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Forensic anthropology population data

Perspective distortion in craniofacial superimposition: Logarithmic decay curves mapped mathematically and by practical experiment☆

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ABSTRACT

The superimposition of a face photograph with that of a skull for identification purposes necessitates the use of comparable photographic parameters between the two image acquisition sessions, so that differences in optics and consequent recording of images does not thwart the morphological analysis. Widely divergent, but published, speculations about the thresholds at which perspective distortion becomes negligible (0.5 to >13.5 m) must be resolved and perspective distortion (PD) relationships quantified across their full range to judge tolerance levels, and the suitability of commonly employed contemporary equipment (e.g., 1 m photographic copy-stands). Herein, basic trigonometry is employed to map PD for two same sized 179 mm linear lengths – separated anteroposteriorly by 127 mm – as a function of subject-to-camera distance (SCD; 0.2–20 m). These lengths approximate basic craniofacial heights (e.g., tr-n) and widths (e.g., zy-zy), while the latter approximates facial depth (e.g., n-t). As anticipated, PD decayed in logarithmic and continuous manner with increasing SCD. At SCD of 12 m, the within-image PD was negligible (<1%). At <2.5 m SCD, it exceeded 5% and increased sharply as SCD decreased. Since life size images of skulls and faces are commonly employed for superimposition, a relative 1% perspective distortion difference is recommended as the ceiling standard for craniofacial comparison (translates into a ≤2 mm difference in physiognomical face height). Since superimposition depends on relative comparisons of a photographic pair (not one photograph), there is practically no scenario in superimposition casework where SCDs should be ignored and no single distance at which PD should be considered negligible (even if one image holds >12 m SCD).

1. Introduction

At short subject-to-camera distances (SCD) it is well-known that the point projection of a 3D scene to a 2D plane in photography renders parts of objects closer to the lens of the camera larger than those positioned further away [1–8]. Point projection additionally causes false impressions of the true edges of 3D spherical objects, like a skull or a face, at short SCDs [1,3,4] (Figs. 1 and 2). These effects are sometimes mistakenly thought to be the product of the focal length of the lens [6] – see [9] for a classic example. This is incorrect since narrow angle lenses (often termed 'telephoto lenses') possess the same view point (or perspective), as wider field lenses, even wide-angle lenses [1]. Focal length of the lens only determines the magnification or the amount of an image that falls in the field of view, not the perspective; so a large focal length will have a larger zoom at any given subject-to-camera distance [1–3,6]. If the view point (including the subject-to-camera distance) remains the same between images, changing the focal length of the lens has no impact on the recorded perspective [1–3,6].

If the subject is not positioned centrally in the field of view of the camera, then stretching of the subject across the image plane can further add to the two aforementioned distortions [1,4] (Figs. 1 and 2). Consequently, camera perspective is very important to consider when photographs of skulls and faces are analysed (Fig. 3) because different SCDs between images, and/or position in the field of view, will prevent legitimate one-to-one comparisons of the craniofacial anatomy as sought by the superimposition procedure [4–8,10–12]. This has not been fully appreciated in the literature where validation studies often fail to report which SCDs were used [13–15], equipment is frequently designed without regard to SCD [16,17] and SCD generally goes under emphasized, e.g., "some effort should be made to replicate the camera distance" [18] p.385. For exceptions, see [6] and [7].

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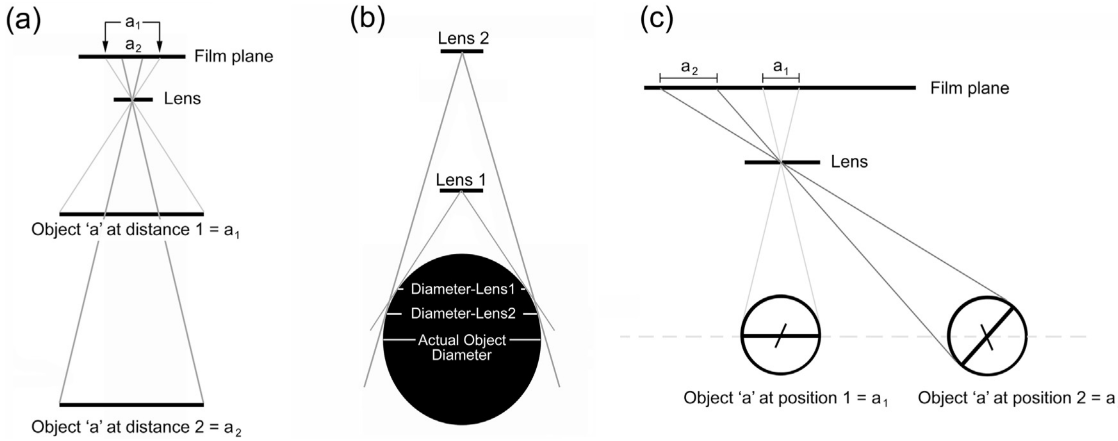

Fig. 1. Perspective distortion associated with the point projection of a 3D scene to a 2D photographic plane. (a) At short subject-to-camera distances, objects closer to the lens are magnified. (b) At short subject-to-camera distances the 'true' edge of spheroidal objects may not be seen. (c) Spherical objects near the edge of the field of view are stretched across the image receptor. Parts (a) and (b) are redrawn after Gavan et al. [3], while (c) is redrawn after Kingslake [1].
Images reproduced from: Stephan [4] with permission from Springer Science + Business Media.

