φθόγγοις τῆς λύρας προσχρῆσθαι, σαφηνείας ἕνεκα τῶν χορδῶν, τόν τε κιθαριστὴν καὶ τὸν παιδευόμενον, ἀποιδόντας πρόσχορδα τὰ φθέγματα τοῖς φθέγμασι· τὴν δ' ἑτεροφωνίαν καὶ ποικιλίαν τῆς λύρας, ἄλλα μὲν μέλη τῶν χορδῶν ἱεισῶν, ἄλλα δὲ τοῦ τὴν μελῳδίαν συνθέντος ποιητοῦ, καὶ δὴ καὶ πυκνότητα μανότητι καὶ τάχος βραδυτῆτι καὶ ὀξύτητα

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10 Byrne 2000, 282; 285 fig. 10.

11 Najock 1996. Compare the difference between the kithara and its representation on vase paintings as analyzed by Psaroudakes 2000.

12 Barker 1995.

13 From now on I will use the English version of the Greek term *heterophonia* for the supposed technique of accompanying a fixed melody with different notes, producing not only unisons, but also concordant and discordant intervals.

> βαρύτητι σύμφωνον καὶ ἀντίφωνον παρεχομένους, καὶ τῶν ῥυθμῶν ὡσαύτως παντοδαπὰ ποικίλματα προσαρμόττοντας τοῖσι φθόγγοις τῆς λύρας, πάντα οὖν τὰ τοιαῦτα μὴ προσφέρειν τοῖς μέλλουσιν ἐν τρισὶν ἔτεσιν τὸ τῆς μουσικῆς χρήσιμον ἐκλήψεσθαι διὰ τάχους. (812de)
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> For this reason they have also to make use of the pitches of the lyre, just because of the exactness of string notes, both the kithara-player and the novice, giving in unison (?) sound for sound. But the different and manifold playing of the lyre, when the strings emit one melody and another one the composer who has put together the melody, and when they set wide intervals against close ones, high against slow tempo, and high against low pitch in concords and discords, and when they fit all kinds of manifold rhythms to the sounds of the lyre in the same way, all of that kind, I say, not to offer to those who shall grasp quickly in the course of three years what is useful in music.

Starting from this passage, traditional argument seems to proceed more or less as follows: "There has been a style of heterophonic lyre-music, which Plato deprecates. As a conservative philosopher, he is oriented on the Classical age before the composers of the New Music deteriorated everything. Thus *real* Greek music did not depart from unison." Consequently the artistic value of Greek music from the Classical period (from which we possess no single melodic phrase) has almost never been doubted, while the earliest extant melodies, dating from Hellenistic times, are not seldom met with disgust.

A careful reading of Plato's text, however, does not justify these conclusions at all. Plato (or, more exactly, his fictive Athenian) does not express his disapproval of the style of music he is alluding to. We can infer so only if we take for granted that the single items of his description bear a negative connotation in themselves; but that would be circular. Certainly other passages on music by Plato, especially the famous ones in the *Republic* have contributed to a quasi-analogous interpretation of the statement in the *Laws*. But we have to keep in mind that even the Socrates of the *Republic* is not so much contrasting contemporary music with older styles: most of the undoubtedly early modes are expelled from the Ideal State (and, on the other hand, the contemporary musician who does not fall into the accepted categories is treated with the utmost respect, even if not allowed to perform[14]). Thus we have first to accept that we must not suppose any chronological order between the two ways of playing the lyre, the note-to-note accompaniment and the elaborated style, on the basis of the passage from the *Laws*. Secondly, we may not even conclude from Plato's words that the note-to-note accompaniment was actually used in practised music. The speaker is simply not talking about playing music; he is discussing the use of an instrument in the classroom. Today, he might say: "One should also use the piano to teach the pupils singing, because it helps greatly in finding the correct note. But we will leave it at just playing the melody, not improvising an accompaniment with harmonic and rhythmic subtleties that might irritate them." To infer from such a prescription that the piano was traditionally not used to play polyphonic or harmonic music would, of course, be ridiculous. It goes without saying that this is not to imply that the lyre played anything like modern piano music, or that it used harmony in the modern sense. But I think it is plausible that the elaborated style was the usual one, that one which everyone deemed appropriate for really playing the lyre, let alone the kithara. We cannot tell, on the other hand, to which extent the note-to-note style was exploited for simple songs, performed on private occasions.

The same phrase for accompanying note-to-note is also used in the Pseudo-Aristotelian Problem 19.9, which is also essential to our discussion:

> Διὰ τί ἥδιον τῆς μονῳδίας ἀκούομεν, ἐάν τις πρὸς αὐλὸν ἢ λύραν ᾄδῃ; καίτοι πρὸς χορδὰς καὶ τὸ αὐτὸ μέλος ᾄδουσιν ἀμφοτέρως·
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> Why is it that it is sweeter for us to listen to solo singing, if someone is singing to the aulos or the lyre[15]? And this in spite of the fact that in both cases they sing note-to-note and the same melody (as the instrument?).

This passage, taken as it is, indeed seems to indicate that this type of accompaniment was the only one known to lyre and aulos players. Still this is impossible in view of other evidence (as the passage from the *Laws*, cited above, and other passages discussed by Barker[16]), especially if we take into account the relatively late date of the *Problems*, which were formulated in a time when professional music performed by star artists was more important than ever before. Given the extremely compressed and often enigmatic language of the *Problems*, it is perhaps best to take the καίτοι sentence as distilling the essence of two thoughts into one sentence: the text might in fact mean, „and this happens *even if* they sing note-to-note and the same melody in both cases", which was not easily to render within the traditional form of a καίτοι sentence, nor necessary to formulate *in extenso* for

14 Rep. 398ab: προσκυνοῖμεν ἂν αὐτὸν ὡς ἱερὸν καὶ θαυμαστὸν καὶ ἡδύν …

15 The meaning may be in fact "sweeter … if to the aulos than to the lyre" (which is the meaning of the same sentence in 922a). Our argument is little affected by this ambiguity.

16 Cf. note 12.

readers familiar with the practices alluded to[17]. But another observation is interesting in our context: The author of the problems finds it necessary to double the expression: πρὸς χορδὰς and τὸ αὐτὸ μέλος[18]. Why would one not suffice? Perhaps the phrase πρόσχορδα/πρὸς χορδὰς does not exactly imply the doubling of the melodic line. Literally translated, it means "to (each) string/note", and I suggest that this applies to the rhythm as well as to the melody, or, since melody is accounted for separately, primarily to rhythm. This interpretation is in perfect accord also with the Plato passage, where the opposite of πρόσχορδα are both melodic and rhythmic embellishments and contrapuncts. Indeed it may even shed new light on Plato's phrase ἀποδιδόντας πρόσχορδα τὰ φθέγματα τοῖς φθέγμασι. Here the two notions are usually taken as pleonastic, the latter explaining the first. But the sense may be more definite, πρόσχορδα providing rhythmical unison, which is the basis for melodic unison, ἀποδιδόναι τὰ φθέγματα τοῖς φθέγμασι. This takes us to another passage from Pseudo-Plutarch, where the "unison accompaniment", πρόσχορδα κρούειν, is contrasted with the "accompaniment below the song", κροῦσις ὑπὸ τὴν ᾠδήν, which is said to have been invented by Archilochus[19]. If we apply our new, primarily rhythmic interpretation of the term to this information, we can no longer infer that pre-Archilochean (lyre) accompaniment was invariably just the replication of the vocal melody. Both melodic heterophony and intervallic play might have been employed, only that seemingly every syllable of the song was accompanied by not more than one strum on the instrument. For the authors of our literary sources this style lay centuries back, and another quotation by Pseudo-Plutarch shows that even the development of the most elaborated styles of heterophonic accompaniment was then musical history[20]: while contemporary (which must mean, fourth century) music loved melodic diversity (ποικιλία) – obviously gained through frequent modulations[21] –, the Classical style used manifold rhythms and sophisticated accompaniment[22].

