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The origins of entasis: illusion, aesthetics or engineering?

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Abstract—A typical characteristic of columns in Doric temples is *entasis*; a slight convexity in the body of a column. Often, and particularly in guide-books, it is suggested that entasis is intended to compensate for an illusion of concavity in columns with truly straight sides. We have investigated whether any such visual illusion exists, both in parallel sided and in tapering columns in a series of experiments, finding little evidence to support any illusion-compensation theory. Further, we explored the possibility that entasis was employed for purely aesthetic reasons, but the results do not support this conclusion. Finally, evidence supporting an engineering role for entasis is presented.

Keywords: Entasis; illusion; aesthetics.

INTRODUCTION

'Entasis', from the Greek word *εντείνειν*, to stretch, means tension or bowing. According to Penrose (1888, p. 39), it is the 'swelling given to a column in the middle parts of the shaft for the purpose of correcting a disagreeable optical illusion, which is found to give an attenuated appearance to columns formed with straight sides, and to cause their outlines to seem concave instead of straight'. Nuttgens, in his 'The Story of Architecture' (Nuttgens, 1999) writes 'Most Greek buildings of this golden period use *entasis*, the device whereby tapering columns are given a slight swelling about a third of the way up to counteract a tendency of the eye to see them as curving inwards from either side. . . ' There are many other sources that concur with this view, e.g. Encyclopedia.com, 2006; Long, 2004; The Columbia Encyclopedia, 2005; Wikipedia contributors, 2006 and this view clearly has a long history, see Vitruvius' treatise, 3.4.5., (1486); Heron's *Definitiones*, first century A.D.; Philon of Byzantion's *Belopoiika*, third century B.C. It is important here to distinguish between the tapering of columns, which is a common perspective device in the Doric order, and entasis, which refers specifically to the convex bulging of the columns to counteract an alleged 'waisting' of columns.

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The first use of entasis is probably in the Later Temple of Aphaia at Aigina, in the 490s B.C., and it is most often seen in Doric temples built by the Ancient Greeks and in Renaissance buildings. The Doric order is the oldest, simplest, and most preferred style in mainland Greece and southern Italy, including Sicily. It is often argued that the Doric order obtained its proportion, its strength, and its beauty, from the human figure (Gill, 2000; Mavrikios, 1965). According to Vitruvius, the Roman engineer and architect of the first century B.C., a Doric column's diameter-to-height ratio is based on the relationship between foot length and height in a man (see Note 1). According to Mavrikios (1965), the relation of the construction to the human figure can be seen in certain formal elements evident in the Doric order (such as entasis) which create an 'aesthetic' weight that makes the appearance of the construction look plastic, or alive (see Korres, 1993). Moreover, according to Haselberger (1999, p. 24), the functional role of entasis is that of supporting the load: 'not as a lifeless, isolated element but … comparable to a muscle in action'.

While the most famous Doric temple is the Parthenon in Athens, built in dedication to Athena Parthenos, between 447 and 438 B.C., the best preserved are perhaps the three temples at Paestum (Poseidonia) on the Amalfi coast south of Naples (Fig. 1). The oldest of these temples is the Temple of Hera I, built in 550 B.C., the Temple of Athena followed in 500 B.C. and the last temple is the Temple of Hera II, built in 470–460 B.C. The columns in all of the three temples have pronounced entasis, most prominently in the Temple of Hera I. The first to document the entasis in the Temple of Hera I, the strongest Greek entasis known, was Piranesi (1778).

There are several refinements in Doric temples in general, which have been consistently reported, apart from entasis. Goodyear (1912), in his *Greek Refinements*, defined these as: 'purposed departures from the supposedly geometrical regularity of the horizontal and perpendicular lines … and from the presumed mathematical equality of their apparently corresponding dimensions and spaces'. These usually include smaller gaps between the corner columns and the remaining columns (this

Figure 1. (See color plate IX) The temples at Paestum. Top: Temple of Hera I (550 B.C.). The first temple to be built at the greek colony of Poseidonia, modern day Paestum, south of Naples. This archaic Doric temple, one of the best preserved in the world, is built of local sandstone and has 9×18 columns on a three step stylobate. All 50 columns of the peristyle have survived and they exhibit pronounced entasis and tapering of the columns. Middle: Temple of Athena (500 B.C.). The smallest of the temples at Paestum, this temple has 6×13 columns. All 34 outer columns survive and while they exhibit entasis it is less marked here than in the temple of Hera I. Bottom: Temple of Hera II (470–460 B.C.). The last of the great temples of Poseidonia, and the largest with 6×14 columns. All 36 outer columns, made of local travertine, survive. The entasis here is less marked than in the two earlier temples, representing a shift from the archaic to the classic Doric style. (Photographs by the first author.)

