THE TRIOS SCANNER COLOR DETERMINATION FUNCTION: AN IN VITRO COMPARISON STUDY

A Thesis

by

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ABSTRACT

Effectively matching a new restoration to the existing dentition is an important objective than can help create a harmonious smile. The 3Shape Trios Color Scanner offers to identify shades of scanned teeth to help improve the esthetic outcome of restorations. The purpose of this in vitro study was to assess the ability of the Trios to identify Vita 3D Master Linearguide shade tabs for overall shade, and across value, hue, and chroma. Tab shades were validated using the Vita Easyshade Compact spectrophotometer. The middle thirds of the tabs were scanned, and the Trios output was recorded. The proportion of scans correctly matched for total shade, and the separate proportions for correctly matched values, hues, and chromas were found. Spearman correlations were computed for tab value versus scan value and tab chroma versus scan chroma. For hue, a chi squared test was used to compare population proportions and machine proportions.

The Trios correctly matched overall shade 75.00% of the time, value 99.29% of the time, and both hue and chroma 77.86% of the time. For the hue chi squared test, the distribution of Trios-reported hues was different from the true population distribution. The machine-reported value and chroma were highly correlated with the tab value and chroma, with correlation coefficients ρ of 0.998 and 0.936, respectively, that were significant at the 0.01 level. There was no trend for value, but scan chroma was the most accurate when tab chroma was between 1.5 and 2.0. Past this range, the Trios had a slight trend of overestimating chroma, and below this range, the Trios had a trend of underestimating chroma. These data suggest that the Trios may be a helpful adjunct for dental shade matching, especially for value determination. However, the final assessment should be made by the dentist and confirmed by the patient.

CONTRIBUTORS AND FUNDING SOURCES

A thesis committee composed of Drs. W.W. Nagy [advisor] and Elias Kontogiorgos of the Department of Restorative Sciences and Dr. David Murchison of the Department of Diagnostic Sciences contributed to this work.

Dr. Emet Schneiderman of the Department of Biomedical Sciences assisted with the statistical test selection for Section 2.

The student completed all other work for the thesis independently.

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1. INTRODUCTION

The creation of visually pleasing restorations, especially in the anterior esthetic zone, is a goal that dentists, laboratory technicians, and patients strive to attain. Effectively matching a new restoration to the existing dentition is an important objective than can help create a harmonious smile. Esthetic parameters include appropriate morphological contour[1-3], proper embrasure forms[4-6], healthy gingival appearance[7-9], use of symmetry[10-13], and tooth characterization[14]. However, one particular aspect of dental esthetics remains consistently challenging and at the forefront of discussion: shade selection. In fact, patient assessment of the acceptability of dental esthetics is more highly influenced by perception of color than any other parameter[15, 16]. In addition, the US Public Health Service includes inadequate color match as a reason for restoration failure, independent of the integrity of the restoration[17].

The gold standard for color matching has been based upon the visual assessment of the dentist (with agreement of the patient) and, at times, the laboratory technician. Most often, this process involves using shade tabs as a reference. However, lighting conditions[18, 19], eye-strain[20-22], the biology of the assessor's eye (color blindness, degeneration, etc…)[23, 24], the psychology of the assessor[25-30], color change of tabs over time (disinfection processes, etc…)[31, 32], and clinical time constraints[33] often affect the final color determination and can lead to less than ideal results[34-38]. Additionally, approximately 8% of men and 2% of women suffer from genetic color vision confusion, also known as "color blindness."[39] This may occur due to the absence of specific cone types in the eye, altered spectral sensitivity, or inadequate color difference signals[40, 41].

