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Abstract:

Predicting the possible age-related changes to a child's face, age progression methods modify the shape, colour and texture of a facial image while retaining the identity of the individual. However, the techniques vary between different practitioners. This study combines different age progression techniques for juvenile subjects, various researches based on longitudinal radiographic data; physical anthropometric measurements of the head and face; and digital image measurements in pixels. Utilising 12 anthropometric measurements of the face, this study documents a new workflow for digital manual age progression. An inter-observer error study (n=5) included the comparison of two age progressions of the same individual at different ages. The proposed age progression method recorded satisfactory levels of repeatability based on the 12 anthropometric measurements. Seven measurements achieved an error below 8.60%. Facial anthropometric measurements involving the nasion (n) and trichion (tr) showed the most inconsistency (14-34% difference between the practitioners). Overall, the horizontal measurements were more accurate than the vertical measurements. The age progression images were compared using a manual morphological method and machine-based face recognition. The confidence scores generated by the three different facial recognition APIs suggested the performance of any age progression not only varies between practitioners, but also between the Facial recognition systems. The suggested this new workflow was able to guide the positioning of the facial features, but the process of age progression remains dependant on artistic interpretation.

1 Introduction

The National Center for Missing & Exploited Children (NCMEC) currently uses an age progression method to assist in the identification of missing children (NCMEC, 2018). In 2015, NCMEC distributed 20,230 photos of missing US children (NCMEC, 2015), and, with the aid of technology, it is becoming more common that long-term missing children are rediscovered (NCMEC, 2016).

Age progression methods alter the shape, colour and texture of a facial image while retaining the identity of the individual (Hunter, Tiddeman and Perrett, 2012). The areas of change are different for adults and children, and during juvenile growth, the skull and associated cartilages change in size and proportion to accommodate the growth and development of the internal organs (e.g. the brain, airway, dentition etc.) and increased body size. However, with the skull shape remaining relatively stable in adulthood, and the changes in face shape includes the continuous growth of cartilage (i.e. the nose and ears) and soft tissue changes, such as the development of wrinkles and skin sagging. Therefore, age progression is often separated into juvenile and adult (Mullins, 2012). This study focuses on age progression for juvenile facial images.

Age progression is challenging for individuals younger than 3 years of age, as facial characteristics are underdeveloped (Mullins, 2012). Age progression is more accurate with images of older children and accuracy is also affected by the quality of the reference photographs (Mullins, 2012). Current research techniques include manual or machine-based digital image processing and drawings by artists (Mullins, 2012). NCMEC in the USA updates an age-progression image every 2 years before adulthood, and every 5 years after age 18 years. These images are used to generate further investigative leads (NCMEC, 2016).

1.1 Manual age progression

A specialised forensic artist often creates manual age progression images by sketching or by utilising photo-editing software (e.g. Adobe Photoshop). The age progression technique varies between practitioners (Erickson et al., 2016) and some practitioners prefer to put more weight on quantifiable growth data, whilst others put more weight on the features of other family members (Taylor, 2000). In order to understand and produce a more accurate depiction, images of siblings and parents at the same age of the progression are often required to help artists to maintain a reliable likeness with biological resemblance (Lampinen et al., 2015). But when these images are not available, a more general reference will be used, such as images of other children of the same age (Mullins, 2012).

The original images should be altered as little as possible to retain certain facial characteristics, by using reference material of other children, and only small portions should be used to avoid resemblance to the templates (Mullins, 2012). Manual age progression methods are subjective, not standardised and often practitioner-dependant (Charman and Carol, 2012; Koudelová et al., 2015; Lampinen et al., 2015).

Based on a cross-sectional north American sample (n=2326), Farkas and Hreczko (1994) provided a set of growth-related linear measurements of the head, face, orbits, nose, lips and mouth. Farkas and colleagues have provided: a comparison of measurements at age one; the total growth difference between ages 1 to 18 years; periods of rapid growth; and the maturation age in each individual measurement. These measurements could be useful to determine the parameter of change required for specific areas of the face. For example, the length of the head matures at around age 10 years for females. Information like this could provide a more 'guided' process of age progression. No matter what method is used, the practitioner must have a good knowledge of craniofacial growth and dental eruption patterns (Farkas, 1994; Taylor, 2000).

1.2 Facial anthropometry

Research related to the facial growth of children is well published in orthodontic related literature. A larger amount of longitudinal data following the growth of children has been established to gain an understanding of the factors affecting growth (Bishara, Peterson and Bishara, 1984; Bjork, 1963; Hans, Broadbent and Nelson, 1994; Kau and Richmond, 2008; Ochoa and Nanda, 2004). Growth studies using longitudinal data are able to document information related to individual variation and this will have an advantage over cross-sectional data (Moss, 1964). Orthodontic standards and treatment methods can then be developed to achieve optimal results for patients, and these standards are used to describe mean trends rather than predicting individual changes, as these changes vary within the same growth period and between sexes (Bishara, Peterson and Bishara, 1984).

Different body systems can have different maturation rates, and the difference in facial growth pattern is interlinked between the developments of organs within the head, the airway, the oral region and the basicranium (Enlow and Hans, 1996; Gill, D. S. and F. B. Naini, 2012). The head shape is determined by the neurocranium configuration, which in turn will have an influence on face types (Enlow and Hans, 1996; Gill, D. S. and F. B. Naini, 2012). Face shape will also be influenced by developmental factors related to the airway, mastication, dentition and occlusion (Franco et al., 2013). Although the distances between the eyes and the width of the nasal bridge remain relatively similar during growth, the eyes will appear to be closer together in relation to the vertical facial dimension at the cheekbones, and the nose increasing in size and height (Enlow and Hans, 1996). With changes to mastication and dentition during growth, the gonial region of the mandible extends laterally from the medial side of the cheekbone, this extension changes the v-shaped child mandible to a more 'squared' adult appearance (Enlow and Hans, 1996). The greatest influential factor for the face is perhaps the nasal area, in comparison to adults, young children and infants tend to have a lower nasal bridge with a 'pug-like' (upturned) nose (Enlow and Hans, 1996). During growth, the mid-face expands as a result of the changes in the anatomical positioning of the airway relative to lung capacity and body size, the male face tends to have a wider and longer nasal region to accommodate for a larger airway capacity (Gill, D. S. and F. B. Naini, 2012; Kuroda, Schmittbuhl and Nanci, 2013).