The remains of Aristoxenian rhythmical theory contain some features that are hard to account for within the framework of our current knowledge. One especially enigmatic point is the notion of the possible extensions of rhythmic schemes, which do not fit into the metrical schemes of our texts[23]. We cannot go into detail here, but I suggest that these reflect Aristoxenus' efforts to describe such rhythmical subtleties as Plato mentions and which are reported to have started in the time of Archilochus. There, and in dance, the conception of rhythmic movements contained within other rhythmic movements makes good sense.

So much about lyre playing. Now that it is clear that heterophony was certainly employed between the strings and the voice, and that we cannot preclude its existence between strings even from the earliest times on, what follows for the playing technique of the aulos? Certainly that we must reckon with at least the same amount of heterophony between singer and instrument, when the aulos was used for accompaniment: for here two musicians are involved, while the kitharist accompanied himself. Besides, from early times on there were occasions when lyres and auloi played together[24]. Lyres then had not more than seven strings, and thus seven notes; but they covered the range of a seventh or an octave. Auloi, on the other hand, with both pipes sounded in unison, would hardly reach the ambitus of a seventh; but due to half-covering the holes, they would be able to play more notes, at least eight "meaningful" notes in the context of a Greek scale[25]. When playing together, both instruments would probably have had to give up their particular advantages, if played in unison. Is it really likely that musicians sacrificed the usual facilities of their instruments just for the sake of unison, and this for centuries, if not millennia? If we are ready to reject such an assumption, we are ending up with ancient heterophony again, this time between different types of instruments.

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17 We can, but need not, alter the text to arrive at the same sense, e. g.: καίτοι ⟨συμβαίνει καὶ τοῖς⟩ πρὸς χορδὰς καὶ τὸ αὐτὸ μέλος ᾄδουσιν ἀμφοτέρως.

18 Barker 1984, 191 ("they sing the same tune with unison accompaniment") understands the second expression of the Greek text as describing the relationship between the two ways of singing, the first between voice and instrument in each case. But this is not the natural order, and accordingly he exchanges the two expressions in his translation. If Barker is right, the following argument is obsolete; but at least our interpretation of the omitted "if" is confirmed: certainly the Greeks did not always sing the same melody.

19 Ps.-Plutarch, De musica 1141a. The subject of the sentence is not entirely clear. From a strict grammatical viewpoint it might be the 5th century composer Crexus, and West 1992, 359, takes it so. But the mention of Crexus was just an afterthought to a specific innovation of Archilochus, who is the subject of the paragraph, and it would seem more than awkward to continue about Crexus' inventions in that context (at least we would expect the sentence to make clear the change of the general subject, by a sentence-initial demonstrative: τοῦτον δὲ οἴονται ...). This is the view of Barker 1995, 45.

20 Ps.-Plutarch, De musica 1138b.

21 Cf. Hagel 2000, 115–119.

22 Cf. Barker 1995, 53 f.

23 Aristoxenus, Rhythmics, Psell. 12, p. 24.11–19 Pearson; Frg. Neap. 14, p. 28.21–29.6 Pearson (for both passages see Pearson's commentary).

24 To give just a few examples from vases: Berlin Antikenmuseum 31573 (ca. 700 B.C.), Berlin 1686 (6th cent. B.C.), Athens 16464 (6th cent. B.C.), Harvard 1960.236 (ca. 500 B.C.).

25 E.g. e-e*-f-g-a-b-b*-c, and ten notes if we add a*-b♭ from the modulating *synēmménon* tetrachord.

As soon as we allow for any kind of heterophony in early Hellenic music, it becomes more than plausible that heterophony took place also between the pipes of the aulos. Why should the auletes have ever restrained themselves from intervallic effects that were in common use elsewhere, especially as they played an instrument so obviously singing with two voices? We are not sure whether the aulos was in continuous use in Greece during the dark ages (though I do not doubt it) or rather re-imported from Asia Minor in Homeric times; but in any case its art was handed down to archaic and Classical Greece through millennia. The stability of its major design during all this time, namely the separation of the pipes, might almost suffice on itself to prove its heterophonic use to the unprejudiced mind: if both pipes had played the same melody, it would have been much more efficient to fix the pipes side by side and cover adjacent holes with just one finger[26], thus gaining at least three extra holes to extend the range of the instrument[27].

Finally there is a passage from Pseudo-Plutarch that provides most valuable information as it is derived almost certainly from Aristoxenus[28]. There we are clearly told about differences between the notes employed in the "melody", μέλος, as opposed to those used in the accompaniment, κροῦσις. The time envisaged is almost as early as one might wish: not the time of the half-legendary piper Olympus, but of his successors up to the Classical period at latest. The *trópos spondeiázōn*, the playing technique of which is under investigation, is only one step further in a development starting with the very archaic *spondeîon* scale, attributed to Olympus: one of its enharmonic *pykná*, so we are told, was divided into quarter-tones, while the second one was still undivided — in the melody, that is. There we would possess the most striking evidence for early heterophonic aulos playing, if we just could be sure if "melody" might not mean "vocal melody:" with heterophonic accompaniment, but only in respect to the voice, not within the aulos. Again it must be emphasized how unlikely it is that a double instrument played in unison in a style of music that made use of heterophony. Even the traditional presupposition of Classical Greek unison would more easily accept the assumption of unison between voice and aulos melody with a certain admission of heterophony in the second pipe. But how likely is it at all that Pseudo-Plutarch is talking about vocal ("aulodic"?), not about purely instrumental ("auletic") music[29]? The older "*spondeîon*" is doubtlessly auletic, but we are not told if it had heterophonic accompaniment. The later style, however, employed almost exactly the same notes in the melody as the older one, only with that additional intermediate quarter-tone. Certainly it is not plausible that the same melodic scale had now changed to the voice while the auletes had disposed of the restrictions, which were characteristic of the *spondeîon*. And indeed we are told that in Aristoxenus' times one could sometimes listen to auletes playing in an archaic style, without the divided semitone. So obviously others played the *spondeîon* less archaically, and did use the melodic scale connected with the "*trópos spondeiázōn*". The difference cannot have been very great, since Aristoxenus' wording indicates that it was not so easy to discern whether the semitone was actually divided or not[30].

