



Preliminary colour characterisation of a Stratasys J750 digital anatomy printer with different fillings and face orientations

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Abstract

Multicolour capability in additive manufacturing could play a key role in certain applications such as surgical training and consumer products. However, the ability to accurately 3D print colours is not well documented and could affect the realism of models produced through these technologies. As a recent system, the Stratasys J750 Digital Anatomy Printer has yet to be analyzed for its colour perception and accuracy, which is quantified through this study. This will allow users of this and similar material jetting systems with an improved understanding of the relationship between digitally applied colours and their result when 3D printed, as well as the influence of certain settings. Thirty-three rectangular prism models with different CMYK and RGB colours, as well as infill materials, were printed on a Stratasys J750 DAP printer. These were scanned on five faces using a Nix Mini 2 handheld colour sensor, documenting readings in CIELAB format. The data were analyzed using the CIEDE2000 colour difference formula, and its recent modifications for 3D printed objects. Results found statistically significant and perceptible differences in colour accuracy among different colours, core materials, and face orientations. It was also observed that the addition of VeroPureWhite as filler material instead of the default SUP706 support improved colour accuracy. The study recommends the following steps to improve colour accuracy: (i) avoid the addition of black (K) manually in CMYK colour space, (ii) use pure white as the base infill material instead of support material, (iii) add a little white (~ 10%–30%) to make samples opaque instead of translucent.

Keywords 3D printing · Additive manufacturing · Multicolour 3D printing · Material jetting · Spectrophotometer

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1 Introduction

In 3D printing applications, colour can be important for a variety of reasons. It can be used to add visual appeal and realism to a printed object or to distinguish different parts or features of the object. For more specialized applications, colour can also play a functional role. For example, using different colours to indicate different types of materials in a printed object for the construction industry, or to highlight areas of anatomy that require special attention in biomedical applications.

Additive manufacturing (AM) has been formally classified by ISO/ASTM standard 52900, with ISO/ASTM 52900:2021 being the most recent standard at the time of writing [1]. ISO/ASTM 52900:2021 identifies six distinct process categories for single-step polymer-based additive manufacturing processing principles. All six process categories along with their colouring capabilities are summarized in Table 1. Almost all the process categories have a derivative that could manufacture parts in distinct solid colours. Printing in solid colours is typically referred to as multicolour printing, where certain sections of the model could be printed in a different solid colour without interrupting the printing process. This is distinct from full-colour printing where a small number of colours can be blended to produce a full spectrum of visible colours and added to the manufactured part voxel by voxel. Only half of the six process categories have mainstream 3D printing systems which can print in full colour as summarized in Table 1.

There can be a few exceptions to the above list, such as the material extrusion Da Vinci Colour full-colour capable printer, which are outliers and do not represent the general trend of colour printing [2]. Similarly, vat photopolymerization has been shown to be able to print in multiple colours in an experimental setup [3]. All four full-colour capable process categories use various forms of inkjet printhead to jet colour droplets on each print layer. Out of the four full-colour capable categories, only material jetting technology does not rely on coloured inks applied

separately in addition to a base material (e.g., powder); instead, the coloured resins are the base material. These resins are directly deposited to form a part and can be mixed to generate the full-colour spectrum, similar to standard inkjet printing technology. It allows this technology to produce highly translucent multicolour models with high gloss and a fine surface finish [4, 5]. Based solely on the advanced and mature inkjet printhead technology, Material Jetting (MJT) 3D printers became a prominent polymer additive manufacturing technology in a relatively short time [6]. MJT has also been known with other proprietary terminologies such as “PolyJet” by Stratasys, “MultiJet” by 3D systems, and “UV curable inkjet system” by Mimaki Engineering [4].

There are multiple colour scales/spaces that can be used to generate a specific colour. Cyan, Magenta, Yellow, Black (White) (CMYK(W)) and standard Red, Green, Blue (sRGB) colour spaces are relatively common in print and digital media, respectively. Both colour spaces can generate millions of colour combinations. The colour values often need to be transformed from one colour space to another for printing. In the 2D printing industry, International Colour Consortium (ICC) profiles are used for colour space conversions [7]. Similarly, most full-colour 3D printing systems have developed ICC profiles for their 3D printers. Different frameworks have been suggested to improve the performance of ICC profiles for 3D printing [8, 9].