If differential SCDs are used to photograph the skull and face, it is not sufficient to simply rescale one image to approximate the size of the other, as broadly recommended [19,20] and/or enticed when zoom lenses are used at skull photography. That is, magnification is not the only issue at hand; differential scaling of the object within the photograph and edge visibility also count, as mentioned above [4,6,21]. Only when the face-to-camera distance is large, and perspective effects small (orthogonal views approximated), can a scaling factor can be safely applied to the skull photograph (which must also be taken at large SCD) to produce a picture that is truly comparable.

Currently, there is no consensus on the distance at which perspective distortions (PD) are to be considered meaningful in craniofacial superimposition. Instead, opinions range widely from <0.5 to <5 m in the published literature, with one report of <13.5 m in the other anthropological literature (see Table 1). This issue must be resolved. The parametric nature of SCD makes it unlikely that a single 'magic' number defines PD's negligibility. Instead, PD will transition in a continuous nature, from large at small SCDs to small at large SCDs. Furthermore, the superimposition process concerns two photographs, so effects of any perspective distortion will be relative. That is, perspective distortion may be large within a single image, but this is inconsequential if the same perspective distortion is possessed by the second other image to be compared. To elucidate the patterns involved, decay curves of PD with increasing SCD must be mapped. So far, this has not been undertaken in the superimposition literature in a comprehensive manner, yet it can readily be achieved by mathematical modelling and practical experiment.

Table 1
Previously reported subject-to-camera distances (floor values) at which perspective distortion is thought to become negligible.

Subject-to-camera distance (m)	References
1	Sekharan [22]
	Lan and Cai [23]
1.5	Glaister and Brash [12]
	Grüner and Reinhard [24]
2	Miyasaka et al. [25]
2.5	Eliášová and Krsek [8]
3	Titlbach [10]
5	Scully and Nambiar [7]
	Hashimoto [26]
13.5	Tanaka et al. [27]

Titlbach [10] provides foundations for these undertakings both in theory and in practice, which is extended here to produce 3D curves of perspective distortion decay across common and applicable subject-to-camera distances. Using basic and well-known trigonometric principles of similar triangles, Titlbach [10] shows how the size of a chord length can easily be calculated at the film plane (see methods and Fig. 4). Consequently, for two identically sized chord lengths placed at different distances from the camera in a single photograph, a ratio of size distortion can be calculated. This information is probative of perspective distortions in craniofacial superimposition where features of the head fall in front or behind others yielding differential magnification, e.g., in frontal views morphological face height (n-gn) is closer to the camera than maximum face width (zy-zy). Furthermore, the decay curves can be used to compare extent of distortions in one image to distortions in another taken of the same subject at a different SCD, as relevant to the superimposition procedure where two independent photographs (one of the face and the other of the skull) are compared.

As Titlbach's [10] calculations concern cord lengths and not spherical objects (that are also effected by edge visibility [3]), they only capture the differential magnification associated with perspective distortion, not edge nuances. Consequently, they are lenient assessments of the total distortion present. Irrespective of this limit, chords facilitate practical tests because they can be easily emulated in practice, e.g., a cube rotated at 45° provides two equal, easily demarcated and measureable edges at a fixed distance from one another [10] (Fig. 5). This enables the distortion metrics estimated by mathematical theory, to be conveniently tested in practice.

2. Materials and methods

2.1. Mathematical model

Titlbach [10] illustrates how the size of a chord recorded at the image plane can be calculated mathematically. The formulae are derived from the basic starting premise that a chord (perpendicular to the line of sight of the camera) can be projected to the film plane by two similar triangles (Fig. 4), such that:

$$\frac{A}{(a-f)} = \frac{A'}{f} \quad \text{and} \quad \frac{B}{(b-f)} = \frac{B'}{f} \tag{1}$$