What is more, acquired color vision confusion is very common. The diameter of the pupil changes as different emotions are experienced, the cornea often yellows with age, and many environmental factors affect vision, such as cigarette smoke, sunlight, and laser exposure[42]. It is not surprising that certain systemic health issues like diabetes, glaucoma, leukemia, Addison's Disease, anemia, multiple sclerosis, Parkinson's Disease, and alcoholism can affect vision[42, 43]. However, many common medications also affect eyesight significantly. Analgesics, antibiotics, antihypertensives, erectile dysfunction drugs, and oral contraceptives have all been shown to alter a person's color discrimination[39, 42, 43]. Even within the population of normal color vision observers, there is a unique mixture of rods and cones around the fovea for each person so that color discrimination can vary significantly[42, 44].

Chromatic sensitivity also changes continuously as a scene is explored. Examples of this include seeing a negative after-image of an object after looking at it for a while (successive contrast), the hue perception of the object being affected by the hue of surrounding objects (simultaneous contrast), and the psychologically ingrained concept of objects themselves having a color that is unchanging despite the lighting of the surroundings (color constancy)[40-42, 45].

Compounding this problem is the fact that natural teeth often have many nuances including varying shades over their surface, different colors and translucencies throughout their three-dimensional structure, and may appear to match a shade tab in one lighting condition, but not in another, a phenomenon known as metamerism[46]. Additionally, because 'shade' is composed of three visual concepts, including value (lightness/brightness, how much light is reflected to the eyes), hue (color or wavelength), and chroma (similar to saturation, how far from grey the color is), true shade matching is often difficult, if not impossible, to achieve across all three parameters. Studies have shown that differences in value between teeth are more readily

apparent to the human eye than similar differences in hue or chroma, making value the weightiest aspect of shade assessment[47-50].

The additive and subtractive properties of light can also be used to help match a restoration to the surrounding teeth[51]. Light emitted from a material, such as the fluorescence of a porcelain or the light from a lightbulb or digital array, involves the additive primary colors: red, green, and blue. These can be mixed in equal parts to create white light. Mixing equal parts of red and blue will create the secondary color magenta, mixing equal parts of blue and green will create the secondary color cyan, and mixing equal parts of red and green will create the secondary color yellow. Mixing the secondary colors will produce the opposite effect, called the subtractive property of light. For example, mixing all three secondary colors will yield black, mixing magenta and cyan will yield blue, mixing cyan and yellow will yield green, and mixing yellow and magenta will yield red[51, 52].

The subtractive property of light is also related to pigments, either applied as extrinsic stains on the surface of a restoration or within the restoration itself and involves the wavelengths that are reflected back to your eyes[51, 52].

One important distinction occurs within the visual arts, such as drawing and painting, where light is reflected from common artists' pigments (subtractive color) rather than mixing of emitted light. In this context, the primary colors are often labelled red, blue, and yellow instead of magenta, cyan, and yellow[53]. In the artist's color wheel, blue and red pigments are mixed to produce violet, blue and yellow pigments are mixed to produce green, and yellow and red pigments are mixed to produce orange[53]. This color mixing theory works because many paints actually have sloped absorption curves so that the same pigment may look different at different concentrations[54]. For example, an 'ultramarine blue' paint may appear either blue or cyan at

different concentrations[54]. Therefore, it is very important to know the context of the color mixing scheme you are using, and to apply the correct terminology.

In a dental setting, if the value of a restoration is wrong, it is better to have too high of a value, so that extrinsic staining can be added to help mask the color difference with the restoration acting as a whiter 'canvas'[46]. If value is too low, adding extrinsic stain will not mask the color error efficiently because the intrinsic color is already too dark. Likewise, low chroma can be masked more easily than high chroma[46]. However, relying on extrinsic pigment to hide a mismatched intrinsic color will increase metamerism[55].

Many shade tab systems are available, and tabs may be arranged in different ways for the selection process. Sproull advocated a system that was well dispersed in color space and ordered systematically, and he favored using the Munsell color arrangement to achieve this[46]. The Munsell system arranges color by three axes. Value is on a vertical axis, with higher value at the top and lower value at the bottom. Different hues move in a circle around the axis. Chroma is organized by rings moving outward from the axis, with less saturated colors being more internal[56].