Figure 2. (See color plate X) Borromini's Trompe-l'oeil gallery at the Palazzo Spada, Rome. The gallery, which appears to be 37 metres long actually only extends for 8 metres. The apparently life-size statue at the far end is 60 cm high. (Photograph by the first author.)

supposedly stops the corner columns appearing isolated); all of the surfaces lean inwards as they rise; and the horizontal lines of the temple (e.g. the stylobate, or temple floor) also sometimes rise slightly in the middle and gently slope downwards towards the corners.

Why did these refinements arise? We have already introduced the widespread notion that entasis compensates for optical illusions, but there are other possible reasons for architects to introduce curvature and tapering into building design. The tapering of columns appears to be a perspective cue to make columns appear taller than they really are, a 'trick' perhaps most audaciously employed by Borromini at the Palazzo Spada in Rome (Fig. 2). The slightly convex surface of a temple floor would ensure rain-water drained away efficiently and requires no more complex reason for its existence. Penrose (1888) entertained the possibility that entasis may have been employed simply for aesthetic reasons — 'an imitation of the practice of Nature in giving almost invariably a convex outline to the limbs of animals' (p. 106). So the purpose of entasis may have been merely 'to please the eye of the beholder by deviating from the rigidity of straight lines' (Tegtmeyer, 1994, p. 374).

In this study we investigate whether there is a 'disagreeable optical illusion' for entasis to compensate for. We go on to examine the possibility that columns with entasis are visually more pleasing.

EXPERIMENT 1

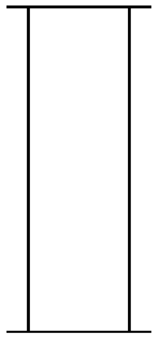
Design and method

A within-subjects design was used to investigate whether parallel columns are perceived as being concave. Schematic column stimuli, which were presented on a computer screen, with subjects indicating whether the columns bulged inwards (concave) or outwards (convex) at their mid-point (Fig. 3a). The method of constant stimuli was used with a total of 7 stimuli, 3 convex, 3 concave and a truly parallel column. The height of the columns was 11.8 cm. The truly parallel column had a width of 3.6 cm (5.1 deg visual angle) with the concave columns having widths at their central point of 3.47, 3.50 and 3.55 cm. The widths at the central point of the convex columns were 3.65, 3.70 and 3.77 cm. These mid-points represent deviations from straight sides of $+/-0.17$, 0.14 and 0.18 deg visual angle.

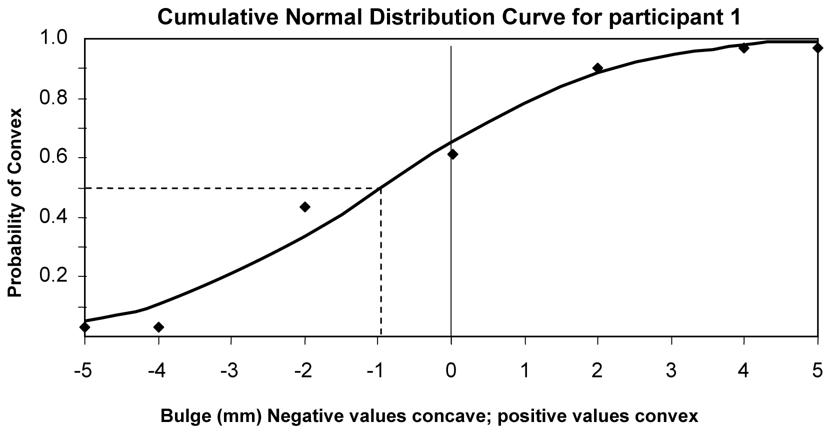
Each column was presented 30 times in a pseudo-random order. Participants ($N = 16$) were sat opposite the computer screen at approximately 40 cm distance. They fixated on a black cross on a white background; the fixation point was replaced with the column stimulus for 800 ms after which their forced-choice response was recorded.