Regardless of the difference in the head-form, face-form or sex, the prepubertal head and face are more brachycephalic, when the nasal region, dentition, jaw (mastication), and airway are not as developed as the neural component (i.e. brain) (Enlow and Hans, 1996). Facial growth is an equilibrium between functional and structural components, when the difference in growth across the ages were compared (e.g. the Bolton standard), this produces a model illustrating a forward and downward expansion seen in many studies (Enlow and Hans, 1996). Enlow and Hans (1996) & Kuroda et al. (2013) described two main head/face types along with three types of facial profiles. Ranges do occur, intermediate head-shapes are described as mesocephalic, and mesoprosopic for intermediate face-shapes. Head-shape does not always correspond with the associated face-shape and Enlow and Hans (1996) described a brachycephalic head shape with a leptoprosopic face shape. Facial variations within and between populations are vast and diverse, regional imbalances during the developmental process in facial growth is an unavoidable event (Enlow and Hans, 1996). This will lead to a difference in face shapes and also asymmetries, therefore using average templates and the averaged growth standards as a guidance in manual age progression is problematic, especially when growth patterns vary between different individuals and populations.

Children can exhibit different growth rates in the lower face and the upper face (Ligthelm-Bakker et al., 1992). Fields et al. (1984) suggested that the differences in the lower face height between long and short face children were related to the morphology of the mandible, where long-face children tended to have a larger gonial angle, greater dentoalveolar component, more intermaxillary space, and a greater posterior upper and lower dental height. Blanchette et al. (1996) observed that growth in the lower anterior vertical facial height in long faces were nearly twice as great, compared to the shorter faces. Different growth rates and face shapes could be an explanation to the inconsistency of vertical facial measurement when compared to the horizontal facial measurements of the same individual at different ages.

Facial type describes the different shapes of the face, previous research have categorised the different faces with facial index (Enlow and Hans, 1996; Hajnis, 1987). Different face types can exhibit different growth patterns (Sassouni and Nanda, 1964). In adults, long-faces tend to be more retrognathic (Enlow and Hans, 1996) with a greater anterior lower face height (Fields et al., 1984), whereas a brachycephalic face tends to have a straighter or concaved profile (Enlow and Hans, 1996). These difference in facial morphology could be related to the shape of the dental arch (Rakosi, Jonas and Graber, 1993), the difference in growth between the different head and face shape is particularly important for orthodontics to plan treatments (Enlow and Hans, 2008). With the palatal size difference between the different head and face shapes, broad faces usually receive expansion treatment, and extraction treatment for long faces (Rakosi, Jonas and Graber, 1993). Dajani (2008) produced regression equations models to predict nasomaxillary growth, and these are beneficial in planning treatment. Research in this field is valuable for age progression research in predicting facial growth.

With the different growth pattern of the face, Euryprosopic (Brachycephalic) face types will appear more juvenile resembling the wide and short facial configuration of a child, where a dolichocephalic face will appear to be more mature (Enlow and Hans, 1996). Could this suggest age progression of a child with a euryposopic face form would be easier to predict? Is facial growth population specific or face type specific?

1.3 Literature measuring growth related changes of the juvenile face

Farkas and Hreczko (1994) measured growth-related changes in North American Caucasian subjects across ages 1 to 18 years old (Cross-sectional). Numerous measurements of the head, face, orbits, nose, ears, lips and mouth were recorded from each year group. For the majority of measurements, females had an earlier maturation rate in comparison to males, with the greatest changes (over 20mm) at the head and face (Table 1) and the smallest changes (below 20mm) at the orbits and the mouth (

Table 2).

Table 1: Growth changes (>20mm) from age 1-18 years (Amended from Farkas and Hreczko 1994)

Linear Measurements	Total growth between 1&18 years mean		Maturation age (Years)	
	mm	% **	Male	Female
Face: Mandibular arc (t-gn-t) *curve line	68.8	30.49	15	14
Head: Craniofacial Height (v-gn)	49.66	28.27	15	11
Face: Maxillary arc (t-sn-t) *curve line	49.6	22.16	14	12
Face: Width (zy-zy)	37.4	38.90	15	13
Face: Depth in Mandibular region (t-gn)	34.7	35.02	15	13
Face: Height (n-gn)	30.7	38.91	15	13
Face: Depth in Maxillary region (t-sn)	28.6	30.65	14	12
Head: Length (g-op)	24.5	14.91	14	10
Head: Width (eu-eu)	23.9	19.31	15	14
Face: upper face height (n-sto)	23.3	48.80	14	12
Nose : Height (n-sn)	20.9	69.55	15	12
Nose : Bridge length (n-prn)	20.5	76.64	15	13

***The total growth in percentage was expressed [Growth difference (mm)/ Mean value at age 1 years] %*

Table 2: Facial growth changes (<20mm) from age 1-18 years (Amended from Farkas and Hreczko 1994)

Linear Measurements	Total growth between 1&18 years mean		Maturation age (Years)	
	mm	% **	Male	Female
Face: Width of the mandible (go-go)	18.7	24.80	13	12
Head: Height of the head (v-n)	18.5	19.14	13	13
Mouth: Width of the mouth (ch-ch)	17.5	51.40	14	14
Face: Height of the mandible (sto-gn)	16.0	50.55	15	12
Nose: Nasal ala length, left (ac-prn)	13.2	67.69	15	13
Orbits: Biocular width (ex-ex)	12.5	16.52	15	13

Nose: Nasal tip protrusion (sn-prn)	9.8	96.55	16	14
Nose: Width of the nose (al-al)	6.9	26.34	14	12
Orbits: Eye fissure length (ex-en)	5.3	20.66	15	13
Orbits: Intercanthal width (en-en)	5.2	19.19	11	8
Mouth: Height of the lower lip (sto-sl)	4.8	36.92	13	9
Mouth: Height of the upper lip (sn-sto)	3.9	23.15	11	5
Orbits: Eye fissure height (ps-pi)	1.2	12.57	11	14

***The total growth in percentage was expressed [Growth difference (mm)/ Mean value at age 1 years] %*

Table 1 and Table 3 depicts the averaged measurements between male and female from Farkas (1994), with each measurement documented across the different age groups up to age 19-25 years old. This can be particularly useful in age progression, where measurements are taken from the photograph of the missing child (Farkas et al.,1994), and the known age is extrapolated according to the average measurements from appendix A of Farkas (1994).