So I suggest that the view that the terms "*spondeîon*" and "*trópos spondeiázōn*" denote different types of music, or even different steps in the development, cannot be upheld, and that the latter is used as a mere variation of the former by Aristoxenus. There was just one *spondeîon*, which was in the fourth century usually played with one melodic enharmonic *pyknón* in the melody, while the other one occurred only in the accompaniment. Although an older style was still heard sometimes, the differences were rather minute. Consequently this type of music belonged to the aulos alone, and the Pseudo-Plutarch passage does indeed prove that a fourth-century author did not perceive heterophonic aulos music as a novelty at all. We have

26 As with the modern *zummara*, cf. e. g. Landels 1999, 43. Keeping the pipes separate only to facilitate the adjustment of the tiny pitch difference between them is certainly not necessary with double reeds.

27 The thumbs might not be able to cover two holes, so we arrive at 4+4 instead of 5 holes.

28 Ps.-Plutarch, De musica 1137d. For a discussion of this passage see Winnington-Ingram 1928; Barker 1984, 255–257. The whole passage shows all signs of a quotation word by word. Aristoxenus has been criticized on making up a wholly implausible story about the origin of the enharmonic. Against this it must be said that Aristoxenus himself is only citing earlier authorities, and that he makes it clear that these offer only suppositions (ὑπόνοοῦσι, which cannot stem from Ps.-Plutarch, who would have used the singular according to his introductory ὡς Ἀριστόξενός φησιν). But this applies only to the origins: for the scalar structure and the accompaniment he draws on his own experience.

29 Barker 1984, 256 f. has once argued for aulodic music simply on the ground that there is melody and accompaniment; but he has since suggested an auletic performance: 1995, 50. This is also West's interpretation: 1992, 359 note 13.

30 How the ambiguity arose is easily understood as the intermediate note was executed by half-covering (or three-quarter-covering?) a finger hole, which happened also during covering or uncovering a hole while continuously sounding the instrument. This is, however, possible only when proceeding from one of the boundary notes of the semitone to the other, and we can conclude that even the more developed style did not use the quarter-tones except in this context.

not even found a hint in the direction that playing in intervals was anything but the usual auletic technique, just as we could not exclude intervallic lyre music from the earliest times on.

Let us now return to the question of aulos scales in the light of the foregoing considerations. First, the notion of "an aulos scale" itself becomes ill-defined if we take intervallic play into account. There is the old hypothesis that in Greek music the lower of two notes formed always the melody, while the higher was perceived as accompaniment, but it is not very well founded, and seems to have lost much of its reputation today[31]. Above all, this theory would reduce the possible compass of aulos melody again to that of one, namely the lower pitched, pipe. Still, it is true that the examples of accompanying notes mentioned in the Pseudo-Plutarch passage are all above the respective melodic notes.

In the design of an aulos pair it must have been of primary importance to have concordant finger holes distributed between both pipes. Concords within one pipe would arise merely as a side effect of unisons and distributed concords. Thus it is confirmed that the traditional major assumption for the evaluation of single pipe scales must be met with suspicion. It might well prove even impossible, except maybe sometimes on the ground of comparisons with extant pairs.

Our theoretical considerations so far have equipped us with the necessary confidence to proceed to the evaluation of the best preserved pair of pipes, which is also that one whose pipes belong together most obviously: the Louvre aulos. This instrument has been described by A. Bélis, who has also tried to interpret the musical relationships inherent in its finger holes[32]. Although her view that the two pipes of unknown date and provenance form a pair has been accepted by West[33], it has met severe criticism by Landels[34], so that we have to ponder the arguments brought forth by both sides. The appearance of the two pipes certainly leads to the immediate impression of a pair: both pipes are equal in length and of exactly the same shape, differing only in the disposition of finger holes. Of these there are nine on one and seven on the other pipe, so none of them could be played with one hand without some mechanism such as the well-known rotating sleeves, which we find on some other extant pipes. There remain, however, no traces of such a mechanism as we would expect. Moreover Landels points out traces of shaping especially around the thumbholes, which seem to make no sense beneath a wrapping of metal. He concludes that the Louvre pipes must be monauloi, single pipes. Still their exact resemblance as well as their preservation as a pair indicates a deeper connection. Have they been monauloi played simultaneously by two instrumentalists? Although this is not entirely impossible, I know of no representation, neither in art nor in literature, which tells of such a practice; so we should exclude this possibility if any other option is available.

Indeed we have to go even further and draw the monaulos theory in general into question. What is our evidence for this type of instrument[35]? It has left almost no traces in the visual arts, and almost all of the few Greek literary testimonies are known just from one source, namely the Deipnosophistae by Athenaeus. These have not always been seen in their context: in the course of the discussion Ulpianus makes mention of the monaulos just to tease the Alexandrinean Alcides:

> … καὶ οὐχ ὡς ὁ παρ᾽ ὑμῖν τοῖς Ἀλεξανδρεῦσι πολὺς ὁ μόναυλος ἀλγηδόνα μᾶλλον τοῖς ἀκούουσι παρέχων ἤ τινα τέρψιν μουσικήν.
> (Athenaios, Deipnosophistae 174b, p. 391.10–12 Kaibel)
> "… and not as with the instrument heard so frequently in your Alexandria, the monaulos, that gives the listeners more pain than any musical joy."

Alcides counters with a list of quotations from Greek authors that mention this instrument[36]. The list is not so very long, and we can be sure that Athenaeus did not pass over sources he was aware of. In some of the fragments that have thus come to us the monaulos is explicitly connected with foreign (or alternatively rustic) culture or seems chosen to invoke non-Greek connotations[37]. The tube of the instrument seems usually to have been made of reed.

If we turn to the interpretation of aulos findings, we will be surprised how many of the extant ancient pipes, and especially of the better preserved instruments, are supposed to be monauloi, given the scarce attestation of the latter in ancient sources against the omnipresent two-pipe aulos.

31 Cf. West 1992, 206 note 41; Barker 1995, 56; Landels 1999, 45.

32 Bélis 1984.

33 West 1992, 100 f.

34 Landels 1999, 279 notes 19 and 30.

35 For the following cf. Howard 1893, 12–14; 18; West 1992, 92 f. note 58; Barker 1984, 159 f. note 3; 264 f. note 20. Why Mathiesen 1999, 195, assumes Athenaeus to have equated the monaulos with the Pan-pipes escapes me, especially as he cites in full a passage in which it is referred to by the singular "reed-stem".

36 Deipn. 175e–176e, p. 394.12–396.10 Kaibel. The monaulos is also mentioned by Pollux, 4.75 (as Egyptian and Carian); Pliny, Historia Naturalis 7.204 (as Pan's invention); Martial 14.63.

37 The monaulos is associated with Egypt, with foreign instruments, and also with Pan. Cf. also the African playing the monaulos in Plutarch, Biogr. Caesar 52.7.4 f.