These equations can be rearranged to:

$$A' = \frac{Af}{(a-f)} \tag{2}$$

$$B' = \frac{Bf}{(b-f)} \tag{3}$$

Since the distance f is very small compared to a, b and d, it can be ignored at the denominator [10] to simplify the mathematics:

$$A' = \frac{Af}{a} \tag{4}$$

$$B' = \frac{Bf}{b} = \frac{Bf}{(a+b)} \tag{5}$$

Perspective distortion (PD) for the two chord lengths A and B at the film plane can be represented as a ratio B'/A' such that:

$$\mathrm{PD}_{\mathrm{Ratio}} = \frac{B'}{A'} = \frac{Ba}{A(a+d)} \tag{6}$$

The latter equation can be reworked into a percentage value for greater user-friendliness, such that:

$$\mathrm{PD}_{\mathrm{Theory}}\,\% = \left(\left(\frac{Ba}{A(a+d)}\right) - 1\right) \times 100 \tag{7}$$

In order to account for PD in craniofacial superimposition then, a pertinent length such as 179 mm for A and B are substituted – a distance that closely corresponds to adult physiognomical face height at approximately 173–187 mm (tr-m) [28] and which approximates: face width (zy-zy) plus an additional 29%; craniofacial height (v-gn) minus an additional 22%; head width (eu-eu) plus an additional 19%; and head length (g-op) minus an additional 9% [28].

If the 179 mm length is represented by the face length of a cube, then Pythagorean Theory for a right angled triangle ($a^2 + b^2 = c^2$) can be used to calculate d as half (0.5*) of the hypotenuse for one of the two right-angled triangles that compose a single face of the cube with adjacent and opposite lengths of A, and converted to meter units by multiplying by a factor of 0.001. That is:

$$d = 0.0005\sqrt{A^2 + A^2} \tag{8}$$

In other words, for a cube face length (A) of 179 mm, d equals 126.572 mm. Thus, the 179 mm length of A is convenient because it yields a distance d equal to mean upper-third face depth (n-t; 127 mm [28]) and is similar to: facial depth (prn-obi) and lower subnasale-aural distance (n-obs) [28]. Consequently, all distances utilised in the above equations (A, B and d) are representative of mean measurements of adult human heads, as reported by Farkas et al. [28], that are pertinent to proper alignment of photographs in craniofacial superimposition. These lengths can, thereby, be used to calculate perspective distortion for serially increasing SCDs from 0.2 to 20.0 m at 0.1 m increments.

2.2. Experimental tests

This mathematical model can be tested in practice by photographing a Plexiglass® cube (Fig. 5) with a 179 mm face length (A or B), precisely replicating the theoretical conditions. In this study, photographs of the above described cube were made at incrementally increasing subject-to-camera distances (0.5–10.0 m) using a full-frame digital Nikon D700 camera body equipped with a fixed 2.8 speed, 60 mm macro Nikkor Lens. Photographs were taken at 0.5, 0.7 and 1.0 m, then with 0.5 m intervals up to 5.0 m, and 1 m intervals thereafter to 10 m.

A portable camera tripod, fixed with plumb line at the image receptor plane, was used so that the camera could be accurately (within a few mm) placed above a straight line marked on the floor at corresponding SCD distances. The camera tripod system was aligned at the 10 m distance, ensuring the subject was central in the field of view, and that the camera line-of-sight was parallel to the floor, before moving to the smallest SCD to begin the sequence of serial image capture with increasing SCD. Since the cube was initially centred at the 10 m mark and each distance fell in direct line, the camera did not require any positional adjustment on the tripod between the images (the subject simply needed to be refocused at each new distance).

The resulting digital .jpeg images with 6144 × 4088 pixel number were imported into Adobe® Photoshop® CS6 v.13.0 (San Jose, CA), where the leading edge (A') and the left lateral edge of the cube (B') were measured. The percent difference between the two measurements (A' and B') was then calculated according to the following formula:

$$\mathrm{PD}_{\mathrm{Practice}}\,\% = \left(\left(\frac{B'}{A'}\right) - 1\right) \times 100 \tag{9}$$

3. Results

3.1. Mathematical model

With increasing SCD, perspective distortion showed a logarithmic decay. That is, PD is very large at short SCDs (>30% at <2 m) with an asymptote towards zero at larger SCD (Fig. 6). With a chord length of 179 mm, a distance between cords of 127 mm, and a SCD of 1 m, the distortion was −11.2% (B' smaller than A'); at 2.4 m the distortion was −5.0%, at 5.0 m the distortion was −2.5%; and at 12 m the distortion dropped to −1.0% (Fig. 6). Varying the distance between the chord lengths (d) provides different degrees of distortion that either makes the decay curve more acute (smaller d) or levels it out (larger d) (Fig. 7). Irrespectively, distortion is very steep when subject-to-camera distance is <2 m.

3.2. Experimental tests

Measurements of the Plexiglass® cube, taken from the photographs, gave PDs that adhered very closely to the mathematical model (Fig. 6). Superimpositions of the cube and a skull photographed at different SCD (0.7 and 4.0 m), and rescaled for size are shown in Figs. 2 and 3 to visually illustrate PD magnitudes.