With digital measurements taken in pixels, this makes comparison with anthropometric studies difficult. Anthropometrical data, such as Farkas (1994) are life-size measurements, and there will be differences when these measurements are translated to photographs. Images are often affected by focal plane, distortion, head pose, facial expression, accessories such as glasses etc. Machado et al. (2017) analysed 10 facial measurements from passport photographs of 1000 Brazilian subjects (n=200) age between 6-22 years. The authors compared nine different measurements of the face using the iris diameter as a fixed reference point. In comparison to interpupillary distance, the authors suggested that the diameter of the iris was the most stable measurement and could be a better reference for facial analysis. This can be particularly useful, as current age progressions are mostly digital, using tools such as Adobe Photoshop where the true measurement/scale is unknown. Farkas et al. (1994) used the endocathion distance (en-en) and the height of the upper lip (sn-sto) as a reference point for scaling the photograph to life-size in order to carry out measurements. Iris diameter could be a more stable reference point for standards in comparison to the method proposed in Farkas et al. (1994). Eight out of nine anthropometry measurements from Machado et al. (2017) were present in the Farkas (1994) study.

1.4 Comparison of anthropometric methods

Anthropometric measurements from Farkas and Hreczko (1994) could be a useful tool for age progression. However, these measurements are not directly transferable to photographic images unless we know the life size of the image (Farkas, Clark and Sills, 1994) and the focal plane. The iris diameter in infants to 8 years of age showed a mean difference of 0.318 ± 0.10 S.E. mm (Ronneburger et al., 2006). Machado et al. (2017) used the iris ratio as a fixed measurement to quantify the growth of other landmarks. Although the two studies are different (Table 3), both are useful for predicting growth in juvenile faces.

Table 3: Machado et al. (2017) Vs Farkas (1994)

	Machado et al. (2017)	Farkas and Hreczko (1994)
Subject's age	6-22 years	0-25 years
Data	Longitudinal and cross-sectional	Cross-sectional
Population	Brazilian	North American

Sex	Non-specific sex	Male and Female

Machado et al. (2017) demonstrated the cumulative growth from 6-22 years of age as a percentage using the iris as a fixed reference. However, Farkas and Hreczko (1994) did not measure the iris diameter or the growth of the pupillary distance, therefore 8 landmarks were compared as shown in Table 4, and the difference between the two studies is shown in Table 5.

Table 4: Eight facial measurements from Farkas and Hreczko (1994)

	Measurement at age 6 years (mm)			Measurement at age 19-25 years (mm)			Growth Percentage (%)
	Male	Female	Mean	Male	Female	Mean	Male & Female
n-sn	40.1	39.3	39.7	54.8	50.6	52.7	32.75
ch-ch	41.7	41.2	41.45	54.5	50.2	52.35	26.30
n-gn	98.5	95.7	97.1	124.7	111.4	118.05	21.58
zy-zy	114.9	113.4	114.15	139.1	130.0	134.55	17.87
al-al	28.6	27.8	28.2	34.9	31.4	33.15	17.55
sn-gn	61.4	58.8	60.1	72.7	64.3	68.5	13.98
ex-ex	80.0	77.8	78.9	91.2	87.8	89.5	13.43
en-en	30.6	29.8	30.2	33.3	31.8	32.55	7.78

Table 5: Comparing growth difference (%) of the facial anthropometric measurements between Machado et al. (2017) and Farkas & Hreczko (1994)

Order	1	2	3	4	5	6	7	8
Machado et al. (2017)	sn-gn	ch-ch	n-gn	n-sn	al-al	ec-ec	zy-zy	en-en
	28.80%	26.31%	26.13%	22.96%	21.15%	14.22%	13.63%	12.07%
Farkas and Hreczko (1994)	n-sn	ch-ch	n-gn	zy-zy	al-al	sn-gn	ex-ex	en-en
	32.75%	26.30%	21.58%	17.87%	17.55%	13.98%	13.43%	7.78%

**Exocanthion (ex)/Ectocanthion (ec) are the same landmark

It is interesting to see the order in difference shown in Table 5, most noticeable with the height of the nose (n-sn), the height of the lower face (sn-gn) and the width of the face (zy-zy). It is uncertain what caused the difference between the two studies, perhaps it is the focal length of the camera and the 2D to 3D translation. The difference may also be due to population and face type, or the possibility of error in landmark placement especially at the zygion (zy). It is most likely to be a combination of all these factors.

1.5 <u>Bolton Standards (1975)</u>

Broadbent, Broadbent and Golden (1975) developed the Bolton standards for orthodontic researchers to compare optimum facial and dental development growth. Their longitudinal study began in the 1930s documenting the facial growth of healthy individuals with normal developing occlusion, the averaged facial templates were derived from 22,000 cephalometric radiographs of 5,000 North American children between age 0-21 years old (Broadbent, Broadbent and Golden, 1975). Averaged facial template transparencies were produced in frontal view for every age from 3-18 years old, and in lateral view from 1-18 years old. These frontal templates could be used as a guide in age progression to estimate facial growth in frontal images of children, but these nonspecific growth templates are not ideal compared to gender-specific models (Erickson et al., 2016).

Young faces are similar between sexes until puberty, at around age 12 years, when the female face reaches maturity and the male face continues to grow into the early 20s (Kuroda, Schmittbuhl and Nanci, 2013). Each individual will have slight differences in the duration and timing of the pubertal growth spurt and the Bolton standards average these differences, resulting in a smooth incremental pattern in facial growth (Broadbent, Broadbent and Golden, 1975). The duration and timing of growth spurts in relation to changes in the facial pattern is also something an age progression cannot predict, and the Bolton standard is unlikely to be an accurate representation of puberty-related facial changes.

As a limitation, the Bolton standard is population-specific (North American), not sex-specific, and represent healthy children with normal developing occlusion. This suggests this template may not represent the current sample size, children of other dental occlusion pattern and individual differences in growth rate. With the x-ray averages taken in the frontal plane, the Balton templates are optimal when using frontal images, which are not always available – and camera distortion could affect the alignment of templates where images are not in frontal view. The Bolton Standard should be used as guidance for age progression.

2 Methodology

Using anthropometric growth data, this study introduced a guided method for digital manual age progression. The 'accuracy' of an age progression was measured using machine-based face recognition, where three commercial Facial Recognition Systems (FRS): Microsoft Face API, Amazon Rekognition, and Face++, were employed to compare the images by producing a similarity score. These FRS are also referred to as APIs (application program interface) (Liu and Wilkinson, 2020).