Results

Data for each participant were plotted as psychometric functions and a cumulative normal distribution fitted, from which the point of subjective equality (PSE), where



(a)



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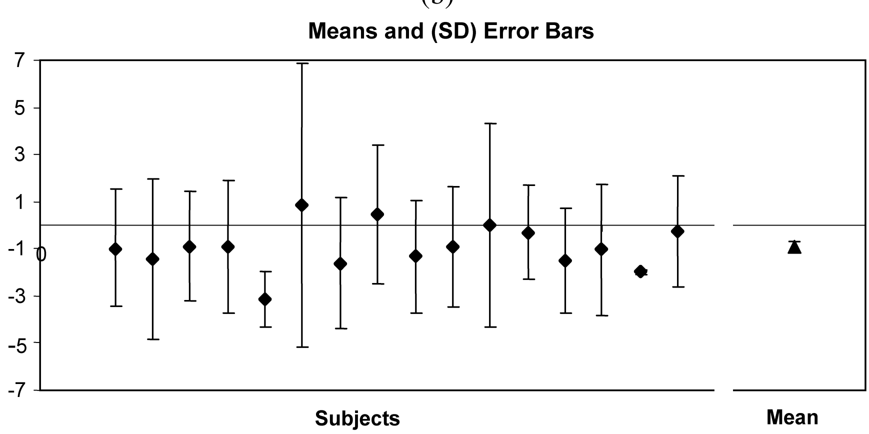


(c)

Figure 3. (a) Stimulus for Experiment 1. Example of the stimuli in Experiment 1. Seven stimuli were employed, 3 whose sides were concave, 3 convex and one with truly straight parallel sides. (b) Raw data and cumulative normal distribution fitted to one subject's data in Experiment 1. The Point of Subjective Equality (PSE) and standard deviation were determined from the fitted psychometric function. (c) Results of Experiment 1. Data for 16 subjects. The horizontal line indicates the position of no illusion. The point at far right is the mean of all subjects.

the columns appeared neither concave nor convex was determined. Example data for one participant are shown in Fig. 3b. The results for all 16 subjects are shown in Fig. 3c. The mean PSE is -0.94 mm, indicating that in order to be perceived as parallel the sides of the column had to be slightly concave. This is clearly in the opposite direction from the expectation of the illusion-compensation theory of entasis, which hypothesises that columns were built bulging outwards in order to be perceived as parallel.

EXPERIMENT 2

In the course of Experiment 1 we noticed that aliasing along the length of the lines could have been acting as a cue for the subjects. To eliminate such cues we ran a second experiment in which the sides of the column were only represented at the top, bottom and mid-point of the column by vertical line segments, 1.5 cm in length, as shown in Fig. 4a. As a result this rendered the task more difficult for the subjects. The truly parallel column had the same dimensions as in Experiment 1, with the concave columns having widths at their central point of 2.3, 2.6 and 3.1 cm. The diameters at the central point of their convex columns were 4.1, 4.6 and 4.9 cm. These mid-points represent deviations from straight sides of $+/-0.5$, 0.14 and 0.18 deg. visual angle The increase in the range of the 'bulges' was necessary because of the increase in difficulty in the task.

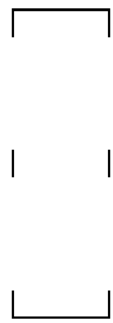
All other aspects of the experiment were identical to those of Experiment 1.

Results

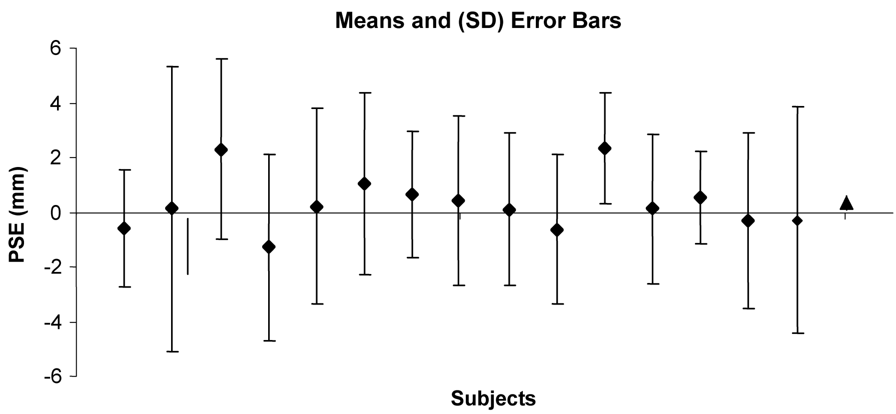
The results were analysed in the same way as in Experiment 1. Data from 15 subjects are shown is Fig. 4b. The mean PSE was 0.32 mm and while this is a positive value and hence in the direction of the illusion-compensation model, it is not significantly different from zero in a one sample t-test. ($t(14) = 1.23$, $p > 0.10$).