4. Discussion

Subject-to-camera distance is a major item of concern for craniofacial superimposition because it has the capability to change the appearance of objects in the field of view, undermining one-to-one anatomical comparisons of separately photographed skulls and faces [4–8,10–12]. Prior lack of consensus on and accounting for this variable has occurred because it has not been thoroughly documented across common SCD ranges (see e.g., Table 1). This paper resolves this gap, mapping the logarithmic decay of PD with increasing SCD using chord lengths as applicable to craniofacial superimposition. At any SCD, PD can be 'looked up' on the decay plots of Figs. 6 and 7 to gauge its influence in terms of differential magnification within and/or between images. In the same fashion, PD can be calculated by entering the necessary parameters into the R-based program, *PerpectiveX*, which has been

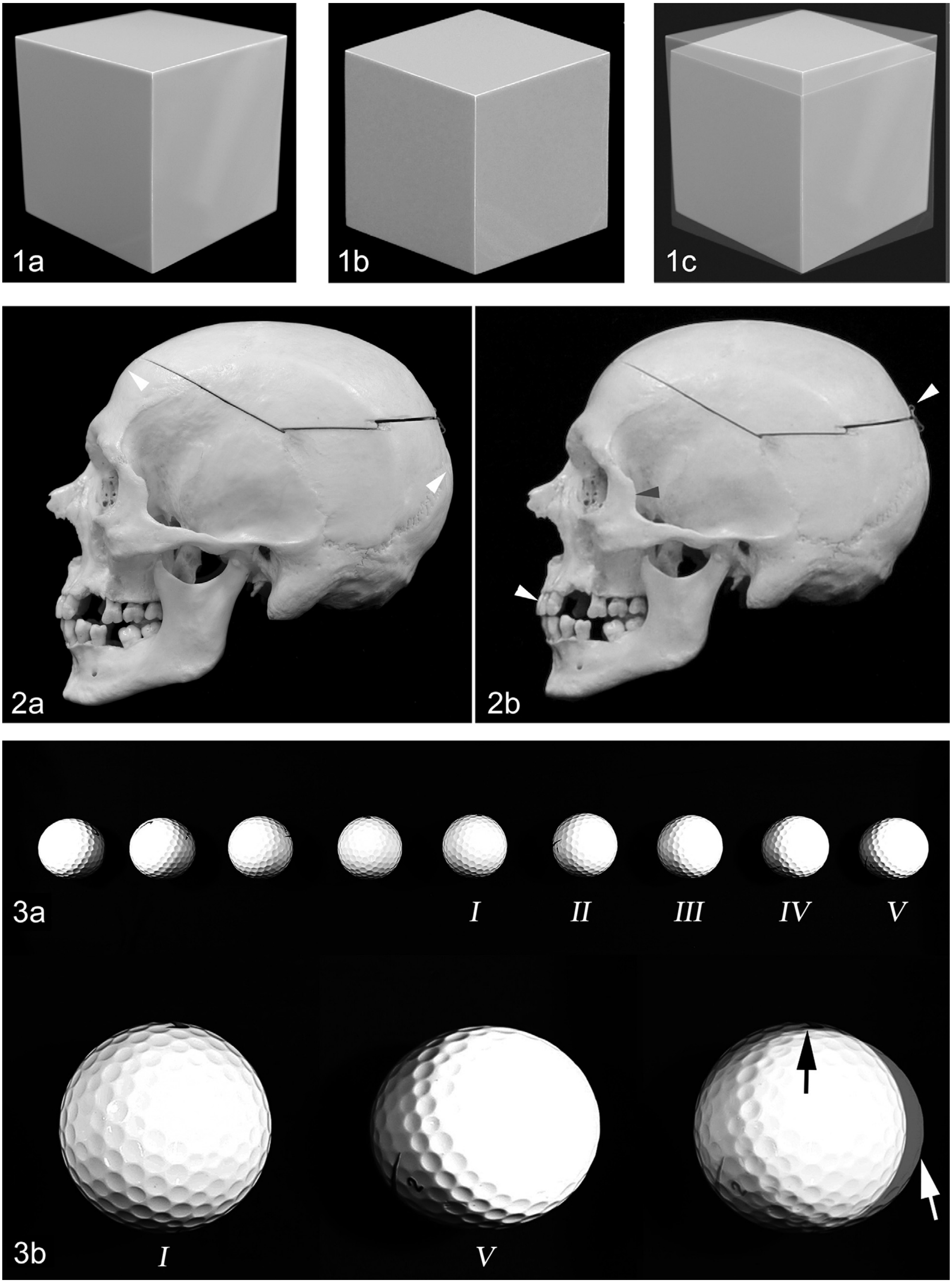

Fig. 2. Photographic demonstration of perspective distortion associated with the point projection of a 3D scene to a 2D photographic plane. Panel 1: change in object shape due to differential magnification with changing subject-to-camera distance. (1a) 179 mm cube photographed with a Nikon D700 camera body fitted with a Nikon 60 mm 2.8 speed lens at a distance of 0.7 m. (1b) The same cube photographed with the same camera and lens, but with a camera-to-subject distance of 4.0 m (the cube has been enlarged post-processing, so that font-bottom to back-top corner distance matches 1a). (1c) Superimposition of 1a and 1b.