Practitioners (n=5) took part in an inter-observer study following the guided method. The repeatability and accuracy of the method were evaluated by comparing the facial measurements.

2.1 Digital manual age progression

Reference images of the biological parents and siblings at the target age of the missing child is optimal. Without those images, more general reference images from other subjects of a similar age has been recommended (Mullins, 2012; Taylor, 2000). However, Mullins (2012) recommends that only small portions from 5-6 different sources should be taken from reference images, to ensure the individual of the reference image is not identifiable.

The general practice to depict growth related changes to a child is by stretching the area of the face just beneath the eyes and elongate the lower 2/3 of the child's face (Mullins, 2012). However, practitioners should note that the head remains roughly the same size after age 3 years (Mullins, 2012), the height of the head (v-n) matures around age 13 years, the width of the head (eu-eu) matures around age 14 or 15 years, and the eye fissure height changes very little at around 1.3mm (Farkas, Clark and Sills, 1994). Table 7 documented the age progression workflow for this study.

Mullins (2012) also suggested altering the neck, clothing and hairstyle. However, the present study explored FRS, so these features were not altered as they were not an area of interest. If dentition is visible, the guidelines suggested deciduous dentition from the original is replaced with permanent teeth (Mullins, 2012), but dentition is highly individualised and is often used in identification (Avon, 2004; Silva et al., 2008). Therefore, the lips were depicted closed so that teeth were not considered in the comparison. In contrast, the inner patter of the ear, moles and scars should remain the same as an important biometric for identification (Mullins, 2012).

The input image was first enhanced to improve the quality before conducting age progression (Lanitis and Tsapatsoulis, 2016). The original images were altered as little as possible to retain facial characteristics (Farkas, Clark and Sills, 1994) and small portions from the reference material of other children were used (Mullins, 2012). The growth prediction was based on measurements from Farkas (1994) and the Bolton standards. Using the guidance by Farkas et al. (1994) and Machado et al. (2017), 11 facial measurements were selected as a guide to estimate facial growth (Table 6). The Bolton templates were also superimposed onto the images for guidance.

As suggested by Machado et al. (2017) and Ronneburger et al. (2006), the iris diameter is a relatively stable measurement throughout growth, and this measurement can be set as a fixed reference. Unlike Machado et al. (2017) where the images were standardised, the quality of images can vary in resolution and subject-to-camera distance. By calculating the percentage of growth differences between two different ages (

Table 8), this ratio can be translated into pixels measured in Photo editing software (Adobe Photoshop).

Table 6.1: Facial anthropometry (Amended from Farkas (1994))

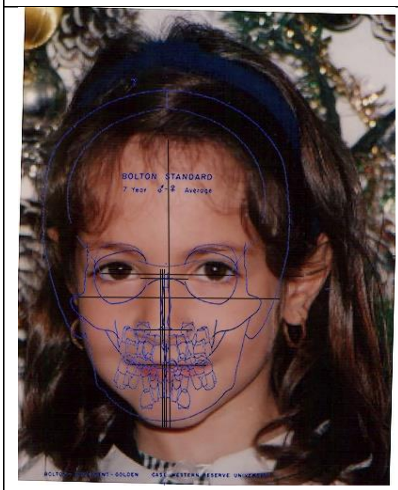
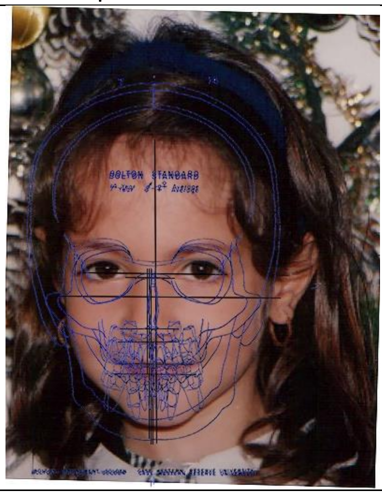
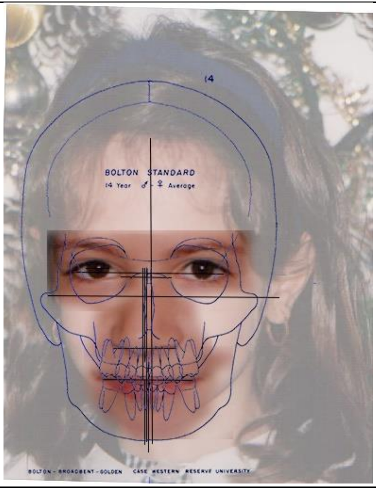
Male (mm)	zy-zy	ex-ex	en-en	al-al	ch-ch	n-sto	n-sn	n-gn	sn-gn	sto-gn	tr-gn
Age 1	96.7	76	27.3	26.5	34.8	49	30.9	80.6	49.9	31.9	143.6
Age 2	98.9	76.2	26.5	25.6	35.2	52.5	33.7	87.5	54.5	36.1	150.1
Age 3	101.4	77.5	27.2	26.1	36.7	54.3	35.3	88.5	55.2	35.6	153.4
Age 4	110.2	77.2	30.3	28.4	38.9	58.9	39.5	96.4	60.1	41.1	157.5
Age 5	111.8	78.7	30.8	28.9	40.7	58.6	38.9	96.7	60.3	42.2	155.4
Age 6	114.9	80	30.6	28.6	41.7	60	40.1	98.5	61.4	41.4	157.6
Age 7	116	79.2	30.2	28.8	42.7	60.4	41.4	99.5	61.1	42.4	161
Age 8	120.5	81.5	31.2	29.8	44.6	61.8	42.1	101.8	61.9	42.2	163.4
Age 9	121.8	82.9	31.7	29.4	45.5	62.3	43.7	102.7	61.7	42.4	163.8
Age 10	121.9	82.8	31.2	30.2	45.9	64.5	45	105.2	63.5	43.3	166.1
Age 11	125.7	85.2	32.6	30.1	46.4	65.4	45	107.1	56.3	44	169.5
Age 12	125.5	85.6	32	31.6	48.2	67.3	47.5	108.1	64.8	44.1	173.5
Age 13	128.5	86.8	32.8	32.4	49.1	68.3	48.8	111.6	66.5	45.7	175.4
Age 14	130.9	86.9	33.1	33.1	50.1	70	49.7	114.1	67.8	46.4	176.4
Age 15	133.5	89.4	33.7	34.2	51.8	73.3	51.9	119.1	70.6	47.8	184.8
Age 16	134.9	89.7	33.4	34	52.1	74.1	53	120.9	71.3	48.9	185
Age 17	139.1	90.7	33.9	34.8	53.5	74	53.2	120.9	70.8	48.5	184.1
Age 18	137.1	89.4	32.9	34.7	53.3	74	53	121.3	71.9	50.1	187.5
Age 19-25	139.1	91.2	33.3	34.9	54.5	76	54.8	124.7	72.6	50.7	187.2