There have been interpreted as single pipes: at least one of the Castellani pipes[38], the fragments glued together into one pipe in the Karapanos collection[39], and now even the Louvre pipes. None of them is, of course, made of reed, and their highly elaborate and expensive design makes an odd contrast with the rustic instrument that we should expect. In the light of the sources, I think it is clear that any identification of a find as "monaulos" should be met with suspicion.

Thus I agree with Bélis and West that we must try to interpret the Louvre pair as one aulos. To do so, it has to be proved, however, that the design of both pipes fits together musically[40]. So we finally arrive at the necessity of undertaking exact calculations to find the pitches and intervals, which were most probably played on the instrument. For this task I have developed special software, which allows experimenting with different effective lengths of reeds. I have started from the following parameters:

– The positions of finger holes as given by Bélis, corrected in one case by 1 mm according to my own computer-aided measurements on her photographs[41].
– The length, diameter and wall thickness of the instrument as given by Bélis, allowing for additional 2.5 mm for the metal wrapping with its rotating sleeves[42].
– A temperature of air inside the instrument of T=27°C, which gives a free space velocity of sound of c=346.9 m/s[43].

The calculations were then carried out as follows, for each finger hole and for the whole pipe with all holes closed:

– A starting frequency was assumed in a first guess, based on the actual physical length (just as in the inaccurate approach described above).
– The end correction was calculated that arises from the additional volume of closed holes further up the tube, which volume contributes to the effective length of the vibrating columns of air[44].
– A second end correction was calculated for the open hole itself, taking into account, if necessary the lattice of open finger holes below it[45].
– The velocity of sound inside the bore was calculated[46].
– From the results, a corrected value for the frequency was obtained.
– Bearing in mind that this frequency was based on a wrong initial assumption, this corrected frequency was again fed into the same formulae, gaining a further corrected value. This process was reiterated until the difference between the results became insignificant.

The process described so far can be assumed to give quite accurate values for the oscillating regime of the fundamental frequency of the note produced from a hole. The pitch of the actual note, however, is determined not only by its fundamental frequency, but also by the regimes of the higher modes. So it was necessary to carry out the same calculations for some of the first modes, too[47]. After some experiment I decided to include the first 10 modes, which should suffice for all practical requirements.

The next step was less easy to take: I had to define to which extent the single modes should contribute to the resulting frequency. It is clear enough that the influence of the first mode should be the greatest, and lessen with the number of mode. On the other hand, one should not underestimate the presence of the higher modes on a reed instrument with such an exciting sound as the aulos is credited with[48]. It was not possible for me to measure the impedances of a replica; a spectrum taken from the note of a mid-range finger hole of a pipe that corresponds in length to the Louvre aulos has to suffice to give an impression of the influence of higher modes[49]. After some experimenting I have decided to apply a very simple formula, and to assign to every mode a weight reciprocal to its number: $w_n=1/n$.

For a given finger hole, however, not all the higher modes can build up their regime, only those whose frequency lies below the respective cutoff frequency. The value of this was calculated using a formula that applies to modern instruments, but can be assumed to give usable results for pipes of the aulos type, too. So it was ensured that only

38 Howard 1893, 58.
39 Masaraki 1974.
40 Bélis 1984, offers an interpretation by setting the distances between the upper end (without any reed!), and the finger holes in relation to each other. This did, of course, not result in meaningful scales, nor even in playable intervals (except perhaps by playing the pipes as end-blown flutes or trumpets). The results of West 1992, 100s are much better but still not precise, due to the methodical shortcomings described above.
41 Hole II on pipe A, according to Bélis' nomenclature: 15.55 cm instead of 15.65 cm.
42 Cf. e. g. Masaraki 1974. From the 3.5 mm found by her we have to subtract a certain amount for reasons of corrosion.
43 As we have to search for the optimal reed extrusion, differences in air temperature will have certain effects on absolute pitch, but virtually none on the intervals, so this parameter does not affect our study very much.
44 Benade 1960, 1597 equation 22a.
45 Benade 1960, 1601 equation 34; 1602 equation 38.
46 Fletcher/Rossing 1991, 177 equation 8.14. Cf. also Byrne 2000, 280.
47 For cylindrically bored reed-driven instruments, the higher modes are represented by the odd partials: $f_n=f_0(2n-1)$.
48 Cf. e. g. West 1992, 105s.
49 See Diagram 1.

those modes enter into the final weighted average that lie below cut-off[50].

But how great is the actual difference between our accurate formulae and the rule of the thumb employed in earlier studies? Let us compare the frequency values for one aulos, namely the Brauron aulos, studied and later re-evaluated by Landels. In Table 1 I print Landels' pitches together with the "accurate" ones. To ensure comparability, I have chosen a reed length that gives a lowest note identical with that of Landels. It turns out that up to the highest finger hole the difference grows up to 75 cents, three quarters of a semitone[51].

If we are not concerned about absolute pitch, it is still possible to arrive at a set of notes with roughly the same structure as Landels' proposed approximate pentatonic tuning over an octave, just somewhat below: 253 – 290 – 331 – 374 – 429 – 506 Hz. But, apart from the octave (by which I have defined the reed extrusion), none of the intervals in this scale is in tune within 20 cents, not even a major or minor third. Viewed against a pentatonic tuning in fifths and fourths there are deviations of ±37 cents.

If we want to get a scale out of the Brauron pipe, we have to extend it to an effective length of over 45 cm. There we find two fifths and three fourths, building a scale with an ambitus of a sixth, which is per se far more plausible than Landels' octave. The errors against Didymus' diatonic scale with great and small whole tones are ±21 cents. The arrangement of tones and semitones runs as follows: TTSTT, with the highest note as *mésē*[52]. A tentative matching of the pitch of this *mésē* with the later notation system[53] leads us to the Hypoaeolian or Hypophrygian key, the former of which we can exclude as belonging to those introduced by Aristoxenus. The Hypophrygian key, however, fits well for an aulos[54]. Still, the arrangement of notes is hard to understand in (Hypo-)Phrygian context[55], and so this one-pipe solution remains as unsatisfactory as earlier attempts.

I have to add a brief account of the software surface that I have designed to use the algorithms described above most effectively[56]. It consists mainly of tools to select different pipes for evaluation and to experiment with different effective lengths just by tracking handles on the screen. A large area is reserved for displaying the results of the current choices:

– The calculated absolute pitches, in Hertz.
– The calculated pitches as intervals from the lowest one, in cents.
– The intervals between adjacent finger holes, in cents.
– The modern pitch equivalents as note names and the deviations from these notes, in cents.[57]
– The ancient note symbol in vocal and instrumental notation for each pitch (as a "standing note"[58]), assuming a pitch of 352 Hertz for the Hypolydian *mésē* (a major third below modern *a*)[59].
– All intervals within one pipe or between both pipes that are in tune within a definable range. The intervals displayed can be chosen from a set of mostly superparticulars, from 2/1 (octave) down to 10/9 (minor whole tone), plus the unison and the ancient concords of an octave augmented by a fifth and a forth.
– The portion of the pitches that corresponds best to one of a set of predefined scales (such as diatonic and chromatic in different ancient tunings, tetrachordal, pentatonic, etc.).