EXPERIMENT 3

In Experiments 1 and 2, columns are represented in the most schematic fashion. Real Doric columns may have a degree of detail at their capitals and bases that might contribute to an illusion that entasis seeks to correct. This notion may be related to the Oppel-Kundt illusion (1855). This illusion shows that a filled distance looks longer than an unfilled distance (Fig. 5a). Therefore if detail at the capital and base of the column contributes to filled space and the central portion of the column is seen as unfilled, then the column might appear concave. The third experiment was a refinement of Experiment 2 with stimuli shown in Fig. 5b. The top and bottom edges of the schematic columns were now divided by nine short vertical lines —



(a)



(b)

Figure 4. (a) Stimulus for Experiment 2. Example of the stimuli in Experiment 2. Seven separations of the central pair of lines were presented. 3 closer than the width of the ends of the column, 3 narrower and one pair co-linear with the end-widths. (b) Results of Experiment 2. Data for 15 subjects. The horizontal line indicates the position of no illusion. The point at far right is the mean of all subjects.

Piaget and Osterrieth (1953) found the Oppel-Kundt illusion (Oppel, 1855) to be maximal with 9–14 lines in the filled interval, whereas Obonai (1933) obtained the maximum effect with 7–13 lines.

Results

The results were analysed in the same way as in Experiment 1. Data from 15 subjects are shown in Fig. 5c. The mean PSE was 0.37 mm which a one sample t-test determined was not significantly different from zero ($t(14) = 1.39$, $p > 0.05$).

EXPERIMENT 4

The schematic stimuli of Experiments 1–3 made no attempt to represent the 3-D nature of columns. In Experiment 4 we investigated whether entasis might compensate an illusory concavity of 3D columns. For this we generated columns

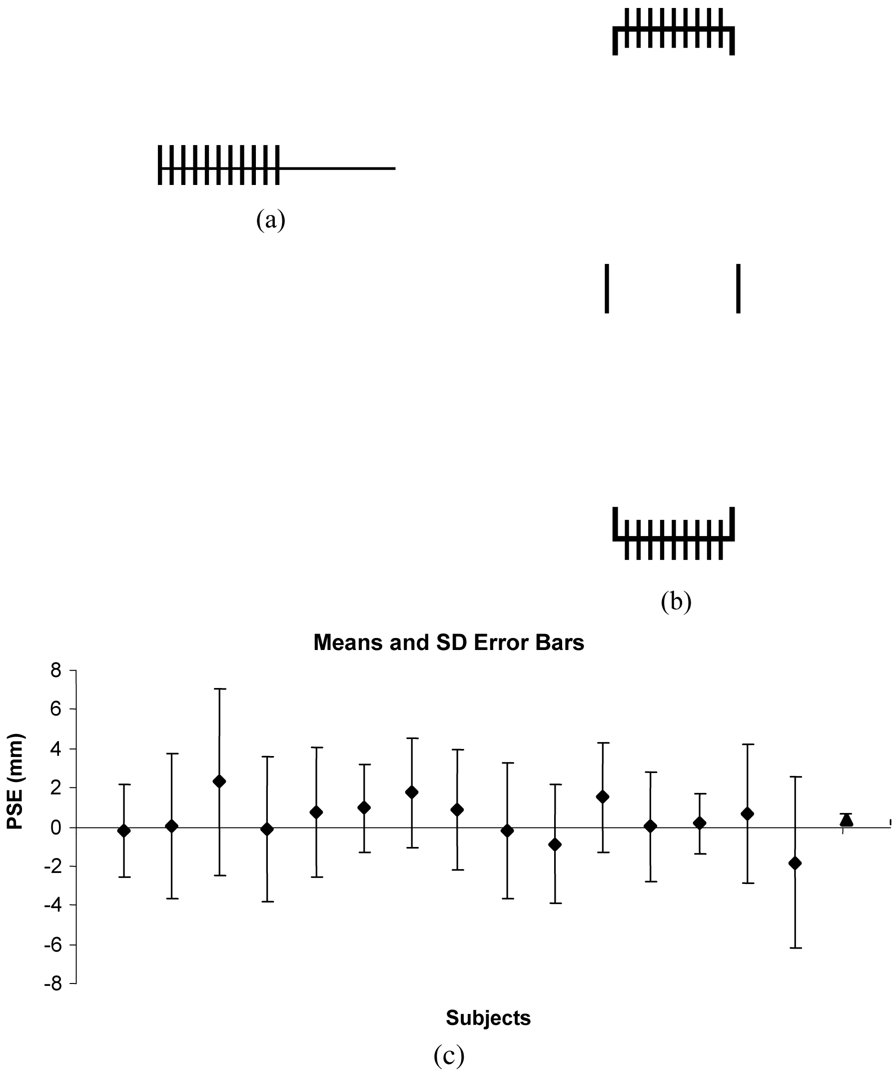
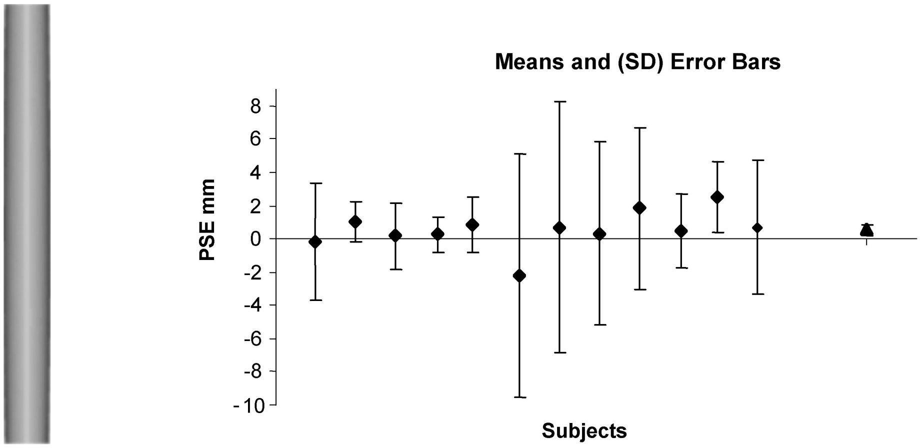


