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INVESTIGATION ON THE IMPLEMENTATION OF OPTICAL REFINEMENTS IN THE PARTHENON FRIEZE RELIEFS

Abstract: *Issues related to visual representations as perspective distortions, optical illusions and refinements were known in antiquity, since a number of architectural monuments are illustrative of such practices. The Parthenon of Acropolis in Athens is a relevant example where this knowledge was probably applied. The present paper aims at providing analytically documented evidence of whether optical refinements were considered in adjusting the background level inclination of the Parthenon west frieze reliefs and in the design of the carved human figures. For this reason, the implementation of optical refinements for avoiding perspective distortions is elucidated and the calculations for their prediction described. Employing this mathematical analysis, optical refinements related to the west frieze reliefs and their background inclination were determined. These diminish optical illusions when a region of the frieze blocks' is observed from a viewpoint on the stylobates' level between two columns. Also presented are characteristic anthropometric proportions per interna--tional standards, and their modifications when optical refinements are applied. These modified proportions of a human body are compared to those of human figures carved on the Parthenon west frieze blocks.*

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The latter were determined via evaluation of their digital data obtained by means of 3D laser scanning. What was revealed, was an impressive conformity between the reliefs' background inclination along with the depicted human body proportions of the Parthenon frieze, and the corresponding ones calculated for avoiding optical illusions due to perspective distortions. These findings give substantial weight to the hypothesis that optical refinements were implemented in the Parthenon west frieze. However, they cannot exclude the fact that the human body proportions followed aesthetic rules and norms of the Parthenon construction period.

Keywords: *Parthenon west frieze; perspective distortion; anthropometric proportions; optical refinements*

Introduction

Issues related to visaual representations, as perspective distortions, optical illusions and optical refinements were known in antiquity, since a number of architectural monuments provide at least empirical evidence of such practices (Le Corbusier 1986; Korres 1999). The complex of the Acropolis in Athens, and particularly the temple of the Parthenon, is the most striking example where this knowledge was perhaps applied at its best (Fletcher and Sir 1996; Bouras 1998; Korres 1999). This *peripteral* temple on the Athenian Acropolis with *hexastyle* double *prostyle cella* was dedicated to the goddess Athena Parthenos, the patron (Polias) of Athens. Its construction began in 447 BC and was completed in 438 BC, although its decoration continued until 432 BC. While difficult to be seen from the ground, since it was positioned almost right under the coffered ceiling of the *pteromata* and partly masked by the columns of the *peristyle*, a significant feature in the architecture and decoration of the Parthenon is the bas-relief frieze illustrated in Pl. 1: 1. It was an uninterrupted band that ran roughly 11.5m above the *stylobate* of the *peristyle*'s columns, along the upper edge of the exterior walls of the *pronaos*, *naos*, *opisthodomos* and *opisthonaos*. It consisted of 115 blocks of approximately 160m in total length and 1m in height (see Pl. 1: 2). The frieze, carved mainly with continuous figured sculpture, represents a procession consisting of human figures and animals, mostly horses. The present paper investigates whether the parameter of perspective distortions influenced the design of human figures carved in the frieze reliefs, as well as the adjustment of their background inclination. Hereupon, based on measurements of sculptured human figures depicted in the west frieze reliefs, characteristic human body proportions were calculated. These were compared to corresponding ones of human bodies, respecting anthropometric standards that were adequately modified using analytical methods. The modifications enable the avoidance of perspective distortions of human figures placed on the frieze and observed from the *stylobates*' level, between two columns.

Optical refinements for avoiding perspective distortions

The first systematic scientific attempt to analytically describe optical phenomena can be found in Euclid's *Optics,* early in the 4th century BC (Kourniati 1998). Through a number of definitions and postulates, Euclid introduced a body of theorems about vision and visual representation. The basic postulates presented in *Optics* related to the described investigations can be freely expressed as follows. The perceived size of an object is related to the distance between the object and the observer (viewpoint). The perceived size of the object and the distance between the object and the viewpoint are always inversely proportional, thus meaning that the more the distance increases the more the perceived size decreases. The related Euclidian statetment describing these dependencies is, in its original phrasing: *Τά ίσα μεγέθη άνισον διεστηκότα άνισα φαίνεται καί μείζον αεί τό έγγιον κείμενον τού όμματος* (statement 5 of Euclid's *Optics* and visual representations in Kourniati 1998, appendix I). Therefore, as shown in Pl. 2 in the case of a high building, when entities of the same height u are located at different distances from the observer, the one nearest to the viewpoint, for example entity 1, is seen as larger (height u_1) compared to entity 2 (height u_2), although both entities possess the same height u. This happens because, as the distance from the viewpoint increases, the objects are gradually seen smaller than they actually are. To avoid such optical illusions due to perspective distortions, optical refinements (corrections) have to be part of the initial design of an object. In this case, the object should be designed adequately modified to appear correct when observed from a specific viewpoint. In the calculation of the corrections, the relevant location of the viewpoint relative to the observed object has to be considered.

Analytical determination of optical refinements

Having explained the rationale behind the artist's need to make optical refinements in order to bypass optical illusions due to perspective distortions, the analytical definition and calculation of these necessary optical corrections is introduced. The conducted procedure in the case of an object of a height U is explained in Pl. 3: 1, 2. The objective is to observe the n vertical equivalent sub-regions u_1 to u_n of this object, as presented in Pl. 3: 1, as of equal size from a certain viewpoint. The position between the object and the viewpoint is fixed and defined by the parameters b and Y. Without optical corrections, the equal-sized n sub-regions $u_1, u_2, ..., u_n$ (=U/n) would correspond to unequal sub-visual angles $\omega_1, \omega_2, \ldots, \omega_\eta$ (see Pl. 3: 1). In this way, according to the principles of visual perception, the unequal sub-visual angles $\omega_1, \omega_2, \ldots, \omega_\eta$ result in a distorted perception as far as the size of each sub-zone is concerned. As already described, the observer perceives the sub-zones closest to him as larger than they really are, as opposed to those that are at a greater distance, whose length he sees as smaller than the actual. To avoid this kind of optical illusion, the perspective distortion of the object when seen from a specific viewpoint should be taken into account and the necessary optical corrections determined, as elucidated in Pl. 3: 2. Keeping the overall height U constant, the heights of the sub-regions must be changed in order to correspond to equal sub-visual angles $\omega_1', \omega_2', ...,$ $\omega_\eta' = \Omega/n$, whereas Ω is the constant sum of the sub-visual angles. In this way, every sub-visual angle ω_i of constant value is associated with diverse sub-regions' heights $u_1', u_2', ..., u_n'$ which can analytically be determined employing the following equations:

$$\Phi=\mathrm{atan}((Y+U)/b) \quad (1)$$

$$\varphi=\mathrm{atan}(Y/b) \quad (2)$$

$$\Omega=\Phi-\varphi \quad (3)$$

$$\omega=\Omega/n \quad (4)$$

$$u_i'=b*\tan(\varphi+i*\omega)-b*\tan(\varphi+(i-1)*\omega) \quad (5)$$

$$i=1, 2, \ldots, n \quad (6)$$

Consequently, the lower sub-regions are shorter than the upper ones. Hence, if optical refinements are employed to bypass optical illusions due to perspective distortions, potential sculptured figures within the height U on the xy level should be appropriately designed, i.e. respectively corrected.