One of the challenges of any full-colour process is the accurate reproduction of colours in a 3D object (output) compared to the input digital file. Several studies have explored the colour reproduction accuracy of AM technologies. A few studies involving the Z-Corp Z510 full-colour binder jetting printer indicated issues leading to colour differences in printed objects [10, 11]. Similarly, another example of powder bed technologies was done by Wang et al. [12] using a ProJet 680 Pro 3D printer (3D Systems) where it was observed that a few post-processing techniques improved the colour accuracy of the printed objects. Most existing studies rely on the International Commission on Illumination known as the Commission Internationale de l’Eclairage Delta E 2000 (CIEDE2000

Table 1 Process categories and their colouring capabilities

| Process category | Colouring capability |
|-------------------------|---|
| Binder jetting | Full-colour inkjet printing onto a powder bed |
| Material extrusion | Multi-colour printing of discrete coloured filament |
| Material jetting | Full-colour inkjet liquid resin printing on a tray |
| Powder bed fusion | Full-colour inkjet printing onto polymer powder (currently only possible with HP Multi Jet Fusion) |
| Sheet lamination | Full-colour inkjet/laser printing onto paper sheets |
| Vat photopolymerization | Single-colour printing (although multi-colour printing of discrete colours is possible with experimental systems) |

or ΔE^{00}) formula and parametric factors based on standards defined for the 2D printing industry, such as digital media and textiles. Only recently, teams led by Xiao [16] have optimized the ΔE^{00} formulas for 3D printed objects by introducing corrections such as an exponent (b) [17] or revised parametric factors (K_L , K_C , and K_H) [18]. These recommendations have not been implemented in most colour accuracy/reproduction studies, especially where ΔE^{00} has been automatically obtained from a colourimeter or spectrophotometer, but are designed to better represent colour as applied to 3D printed geometries.

Colour verification studies have been conducted on MJT technology such as the investigation of a standard Stratasys J750 on the effects of finish types on colour appearance [13]. Golhin et al. [14] tested a Stratasys J55 for colour accuracy and surface properties and concluded that the colour differences in the majority of the samples were significant enough to be noticeable by an inexperienced observer. In a recent comprehensive study of colour 3D printing, an HP Jet Fusion 580 3D printer was tested for colour accuracy with multiple print orientations and surface finishes [15]. This study was unique in its comparison of 3D printed samples to the original digital files and found that designing coloured textures digitally in the CMYK colour space resulted in better accuracy compared to using the sRGB colour space. In most 3D printing colour case studies, the accuracy of full-colour 3D printing setup had deviations, as concluded in a comprehensive review of colour production by Yuan et al. [16].

Furthermore, a limitation observed in most studies is that samples are relatively thin, flat, and opaque [11, 13, 14]. There is little or no emphasis on other parameters such as vertical surfaces, translucent objects, filler materials, manual colour mixing, and complex geometries, which are typical settings requiring input for material jetting 3D printers. Specifically, for the relatively new Stratasys J750 DAP there is limited data to understand its colour accuracy and behaviour, which is critical considering the machine is specifically marketed for producing anatomical models. The Stratasys J750 DAP is a material jetting printer similar to the base model J750, having additional capabilities such as printing in special biomimicking resins (e.g. GelMatrix™, TissueMatrix™). [16–18]

To provide the latest colour accuracy information, this study applies the updated ΔE^{00} calculations to 3D-shaped samples produced on a Stratasys J750 DAP in various solid and translucent colours. These were tested for colour accuracy, compared to the original digital inputs, as well as colour variation on different sides and with different print parameters.

2 Method

2.1 Sample design

A three-dimensional model of a rectangular prism measuring $20 \times 20 \times 15$ mm was modelled in Meshmixer (Autodesk, San Rafael, CA, USA). A protruding cone was added on one side to enable the identification of all sides uniquely (cone pointing towards the top face). The geometry was then exported as an STL file.

2.2 Colour and material settings

The STL file was imported into GrabCAD Print (Stratasys, Rehovot, Israel) version 1.68.10.19783, the software used to specify print parameters for the J750 DAP. 23 copies of the part were arranged on the build plate having the same orientation. A selection of CMYKW and RGB colours as shown in Table 2 was applied using manual colour settings.

A sampling technique similar to quota sampling was used to explore a suitably broad range of combinations, where all primaries of each colour scale were divided into three shades (pure, brighter, darker) except black which was equally divided into five shades to measure the grayscale from black to white. It should be noted that RGB and CMYKW colour spaces react differently towards light and dark shading; in RGB high values are brighter while in CMYKW higher percentages mean a darker output (except for White (W)).

The following tray materials were installed in the printer for producing the samples: Agilus30Clear, VeroBlack Plus, VeroCyan-V, VeroMagenta-V, VeroPureWhite, VeroYellow-V and SUP706. The print mode used was High Mix. The model type was selected as “general” and the finishing type as “Matte”. The support material was used as the core material with a start depth of 2.5 mm. The rest of the settings were left as default.

After printing the first batch of samples, a selection of samples as shown in Table 3, particularly those that had printed with translucency in the first batch, were printed separately as a second batch to test the effect of using a “white” core instead of support.

2.3 Additive manufacturing and post-processing

The print duration and material usage are shown in Table 4. All samples were 3D printed on a Stratasys J750 DAP Printer. The printed samples were covered in support material except for the top face, a feature that is generated automatically by the GrabCAD print slicer. The designed and printed samples on the print bed are shown in Fig. 1.