The Vita 3D-Master Linearguide system (Vita North America, Yorba Linda, CA) uses a process that first selects the most appropriate value of the baseline reference tooth and then assesses hue and chroma in an orderly progression (Figure 1). It organizes tabs into different groupings. The first array of tabs is organized by differing value options, but these tabs share hue and chroma. The subsequent five arrays are organized by chroma and hue within the same value group. There are a total of 35 tabs, but only 29 shades, because some tabs are repeated within different groupings. Each tab has value, hue, and chroma listed separately on it for each total shade. This system was also designed to be interpolated, meaning that there are equal interval

spaces between each value option and each chroma option on the Munsell scale[57]. This is in contrast to systems like Vita Classical Shade Guide (Vita North America, Yorba Linda, CA) in which differences between shade are not equal. For example, A2 is not halfway between A1 and A3 on any color parameter. With the Linearguide, intermediate restoration 'shades' may be recreated in the lab that are not possible with other shade systems. In theory, the ceramist would be able to duplicate the shade 0.5M1 using half 0M1 and half 1M1 if the dentist requested it. However, independent studies have failed to show that the 3D Master system is truly interpolated[58]. However, these tabs are more uniformly spaced and better represent natural tooth colors than other systems[59, 60].

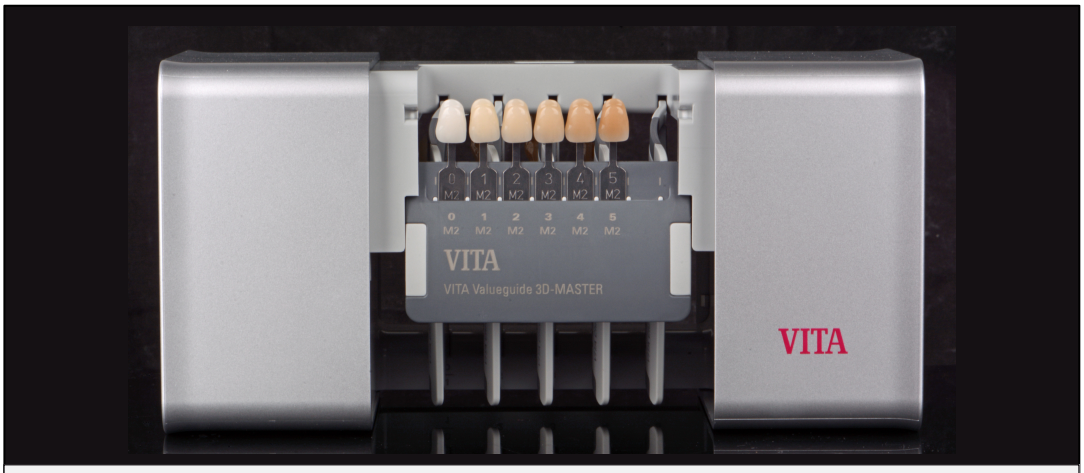

Figure 1.

Vita 3D-Master Linearguide

According to Brewer, spectrophotometers are some of the most accurate color assessment tools[42]. The Vita Easyshade Compact features 19 fiberoptic bundles and a probe tip of approximately 5mm in diameter (Figure 2). A halogen light within the machine illuminates the bundles in the probe periphery so that light is directed onto the tooth. Bundles within the interior

of the probe tip receive light returning from the tooth and deliver it to various filters and photodiode arrays so that spectral reflectance of the scattered light can be measured in bandwidths of 25 nm. When in tab mode, the Easyshade then interprets the results and displays the closest Vita 3D Master shade[42]. Most color assessment is completed on the middle third of the facial or buccal surfaces, because teeth are likely to be more translucent at the incisal/occlusal edges and may be darker near the cervical aspects[61].

Figure 2.