Furthermore, to avoid optical illusions, the dimensions in the z direction should also be corrected considering the dependencies presented in Pl. 3: 3, 4. Applying the previously described methodologies, for an observer to perceive the dimension t_1 as equal to t_n at the vertical distance U (see Pl. 3: 3, 4), the angles of observation ω_1 and ω_n must be equal. Hence, the dimension t_n must be corrected to t_n' using the following equation:

$$t_n'=(Y+U)(\tan(90-\varphi_{nr}+\omega_1)-\tan(90-\varphi_{nr}')) \quad (7)$$

whereas:

$\varphi_{nr}{}' = \varphi_{nr}$ (8)

$\varphi_{nr} = \mathrm{atan}(Y/(b-t_1))$ (9)

$\omega_1 = \varphi_{1r} - \varphi_{1l} = \mathrm{atan}(Y/(b-t_1)) - \mathrm{atan}(Y/b)$ (10)

According to the described analytical methods for defining optical corrections, although the volume V possesses a trapezoidal cross section, an observer perceives this volume as being orthogonal. In this way, an optical illusion due to perspective distortion is avoided.

Calculation of optical refinements adjusted to the west frieze data

The optical corrections depend on the position of the viewpoint. Hereupon, three regions could be considered as potential standing places to observe the west frieze of the Parthenon (Stillwell 1969; Ashmole 1972; Osborne 1987; Marconi 2009). A viewer could have been standing on the terrace outside the temple at the front of the *opisthonaos*, or between two columns of the *peristyle*, or even within the *peristyle* on the *stylobates*' level. On the one hand, an observer on the terrace could have seen the west frieze as a series of long panels framed on both sides by the *peristyle*'s columns and their capitals (Marconi 2009). Moreover, because of the long horizontal viewing distance of about 14m and the lower terrace level of approximately 2m compared to that of the *stylobates*' (Stillwell 1969; Orlandos 1978), the frieze background inclination would not have been perceivable due to restrictions set by the human eye acuity, as clarified in the following. On the other hand, a visitor would have not been able to enjoy a full view of the frieze within the *peristyle* since the relevant space is narrow and the observation angle too sharp. Therefore, in the frame of the present study, the most likely places for enabling an undisturbed view of west frieze regions were considered to be between the *peristyle*'s columns on the *stylobates*' level, as demonstrated in Pl. 4. From these places, an observer would look up more comfortably, at a less sharp angle compared to positions within the peristyle. However, because of the still sharp observation angle and the considerable distance from the eye due to the height of the frieze blocks on the architraves, the frieze reliefs appear distorted. Hence, it can be supposed that the sculptors were aware of this problem and the reliefs' tilt and the human figures' proportions were probably adjusted in order to avoid optical distortions.

For adjusting the previous parameters, the horizontal distance b between the viewpoint between two peristyles' columns and the relevant frieze region is considered to be approximately 4m (Orlandos 1977). In order to define the vertical distance Y between the observer and the viewed object, an assumption regarding the height of an average man of that period was made. Taking the height to be 1.65m, his eyes (viewpoint) should be about 1.5m higher than the zero reference level. Moreover, considering that the height of the frieze U amounts approximately to 1m and that it is set roughly at 11.5m above the zero reference level associated with that of the *stylobates*, the relative vertical distance Y of the viewed object from the viewpoint is around 10m. These distances will be referred to in the following sections as 'the west frieze data'.

The application of equations (1) to (6) for calculating the necessary optical refinements to avoid perspective distortions is demonstrated in Pl. 5. To the left, the displayed human body is divided into n=eight zones of equal length. Hereupon, the equation (5) was used for determining the individual height's corrections u_1 to u_8 of the introduced eight sub-zones. The results of these calculations are graphically demonstrated on the right in Pl. 5. An observer perceives the eight sub-zones as equal in length from the indicated viewpoint if the higher zones are adequately stretched, and the lower ones are shrunken compared to their actual size. According to the table at the bottom of Pl. 5, the percentage increase in the upper top sub-zone u_8' corresponding to the head height reaches roughly 7.5%, whereas the length of the lowest sub-zones u_1'+u_2' related to the shin length decreases at a percentage of 6.12% compared to the actual sizes of u_8 and u_1+u_2 respectively. These data remain almost constant if the distance b varies within a range of 3m to 4m. Furthermore, these data are considered for determining characteristic human body proportions optically corrected, as described in the next session.

The potential application of optical refinements, also in the perpendicular direction to the drawing surface of the human figure presented in the previous Pl. 5 may explain the inclination of the background level of the Parthenon frieze reliefs, as described in the publication (Bouzakis *et al*. 2016). The front plane of the reliefs is set at a right angle to both the upper and lower faces of the frieze blocks. The volume V, shown in Pl. 6, envelops the frieze reliefs and is associated with the sculptors' working space (Bouzakis *et al*. 2016). It possesses a trapezoidal cross section with lengths of the short parallel lower and upper sides of 47mm and 55mm respectively (see the right side of Pl. 6). If these sides had a common length of 47mm, as exhibited in the left side of Pl. 6, the observation angle ω_n of the upper side would be smaller compared to the lower one ω_1. In this way, an observer would perceive the width t of the frieze relief enveloping volume as decreasing versus its height U. To avoid this optical illusion, the upper volume side t_n had to be larger compared to the lower t_1 and associated with the same observation angle ω_n' as that of t_1, namely ω_1, which in the present case amounts to approximately 0.232° calculated by means of equation (10). Employing equation (7), considering that ω_n' is equal to ω_1, i.e. equal to 0.232°, the enveloping volume's upper width t_n' is determined to 50.5mm, i.e. slightly smaller compared to the actual width t_{na}' of 55mm determined on the frieze blocks (Bouzakis *et al*. 2016). The actual width t_{na}' corresponds to the observation angle ω_{na}' which can be calculated with the aid of the following equations:

$$\omega_{na}'=\varphi_{nr}'-\varphi_{nl}' \quad (11)$$

$$\varphi_{nr}'=\varphi_{nr} \quad (12)$$

$$\varphi_{nl}'=\mathrm{atan}((Y+U)/(b-t_1+t_{na}')) \quad (13)$$

$$t_n'=(Y+U)(\tan(90-\varphi_{nr}+\omega_1)-\tan(90-\varphi_{nr})) \quad (14)$$

It has to be taken into account that during the construction period of the Parthenon in order to determine t_n', graphical and not analytical methods were available where the design of ω_n' with the value of ω_1 was required. In this way, the developed slight deviation of 0.021° between $\omega_n'=0.232°$ and $\omega_{na}'=0.253°$ is reasonable and justified by the drawing's uncertainties. Hereupon, it can also be assumed that this deviation was intentionally introduced considering the visual acuity of the human eye. More specifically, the ability of the human eye to distinguish fine details is often quantified by minimum visual acuity. This metric is based on the smallest separation at which two parallel lines can be discriminated from one another by the human eye (Cameron *et al*. 1999). The most commonly cited value for the visual acuity of the human eye amounts to approximately a minimum observation angle of 0.017^0. This value is highly influenced by the contrast and luminance level of both the target and its background. Since an observation angle of 0.016^o associated with the difference between the ω_1 and ω_n angles (see Pl. 6) is slightly lower than the previously mentioned minimum visual acuity angle and moreover, the frieze was not well-lit because it was positioned almost right under the coffered ceiling of the *pteromata*, the reliefs' background inclination would not have been perceivable. Hence, the sculptors tried to avoid a visual obscurity concerning the reliefs' background inclination by empirically increasing the difference between the ω_1 and ω_n angles up to 0.037^0 in order to become sufficiently larger than the minimum visual acuity.

Furthermore, applying the equation (11) for U/Y/b equal to 1/12/14 m respectively (see Pl. 6), i.e. for the case of observing the frieze reliefs from ground on the terrace, the difference between the relevant ω_1' and ω_{na}' angles is determined to be *c*. 0.017^0. In this way, due to the above-described reasons, the reliefs' tilt is not perceivable and would have been rendered superfluous if it was observed from the terrace. Taking into account the previous dependencies, the possibility of implementing optical refinements when adjusting the Parthenon frieze reliefs' background inclination cannot be excluded.

Anthropometric proportions and their optical refinements adjusted to the west frieze data

To enable a comparison between characteristic human body proportions as carved on the Parthenon frieze blocks with corresponding ones of an average human body, some basic human body proportions based on anthropometric measurements are introduced. Thus, the Golden Section, or 'Divine Proportion' of the human body, with reference to the Vitruvian Man of Leonardo da Vinci (Zwijnenberg 1999; Neufert 2000), and international standards regarding ergonomics and body dimensions of people (*DIN* 33402-2 2005) were applied. According to these references, characteristic proportions between parts of the human body exist. More specifically, if an average person's height is equal to a, as shown in the left part of Pl. 7, the length of the head is equal to a/8, or a/7.95 of the height according to Neufert (2000) and *DIN* 33402-2 (2005) respectively. Moreover, the proportion of the shin length to the human body height equals 1/4 and 1/3.8 respectively using the above references. Furthermore, for determining the necessary optical refinements in order for both the head and the shin of an average man to be perceived by an observer with physical proportions when viewed according to the Parthenon west frieze data, the calculated optical corrections presented in Pl. 5 were considered. The 'height/ head' and the 'height/shin' proportions, if the human body height a is equal to the height U of Pl. 5, are calculated by means of the following relations:

$$\text{height/head}=U/u_8'=1/0.1250=7.44 \quad (15)$$

$$\text{height/shin}=U/(u_1'+u_2')=1/(0.1162+0.1185)= 4.26 \quad (16)$$

The values of U, u_8', u_1' and u_2' are taken from the table at the bottom of Pl. 5. Thus, for avoiding perspective distortions the upper regions of the human body should be stretched compared to their actual size, while the length of the lower ones should be reduced. In this way, it is inevitable that their relative human body proportions of 'height/head' and 'height/ shin' should also vary from the physical ones. Considering the west frieze data, the ratio 'height/head' diminishes compared to the physical one, while the ratio 'height/shin' increases, as presented on right of Pl. 7.

Determination of anthropometric proportions in human figures carved on the Parthenon west frieze blocks and their comparison to corresponding physical ones optically corrected

To investigate whether the human bodies depicted in the Parthenon west frieze were carved with optical refinements, their head and shin lengths were determined. This determination was performed by evaluating the digital database of the Parthenon west frieze blocks created by means of 3D laser scanning, as described in reference (Bouzakis *et al*. 2016). To avoid measurement divergences related to the positioning of the figures on the block reliefs, almost standing human figures were selected. More specifically, the standing human figures carved on the west frieze blocks WF_III, WF_V, WF_XII and WF_XVI were evaluated, as exhibited in Pl. 8. The selected human figures were the P4 (WF_III), P6 (WF_III), P9 (WF_V), P22 (WF_XII), P23 (WF_XII) and P30 (WF_XVI). The numbering of the blocks and the figures was conducted according to Jenkins (1994).

The determination of the head and shin dimensions, as well as their proportions to the standing human figures depicted in the west frieze reliefs, is elucidated in Pl. 9. The length of the head and shins of the individual human bodies was defined by evaluating the digital database of the 3D frieze reliefs (Bouzakis *et al*. 2016). Characteristic results of such an evaluation related to human figures P4 and P6 of the third west frieze block are displayed in Pl. 9: 1. The horizontal lines of the human body's dimensions are indicative and refer to the relevant dimensions of the digital 3D models of the reliefs. The determination accuracy is estimated to be less than 1mm. The same procedure was followed for all selected human figures of the west frieze blocks. The attained results for the height, head- and shin-length are inserted in the corresponding columns of the table in Pl. 9: 2. Based on these results, the corresponding ratios 'height/head' and 'height/shin' were calculated. These are displayed in the last two columns on the right of the previous table.

A comparison between these ratios and the corresponding calculated ones, as described in Pl. 7, can be observed in Pl. 10: 1, 2 for the 'height/head' and 'height/shin' proportions respectively. It is obvious that the actual heights to head and shin proportions of the standing human figures in the west frieze reliefs converge sufficiently with the optically corrected ones considering the west frieze data. This fact supports raising the hypothesis of the existence of analytically determined optical refinements in the hu--man figures carved in the Parthenon west frieze blocks to achieve better perspective representations. Hereupon, it cannot be excluded that the initial human body proportions were deliberately differentiated from those derived from a real human body, following specific aesthetic rules and norms of the Parthenon construction period (Kokkorou-Alevra 1990). However, the exact conformity of the human figure's proportions and of the reliefs' background inclination to related calculated data strengthens the assertion that aspects of optical refinements were implemented in the Parthenon frieze.

Conclusions

The implementation of optical refinements for avoiding perspective distortions when the Parthenon frieze reliefs are observed from the *stylo--bate*'s level was investigated. The presented results give reasons to assume that optical corrections were employed in the carved human figures in the Parthenon frieze reliefs and in adjusting their background inclination. The deviations from the physical anthropometric proportions of the carven human figures, which converge with the results of related calculations, offer support for the employment of optical corrections to avoid optical illusions due to perspective distortions. Moreover, the conformity of the frieze reliefs' inclination with the analytically determined one con--sidering optical refinements, further ascertain the potential application of optical corrections. Although these findings may be elucidated according to aesthetic rules and norms of the Parthenon construction period, the compliance between actual and calculated frieze data for avoiding perspective distortions, as described in the paper, renders the implementation in antiquity of mathematically estimated optical refinements possible.