Table 2 Colour sampling of batch 1

| CMYK (%) | Cyan | Magenta | Yellow | Black | White |
|-------------------|------|---------|--------|-------|-------|
| White | 0% | 0% | 0% | 0% | 100% |
| Light grey | 0% | 0% | 0% | 25% | 75% |
| Grey | 0% | 0% | 0% | 50% | 50% |
| Dark grey | 0% | 0% | 0% | 75% | 25% |
| Black | 0% | 0% | 0% | 100% | 0% |
| Dark cyan | 70% | 0% | 0% | 30% | 0% |
| Cyan | 100% | 0% | 0% | 0% | 0% |
| Light cyan | 70% | 0% | 0% | 0% | 30% |
| Dark Magenta | 0% | 70% | 0% | 30% | 0% |
| Magenta | 0% | 100% | 0% | 0% | 0% |
| Light Magenta | 0% | 70% | 0% | 0% | 30% |
| Dark yellow | 0% | 0% | 70% | 30% | 0% |
| Yellow | 0% | 0% | 100% | 0% | 0% |
| Light yellow | 0% | 0% | 70% | 0% | 30% |
| RGB (0–255 units) | Red | Green | Blue | | |
| Light red | 255 | 127 | 127 | | |
| Red | 255 | 0 | 0 | | |
| Dark red | 168 | 0 | 0 | | |
| Light green | 127 | 255 | 127 | | |
| Green | 0 | 255 | 0 | | |
| Dark green | 0 | 168 | 0 | | |
| Light blue | 127 | 127 | 255 | | |
| Blue | 0 | 0 | 255 | | |
| Dark blue | 0 | 0 | 168 | | |

Table 3 Colour sampling of batch 2

| CMYK (%) | Cyan | Magenta | Yellow | Black | White |
|-------------------|------|---------|--------|-------|-------|
| White (b) | 0% | 0% | 0% | 0% | 100% |
| Dark cyan (b) | 70% | 0% | 0% | 30% | 0% |
| Cyan (b) | 100% | 0% | 0% | 0% | 0% |
| Light cyan (b) | 70% | 0% | 0% | 0% | 30% |
| Dark Magenta (b) | 0% | 70% | 0% | 30% | 0% |
| Dark yellow (b) | 0% | 0% | 70% | 30% | 0% |
| Yellow (b) | 0% | 0% | 100% | 0% | 0% |
| Light yellow (b) | 0% | 0% | 70% | 0% | 30% |
| RGB (0–255 units) | Red | Green | Blue | | |
| Red (b) | 255 | 0 | 0 | | |
| Blue (b) | 0 | 0 | 255 | | |

Following 3D printing, the samples were cleaned with a high-pressure water jet to remove the support material and any remaining residue. After the clean-up, samples were washed under flowing tap water and dried in ambient air.

The samples were then stored, away from sources of bright light for a few days. The samples were observed and compared visually for qualitative analysis as shown in Fig. 2

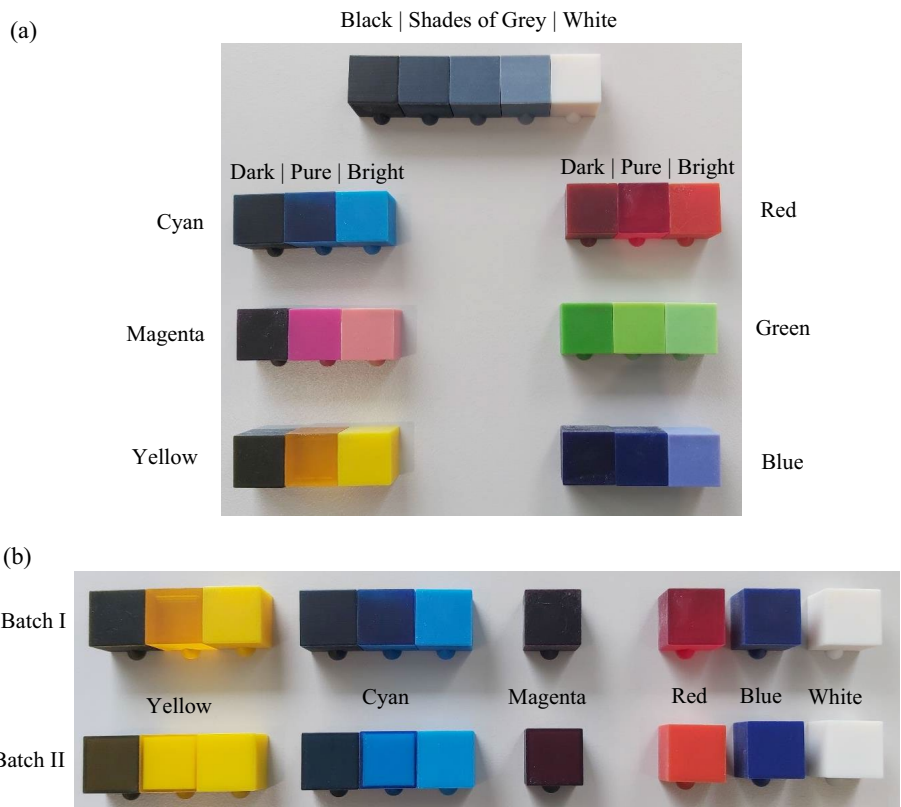
Table 4 Print and material estimates from GrabCAD software

| Tray estimations | Batch I | Batch II |
|------------------------|----------|----------|
| Print time | 2 h 39 m | 5 h 26 m |
| Total materials | 187 g | 162 g |
| Total support (SUP706) | 164 g | 65 g |
| Agilus30Clear | 5 g | 12 g |
| VeroBlackPlus | 27 g | 16 g |
| VeroCyan-V | 33 g | 22 g |
| VeroMagenta-V | 33 g | 18 g |
| VeroPureWhite | 58 g | 72 g |
| VeroYellow-V | 31 g | 22 g |