Table 6.2

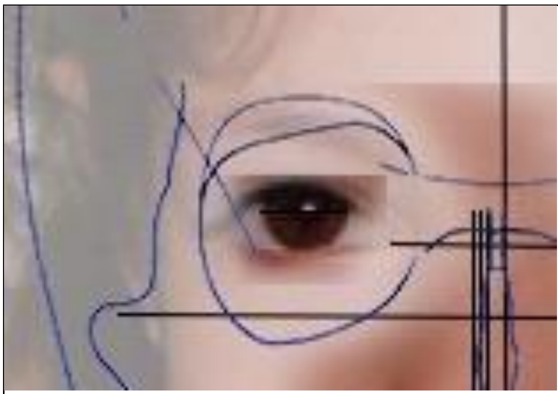
Female (mm)	zy-zy	ex-ex	en-en	al-al	ch-ch	n-sto	n-sn	n-gn	sn-gn	sto-gn	tr-gn
Age 1	95.6	75.3	26.9	25.9	33.3	46.5	29.2	77.2	47.3	31.4	141.1
Age 2	97.9	75.5	26.6	26.1	35	50.7	32.6	83.8	51.7	34.4	145.8
Age 3	101.2	77.3	27	25.9	36.3	53.4	34.6	86.9	54.3	35.5	148
Age 4	106.8	75.3	29	27.8	37.9	56.1	37.8	92.6	57.8	40.2	145.2
Age 5	109.4	76.5	29.4	28.5	39.5	58	39.3	96.5	59.4	41.3	151.9
Age 6	113.4	77.8	29.8	27.8	41.2	57.9	39.3	95.7	58.8	40.3	155
Age 7	115.8	79.4	30.1	28.6	42.4	59.7	40.7	98.3	59.7	40.7	158.9
Age 8	117.3	79.2	30.5	28.5	43.1	60.4	41.5	98.1	59.3	40.6	159.3
Age 9	119.4	81.4	31.1	29.2	44.6	62.3	43.6	101.3	59.9	40.9	161.6
Age 10	120.7	81.8	31.2	29.6	44.9	63.2	44.5	103.9	62.2	42.5	164.4
Age 11	122.5	82.8	31.6	29.9	45.9	64.4	45.7	104.7	62.1	42.2	164.3
Age 12	123.6	83.6	31.6	30.9	46.5	66.3	47.2	108.2	64.6	44.1	168
Age 13	126.8	85.4	32.2	31	48.1	67.3	48.2	109.1	63.9	43.5	168.6
Age 14	128	85.3	32.4	31	47.5	68.2	49.1	110.7	64.8	44.2	170.8
Age 15	129.7	87	32.7	31.7	49.1	68.8	49.2	111	64.1	43.5	170.7
Age 16	130.6	86.9	31.8	31.6	48.9	70.4	50.4	113.5	65.9	44.7	172.1
Age 17	131.1	87.6	32.5	31.9	49.4	68.9	49.2	112	65.3	44.7	172.7
Age 18	129.9	86.8	31.6	31.4	49.8	68.1	48.9	111.8	65.5	45.2	172.5
Age 19-25	130	87.8	31.8	31.4	50.2	69.4	50.6	111.4	64.3	43.4	173.3

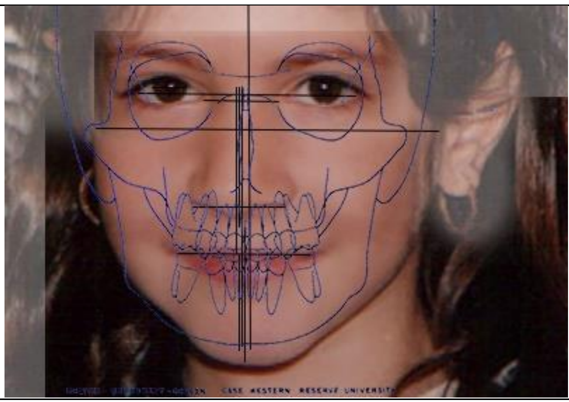
Table 7: Age progression workflow

1: Source image	2: Enhance image	3: closed lips
		
Original image: Age 7	Enhance the image to improve the quality before making any changes	‘Closed lips’ should be depicted before the measurements; an opened jaw should be ‘corrected’ by moving the chin and gonial angle slightly upwards.

4: 12 measurements	5: Extrapolate	6: Facial features
		
Age 7 measure in pixels	Calculate, extrapolate and centre the measurements, Bolton standard can be used as a guideline	Copy and place the facial features (eyes, nose and lips) from the original image (Age 7) onto the extrapolated measurement lines

7: Progression [manual image manipulation]





7.1	Stretch the original image (forehead, the width of the face, ears and the lower 1/3 of the face) to match the measurements
7.2	The width of the head can be reduced by using the warp or distort tool in "free-transform"
7.3	The diameter of the iris and the height of the eyes remain unchanged
7.4	Stretch the width of the eyes to match the ex-ex, check the position of en-en
7.5	Without changing the size, place the original iris back on top of the stretched eyes
7.6	Stretch the width and height of the nose to match the measurements
7.7	Stretch the width of the lips to match the measurements. A smile is unique, no drastic changes to the mouth and lips (Mullins, 2012)
7.8	Add shadows to sides of the nasal body and alter the tip of the nose to be slightly downward pointing (so the nose appears to be less button like, taller and wider)
7.9	Widen the chin and jawline according to the estimation, warp or 'liquify' for a more define the jawline. Addition of smile lines, remove baby fat and sharpening the angle of the lower jaw (Mullins, 2012)
7.10	Stretch the dimension of the cheeks from below the eyes if necessary
7.11	Reposition and deepen the nasolabial folds, and any other creases if necessary
7.12	Texture from another individual at a similar age may be used
7.13	Darken and thicken the eyebrows if necessary
7.14	Blend the features together to generate a final image
Practitioners should make alterations where the depiction remains a 'convincing face'. This process helps to guide the 'growth' aspect of the age progression.	