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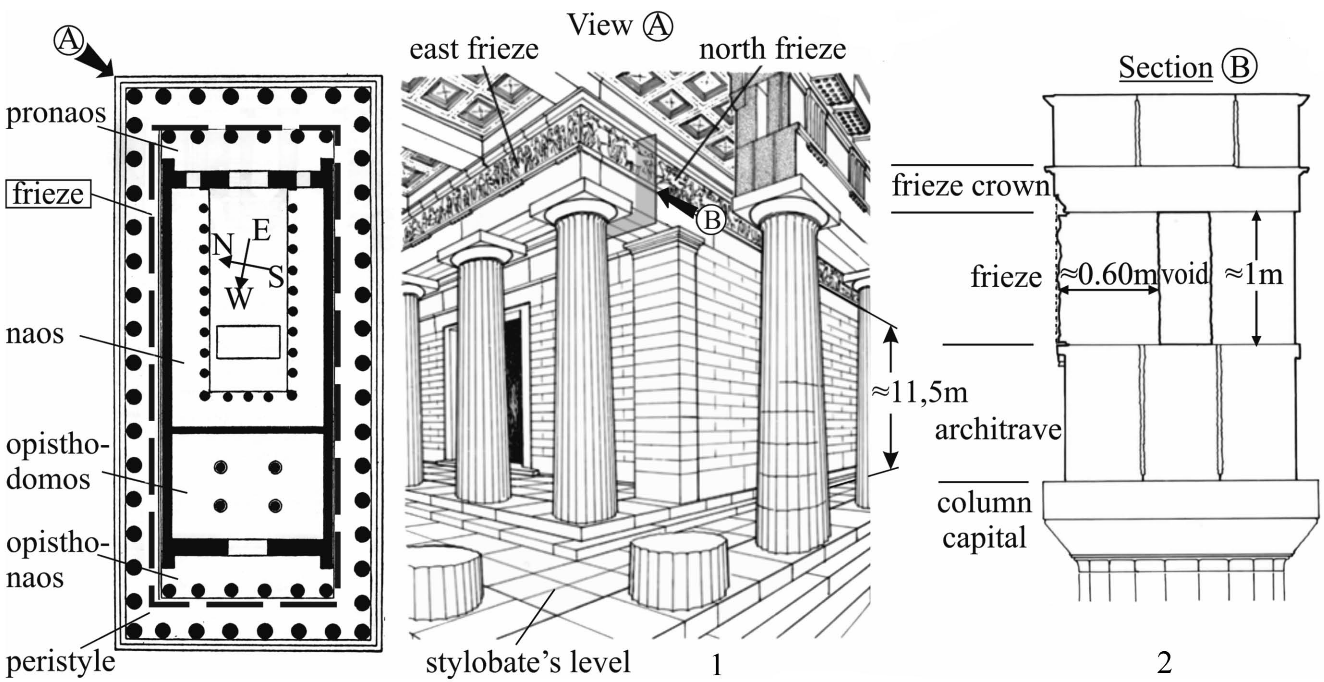
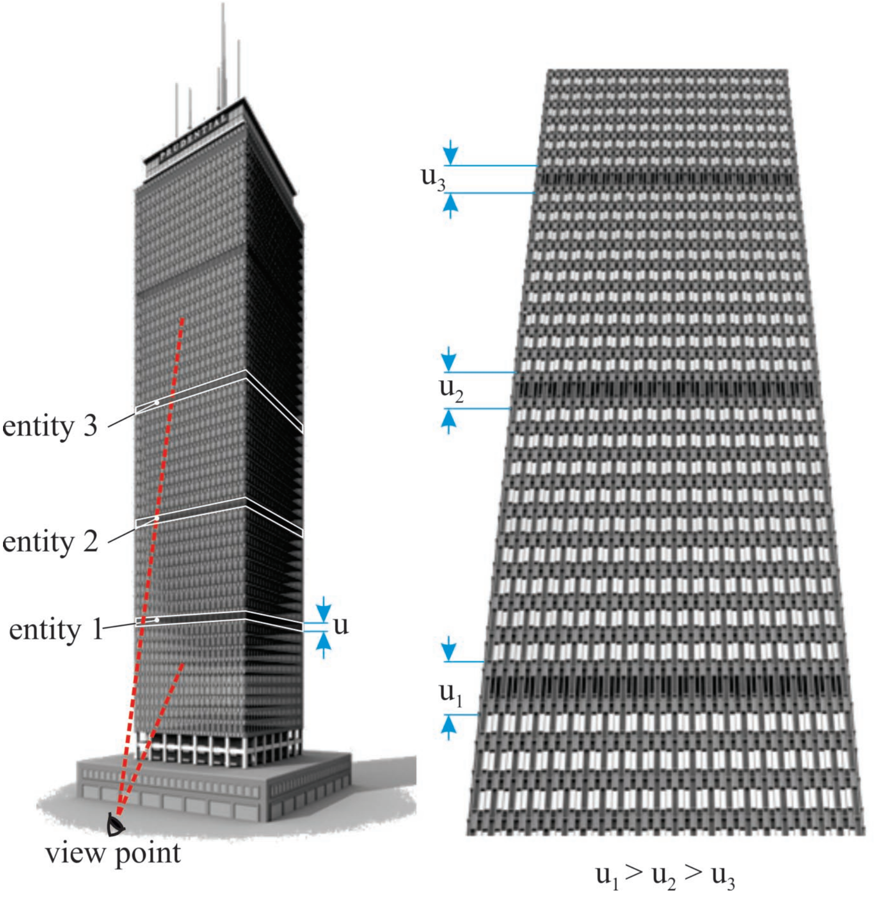
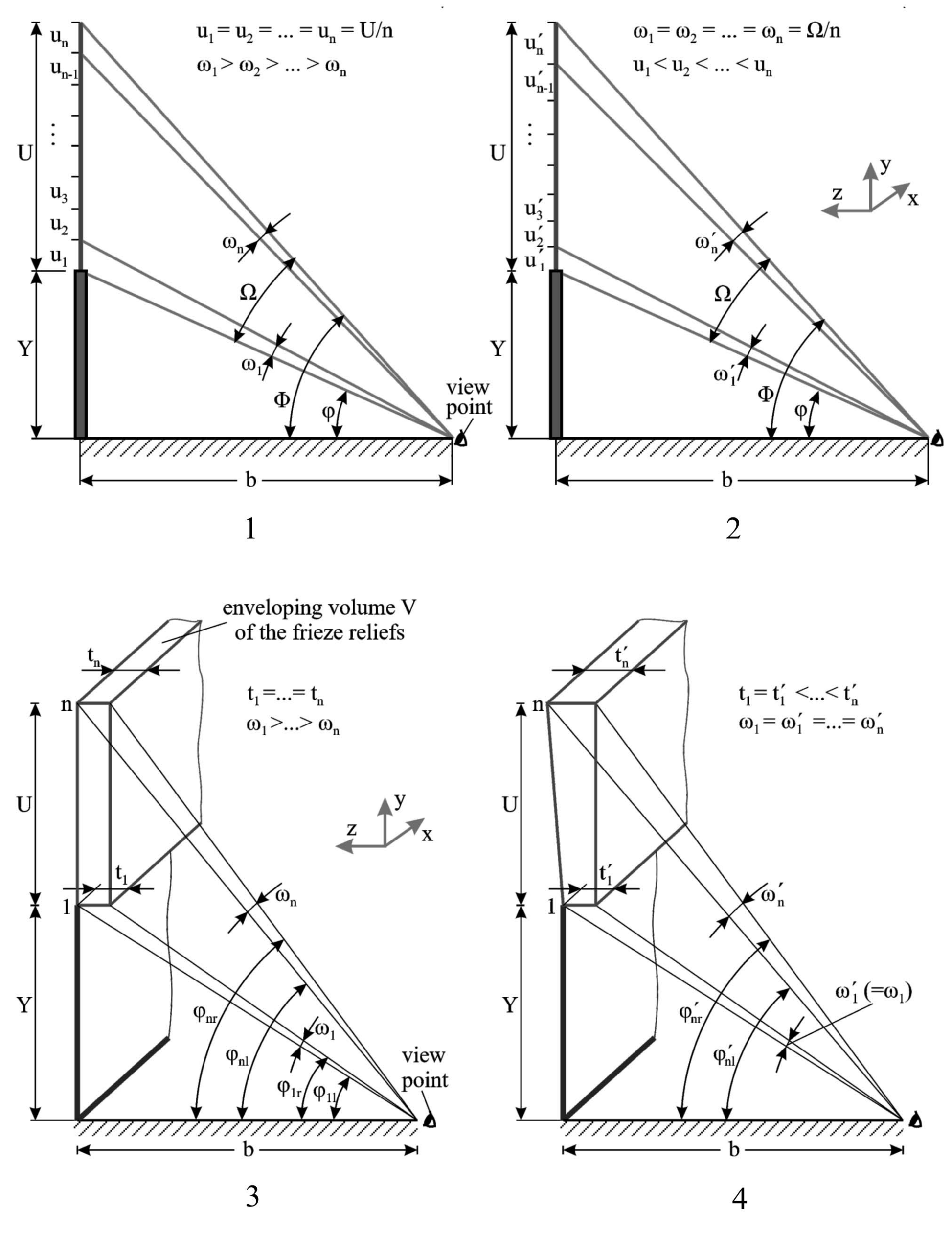