Vita Easyshade Compact Spectrophotometer

With emerging technology, it has been suggested that computer programs might aid the dentist in color assessment and relieve some of these difficulties. The Trios Color Scanner (3Shape North America, Warren, NJ) is a recent addition to the dental marketplace, which, on top of its topographical scanning capabilities, offers to accurately identify shades of scanned teeth to improve the esthetic outcome of restorations (Figure 3). The exact way the Trios functions is unknown because its scanning and color mechanics are proprietary. However, some sources suggest that it uses confocal microscopy and an oscillating light source, either oscillating

over time or space, which is able to interpret variations in the focal plane to yield 3D surface information on a pixel-by-pixel basis[62]. However, few studies have assessed the efficacy of this color-matching feature[63, 64].

Figure 3.

The 3Shape Trios Digital Scanner

The purpose of this in vitro study is to assess the ability of the Trios scanner to accurately identify Vita 3D Master Linearguide shade tabs. Accuracy will be assessed based upon:

1.) The proportion of scans in which total shade was correctly matched.
2.) The proportions of correct match for separated value, hue, and chroma parameters.
3.) Chi squared analysis of hue to determine if the hues reported by the Trios differ significantly from the population proportions of hue, with the null hypothesis being that the population proportions and the proportions reported by the machine would not be statistically significantly different.
4.) Spearman correlation of tab value and chroma to the machine-perceived value and chroma, with the null hypotheses that there were no statistically significant relationships between the true value or chroma and the value and chroma reported by the Trios.

2. MATERIALS AND METHODS

New Vita 3D-Master Linearguide tabs were obtained from the manufacturer. Unused nascent tabs were employed to avoid the potential for color change seen with older tabs and tabs that have been exposed to chemical agents. A total of 35 tabs with 29 shades were scanned four times, for a total of 140 scans. For each tab, the shade, the value, the hue, and the chroma were recorded along with the shade, the value, the hue, and the chroma reported by the Trios and whether a total match had been made. Also, because of manufacturing variations and tolerances, it was possible that the shade reported on each tab was not accurate[65, 66]. To validate tab color, a spectrophotometer (Vita Easyshade Compact, Vita North America, Yorba Linda, CA) set for tab mode was used to ensure shade trueness.

The Trios workflow involves completing shade assessment after morphological scanning is completed. However, in our pilot study, the Trios knit parts of one tab to another because of their identical shape. For efficient data acquisition, this issue was overcome by using a putty (3M ESPE Express STD lab putty) and gingival moulage (Gingifast by Zhermack) matrix mimicking

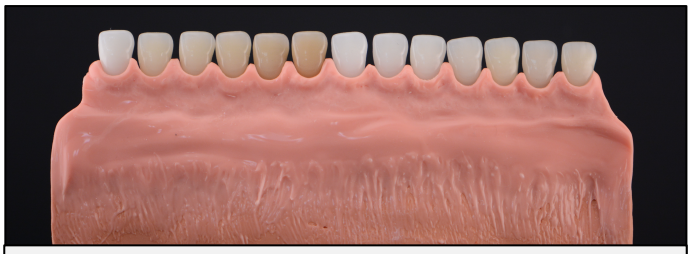

Figure 4.

Tabs Arranged in Gingival Matrix

gingiva, that was fabricated to hold the tabs (Figure 4). Slight variations in morphology of the matrix allowed different tabs to be scanned as separate teeth.

The Trios scanner was calibrated for morphology and color output prior to each tab scanning session as per the manufacturer's instructions (Figure 5a, 5c-d). A new scanner head which was free of watermarks, dust, and scratches was utilized for the scanning (Figure 5b). Tabs to be scanned were positioned in the gingival matrix and the complex was placed upon a piece of pink construction paper to act as a backdrop with a color approximating oral tissues. The scanner head was positioned parallel to the tab complex as scanning proceeded. Any areas not captured during the first pass over the tabs were attained by slightly rocking the scanner head over the area until the screen showed that it had been replicated.