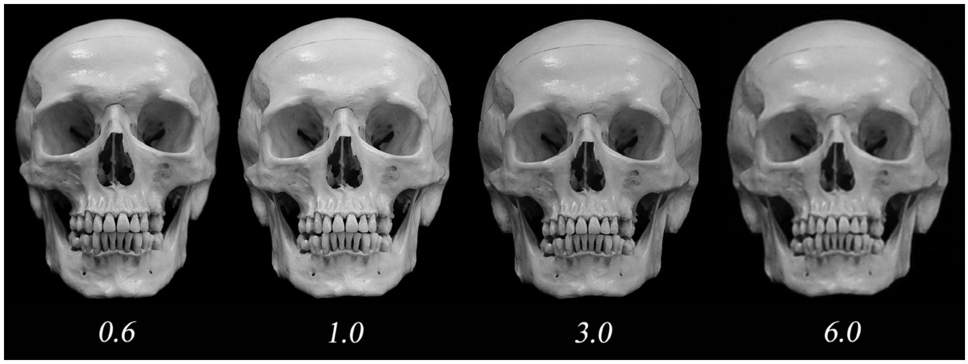

Fig. 3. Example of perspective distortion of a skull, in frontal view, at SCD ranging from 0.6 to 6.0 m. The same skull, in the exact same position is depicted in each case, using the same Nikon D700 camera body equipped with a Nikon 60 mm 2.8 speed lens. Images have been scaled to produce skulls of the same vertical height. Resolution of the skull decreases as a function of increasing SCD without corresponding increases in focal length of the lens (most noticeable at 6.0 m). Note that the zygomatic arches exceed the cranial breadth at 0.6 m, and are well within the cranial limits at 6.0 m.

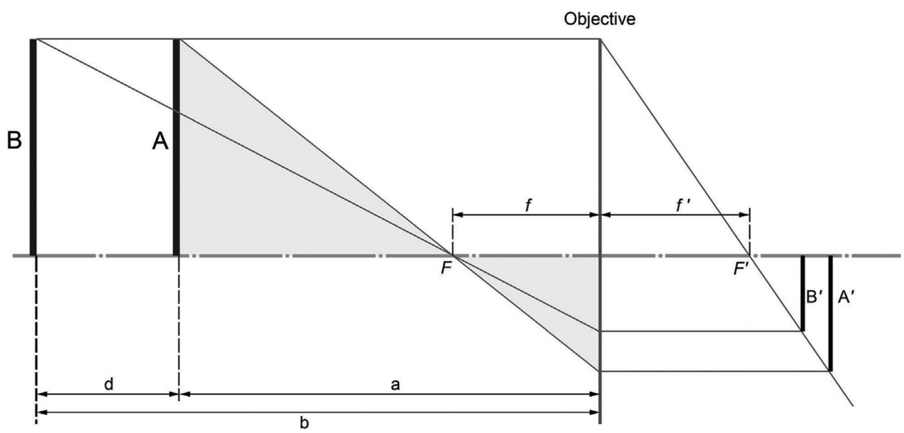

Fig. 4. Titlbach's [10] geometrical summary of perspective distortion during point projection of a 3D scene to a 2D film plane. *A* and *B* represent objects of identical real-life size, but they fall at different distances from the objective lens of the camera, *a* and *a* + *d* respectively. *F* is the focal point and *f*, the focal distance. *A*′ and *B*′ are the film plane representations of *A* and *B*.

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The close correspondence of perspective distortion values obtained by practical experiment and those derived mathematically provide robust validation of the approach and values generated. These counter some prior claims in the literature that perspective distortion is negligible at specific SCDs, e.g., of 2 m [12,22–25]; and that PD is already smaller than 3% at SCD of 2.5 m [8]. Instead, the data illustrate that for the larger and more global face dimensions 3% distortion is obtained at SCD of 4.1 m. At SCD of 2 m or less, PD is considerable being equal to or larger than 6% and exponentially increasing in steep cliff-like fashion at SCD <1 m. The absolute perspective embedded within a single image, as focused on previously in the literature [7,8,10,12,22–27], is also shown not to be a core concern since superimposition depends not on one but two images. Consequently, relative difference in perspective between the skull and the face image is the key. Large perspective distortion may exist within one image, but it is inconsequential if the same perspective distortion is possessed by the second other image to be compared. Consequently, attempts to define a single subject-to-camera distance at which perspective distortion becomes negligible (Table 1) holds little practical applicability because relative differences count most.