8: Final image

Original image (L); Age progression to age 14 (R)

The mean difference in iris diameter between 3 months to 8 years old is approximately 0.818mm, with an average size of 10.70 +- 0.73 mm in diameter between all subjects (Ronneburger, Basarab and Howland, 2006). This range was between 8.9-12.6mm and showed no significant correlation to the child’s age or sex (Ronneburger, Basarab and Howland, 2006).

The image was imported to Adobe Photoshop CC 2019 in Step 1, and enhanced in step 2 (

Table 7). Step 3 measured the 12 landmarks including the iris diameter. By adopting the methods proposed by Farkas et al. (1994) and Machado et al. (2017), the image was translated to 'life-size' from pixels (Age 7 est. mm) using the iris diameter as a fixed measurement at 10.7mm (

Table 8). The translated measurements in millimetres were compared with the Farkas standard at the original age of the photograph (Age 7). The difference between the target age (Age 14) and source age (Age 7) from the Farkas standard was calculated as a ratio difference (Ratio =Target age/Source age). This ratio was then used to extrapolate the difference in the estimated measurement both in millimetres (age 14 est.mm) and in pixels (est. pixels). Once the measurements were extrapolated in Step 5 together with the Bolton standards (Broadbent, Broadbent and Golden, 1975), the image was manually manipulated in Step 6 and 7. The measurements and template was used as a guidance for the age progression method to produce a final image.

Table 8: Example of measurement estimation

Subject FF073							
				Digital image [Iris: Pixel > mm ratio = 0.428]			
	Farkas Norms (mm)				est. mm		
Farkas Standard	Age 7	Age 14	Ratio difference	Image (pixel)	Age 7	Age 14	Est. Pixels
iris				25	10.7		
zy-zy	115.8	128	1.11	214	91.59	101.24	236.55
ex-ex	79.4	85.3	1.07	144	61.63	66.21	154.7
en-en	30.1	32.4	1.08	51	21.83	23.5	54.9
al-al	28.6	31	1.08	62	26.54	28.76	67.2
ch-ch	42.4	47.5	1.12	81	34.67	38.84	90.74
n-sto	59.7	68.2	1.14	102	43.66	49.87	116.52
n-sn	40.7	49.1	1.21	79	33.81	40.79	95.3
n-gn	98.3	110.7	1.13	168	71.9	80.97	189.19
sn-gn	59.7	64.8	1.09	89	38.09	41.35	96.6
sto-gn	40.7	44.2	1.09	66	28.25	30.68	71.68
tr-gn	158.9	170.8	1.07	307	131.4	141.24	329.99

**est = estimated

By comparing the estimated landmarks to the Farkas Standard, this method resulted in measurements tailored to the image by using a ratio of growth for each landmark. The accuracy of this method will be affected by a number of factors: The quality of the source image, such as subject-to-camera distance, definition, lighting, head-pose, facial expression, hair and glasses; Individual growth pattern/heritage of the individual (Farkas and Bolton's standards were both based on a North American population); Artistic interpretation.

2.2 Inter-observer study

Using a subject from the OACAD database (Liu, 2018), one original image at three years old from subject OAM002 was chosen (Figure 1). Five practitioners were asked to generate two age progressions to age 6 and 13 years old based on the original image using the guided method described above. The measurements taken by the practitioners were compared, the likeness between the progressions was compared manually, and the age progressions were also compared to the target images using three FRS.

Original
Age 3 years | Target image
Progression 1: Age 6 years | Target image
Progression 2: Age 13 years

Figure 1: An example of manual age progression using guided methodology (OAM002) from the inter-observer test

3 Results

Some age progressions achieved a higher score when compare to others, (e.g.Practitioner D's 3-6yrs age progression). However, there was no overall significant difference in similarity score between the practitioners [$F(4,25)=0.189, p=0.942$]. There was a significant difference between the age progressions (Figure 2): 3-6yrs Vs 3-13yrs [$F(1,24) = 194.25$, $p < 0.000$]. This difference suggests the target image was more dissimilar to the age progression with an increased age gap.

There was a significant difference between the FRS [$F(2,24) = 8.57$, $p = 0.002$]. Amazon ($M = 57.49$, $SD = 30.60$) and Face ++ ($M = 55.97$, $SD = 23.97$) were significantly different to Microsoft ($M = 42.13$, $SD = 22.11$). Microsoft achieved lower similar scores across the majority of comparisons, this suggest machine-based face recognition can vary greatly.

Table 9: FRS Similarity Scores of the different age progressions between practitioners

Similarity score %	Practitioner				
	A	B	C	D	E
FRS	Age progression: 3-6yrs				
Microsoft	69.8	62.7	56.1	70.5	56.7
Amazon	87.9	89.4	67.5	96.8	78.6
Face++	80.8	78.1	70.9	85.5	75.6

Age progression: 3-13yrs					
Microsoft	28.8	10.6	25.8	19.7	20.6
Amazon	30.3	21.9	18.5	28.0	56.0
Face++	43.1	30.6	31.0	34.1	30.0