As any change in effective length in a pipe is immediately reflected in all of these categories, it is very easy to determine the most plausible relation-

50 I have tested the accuracy of the predictions of these algorithms against the average of 10 series of measurements on an aulos of the length of the Louvre pipes (although with finger holes not so near the mouthpiece as on the higher Louvre pipe). Each measurement included the pitches from 6 finger holes as well as the pipe with all holes closed. Some came from staccato, some from legato playing. The predicted frequencies lay usually within one standard deviation from the measurements, while the average amount of difference between prediction and measurements was not more than 11 cent.

51 These values are based on an air temperature of 27°C. If we substitute the somewhat implausible "18°C from the player's lungs" assumed by Landels 1999, 273, the maximum difference based on the same lowest note amounts to 100 cents.

52 Here I agree with Byrne 2000, 281 with note 14 (even if I find the tuning not so "familiar"). I hesitate, however, to accept his general rule of distances: it cannot apply to instruments of any size, since both the maximum and the minimum distance of finger holes are naturally limited.

53 See below. When Landels 1999, 273–275, discusses the notational signs which might have been used for the notes proposed by him he seems to ascribe modern pitch equivalents to those modern note names that are traditionally used for transcribing ancient notation (mistaking the structurally equivalent notes, in which unaltered ancient note signs are rendered by unaltered modern note names, for "the traditional pitch equivalents"; cf. also 227). But these are to be taken about a third lower. Thus his proposed pitches actually fall out of his supposed original range of the ancient notational system.

54 In Aristoxenus, Harm. 37.26, p. 47.6 f. Da Rios, the manuscripts give τὸν ὑποφρύγιον αὐλόν, where we would expect τόνον. If this is the correct reading, it testifies the most intimate connection between the Hypophrygian key and the aulos.

55 For Hypophrygian we would expect something like TSTTST; cf. West 1992, 183; Hagel 2000, 172 Abb. 23; 178 Abb. 25; 184 Abb. 27.

56 See Diagram 2.

57 These pitches are not printed in Diagram 2.

58 These are the bounding notes of each tetrachord, and those with clearly defined pitch in relation to each other in the ancient notation. The pitch of the "movable notes", on the other hand, depended on the tuning.

59 Cf. West 1992, 273–276.

ships for which the instruments have been bored. I have also included an algorithm that performs a search for the constellation of effective lengths that give the greatest number of intervals out of a chosen set, but it is hardly necessary to use this tool, except for confirmation.

To make the scales and intervals audible, I have also provided audio output: the holes on each pipe can be accessed by a row of keys on the keyboard, so that it is possible to explore the tunings by actually "playing" both pipes together[60].

In the case of the Louvre aulos the optimal effective reed extrusions can be determined with great confidence as about 4.6 cm on the lower and 4.2 cm on the higher pipe. It has to be noted, however, that reed cavities tend to have an effective volume considerably higher than their physical volume, so the real extrusion might have been somewhat smaller. Since we know that the reeds of both pipes differed slightly in their acoustical properties[61], and since we have found that the "lower" reed is needed on the lower pipe, we will perhaps not go wrong to attribute the calculated 4 mm of effective difference between both reeds to their different properties rather than to an actual different extrusion: the slacker reed, per se more apt for playing low notes, was used on the lower pipe, and at the same time made up for the additional finger hole cavities on the other pipe. Thus an irritating mismatch between the positions of both pipes in regard to the player's mouth was avoided.

With such reeds and all finger holes closed, both pipes have sounded a lowest note of about 178 Hertz, a bit above modern F. Table 2 gives a list of the consonant (in the ancient definition) superparticular intervals between both pipes that are less than 20 cents off. It is significant that in this table unisons, octaves, fifths and fourths dominate clearly over the minor intervals (given only for the sake of argument), which we would expect to be much more prominent in a random scale: while we encounter 22 intervals of the category of those four that are relevant for the scalar structure, there are not more than 13 instances of the four smaller ones[62]. The major consonances within each pipe, which cannot be played simultaneously but only melodically, are listed in Table 3.

Still more important than the existence of a fairly large number of concordant intervals, although related with it, is the question of an interpretable scale. And here we find that the notes on both our pipes work together nicely to build a diatonic scale ranging over an octave and a fourth. If we put aside absolute pitch for a moment, the scale runs from A to d', or, in ancient terms, from *proslambanómenos* to *paranétē diezeugménōn*, the latter being at the same time also *nétē synēmménōn*. Of the eight diatonic tunings transmitted by ancient scholars our scale matches best Ptolemy's "tense diatonic", with tetrachords of the form 16 : 15 – 9 : 8 – 10 : 9. Viewed against this tuning, the average deviation of our scale amounts to not more than 9.7 cents[63].

So far we have passed over an additional parameter that we are not able to get hold of by means of mathematics: the behaviour of the reed. M. Byrne stresses that its effective length must not be treated as a constant, and gives measurements to prove this fact[64]. Unfortunately we are not told the exact layout of his experiment.[65] According to my experience only high finger holes are affected noticeably, given that the diameter of the circular lower opening of the reed equals that of the main bore. The reed insert in ancient auloi is obviously designed to insure such a smooth connection[66]. In any case we have to reckon at least with a certain flattening of the highest note[67]. In our mathematical reconstruction, the topmost note lies about 30 cents too high to sound a concord fourth or fifth with the respective lower holes. About half of this deviation is accounted for by our assumption of the "tense" tuning, which does not include concords at this point of the scale. The other half, at least, will be due to the flattening effect of the reed;

60 For sound programming the Windows MIDI API functions have been used. To achieve the exact pitches, I have qualified the notes by 'pitch wheel' commands, on separate channels for each pipe.

61 Theophrastus, Hist. plant. 4.11.7. Cf. Barker 1984, 189 note 12.

62 The significance of this result can be guessed to about $p = 0.029$.

63 With reed lengths of 4.82 cm and 4.24 cm we come even slightly closer to the equally tempered scale of Aristoxenus (which is also our modern diatonic), with an average deviation of 7.5 cents. In this setting, however, the intervals are much less well tuned.

64 Byrne 2000, 280; 184 fig. 2.

65 Especially the relation of reed diameter and bore diameter, and the nature of their junction, would be of interest.

66 In the Louvre pipes, for instance, there is a step of approximately 0.85 mm at the end of the insert which presumably reflects the wall thickness of the reed at its lower end; cf. Bélis 1984, 114 fig. 7. This may well be the wall thickness of a length of *arundo donax* of suitable diameter once the pith has been scooped out.