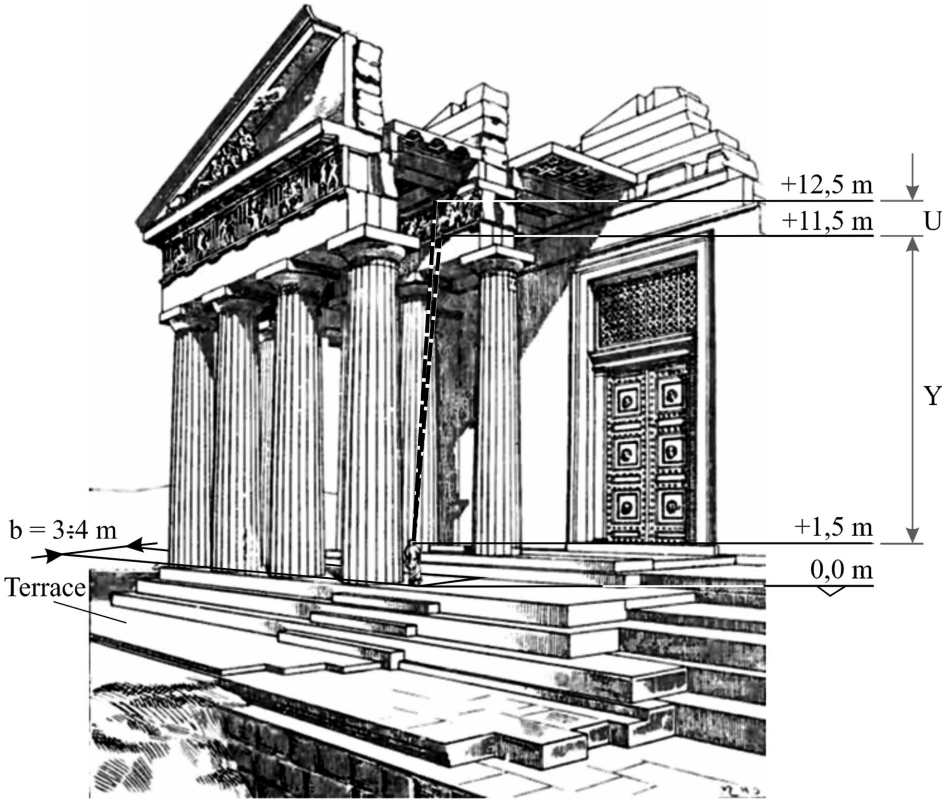
Pl. 1. 1 – The positioning of the frieze reliefs in the Parthenon temple;
2 – Main dimensions of the frieze blocks. Drawings by the authors based on figures of Orlandos 1977



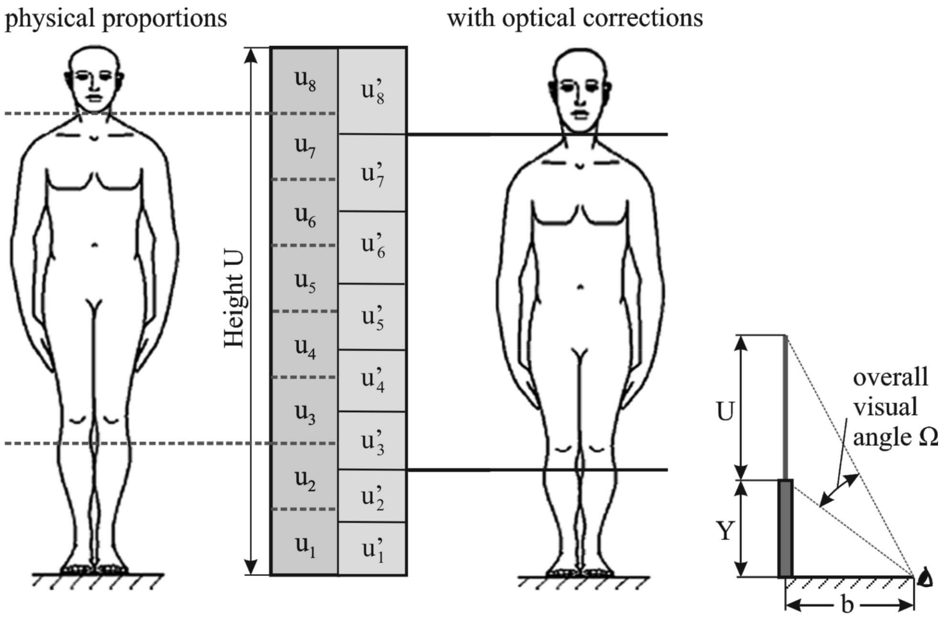
Pl. 2 – Optical illusions due to perspective distortions of equal dimensions at diverse distances from a certain viewpoint. Drawings by the authors