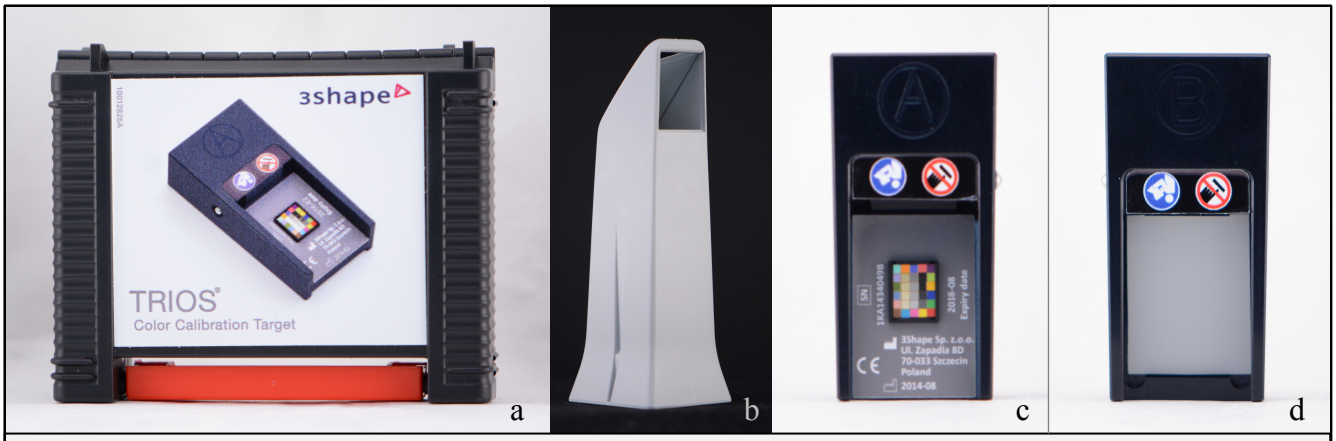

Figure 5.

Calibration Object and Scanner Head:
5a.) Protective Trios calibration kit box
5b.) Clean scanner head, free of debris, scratches, and watermarks
5c.) Calibration object side A
5d.) Calibration object side B

On the color assessment screen, each tab was assigned a 3D Master shade by selecting a point within the middle third of the tab, as suggested by the manufacturer (Figure 6). However, in our pilot studies, multiple shades were often reported with even slight variations of cursor position. Because of this, the cursor was clicked only once for each reading and the shade given with that click was the shade that was recorded.

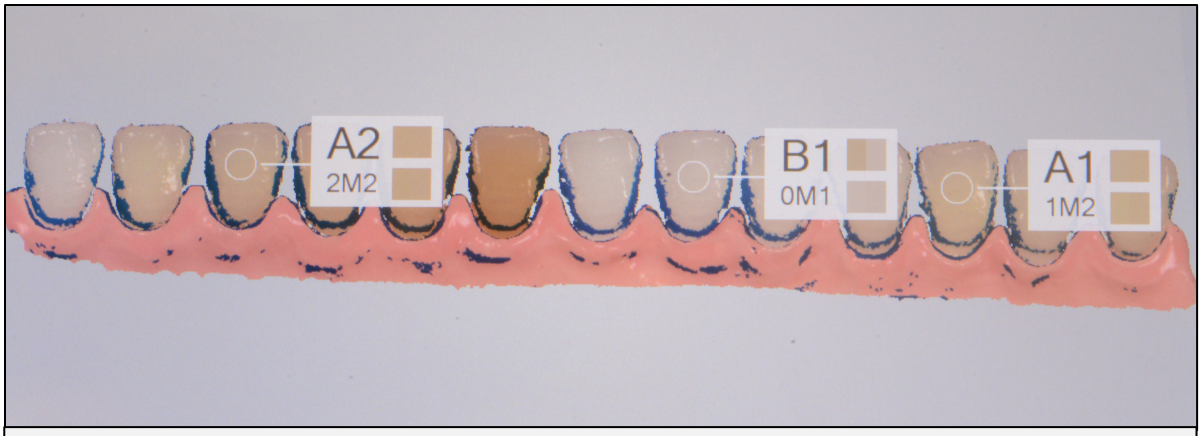

Figure 6.