67 In my experiments with auloi bored according to calculations this problem was always present, and I had to sharpen the highest note either by means of embouchure or by widening the finger hole or both. Curiously enough, the highest finger hole on the Louvre aulos is also wider than the rest. I can only assume that this was done to decrease the necessary span of the fingers; for the hole positions were certainly not based on calculations but on centuries of experience: simple Pythagorean mathematics would not have led to playable results. When we read that the manufacturers of auloi use simple ratios (Ps.-Aristotelian Problems 19.23), this is probably derived from a superficial inspection of their results, or reflects Pythagorean claims.

and perhaps this effect was even larger, and concords are intended. It is equally possible, however, that the larger hole was supplied for the "tense" tuning, if needed, but that it could be reduced to normal size by partially covering it with the help of (for instance) the rotating sleeves, in order to play in a more concordant tuning, which was certainly needed for modulations[68]. Our conclusion here depends on how great we believe the reed effect to have been. If we assume a flattening of 30 cents, there was no "tense" tuning, which requires a lowering effect of only 15 cents. The pitch of the note an octave below the highest one, however, seems also to point to "tense" tuning; but certainly we cannot base conclusions on mathematically reconstructed differences of 15 cents without additional evidence.

At least we can be sure about the layout of the diatonic scale itself. When we inspect it more closely, we find that almost every note on the pipe with more finger holes has its counterpart on the other one. The only exception is the lowest finger hole, which is unique on the lower pipe[69]. But not all respective holes are in unison with each other within our limit of 20 cent. Nevertheless all the "standing" notes, which build the tetrachordal framework, are in unison, namely A – (D) – E – A (D, the *hyperypátē*, being a standing note in the modulating neighbour keys[70]), but only one out of three "movable" notes (F). This might hint at a design that provides for different tunings within one instrument; but admittedly, seven pairs of holes are too limited an evidence to draw statistically valid conclusions[71].

The most obvious difference occurs between the two holes that give the *likhanós mésōn*, marked as "G" in Diagram 2. Here the lower note poses a special problem as it is not in the concord of a fifth or fourth with any other finger hole. With this "displaced" note (according to modern ears), its tetrachord runs as follows: 107 – 167 – 230 cents. This resembles very much the ancient "soft" diatonic tuning, which is given as 100 – 150 – 250 cents by Aristoxenus, and as 84 – 183 – 231 cents by Ptolemy[72]. At the same time, the lowered "G" hole facilitates the production of a semitone above the note below, when playing a chromatic tetrachord: all the chromatic *likhanoí* had to be achieved by partially covering the diatonic ones. Why then don't we find a respectively lowered *likhanós* in the lowest tetrachord (*likhanós hypátōn*, "D")? This might have to do with modulation: the diatonic *likhanós hypátōn* occupies a position that in the neighbour key becomes a "standing" note, which was probably useful to have available on both pipes[73]. The *likhanós mésōn*, on the other hand, became a "standing note" only one key further; thus it was needed less often and it was sufficient to have it on just one pipe. In the light of the concurrent evidence it seems now likely that the other tetrachords were indeed designed for "tense diatonic", which however need not imply that this tuning was actually employed most frequently. Its advantage was that it implemented the highest tunings of both movable notes. Consequently all the other tunings could be achieved on the aulos by partially covering the respective finger holes (e. g. by means of rotating sleeves) or even by cross fingering[74].

Our calculations are further confirmed by the surprising concurrence that we encounter an exact unison of both pipes with all holes closed exactly at the setting that gives the overall maximum of consonances: here it is most obvious that the differences in behaviour between the two reeds are meant to balance the differently shaped bores with their unequal number of finger holes. At the same time these low notes have their exact counterparts at the octave. These represent the *mésē*, the central note of the ancient system, from which all other notes were perceived to derive their musical meaning. As the *mésē* is the highest note that is present on both pipes, it is ensured that it can be sounded together with every other note.

Only one note is significantly out of tune according to our calculations. It is the second lowest note, the *hypátē hypátōn*, structurally equivalent to our "B", and labelled so in the diagram. It appears to be 30 cents to high. As a "standing note" its position does not vary with the tuning, so another explanation has to be found. I suggest that the corresponding hole, which is the lowest one, was drilled on a less remote place (about 7 mm from the calculated optimal position, that is) to

68 If used as a diatonic *paranḗtē*, the required pitch depended on the tuning; if used as *nḗtē*, *synēmménōn*, a pitch a fourth above *mésē* was indispensable.

69 If this needs explanation at all, it might be related to the fact that this note ("B"), unlike all other ones cannot build both a fifth and a fourth with other notes (the "F" can, because there is a "C" both above and below it).

70 Lydian, Hypophrygian, Phrygian, that is, according to the following conclusions.

71 According to Sattherwaite's approximative test for differences between the means of two sets of measurements with markedly different standard deviations, the significance level amounts to $0.349<p<0.384$.

72 For lists of ancient tunings converted to cents, see West 1992, 166–170.

73 According to the following interpretation, the Lydian *proslambanómenos*: the note most plausibly used as a drone – when playing with a drone, that is; cf. the fascinating considerations in Byrne 2002.

74 Cf. Diagram 3. The effect of cross fingering on an aulos with its relatively large finger holes in respect to the bore is minute.

make it easier to reach with the little finger[75]. To decrease its pitch, the metal wrapping could again have been used. If the hole was indeed permanently partly blocked in this way, we must raise the question why the aulos maker has not drilled a smaller hole right away. If we do not want to take our refuge to implausible theories such as tradition or lack of tools, I can offer only one suggestion. I think it is possible that the art of aulos-making used templates (either working instruments or tables derived from these) that gave not so much ready-made recipes for standardized instruments but pitch structures in relation to numbers of finger holes. The instruments themselves may have varied considerably according to the players' special wishes[76]. The information a designer needed was then, where to drill holes to give certain concordances, if a certain number of further holes was needed between or above these. The placement of these other holes does not affect those intervals very much. But it must have been known that omitting a hole or changing its diameter considerably may indeed distort the intervals (because it changes the effective length of the tube). In the case of finger holes these distortions could certainly have been mended with some playing skill. The lowest note, however, would have needed a greater length of tube for any missing finger hole, which was neither possible to add afterwards, nor possible at all if equally shaped pipes were desired. So it was good advice to drill a standardized diameter of holes in any case, and to cover the cavity in a second step where necessary, with minimized effect on the effective length. In the case of our pipe, the effect of a smaller hole would admittedly be minute, but it increases with decreasing distance to the mouthpiece.

It is now generally agreed that the ancient notational system (in its evolved form, at least) implies a notion of fixed pitch. It was even possible to relate the ancient notation to absolute pitches with reasonable accuracy, and to establish the central note "Hypolydian *mésē*" as about a major third plus/minus a semitone below our *a* of 440Hz. This enables us to determine the key in which the Louvre aulos played. In Diagram 4 its *mésē* of about 356Hz is printed against the accepted ranges of the *mésai* that might be applicable. Of these we can rule out the Hypoaeolian, both because it is too low and because of its lack of importance as a scale. The Dorian cannot be excluded with certainty, as far as pitch is concerned; but in spite of its famous name, its use is virtually not attested in the musical fragments, and the Louvre aulos is most probably not so old that it could stem from a time when the Dorian was still flourishing[77]. So we will not go wrong if we conclude that the key of the Louvre aulos is actually Hypolydian, and we are confirmed by the fact that over half of the extant ancient melodies are notated in the Hypolydian or its neighbour key, the Lydian.