Since life-size facial photographs are recommended to be used for superimposition [6,12,19,20], a 1% difference in perspective distortion should serve as the error ceiling to yield small metric differences that are unlikely to thwart the morphological examination. At life-size, even a 1% difference in physiogomical face height translates to a 2 mm difference that threatens

Panel 2: Change in a spherical object's edge due to change in SCD: (2a) skull photographed with a Nikon D700 camera body fitted with a Nikon 60-mm 2.8 speed lens at 0.6 m; and (2b) the same skull photographed with the same camera and lens, but at a subject-to-camera distance of 3.0 m. Note: (i) the marked contribution of the frontal eminence and the occipital bun to the skull outline in 2a but not 2b (white arrows in 2a); (ii) the left maxillary central incisor and the superior hinge for the calotte, which is visible in 2b but not 2a (white arrows in 2b); and (iii) the more posterior placement of the zygomatic region in 2b compared to 2a (grey arrow). Panel 3: Elongation of a spheroidal object at the edge of a camera's field of view. (3a) A photograph of nine golf balls spread across the field of view of a Canon EOS 6D camera body fitted with a Cannon EF 24 mm 4.0 speed macro lens at a distance of 0.6 m. (3b) Close up view of the center ball (*I*), the right most lateral ball (*V*), and a superimposition of the two. Note the elliptical shape of *V* in contrast to *I* and mismatched margins in superimposition alignment (arrows).

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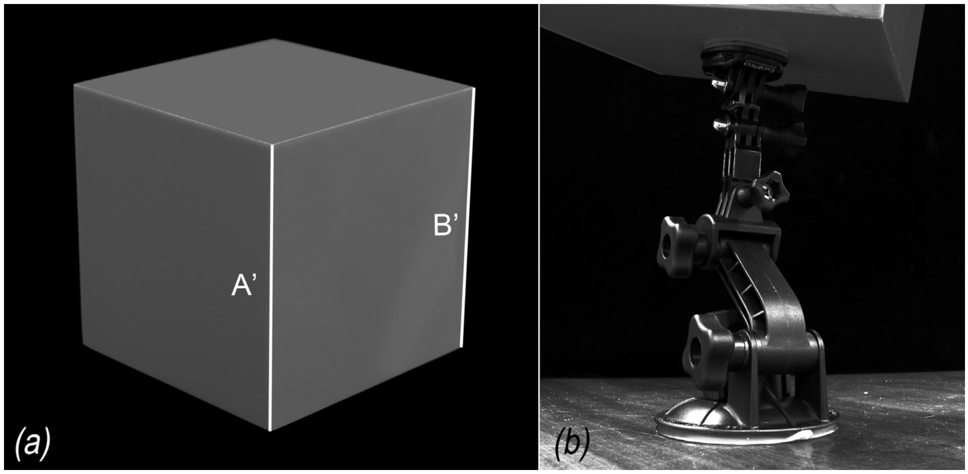

Fig. 5. Plexiglass® cube with 179 mm length faces as used in this study. (a) In this photograph, the cube is tilted towards the camera to reveal its top edge and shape: A' = leading edge; B' = lateral left edge. For the experiment the cube was positioned horizontally to directly face the camera, so the top face was not exposed. A black drape has been placed around the cube's stand so that the cube 'floats' against the black backdrop. b) Cube stand.

accuracy of comparison. Any larger percentage differences yield unacceptable degrees of mismatch, e.g., 2% of physiognomical face height = 4 mm error. Fig. 6 shows that 1% distortion using pertinent craniometric dimensions is achieved within an image at an SCD of 12 m. This is very close, and only slightly lower, than the estimate of 13.5 m provided by Tanaka et al. [27]. Consequently, because PD effects are less at large SCDs, it is unnecessary to precisely match skull photography distances to those employed for a face photograph acquired at ≥12 m. At 12 m precisely, it permits any distance ≥6.1 m to be used for skull photography because the relative difference in perspective distortion will fall within the 1% tolerance bounds. At shorter subject-to-camera distances the importance of precisely matching subject-to-camera distances becomes much more apparent, such that at a face-to-camera distance of 3 m, the skull-to-camera distance must be 3 ± 1 m to fall within the 1% tolerance range. At a face-to-camera distance of 1 m, skull-to-camera distance must be replicated with less than 0.1 m error so not to exceed the 1% tolerance level.