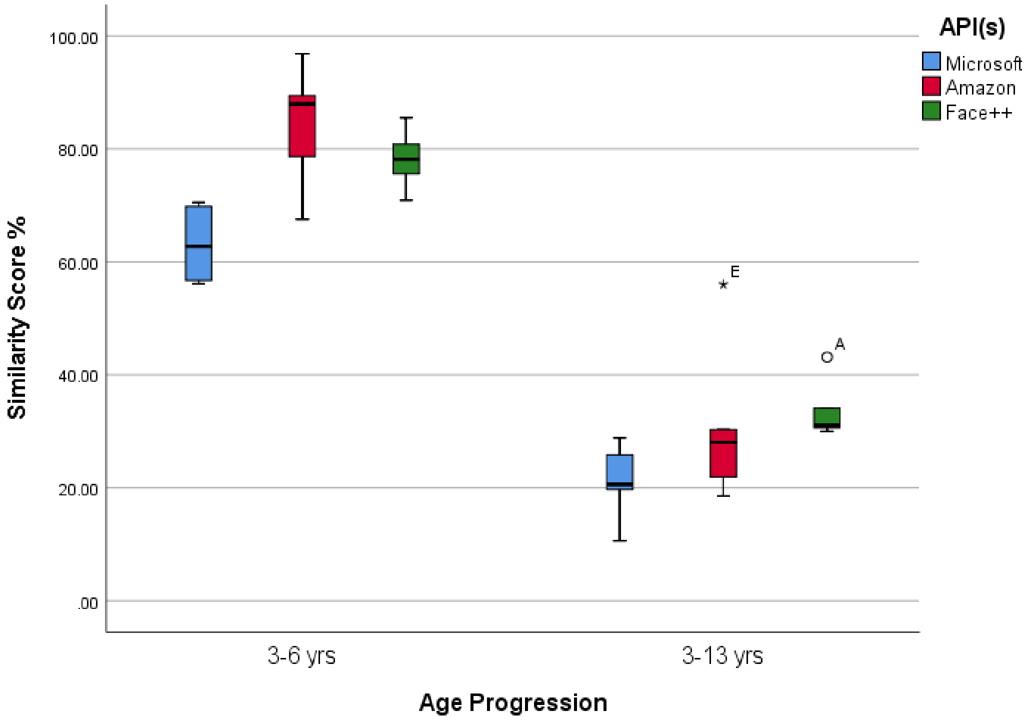


Figure 2: Facial recognition scores of the two age progressions from the three different APIs

The outline of the age progressions were compared to the target image(s) (Figure 3**Error! Reference source not found.**). Visually, facial features that varied the most between practitioners were: face shape, jawline, lip shape, and the positioning of the eyebrows. These features were not guided by the measurements, and differs in relation to artistic interpretation. The most consistent features were nose width and shape.

Figure 3: Outline of the age progression(s) compared to the target image

Practitioners				
A	B	C	D	E
Age progression 3-6 yrs				

The facial measurements of the original image between the practitioners were compared in Table 10. tr-gn showed the largest variation (33 pixels) when compared to other measurements, measurements involving the nasion (n) showed the largest difference in percentage, this suggests the landmark placement of nasion was more inconsistent when compared to other landmarks.

Table 10: Variation in pixel measurements of the original image between practitioners (n=5)

Measurements (Pixels)	Min	Max	Median	Difference	Difference (%) *
iris	17	17.06	17	0.06	0.35
ex-ex	113	117	115	4	3.48
sto-gn	50	52	52	2	3.85
ch-ch	54	57	56	3	5.36
en-en	48	51	51	3	5.88
al-al	47	50	48	3	6.25

zy-zy	172	188	186	16	8.60
tr-gn	203	236	233	33	14.16
sn-gn	70	82	79	12	15.19
n-gn	126	151	136	25	18.38
n-sto	76	100	84	24	28.57
n-sn	54	73	56	19	33.93

* Percentage difference (%) was compared to the median value.

The extrapolated measurements of the age progressions were compared to the target images (**Error! Reference source not found.**

Table 11). Results suggest the actual measurements of the target image were mostly within the rage of the predictions. The guided method underestimated ex-ex and overestimated sto-gn in both age progressions (3-6yrs and 3-13 yrs). Measurements in the 3-13 year progressions were more variable and more actual measurements were outside the predicted range: underestimation of al-al and tr-gn; overestimation of en-en and n-sn. This suggests the prediction was more unreliable with an increased age gap. The difference between the target image and the predictions were different between the two age progressions, 7/11 measurements (Median) were above the target, this could suggest the method is likely to overestimate.

Sto-gn is one of the most repeatable measurements; the result suggests the overestimation is more apparent in the 3-6 years age progression, (12% vs 2.7%). Similarly, the over estimation of sn-gn was more apparent in the 3-6yrs age progression (3.38% Vs -2.9%). The difference with the measurements involving the nasion (n-sto and n-sn) were also 10.3-12.2% more (overestimation) in the 3-13yrs age progression in comparison to the 3-6yrs. This suggest the prediction of the vertical facial measurement were more inconsistent across the aging face when compared to the horizontal facial measurements.

Table 11: Variation in pixel measurements of the age progressions compared to the target images

Age Progression: 3-6 years					
Measurements (Pixels)	Min	Max	Median	Target	Difference (%)
ex-ex	116.65	120.77	118.71	126	-5.79
al-al	51.50	54.79	52.60	55	-4.37
tr-gn	208.56	242.46	239.38	247	-3.09
n-sto	83.98	110.50	92.82	93	-0.20
en-en	54.00	57.38	57.38	57	0.66
ch-ch	61.36	64.77	63.63	63	1.00
n-sn	61.34	82.93	63.61	62	2.60
sn-gn	77.86	91.21	87.87	85	3.38
zy-zy	194.90	213.03	210.76	203	3.82
n-gn	140.24	168.06	151.37	145	4.39
sto-gn	58.15	60.47	60.47	54	11.99
Age Progression: 3-13 years					
tr-gn	232.11	272.13	266.42	291	-8.45

al-al	58.34	62.07	59.59	64	-6.90
ex-ex	126.56	128.80	128.80	134	-3.88
sn-gn	87.94	98.79	95.17	98	-2.89
sto-gn	66.75	66.75	66.75	65	2.70
zy-zy	217.97	238.24	235.71	227	3.84
ch-ch	72.25	76.26	74.92	72	4.06
en-en	59.09	61.50	61.50	58	6.03
n-gn	157.63	190.41	171.50	161	6.52
n-sto	91.82	125.78	105.66	96	10.06
n-sn	71.89	100.92	74.65	65	14.85

** Percentage difference (%) was compared to the actual measurement of the target image

4 Discussion

Forensic age progression is dominated by forensic artists, and a good knowledge of facial growth is necessary (Mullins, 2012; Taylor, 2000). The trends of facial growth have been described, with only a few examples of manual depictions quantifying growth by measurements (Farkas et al.,1994; Machado et al., 2017). Anthropometric measurements are quantifiable, therefore, the artistic variability should reduce with the aid of the guided method for digital manual age progression. This study compared the depictions created by five different practitioners, and the results showed that facial measurements involving the landmarks Nasion (n) and Trichion (tr) were the most unreliable. However, the landmark nasion had been previously reported as one of the most reliable landmarks (Campomanes-Álvarez et al., 2015), and this contradicts the conclusion drawn in the current study. The nasion is defined as *"The midpoint on the soft tissue contour of the base of the nasal root at the level of the frontonasal suture"* (Campomanes-Álvarez et al., 2015). The subject measured in the inter-observer study by the three practitioners was 3 years old and the region of the nasal root was underdeveloped, flat and ill-defined. This could have explained the decreased in precision of landmark placement.