Fig. 1 First batch samples on print bed. **a** In GrabCAD print workspace. **b** Printed samples in J750 print bed (colours not to scale)

Fig. 2 Printed and post-processed samples **a** Batch 1 samples segregated in colour groups. **b** Batch 2 samples in the bottom row along with their equivalent Batch 1 samples in the top row for comparison



2.4 Colour measurements

The five flat surfaces of all samples were scanned with a Nix Mini 2 (Nix sensor Ltd, Ontario, Canada) handheld colour sensor. The colour sensor was connected to an Android device wirelessly and controlled via the Nix Toolkit application provided by the OEM. The colour readings opted to be in CIELAB colour space. The technical specifications and settings for the Nix Mini 2 colour measurements are shown in Table 5.

The colour scans were taken in an indoor environment without any bright light in close vicinity as shown in Fig. 3. The five faces were named Top, Bottom, Face 2, Face 3, and Face 4 (with Face 1 containing the cone and hence not flat). All faces were identified relative to the protruding cone shape on Face 1. All readings were recorded manually in a Microsoft Excel spreadsheet against their respective original colour values.

2.5 Data analysis

The experiment generated a total of 33×5 (165) unique colour readings with each having three parameters, that is, L^* , a^* and b^* . L^* indicates the lightness with a value of 100 indicating white and 0 indicating black. a^* indicates the difference between red and green with red on the positive side, and b^* indicates the difference between yellow and blue with

Table 5 Nix Mini 2 OEM specifications

| Property | Value |
|-----------------------|--------------------------------------|
| Calibration | Automatic |
| Illuminant | D50 (ISO 3664:2009) |
| Observer angle | 2° |
| Measurement condition | M2 UV Excluded ISO 13644:2017 |
| Light source | 2×High CRI, broad spectrum white LED |
| Optical resolution | Tristimulus colourimeter (CIE XYZ) |
| Repeatability | 0.1 ΔE |
| Measurement geometry | 45°:0° optics |
| Measurement port | 13 mm diameter |

**Fig. 3** Sample scanning with Nix mini 2 colour scanner

yellow being on the positive side. The data were organized and grouped to show a unique sample in a row and a unique face in a column. To numerically calculate the perceptible colour difference, ISO/CIE 11664-6:2014 recommends ΔE^{00} colour difference formulae Eq. (1) which uses CIE $L^*a^*b^*$ space [19]. These mathematical equations and relations were incorporated into the spreadsheets with assistance from the work done by Sharma et al. and Lue et al. [20–22]. These calculations use parametric factors K_L , K_C , and K_H . CIE recommends K_L , K_C , and K_H to be unity under reference conditions for 2D objects and $K_L=2$ for textile samples. For 3D-printed objects, these parametric factors still need standardisation. Recent work by He et al. and Huang et al. [17, 18] on 3D printed objects suggested $K_L=1.5$, and $K_L=1.23$ (along with a power function $B=0.55$), respectively. The work of Huang et al. being more recent, more comprehensive and catering to different 3D printed shapes, their suggested constants and modifications have been applied in this study ($K_L=1.23$, $K_C=1$, $K_H=1$, $B=0.55$) [17].

$$\Delta E^{00} = \left(\sqrt{\left(\frac{\Delta L'}{K_L S_L} \right)^2 + \left(\frac{\Delta C'}{K_C S_C} \right)^2 + \left(\frac{\Delta H'}{K_H S_H} \right)^2} + R_T \left(\frac{\Delta C'}{K_C S_C} \right) \left(\frac{\Delta H'}{K_H S_H} \right) \right)^B \quad (1)$$

Where ΔL , ΔC , and ΔH are differences in lightness, chroma, and hue, respectively, while (S_L , S_C , and S_H) and (K_L , K_C , and

K_H) are weighting functions and parametric factors, respectively. B is the power function specifically for 3D objects. ΔE^{00} was calculated for 165 CIE $L^*a^*b^*$ readings and plotted in graphs and charts for visual analysis. For each colour value, readings from all five sides were averaged and ΔE^{00} was calculated for those readings as well to reduce any possible error caused by a single reading.

3 Results

Upon visual inspection of Fig. 2, it was observed that pure Cyan, Magenta, and Yellow resins are printed as translucent. The translucency of samples printed with primary colours may alter their visual colour perception and colour measurement. It was also observed that the addition of black resin significantly reduced the translucency, however, the addition of white colour made the samples completely opaque as shown in Fig. 2.