The lowest note of the aulos, sounded from the main bore with all finger holes closed, was called *bómbyx*[78]. On the Louvre aulos we have found that it has the scalar function of the *proslambanómenos*, and it is certainly not by chance that we find both terms linked also in the Pseudo-Euclidean *Division of the canon*:

> ἔστω τοῦ κανόνος μῆκος, ὃ καὶ τῆς χορδῆς, τὸ ΑΒ, καὶ διῃρήσθω εἰς τέσσαρα ἴσα κατὰ τὰ Γ, Δ, Ε. ἔστα ἄρα ὁ ΒΑ βαρύτατος ὢν φθόγγος βόμβυξ. οὗτος δὲ ὁ ΑΒ τοῦ ΓΒ ἐπίτριτός ἐστιν, ὥστε ὁ ΓΒ τῷ ΑΒ συμφωνήσει διὰ τεσσάρων ἐπὶ τὴν ὀξύτητα. καί ἐστιν ὁ ΑΒ προσλαμβανόμενος …
>
> (Sect. can. 19)
>
> Let there be the length of the canon, which is also that of the string, BA, and let it be divided into four equal parts in the points C, D, and E. Thus BA, being the lowest note, will be the *bómbyx*. And the same AB is epitritic (4 : 3) to CB, so that CB will sound a concordant fourth above AB. And AB is *proslambanómenos* …

The author is thinking about the division of a string, and still he calls his lowest note *bómbyx*, by a term that stems from the reed instruments. But it is clear that *bómbyx* is not just a synonym for "lowest note"; rather being the latter implies becoming the former. This can mean only that in the context of finding a tuning *bómbyx* has become the technical term for the starting point in relation to which the other notes have to be established. May we take this as a hint that in the time when the *Division* was written auloi usually played the *proslambanómenos* as their lowest note? This would imply an immense effect of music theory on instrumental practice. There was,

75 This depends on how we think the lower pipe was fingered. I suggest to credit professional auletes with a bit more skill than Bélis 1984, 115, does: the upper five holes can be fingered simultaneously without much exercise, and so I believe can the lower four, if perhaps not with the finger tips. Given the relatively wide spacing between the second and the third hole from the bottom of the instrument, however, it is a great relieve to have the distance between ring finger and little finger decreased.

76 For the star performer ordering (or in this case cancelling) special features cf. Ps.-Plutarch, De musica 1138a.

77 Moreover, the compass of the instrument speaks against a Dorian scale, especially if we assume it to be relatively early: while the *nḗtē diezeugménōn*, which was typical for the old Dorian mode, is absent (at least in the first mode), the *tetrákhordon hýpaton* is very prominent, which is said to have been completely alien to original Dorian aulos playing (Ps.-Plutarch, De musica 1137d).

78 Cf. Aristotle, De audibilibus 800b; Metaphysics 1093b; Theophrastus, Hist. Plant. 4.11.3; Barker 1984, 187 note 4; West 1992, 87 note 30.

at any rate, the mediating force of notation, which reflected Aristoxenian theory but was without doubt used by instrumentalists.

On the other hand, we wonder why on our pipes the Hypolydian scale should have been extended down to the lowest note of the scalar system, at the expense of much more prominent notes at the top. In the light of its relation to other keys, we should expect the main range of the Hypolydian to extend at least to *nḗtē diezeugménōn* or some notes above[79]. This leads us finally to the question of overblowing. I am convinced it is no coincidence that the ambitus of the Louvre aulos is exactly an octave and a fourth: since the cylindrical instrument overblows to the octave plus fifth, its scale could be extended upwards seamlessly, just as on the modern clarinet[80]. This was certainly no technical problem. When sounding high first-mode notes on one pipe, I have sometimes found it more difficult to play low notes on the other pipe simultaneously than to overblow them to the second mode.

Thus we arrive at a coherent interpretation of the Louvre aulos not only as an instrument but also as embedded in its context of the ancient scalar system. I think that this coherence should suffice to disperse the last doubts that the Louvre pipes belong to the same instrument[81], and that an intervallic playing technique was standard at least at the time when it was built[82].

79 Cf. the tentative reconstruction of Aristoxenus' scalar diagram in Hagel 2000, 184 Abb. 27.

80 The only shortcoming is that it was not possible to insert a semitone above the highest note of the first mode, *nḗtē synemménōn*, which modulations to the Phrygian (and perhaps the Hypophrygian) scale might require.

81 The complete lack of traces of metallic layers, if not explainable chemically, might be accounted for by the suggestion that the instrument was not completed. To the question of the alleged shaping of the finger holes I can contribute little, not having seen the instrument. In any case, the rims of holes are especially subject to natural loss of substance. On the other hand, shaped finger holes were certainly not less useful on metal-wrapped instruments; and if the thin inner metallic layer was meant to facilitate fingering in this way, it could do so only by reproducing the shape of the wooden corpus underneath. The oddly shaped additional minute cavity that results from closing a hole of this kind by means of a rotating sleeve (with its necessarily smooth inner surface) hardly affects tone production, according to my experiments. Alternatively, unwanted finger holes on this wooden instrument might have been closed by wooden pegs or even lumps of wax (cf. Becker 1966, 137–143), which, however, could not have been changed without interrupting the performance.

82 The present paper is based on research supported by the Austrian Academy of Sciences through APART (Austrian Programme for Advanced Research and Technology).

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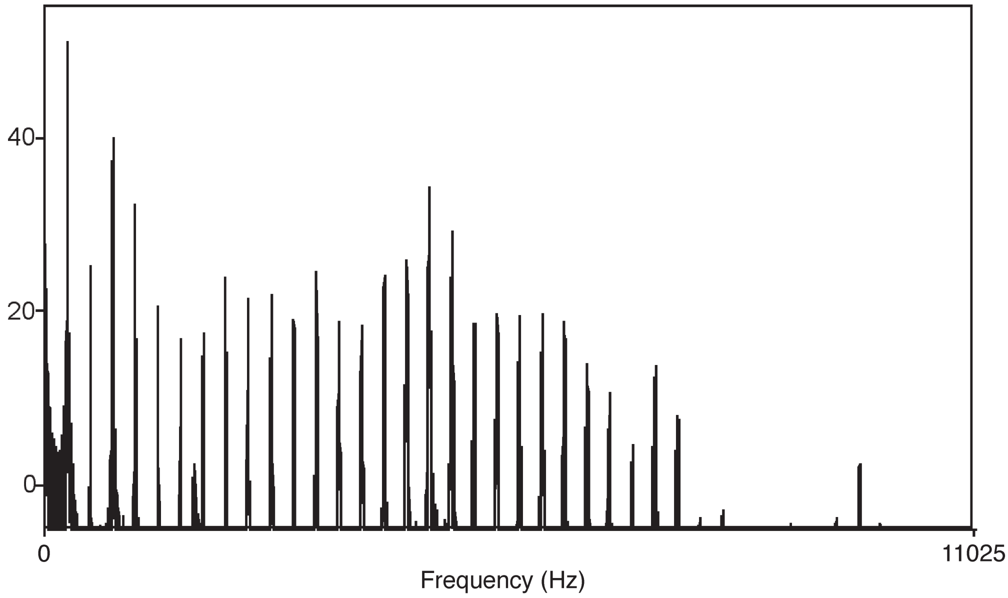

Diagram 1 External spectrum of aulos tone from mid-range finger hole.