The Shade Assessment Screen with Examples of Color Selections

Data analysis was achieved using a variety of methods. The proportion of scans in which total shade was correctly matched was computed. Similarly, proportions of correct match were also found for separated value, hue, and chroma parameters.

To tease out any biases of the machine for a particular color parameter, value, hue and chroma were then further evaluated in more detail. For value and chroma, the tab numbers were compared to the machine-made determinations for that tab. Scatterplots of tab value and chroma versus scanner value and chroma were made to assure monotonic data and to visually assess any trends. Lastly, Spearman correlations were computed to yield information about the strength of the relationship between tab value and reported value and tab chroma and reported chroma.

Nonparametric methods were used because independent studies failed to substantiate the manufacturer's claim of interval value and chroma parameters[58].

For hue, a chi squared test was used to compare population distributions to the machine-reported distributions. For hue, the true population proportions are 65.71% for M, 17.14% for L, and 17.14% for R based upon the frequency of those hues out of the total tab selection. Analysis was completed using a 95% level of confidence ($\alpha = 0.05$). Statistical analysis was performed with SPSS v25 (SPSS Inc., Chicago IL) and Hay's Statistics, 4th ed. Appendix E[67].

To put shade determination in a clinical context, where the gold standard is dentist assessment, the machine accuracy was then compared to human accuracy reported in the literature, as discussed in Section 4.

3. RESULTS

All manufacturer tab shades were validated as true representations of their shade using the Vita Easyshade Compact. The Trios correctly matched overall shade 75.00% of the time. Value was correctly matched 99.29% of the time, with only one mismatch out of 140 total scans. Both hue and chroma were correctly matched 77.86% of the time.

For the hue chi squared test, chi squared was found to be 20.63 versus the 5.99 or less needed for acceptance (Table 1).

Hue	Observed frequency (O_j)	Expected frequency (E_j)	O_j-E_j	$(O_j-E_j)^2/E_j$
L	4	0.1714(140) =24	-20	16.67
M	111	0.6571(140) =92	19	3.92
R	25	0.1714(140) =24	1	0.042
				X^2= 20.63 df= 2 α= 0.05 X^2 > 5.99 (from X^2 distribution)* Reject H_0

Table 1.

Chi Squared Assessment for Hue

* Hays, WL. (1988). Appendix E of *Statistics, 4th ed*. Holt Rinehart and Winston.

For value and chroma, scatterplots confirmed monotonic data (Figures 7 and 8). There was no trend in mismatch for value, because only one scan was a mismatch. For chroma, the most accurate scanning was achieved when tab chroma was between 1.5 and 2.0. When tab chroma increased past this range, the Trios had a slight trend of overestimating chroma. When tab chroma decreased past this range, the Trios had a trend of underestimating chroma.