To observe the overall colour accuracy of each sample, the mean of CIE $L^*a^*b^*$ values measured on all five faces was used. ΔE^{00} was then computed between the mean measured value and the selected colour value. The ΔE^{00} of all samples is shown in Fig. 4.

The highest and lowest ΔE^{00} calculated are 9.5 and 2.1, respectively. Black, white, and grey shades had a range of 5.3–2.1 ΔE^{00} , while the RGB samples had a range of 5.7–3.3 ΔE^{00} . On the other hand, CMYKW samples showed a range from 9.5 to 3.9 ΔE^{00} , higher than other groups. Black showed the minimum ΔE^{00} of 2.15 followed by the white of the second batch with 2.8 ΔE^{00} .

The differences in ΔE^{00} between the samples printed with support and white cores are shown in Fig. 5. All samples printed with VeroPureWhite core material showed lower ΔE^{00} compared to those with the support material core, meaning they better represented the original digital colour input. The difference between ΔE^{00} was most significant in pure yellow samples approaching 4.9 ΔE^{00} . On the other hand, the white sample could be observed to have the least impact with just a difference of 0.2 ΔE^{00} .

For observing the impact of face orientation on colour accuracy, ΔE^{00} was computed for each of the 165 faces with respect to their designed colour value. These values were plotted in groups of five for each sample as shown in Fig. 6. On close observation, it can be observed that the top sur-

face has shown better colour accuracy in some samples. To establish the significance of this difference, an analysis of

Fig. 4 ΔE^{00} measured for all samples. Samples that were printed with both batches have markers (a) and (b) denoting the first and second batches, respectively

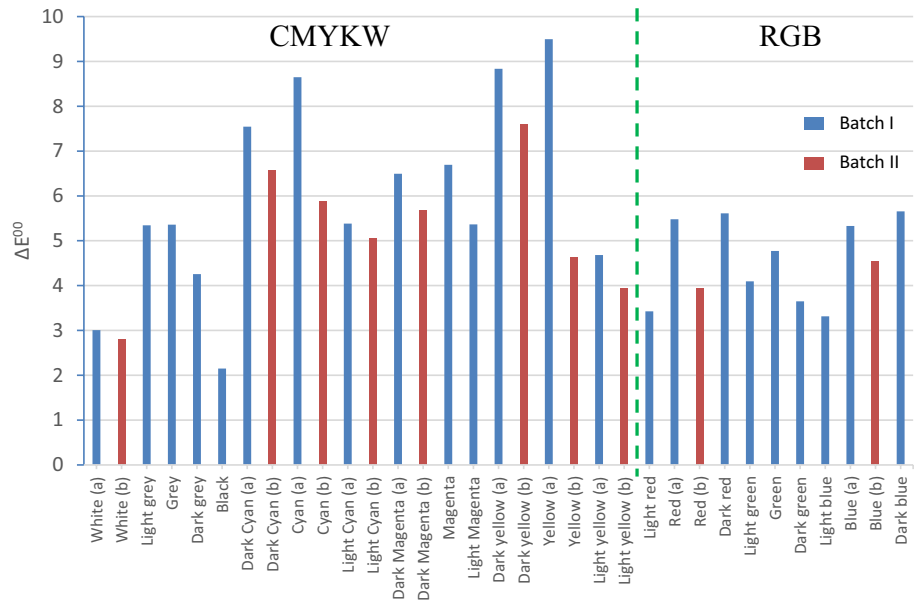
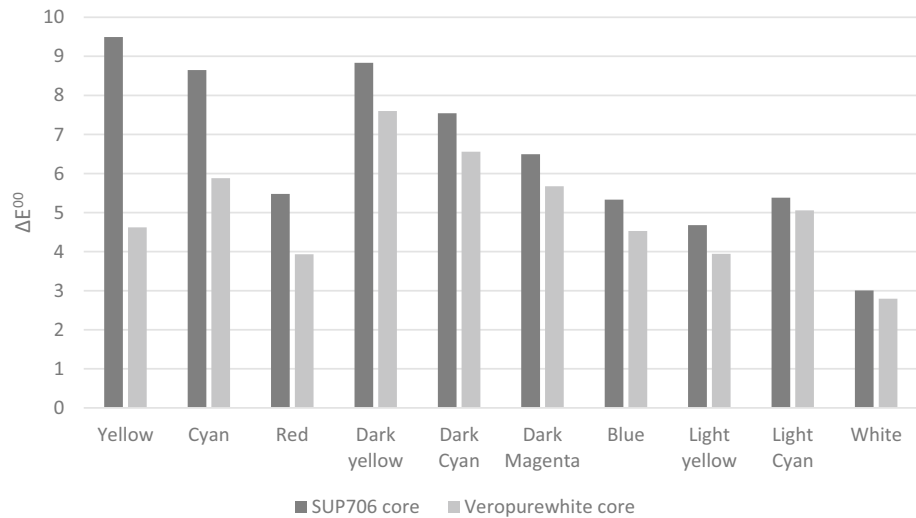


Fig. 5 ΔE^{00} for samples with SUP706 as core a and Veropurewhite as core b



variance (ANOVA) with repetition test was performed using the five paired sets.