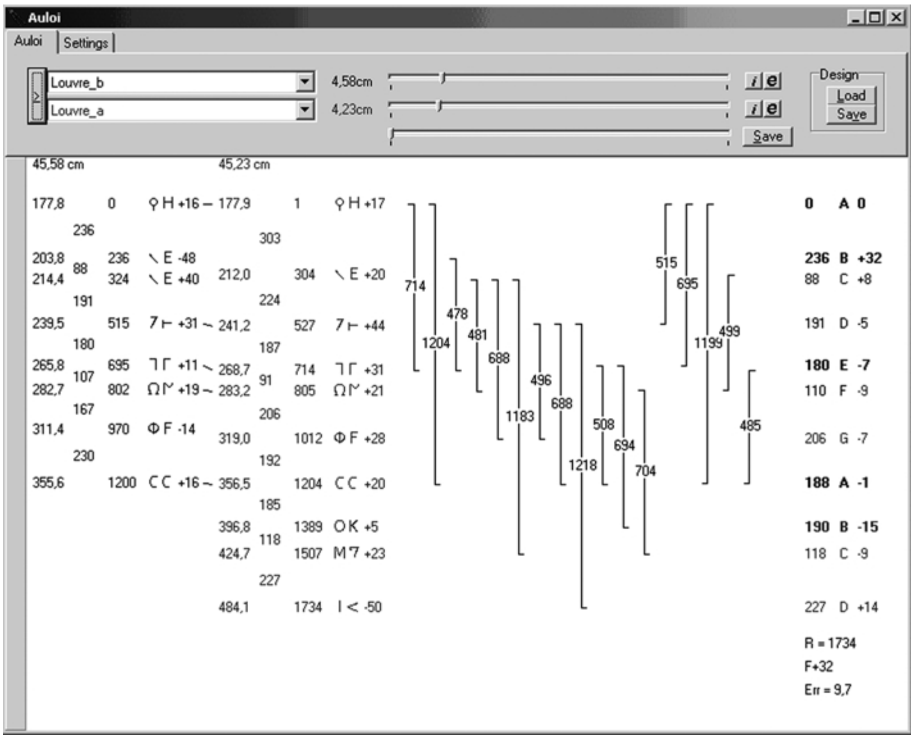

Diagram 2 Louvre aulos scale.

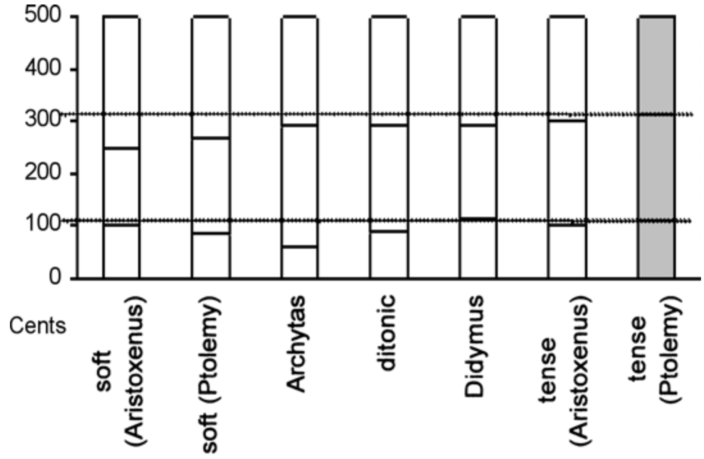

Diagram 3 Diatonic tetrachord tunings given by different ancient authors: Ptolemy's "tense diatonic" implements the highest movable notes.

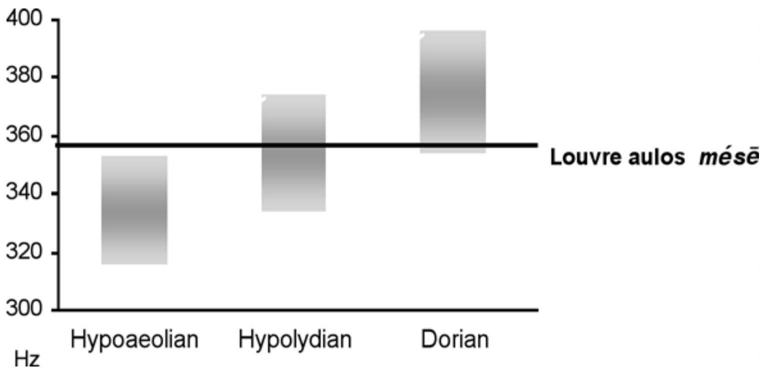

Diagram 4 Determining the key of the Louvre aulos.

Frequencies in Hertz		Difference in cents
Landels	"accurate"	
258	258.0	0
296	296.5	3
335	339.1	21
377	384.6	35
430	442.6	50
504	526.2	75

Table 1 Differences between the usual and the accurate prediction of aulos pitches.

Interval	Hole B	Hole A	cents off
Unisons			
1/1	0	0	+1
1/1	3	2	+12
1/1	4	3	+19
1/1	5	4	+3
1/1	7	6	+4
Octaves			
2/1	0	6	+4
2/1	7	0	–1
2/1	2	8	–17
2/1	3	9	+18
Fifths			
3/2	0	3	+12
3/2	4	0	–7
3/2	2	5	–14
3/2	3	6	–14
3/2	4	7	–8
3/2	5	8	+2
Fourths			
4/3	3	0	+17
4/3	1	3	–20
4/3	5	1	+1
4/3	2	4	–17
4/3	3	5	–2
4/3	4	6	+10
4/3	7	3	–13
"Discords"			
5/4	4	1	+5
5/4	2	3	+4
5/4	5	6	+15
5/4	7	4	+8
6/5	0	1	–12
6/5	2	0	+8
6/5	4	5	+1
6/5	7	8	–8
7/6	5	2	+8
7/6	6	3	–11
8/7	1	0	+4
8/7	3	1	–20
8/7	6	6	+3

Table 2 Unisons and major superparticular intervals between the Louvre pipes, up to an error of 20 cents (finger holes numbered from the farther end, with 0 for the whole tube).

Interval	Hole 1	Hole 2	cents off
Louvre B			
2/1	0	7	0
3/2	0	4	–7
3/2	3	7	–18
4/3	0	3	+17
4/3	2	5	–20
4/3	4	7	+6
Louvre A			
2/1	0	6	+3
2/1	1	8	+3
2/1	2	9	+6
3/2	0	3	+12
3/2	1	5	+6

Table 3 Octaves, fifths and fourths within each of the Louvre pipes, up to an error of 20 cents (finger holes numbered from the farther end, with 0 for the whole tube).