Zygomatic width (zy-zy) was consistent between the five practitioners (difference of 8.60%). Zygion is "*the most lateral point on the soft tissue contour of each zygomatic arch*", and this measurement has been previously reported as one of the landmarks with the highest variation (Campomanes-Álvarez et al., 2015). To measure the width of the face, the contour outlining the widest part of the face could vary in the vertical position, but remain consistent with little variation in the actual measurement through the vertical area.

Anthropometry is able to guide feature location in age progression to a certain degree, but the process of age progression remains variable due to artistic interpretation, especially at certain facial features, such as face shape and jawline, where the current method does not provide a guide.

The reliability of age progression images has been explored previously (Erickson et al., 2016; Lampinen et al., 2015) by comparing depictions of the same individual created by different artists. In these studies the assessment of reliability was based on human perception and the authors concluded that the depictions varied in resemblance to the target. The current study used three different machine-based facial recognition systems, the results not only showed a difference in confidence score between the depictions of different practitioners, it also showed variation between the different FRS. Similar to humans, the ability to recognise faces can vary, and these systems should be treated with caution in experimental design. The variation in the different FRS was explored by (Liu and Wilkinson, 2020).

Erickson et al. (2016) suggested that experience of the practitioner could be a contributing factor to performance. However, Lampinen et al. (2015) found no correlation between resemblance to the target and experience/training. Both studies had suggested various strategies to combat artistic variability. Lampinen et al. (2015) showed an improved recognition rate by morphing together of all the depictions created by different artists, whereas Erickson et al. (2016) suggested artists should work together with models of an age predictive algorithm. The sample size of the current study is too small to draw a conclusion on the different experience of practitioners. Based on the confidence scores of the FRS, the variation between the age progressions suggests artistic variability.

4.1 Physical limitation: Facial growth

For an age progression to be effective, the images have to represent what the child currently looks like and be able to provide improvements over an outdated photograph (Lampinen et al., 2010). Understanding the changes in facial growth from childhood to adulthood is key to developing or using any age progression methods or tools. The use of averaged growth pattern in an age progression may be an inaccurate representation of the child, as developmental rates vary between individuals even within a population, and these variations will introduce errors into age progression techniques (Lampinen et al., 2010). This could be the factor for an underestimation in ex-ex and overestimation in sto-gn. The subject used within this current study is unlikely to be represented by the North American Caucasian population from Farkas and Hreczko (1994), where the ratio was derived from. Information related to face types across populations should be explored in future studies.

4.2 Physical limitation: Images

There are three physical limitations relating to image use. Firstly, the quality of the reference/source photo; secondly, the quality of the age progression; and thirdly, the quality of the target images for matching using computer algorithms.

Challenges in pose, illumination and expression of the image have been an area of interest in machine-based facial recognition, and this is even more challenging with the change in shape and texture of the face related to ageing in children (Chellappa, Sinha and Phillips, 2010). The source image will influence the quality of the age progression (Lanitis and Tsapatsoulis, 2016) and in most cases, the reference (original) images will not be of 'studio-posed' quality, with unconstrained facial expression and head position making measurements and proportional predictions difficult (Farkas, Clark and Sills, 1994; Lanitis and Tsapatsoulis, 2016). If available, frontal images should be used as the basis for an age progression (Lanitis and Tsapatsoulis, 2016). Frontal view images were used in the current study, however it is uncertain how these images compare to the standardised passport photographs from Machado et al. (2017) and whether this had an effect on the measurements.

Manual age progression is a subjective method involving a high level of artistic judgment, and the quality of the likeness produced can vary between different artists (Frowd, Erickson and Lampinen, 2014). There are currently no standardised methods or training, and depiction of the same individual can vary in style depending on the source material and personal judgment (Erickson et al., 2016). Erickson et al. (2016) suggested that there is a correlation between the experience of the artist and the similarities between the age progression and the target image.

The quality of the target image can also limit the match rate using FRS. In terms of indecent images of children, images are likely to vary in illumination, pose and facial expression. These limitations are variable factors that are difficult to control and problematic for identification.

The minimum interocular distance on a passport specification is 120 pixels (ISO/IEC 19794-5). Resolution of an image can affect the performance of an FRS (Hennings-Yeomans et al., 2008) and Boom et al. (2006) suggested a resolution of 32 X 32 pixels as optimal. Undoubtedly, image resolution will have an effect, but the ‘optimal’ may vary between different FRS and environmental conditions. For example, Grother et al. (2017) suggested that the optimal resolution for identification from turnstile video clips is between 20-55 pixels. Recognition using standardised passport images is certainly different to recognition in the wild, and factors such as noise, blurring, pixels and brightness will affect the algorithm (Dodge and Karam, 2016; Grm et al., 2017).

Research has incorporated different methods to improve super-resolution for face recognition (Hennings-Yeomans, Baker and Kumar, 2008a, 2008b; Kong, Zhang and Cheng, 2013; Lin et al., 2007; Wheeler, Liu and Tu, 2007). Super-resolution/reconstruction is used to enhance low-resolution poor surveillance footage, although it is able to generate a higher resolution from a low-resolution image, this process often generates distortion and artefacts (Hennings-Yeomans, Baker and Kumar, 2008b; Lin et al., 2007).

Photography is subjected to distortion including optical distortion from the camera lens, and perspective distortion from subject-to-camera distance (Mansurov, 2017a). Perspective distortion can impair facial recognition in human perception (Liu and Chaudhuri, 2003; Liu and Ward, 2006), thus many researchers have developed methods to estimate subject to camera distance or even to correct such effect (Gallagher, 2002; Lades et al., 1993; Mansurov, 2017b; Stephan, 2015; Wu et al., 2013). It is known that camera distortion can affect machine-based facial recognition (Lin, 2000), but how does perspective distortion affect facial recognition in the wild? Certainly, this will have an effect on the methods applied to age progressions, especially when performing facial anthropometry.

5 Conclusion

Age progression could further improve the recognition rate of juvenile faces. This study documented a new workflow for digital manual age progression using a combination of previously published methods. The proposed age progression method for children recorded satisfactory levels of repeatability with facial measurements at the nasion (n) showing the most inconsistency. Measurement tr-gn showed a large variation between the participants, trichion (tr) is often masked by hair and therefore this facial measurement is less useful and should be excluded from the prediction measurements when the hairline is not visible. Overall, the vertical measurements were less accurate when compared to the horizontal measurements. This study suggests the measurements are able to guide the positioning of the features to a certain degree. However, even with the help of the guided method, the process of age progression remains variable due to artistic interpretation.

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