Pl. 3. 1 – Reduction of the observation angles ω_i of equal sized sub-zones u_i as their distances from the viewpoint increase; 2 – Optical corrections of the sub-zones sizes u_i to u_i' for attaining equal observation angles ω_i';
3 – Visual perception of the side t_i of the frieze reliefs enveloping volume V as decreasing versus its height U due to diminishing of the relevant observation angle ω_i;
4 – Optical correction of the volume V sides t_i for equalizing the corresponding observation's angles ω_i'. Drawings by the authors

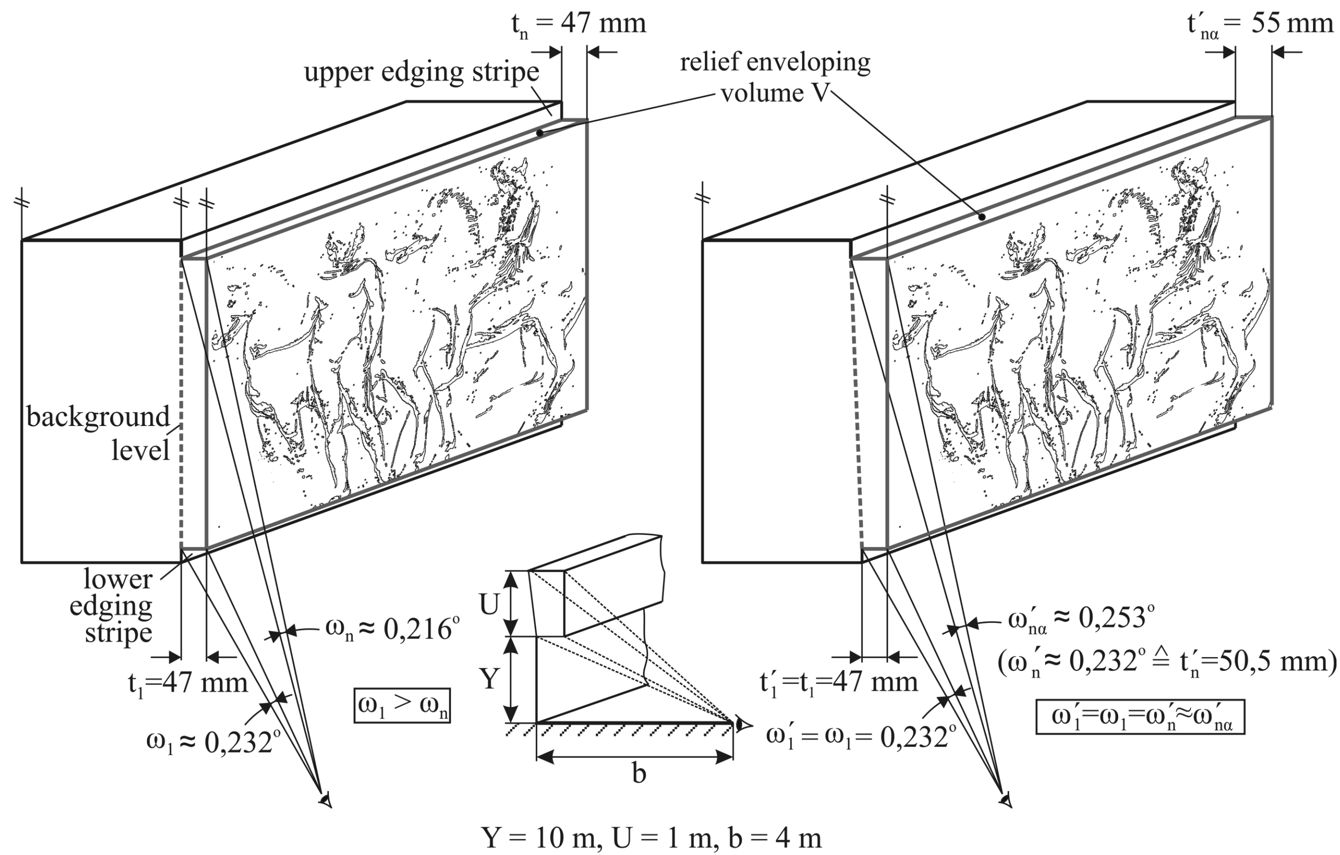


Pl. 4 – Geometrical data related to the most likely viewpoint of a west frieze relief region from the stylobates' level. Drawings by the authors