Figure 5. (a) The Oppel-Kundt illusion. The rightmost vertical line bisects the horizontal. Apparently the presence of the vertical 'ticks' makes the left half of the line look longer than the unbroken right half. (b) The stimulus for Experiment 3. Stimuli for this experiment differed from Experiment 2 only in the addition of the 'Oppel-Kundt' ticks at top and bottom. (c) Results of Experiment 3. Data for 15 subjects. The horizontal line indicates the position of no illusion. The point at far right is the mean of all subjects.

with AutoCad software. The column was 10.0 cm (14.0 deg) in height and 1.0 cm (1.4 deg) in width and was shaded in grey-scale. An example of the stimulus is shown in Fig. 6a. Details of the experiment were again as in the previous experiments except that stimuli were now presented for 100 ms since concavity or convexity of the columns was more apparent in this three-dimensional version.



(a) (b)

Figure 6. (a) Stimulus for Experiment 4. Example column stimulus in Experiment 4. Stimuli generated by AutoCad and given a 3D appearance by appropriate shading. (b) Results of Experiment 4. Data for 12 subjects. The horizontal line indicates the position of no illusion. The point at far right is the mean of all subjects.

Results

Data from 12 subjects are shown in Fig. 6b. The mean PSE was 0.53 mm which again was not significantly different from zero ($t(11) = 1.60$, $p > 0.05$).

EXPERIMENT 5

Experiments 1–4 have investigated the possible presence of an optical illusion in truly parallel columns such that they might appear waisted in the middle. These experiments have examined entasis as a compensation for such an illusion independently from another architectural device in the construction of Doric columns, namely, the pronounced tapering in the columns as they rise. Often the most pronounced entasis is seen on columns with severe tapering, while truly parallel columns show more subtle application of entasis. This raises the possibility that there is an interaction between entasis and tapering in columns.

The stimuli for Experiment 5 were generated with POV-Ray software and represented a temple front with 6 columns (Fig. 7a). All the columns were generated with a taper, the diameter of each column at its top being 80% of its base diameter. The curvature (entasis) of the columns was determined by a cubic spline which set the maximum deviation from the straight sides half-way up the columns. The columns were 10.3 cm (14.4 deg) tall, tapering from 1.9 cm (2.7 deg) diameter at the base to 1.5 cm (2.1 deg) at the top. With straight tapering sides the width at half height of the columns was 1.7 cm (2.4 deg). The spline introduced subtle bulging and waisting of the columns making their midpoint widths 1.60, 1.63, 1.67, 1.73, 1.77 and 1.80 mm. The experimental design and method remained the same as the previous experiments, with each presentation being 1000 ms. Each subject made 60 responses to each of the 7 stimuli.

Results

Data for 20 Subjects are shown in Fig. 7b. The mean column width perceived as being straight was 16.96 mm where a truly straight column would have had a width of 17.0 mm. This deviation is clearly not significant ($t(19) = -1.89$, $p > 0.05$), showing no indication of a perceived waisting of the tapering columns.

EXPERIMENT 6

Having failed to discover any evidence that entasis counteracts an illusion of parallel columns appearing concave, we carried out a final experiment to determine whether entasis might be an aesthetic preference. For this experiment we generated a schematic temple, mimicking the proportions of the Parthenon (Fig. 8a) with two heights of bulge on the component columns; halfway up and a third of the way up. The design of the experiment followed that of Blount *et al.* (1975).