There are five paired sets of 33 readings with each set representing a unique face. Statistical significance was calculated in MS Excel with a significance level of 0.05 as shown in Fig. 7.

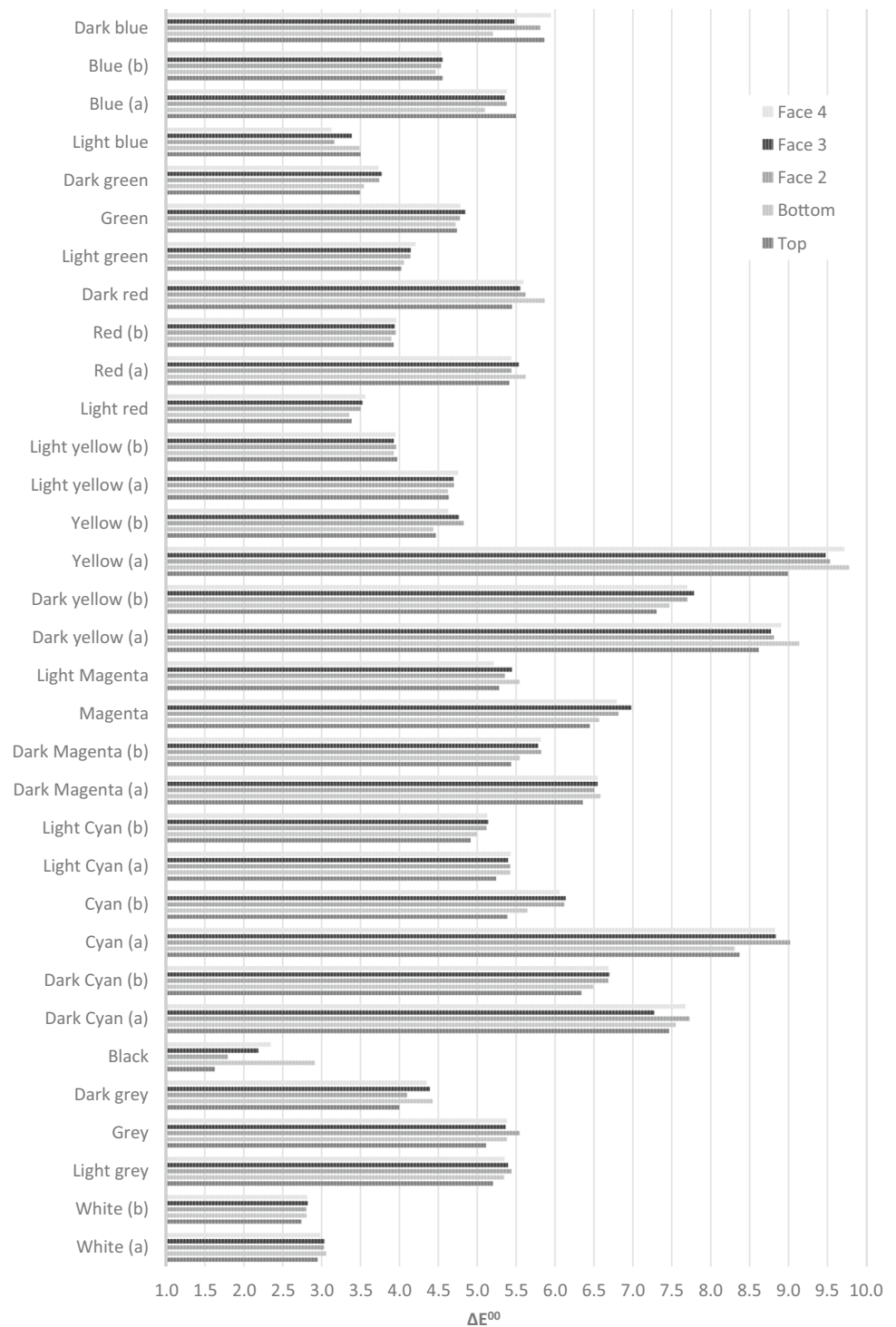
The statistical analysis gives p-values much less (0.000007) than the target 0.05. It implies that there was a statistically significant difference in ΔE^{00} values between at least any two faces. A closer observation of the Mean ΔE^{00} for all five faces reveals that the top face has the lowest mean ΔE^{00} (5.17) which gives a hypothesis that the top face is primarily contributing to the significant variation. To test this hypothesis, another ANOVA test is performed among the four faces excluding the top face.

The second ANOVA test resulted in a p-value of 0.405 which is much larger than the target of 0.05. It implies that the null hypothesis is true and variation between groups is insignificant. It suggested that only the top face is showing a statistically significant variation among all five faces.