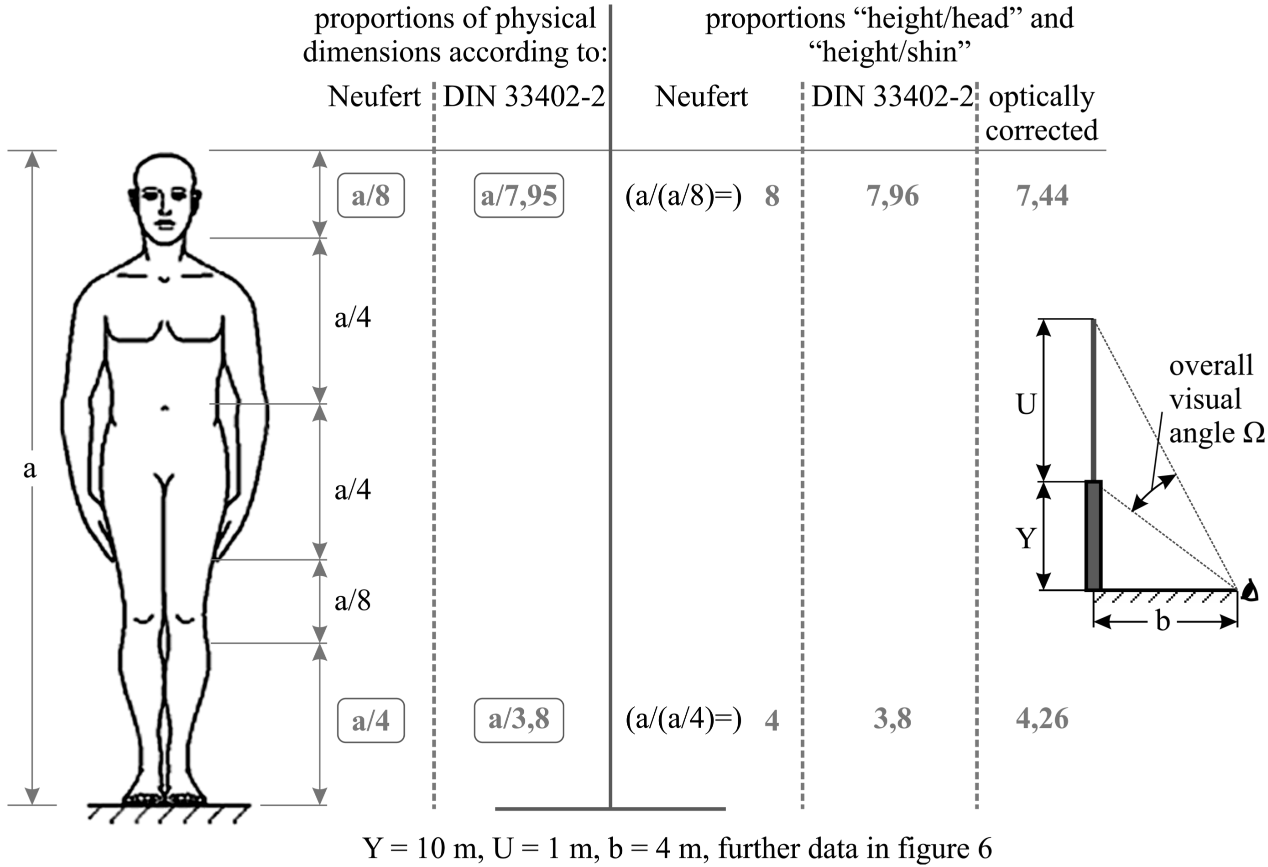


i	1	2	3	4	5	6	7	8
u_i [mm]	0,1250	0,1250	0,1250	0,1250	0,1250	0,1250	0,1250	0,1250
u'_i [mm]	0,1162	0,1185	0,1210	0,1235	0,1261	0,1288	0,1315	0,1344

Pl. 5 – Calculated optical corrections of a human body figure in the Parthenon frieze for observation from its most likely viewpoint without visual illusions due to perspective distortions. Drawings by the authors based on a figure of G. Niemann in Orlandos 1978

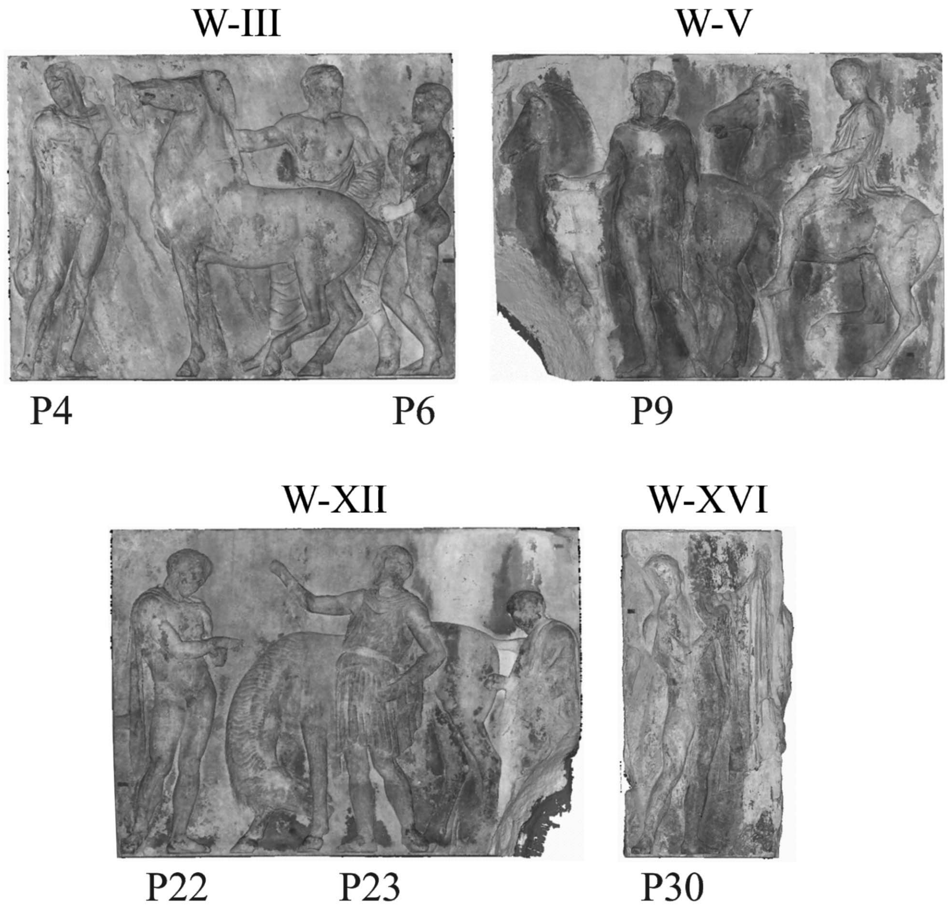


Pl. 6 – Calculation of the optically corrected upper side t_n' of the reliefs' enveloping volume V for equalizing the observation angle ω_1 to ω_n.
Comparisons of the upper side actual size t_{na}' and observation angles ω_{na}' to the determined ones t_{na} and ω_n, respectively.
Drawings by the authors