Design and method

A within-subjects design was used to investigate the preference of subjects when shown temples with different degrees of entasis. Five temples were generated with POV-Ray software; in one the columns were parallel, in two others the columns were convex (entasis) with the maximum bulge one-third and half-way up the column and in the final two temples the columns were concave, with the minimum diameter one-third and half-way up the columns. All possible pairs of the five temples were presented twice (20 presentations) to counterbalance any order effects. Subjects ($N = 30$) indicated which of the pair of images they preferred.

Results

The frequency of preference for each stimulus is shown in Fig. 8b. Clearly there is no preference for columns with convex entasis, as both versions with the classical application of entasis are the least preferred shape for the columns in the temple.

Figure 7. (See color plate XI) (a) Stimulus for Experiment 5. Example stimulus in Experiment 5. The 6 columns show tapering from bottom to top, the top column width being 80% of the bottom. (b) Results of Experiment 5. Data for 20 subjects. The horizontal line indicates the position of no illusion. The point at far right is the mean of all subjects.

Figure 8. (See color plate XII) (a) Stimuli for Experiment 6. Examples of the schematic temples used in Experiment 6. The left temple has columns slightly waisted half way up. The right temple has columns slightly bulging out half way out. (b) Results of Experiment 6. Mean preference ratings for different column shapes from 30 subjects.

DISCUSSION

An optical illusion

In a series of experiments to investigate whether the application of entasis to Doric columns has been used as a device to counteract an 'optical illusion', our results suggest emphatically that no such illusion exists to be compensated for. This result might be thought as not very surprising as the degree of entasis seen in some temples is so apparent that it would represent a massive over-compensation of an illusion rather than its cancellation. However entasis in some buildings, for example the Parthenon, the Erechtheum and the Theseum in Athens, is so subtle that it used to be supposed that the columns had parallel sides.

Our experiments have used schematic versions of the columns of a real Doric temple and it is possible that some feature of the real temple that we have omitted is responsible for the illusion that entasis corrects. The obvious possibility here is that areas of light and shade could contribute to the misperception of the columns. The irradiation illusion (Helmholtz, 1866/1962) demonstrates that objects seen on a bright background seem smaller than when seen on a dark background, and this has been cited as the reason why the Parthenon's corner columns, more likely to be seen against the bright sky, are thicker than those columns seen against the dark *cella* background.

Could it be that the tops and bottoms of the columns appear brighter and therefore wider than the dark central portions of the columns? This seems unlikely though it was suggested by Penrose (1888), who considered the case of a straight sided column standing detached in a portico. The upper and lower parts of the column might appear relatively brighter and therefore broader than the intermediate parts, the upper part because its brightness could be enhanced against the relatively deep shade under the portico, and the lower part because of the greater amount of light being reflected from the ground. This suggestion deserves empirical testing, but is beyond the scope of the current paper.

Aesthetics hypothesis

The range in the degree of entasis applied in columns between different temples suggests that this refinement may have more to do with aesthetics rather than the elimination of an illusion (Mitrović, 1999). It has been suggested that the purpose of entasis was to give the column an organic structure, just like the Caryatids, and to avoid machine-made straightness. The fact that there are no absolutely straight lines on the Parthenon confers a subtle organic character to a geometric structure. It is true that the columns of the *peristyle* in the Parthenon taper on a slight arc as they reach the top giving the impression that they are swollen from entasis. This may have been intended to create the impression that the columns were burdened by the weight of the roof; a subtle feature that reflects anthropomorphic imageries to otherwise inorganic objects (http://www.ancient-greece.org/architecture/parthenon2.html). Coulton, (1977) further supports this notion and claims that entasis was applied in order to save the temple from a mechanical, lifeless appearance and also to create a desirable tension between what the eye saw and what the mind recognised as the underlying form. It is likely that in ancient times when columns were designed, bulging out figures, either organic or inorganic, were aesthetically preferred. In Experiment 6, the concave columns were slightly preferred over parallel and convex ones, which does not support this idea, but we must remember that this might merely reflect today's social norms that favour slim or even inward structures.

Secondly, a further aesthetic idea supporting the employment of entasis comes from the analysis of the Parthenon by Mavrikios (1965). Here it is suggested that the design and structure of the columns was intended to make the column 'rise up and not to reach upwards'. Mavrikos believes that the purpose of the tapering of the columns, together with entasis, which contains 'dynamism', was to give a feeling of rising up in order to receive and carry the load from the roof and at the same time to transmit a feeling of downward movement to the earth. An investigation of the aesthetic preferences of the Greeks of 2500 years ago is outside the scope of this paper, but we have established that if there was a preference for bulging columns in ancient Greece, that preference appears not to be shared with us in the 21st century.