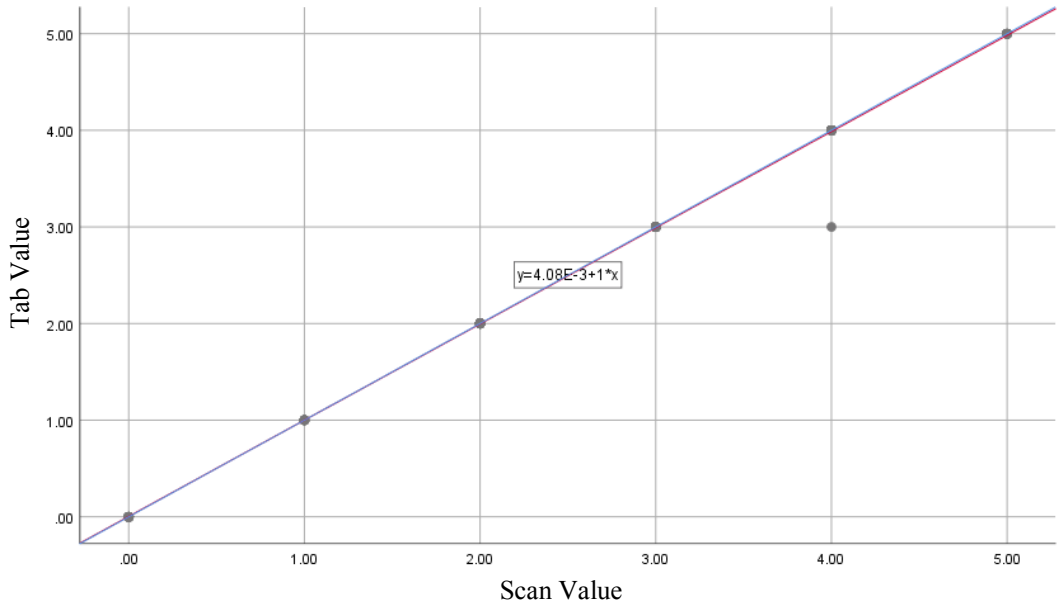

Figure 7.

Scatterplot of Tab Value Versus Scan Value

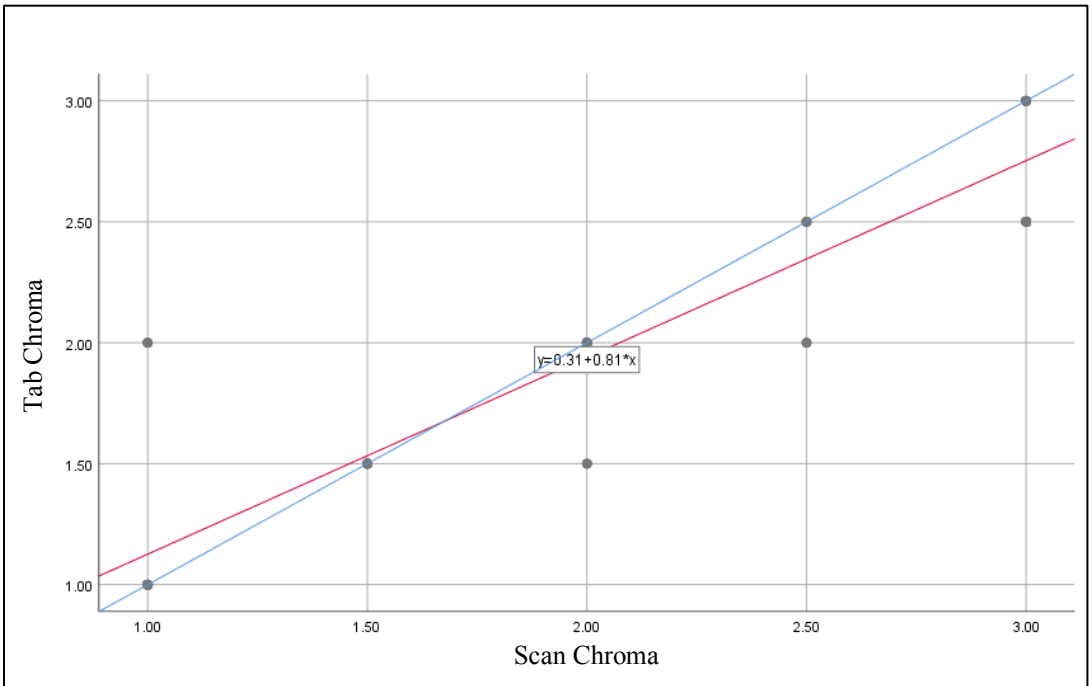

Figure 8.

Scatterplot of Tab Chroma Versus Scan Chroma

For value, the machine-reported value was highly correlated to the true tab value, with a correlation coefficient ρ of 0.998 that was significant even at the 0.01 level (p less than 0.01) (Table 2). For chroma, the machine-reported chroma was also highly correlated to the true tab chroma, with ρ of 0.936 and p less than 0.01 (Table 3).