Since facial photographs acquired at >12 m are exceedingly rare for superimposition comparisons (images will be blurry without large focal length lenses), and because superimposition depends on relative comparisons of a photographic pair (not one photograph), there is practically no scenario in superimposition casework where subject-to-camera distances should be ignored. Prior claims that perspective distortion becomes negligible at a fixed subject-to-camera distance somewhere between 0.5 and 5 m (see Table 1) are mistaken. Perspective distortion is an inherent factor of point projection of a 3D scene to a 2D plane and its importance varies as a factor of the subject-to-camera distances used for *both* the skull and the face photograph. This is important to underscore since 1 m photographic copy-stands are commonly employed for any and all superimpositions, irrespective of the face-to-camera distance originally used for face acquisition (see

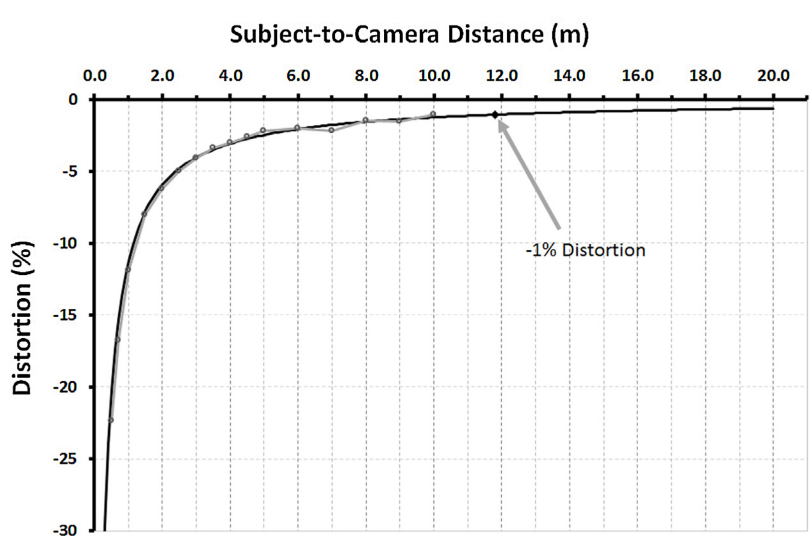

Fig. 6. Percent distortion of the two 179 mm cube lengths (A and B; see Fig. 4) separated by 126.572 mm, as represented in Figs. 4 and 5. Black line represents mathematical predictions of distortion after Titlbach [10] (PD_{Theory}%), using equations described in the Section 2. Grey line represents experimentally observed distortions ($PD_{Practice}$%) measured from photographic images of the 179 mm square cube photographed using a Nikon D700 camera body fitted with a Nikon 60 mm 2.8 speed lens.