Engineering hypothesis

The idea that entasis was employed for purely engineering reasons has a long history. As early as 1773 Lagrange proposed that entasis served to increase the strength of a column. Keller (1960) showed that the strongest column is not cylindrical, but rather tapered along its length, being thickest in the middle and thinnest at its ends. According to Keller, this shape gives a buckling load that is 61.2% larger than that of a cylinder. Recent work by Cox (1992) showed that a 'stunted cycloid' is stronger by a factor of $4/3$ than a cylindrical column of the same length. Even more recently, Atanackovic and Glavardanov (2004) have used Pontryagin's maximum principle to determine the optimal shape of a heavy compressed rod, stable against buckling. It was again found that the optimal shape of a column shows entasis. Therefore a column with entasis would make the columns lighter for the same compressive force.

CONCLUSION

We have examined different explanations for the application of entasis to the Doric columns of classical (or modern) buildings. We have found little evidence that the convexity of the columns counteracts and cancels some 'optical' illusion. Nor can we provide support for any aesthetic reason for the practice, though the aesthetics of Ancient Greece may have been very different from that of 21st Century Europe. We appear to be left with a purely engineering reason for entasis, namely, that the slightly bulging column will provide a greater strength-to-weight ratio than a parallel column. However, to claim that this is the complete explanation seems premature to us. Research with stimuli that appear closer to real temples is clearly needed as is a fuller appreciation of the aesthetics of ancient Greece.

Acknowledgements

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NOTES

1. If this is so, and it seems plausible when considering the dimensions of the Parthenon — column height 10.3 m and width 1.9 m giving a reasonable ratio of 5.4 to 1 — it cannot hold for earlier temples, e.g. those at Paestum (see Fig. 1) where the ratio is closer to 4.0 to 1. This would require the temples to have been built by a race with implausibly enormous feet.

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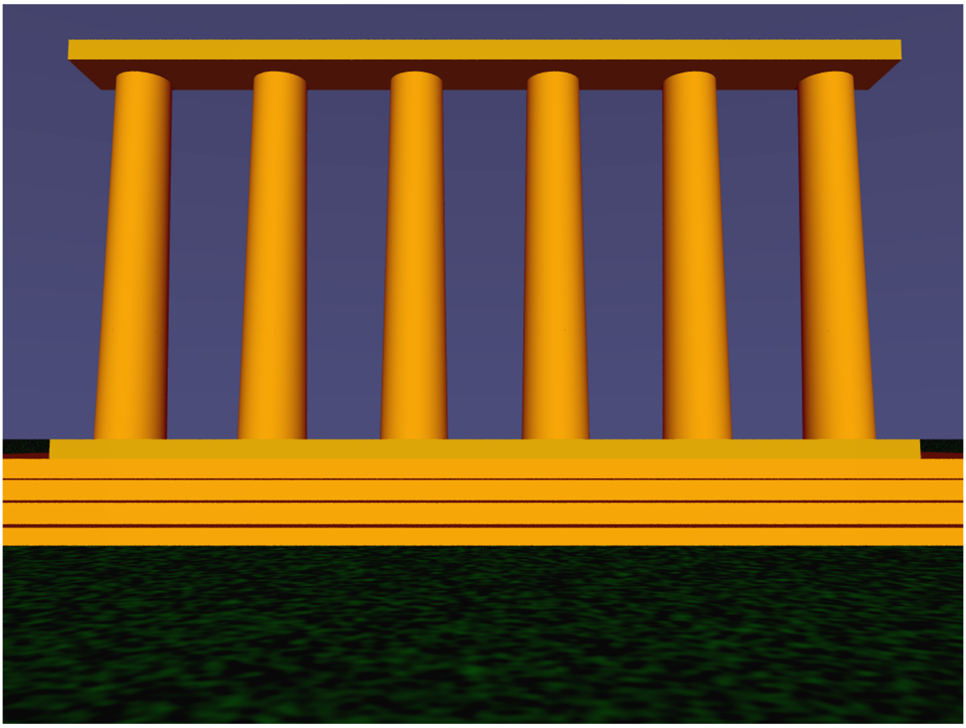
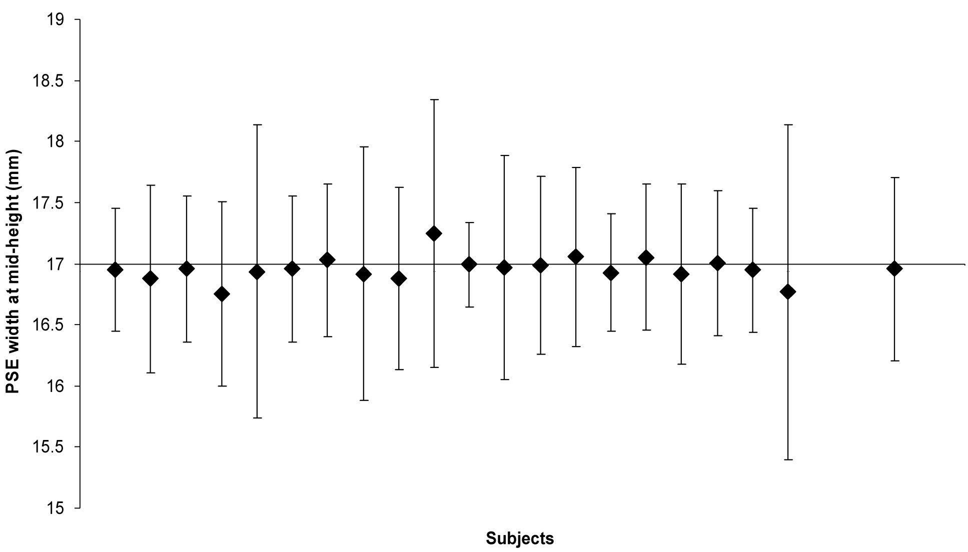
Plate IX