4 Discussion

The ΔE^{00} values calculated for different colour samples show a perceptible colour difference at first glance. However, determining an “acceptable” ΔE^{00} is subjective and depends on the application. Numerous studies provide different values of acceptable ΔE^{00} depending on the industry, material, print method, method of calculation, and

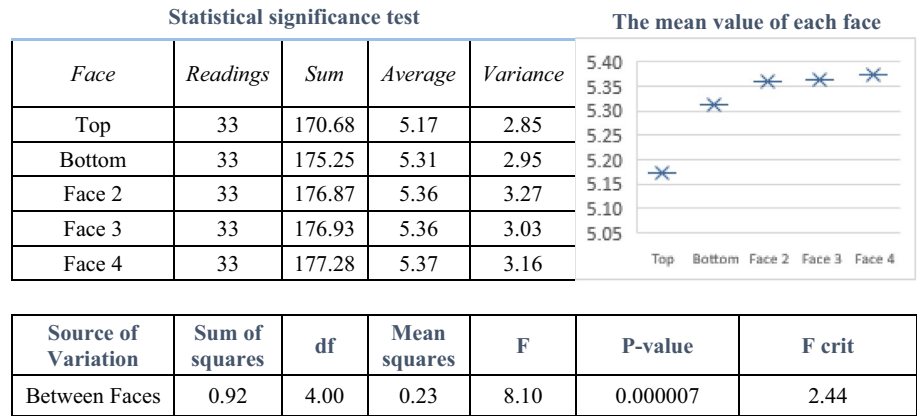
Fig. 6 ΔE^{00} for all five faces of each sample



other factors. These values also depend on which CIE ΔE formulation has been used and how the associated parametric factors have been applied in ΔE^{76} , ΔE^{94} or ΔE^{00} . Furthermore, these constants/factors are standardized for mature industries such as digital media or textiles, but in multicolour/full-colour 3D printing, there is significant room for improvement.

The difference between ΔE^{00} values observed in CMYK(W) and RGB samples could be due to many factors, one of which is the fact that in CMYK(W), the printer may or may not use its colour profiler since the resin materials are CMYK(W) primaries as well. However, for RGB, the colours are transformed into CMYK(W) by the inbuilt ICC colour profiles such as the “(*) X-Rite i 1 Profiler CMYKW

Fig. 7 Analysis of variance (ANOVA) with repetition



(Relative Colourimetric)” profile. Although this implies that the results for CMYK(W) should have been most accurate, instead the mean ΔE^{00} for RGB samples was relatively lower. As such, the average ΔE^{00} for all RGB samples is almost $4.18 \Delta E^{00}$ while for CMYK(W) samples it is almost $5.1 \Delta E^{00}$ (Only considering samples with VeroPureWhite core where applicable). CMYK(W) samples’ mean ΔE^{00} was also increased by dark samples where the black resin was added in translucent primaries and visibly reduced the accuracy of printed samples. The range of ΔE^{00} could also be reduced if a few outliers are removed such as all CMYK(W) samples with support material core and dark CMYK(W) samples. For this experiment, average ΔE^{00} for CMYK(W) samples without considering any “Dark shaded” samples is $4.68 \Delta E^{00}$, that is $0.41 \Delta E^{00}$ lesser than the above mentioned CMYK(W) average but still an $0.50 \Delta E^{00}$ higher than RGB samples.

The visual inspection showed that the samples were uniformly coloured with a perceived colour accuracy except for some CMYK(W) samples containing 30% black (K). The added black resin in the translucent primary made it look much different than the original. This behaviour could be confirmed from the measured L^* values of Dark Cyan, Dark Magenta, and Dark Yellow samples which are all less than 17 in the first batch and less than 27 in the second batch (The higher the brighter). Though this effect might not be surprising in translucent material, the slicing software GrabCAD Print doesn’t suggest this will be the result as shown in Fig. 8.

It was observed that the core material in samples had a major impact on colour accuracy and perception. The results showed a clear trend of higher colour accuracy by selecting VeroPureWhite as the core material in batch 2 as shown in Fig. 5. A probable explanation could be that in translucent samples, the core material is visible and plays a crucial role in the colour measurements since the support infill material is translucent as well, it gives a deviated reading. It is evident from Fig. 5 that the top six samples with the biggest

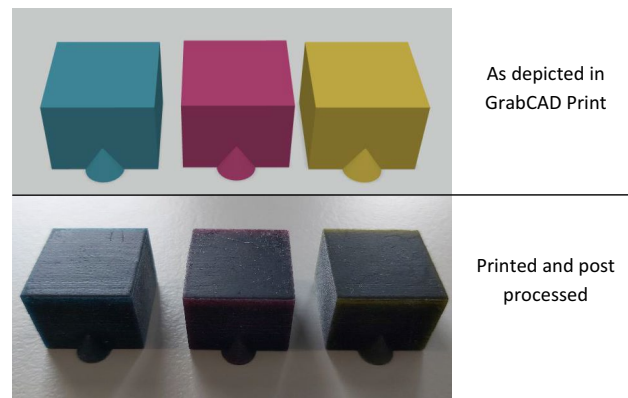


Fig. 8 Comparison of dark cyan, dark magenta, and dark yellow samples

change in ΔE^{00} with a change in core material, are translucent. It should be noted that with VeroPureWhite (White (b) $87.8L^*$, $-0.7a^*$, $-2.4b^*$) as the core material, the GrabCAD print application doesn’t allow the users to modify the “core start depth,” nor does it allow them to select a specific white resin if there are multiple shades of white present. Further evaluation of ΔE^{00} differences between the first and second batches reveals that the most improvement was in translucent primaries such as Yellow (4.9) and Cyan (2.8) while the least effect was on opaque samples such as white (0.2) and light Cyan (0.3) Fig. 5.