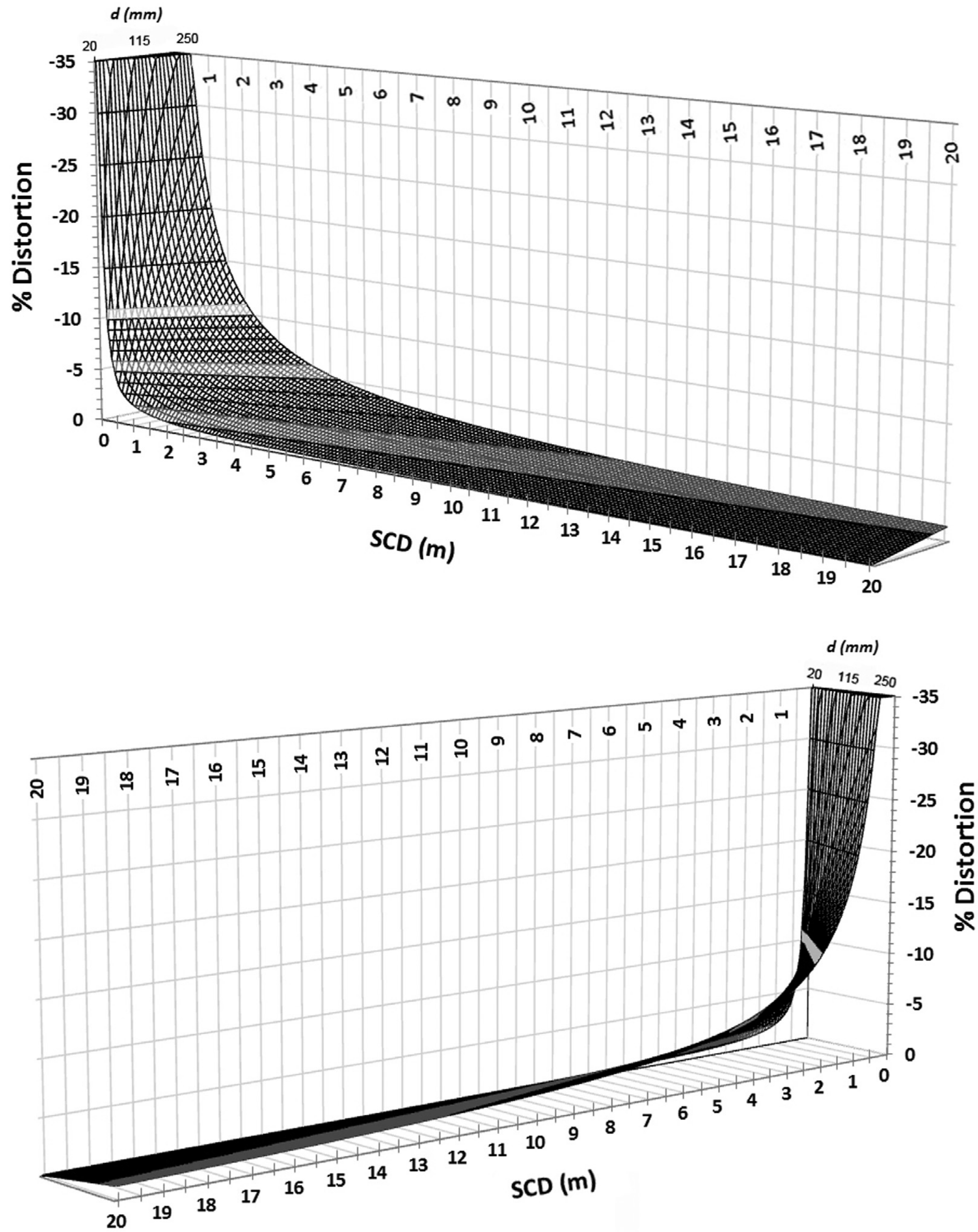

Fig. 7. 3D surface mesh plots of mathematically derived PD for two 179 mm lengths as a function of SCD and the distance between the lengths (d). Grey lines on surface mesh of top plot mark 1–2, 5–6, and 10–11% distortion thresholds respectively. Lower plot shows a 320° rotated view to better visualize cliff-like nature of the PD curve at SCD <1 m, irrespective of the d value.

e.g., [29,30] or Fig. 8). This is clearly not appropriate since the vast majority of facial photographs possess a SCD >1 m – with the exception of the so-called 'selfie'. Images derived at ≤1 m can only be legitimately compared to facial images acquired at similar short SCDs and 1 m copy stands are indeed useful for this purpose. These stands should not, however, be used as a blanket protocol for any or all facial photographs.

Currently, there are several mechanisms for determining the subject-to-camera distance in facial photographs used for craniofacial superimposition. First, consultation with the photographer who took the facial photograph can often clarify the SCD, and other camera details/settings, used [4,12,21]. Second, the metadata can be used to extract rough estimates of the SCD as used for digital images. Third, if inanimate objects are located in the photograph, ideally close to the focal plane in high resolution images, the position of the camera can often be approximated by scene reconstruction and regions of the image in focus [12]. If none of these options are feasible then the craniofacial identification expert is in ambiguous territory and presently must relying on trial and error [6]. Reliable determination of subject-to-camera distance from photographs of the face alone without any distinguishing background items is not currently possible (although some trends in 2D skull shape have been recorded [8]) and remains an avenue for future research. This also applies to the reliable registration of skulls and faces when no hard tissue landmarks are visible (i.e., mouth shut position).

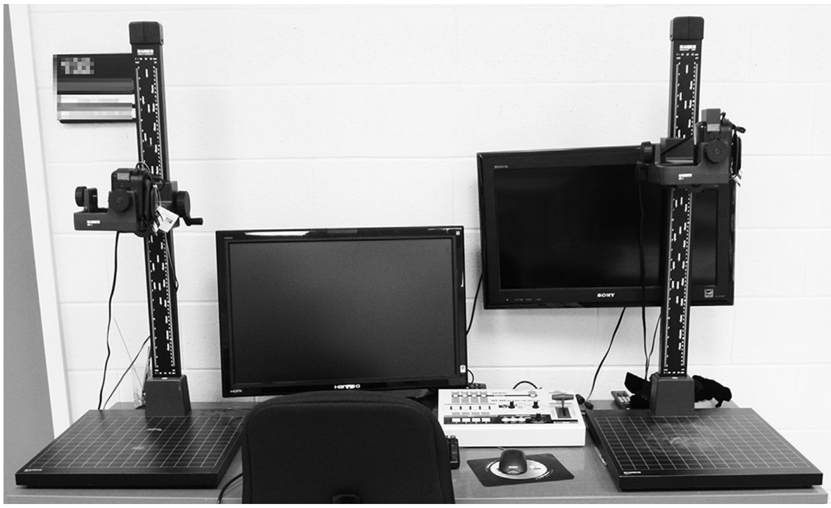

Fig. 8. Example of commonly employed 1 m photography copy-stands for craniofacial superimposition via video projection at the former JPAC-CIL [29], now DPAA – US Defense POW/MIA Accounting Agency. Also see Sauer et al. [30] p. 435 for another example of near identical setup.

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