P. Thompson *et al*., Figure 1.

P. Thompson *et al*., Figure 2.

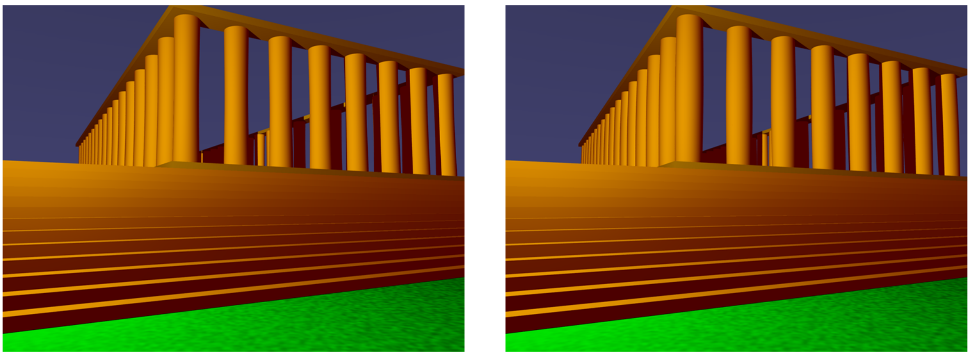


(a)

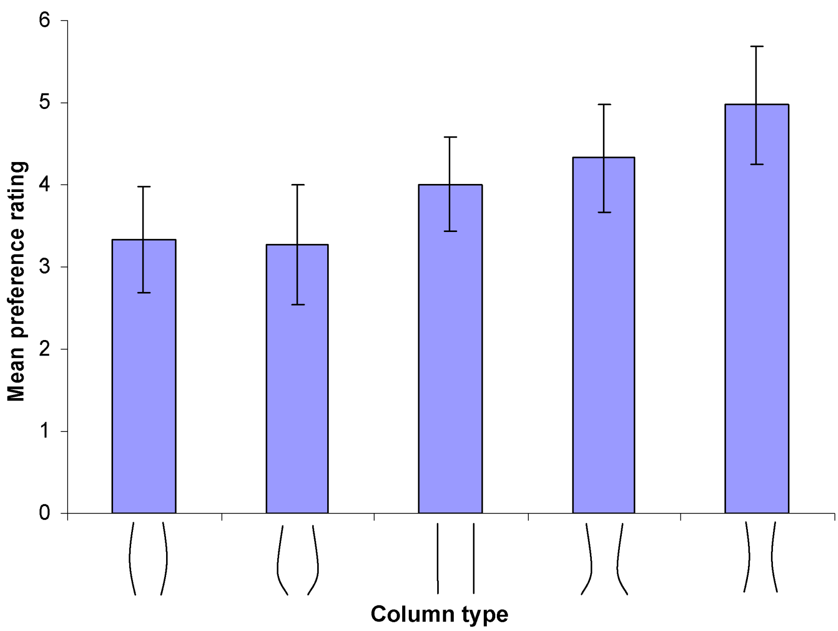


(b)

P. Thompson *et al*., Figure 7.



(a)



(b)

P. Thompson *et al*., Figure 8.