Colour accuracy due to the orientation of faces shows that the top surface had a statistically significant advantage over the other four faces. This deviation could be linked to the observation that the top surface was not covered by support material while all other surfaces had support material which was removed and washed during post-processing. Furthermore, the top and bottom surfaces had a shinier surface finish compared to the sides which were relatively rough and print layers were noticeable at close inspection. Rougher surfaces not only reduce the light reflecting on the

colourimeter but could also hold support material particles, hence affecting the colour readings. Though the difference in ΔE^{00} is statistically significant, in colour perception calculation, it is much less significant and may not make any difference in most colour 3D printing applications. Further research is required to validate these hypotheses.

There were some colour marks observed on some samples as well, also referred to as colour bleeding in the printing industry. Though these marks were not on all samples, they could have a significant effect on complex multicolour models. Colour bleed marks can be made due to various reasons depending on how the colour is mixed and jetted from the print head. The tray arrangement was modified in the second batch to isolate the cause however, there were similar marks on the second batch too. Furthermore, the 3D printer used in this experiment was a DAP-capable one that uses other soft biomimicking materials; despite the purging cycles, this colour bleed could be a side effect of using such soft materials through the same print head. However, the exact technology and jetting method/sequence are proprietary to the OEM, hence further analysis is difficult.

These observations align with the literature, which suggests that in addition to the colour value, colour accuracy and colour perception also depend on factors such as translucency, opacity, texture, glossiness, shape, and size [16]. Moreover, fabrication in a layer-by-layer process could significantly impact the colour perception of the outer layer depending on what colour the layers underneath as observed in this experiment with the core material. This effect allows the application of various 3D colour contouring techniques to be explored and applied in 3D printing [23].

It should be noted here that colour measurement of 3D objects, let alone 3D printed objects with rougher surface finish and translucency, is still under development and most of the tools which are being used for it were designed for 2D printing and digital applications. Technical committees, such as the CIE Technical Committee (TC) 8–17 which was tasked to work on methods for evaluating colour differences between 3D colour objects, are currently developing techniques and methods to perform more accurate measurements [24]. The developments resulting from these activities generate further research opportunities in this domain. It is also important to note that this was a preliminary study to test a small subset of possible print settings and combinations; other combinations could be made by changing the ICC profile, colour selection method (Pantone or HSL), different tray arrangements, different surface finish, a larger collection of colour samples, and others.

In biomedical applications where additive manufacturing has many advantages, one of them is mimicking complex geometries. Multicolour anatomical models are fabricated with the help of additive manufacturing for

surgical planning, teaching/ learning anatomy, and hands on surgical training [5, 25–28]. In this context, the addition of complex and realistic colour texture could make a significant difference in realism. Subtle variations in shades of red and pink can identify important anatomical structures and be used to guide surgery. Being able to accurately replicate these in a 3D printed training model, for example, is critical to the learning of medical trainees. The relevance of realistic appearance along with haptics in surgical training models could be inferred from a recent survey which showed that a realistic visual appearance is the third most important quality of a training model after haptics and geometric accuracy [29]. The findings from the current study could help in achieving the goal of 3D printing accurate and realistic appearance in surgical training models, though further research would be needed to explore the role of other parameters.

5 Conclusion

To better understand the accuracy of full-colour 3D printing using material jetting technology, this research work tested a Stratasys J750 Digital Anatomy Printer with different parameters. 33 samples in two batches (support SUP706 infill and VeroPureWhite infill) were 3D printed, post-processed and had colour measurements taken on five faces. Analyses resulted in several conclusive recommendations: The first one is to avoid the manual addition of black in any primary colour to make it a darker shade since it can give undesirable and inaccurate results. The second one is to add VeroPureWhite as the base infill material instead of support SUP706, where colour accuracy is crucial. The third one is related to the naturally translucent nature of CMYK resins, with a suggestion to add a small percentage of VeroPureWhite in the colour mix to make the samples opaque and improve their colour accuracy. The fourth one is a suggestive recommendation to print a test sample before starting to print a significantly large multicolour model, particularly where accurate representation of colours is critical.

The results and recommendations from this work can be used to make better decisions for colour 3D printing and to further investigate and improve the technology. It is suggested that the research should be expanded with different resins and printing parameters.

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Declarations

Conflict of interest There are no other financial or non-financial interests to declare.

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