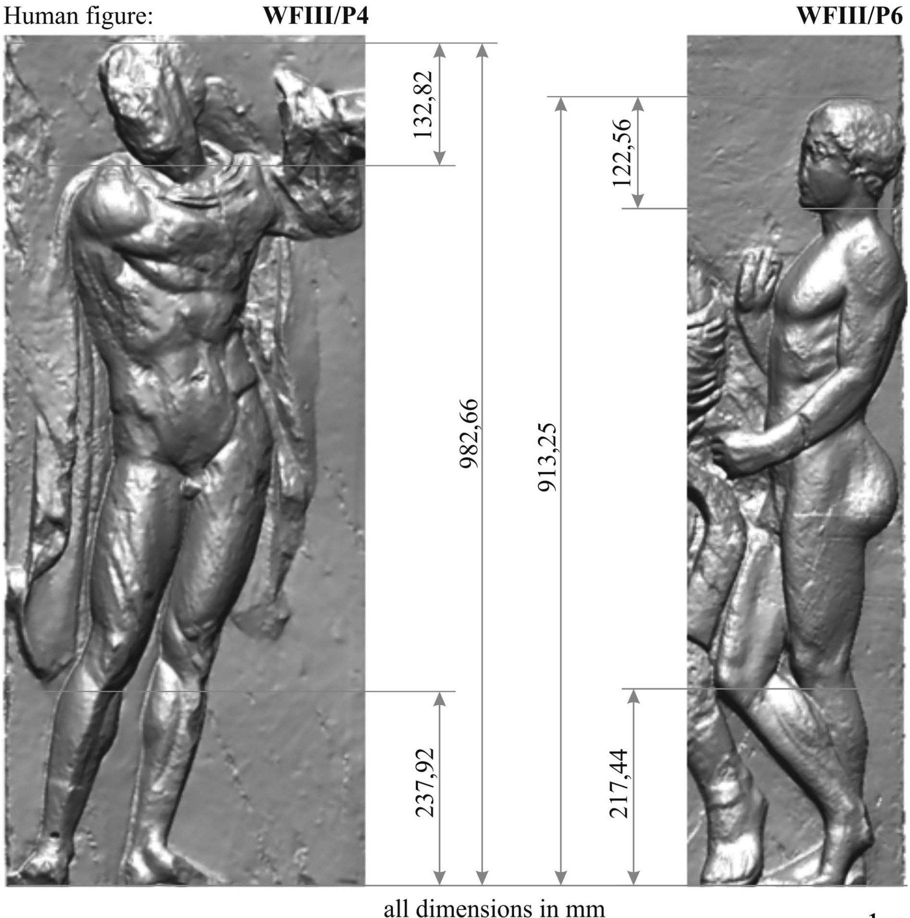


Y = 10 m, U = 1 m, b = 4 m, further data in figure 6

Pl. 7 – Characteristic physical human body proportions according to Neufert (2000) and *DIN* 33402-2 as well as optically corrected ones considering the west frieze data. Drawings by the authors



Pl. 8 – The human figures in standing position carved in the Parthenon west frieze. Numbering of human figures after Jenkins 1994. The digital surface models of the west frieze blocks were created based on numerical data attained by laser scanning (Bouzakis *et al*. 2016)

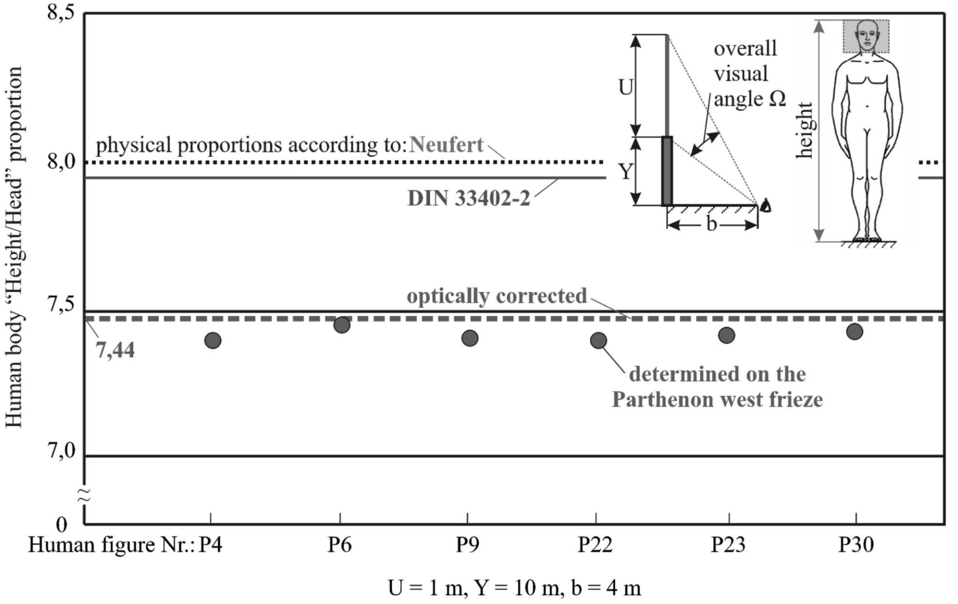


1

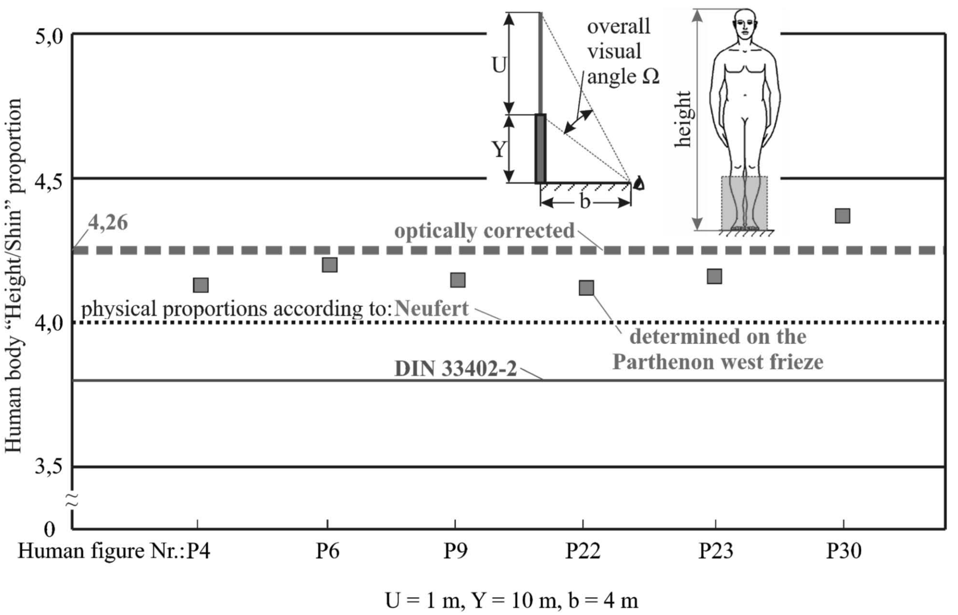
Numbering after Jenkins	Height	Head	Shin	Height/Head	Height/Shin
	(mm)			(-)	
WF_III_P4	982,66	132,82	237,92	7,40	4,13
WF_III_P6	913,25	122,56	217,44	7,45	4,20
WF_V_P9	946,33	127,67	227,80	7,41	4,15
WF_XII_P22	935,65	126,41	227,09	7,40	4,12
WF_XII_P23	956,84	128,88	229,69	7,42	4,16
WF_XVI_P30	933,40	125,53	213,48	7,43	4,37

2

Pl. 9. 1 – Characteristic dimensions of standing human bodies carved in the Parthenon west frieze determined via evaluation of their digital data by 3D laser scanning; 2 – Calculated human body proportions based on the previous dimensions. By the authors



1



2

Pl. 10. 1 – Optically corrected 'height/head' proportion and its comparison to the corresponding ones of the standing human figures carved in the west frieze reliefs; 2 – Optically corrected 'height/shin' proportion and its comparison to the corresponding ones of the standing human figures carved in the west frieze reliefs. Drawings by the authors