Correlations

			Tab Value	Scan Value
Spearman's rho	Tab Value	Correlation Coefficient	1.000	.998**
		Sig. (2-tailed)	.	.000
		N	140	140
	Scan Value	Correlation Coefficient	.998**	1.000
		Sig. (2-tailed)	.000	.
		N	140	140

**. Correlation is significant at the 0.01 level (2-tailed).

Table 2.

Correlation of Tab Value to Scan Value

Correlations

			Tab Chroma	Scan Chroma
Spearman's rho	Tab Chroma	Correlation Coefficient	1.000	.936**
		Sig. (2-tailed)	.	.000
		N	140	140
	Scan Chroma	Correlation Coefficient	.936**	1.000
		Sig. (2-tailed)	.000	.
		N	140	140

**. Correlation is significant at the 0.01 level (2-tailed).

Table 3.

Correlation of Tab Chroma to Scan Chroma

4. DISCUSSION

The purpose of this study was to evaluate the accuracy of the Trios color assessment feature. A new color matching tool should be compared to the gold standard matching method, in this case dentist visual assessment, to judge whether or not its use is truly beneficial in clinical practice. Even if the machine yields some mismatches, this error may be less than human error and its use may help bolster clinical outcomes.

Overall Matching Capacity

Because shade determination is so complex, the literature reports a wide range of human color matching abilities; humans correctly match shade approximately 35-74% of the time[23, 34, 49, 66, 68-71]. Many of these studies use different shade tab systems, no shade tabs (spectrophotometers, matching between assessors, combined assessment methods, etc…), or a limited number of tabs from which the dentist may choose, making it difficult to draw straightforward conclusions. However, in a general sense, because the Trios matched shade correctly 75% of the time, our results suggest that it may be equally or better equipped to determine shade than the human eye, if correctly calibrated. Although human color matching is prone to error, it should be noted that many imperfectly matched restorations are still considered clinically acceptable[72].

Value Matching Capacity

Of all the color parameters, value is the most integral for acceptable color matching because humans are better able to discern differences in value than in the other color factors[73].

The Trios was highly accurate when making value assessments. Out of 140 scans, the machine only misallocated value once, yielding a 99.29% correct match rate. The incorrect match was also only wrong by one value interval. Gomez found the value readings from a spectrophotometer and the dentist in his study to be equivalent[49]. However, other research shows that participants trained in color assessment will have better value matching capabilities than a spectrophotometer, while untrained participants will make worse assessments than the machine[74].

Hue Matching Capacity

The null hypothesis was rejected: The Trios allocated hues differently than their true population proportions, indicating error was present.

For R tabs, expected and actual counts were only off by one integer. The expected population proportion for R tabs was 17.14% and the Trios yielded a proportion of 17.86%, with less than 1% of a difference. However, proportions can appear similar without being accurate. For example, the proportion could be the same because it was accurate, and R's were allocated to R's, or because some L and M tabs were misallocated to R hues and some R tabs were misallocated to L or M hues. When we examine the data further, we see that the latter was the case. Of the 24 R tabs, only 17 were correctly allocated to R hue. Seven R tabs were misallocated to M hues, but R's were never misallocated to L's. Four L's and 4 M's were misallocated to R's. About 70.83% of the time, R's will be correctly allocated, but when they are not, there is a trend for them to be put in the M hues.

The scanner had even more difficulty when L tabs were evaluated. Out of 24 expected L's, only 4 were actually chosen as L hues, for a scanner proportion of 2.86% versus the 17.14%

population proportion. L tabs were frequently misallocated to M and R hues. In fact, L tabs were misallocated to M hues more frequently than they were correctly allocated to L hues, 66.67% of the time versus 16.67% respectively, and equally allocated to R hues. However, R and M tabs were never misallocated to L hues. This shows a trend of L tabs being incorrectly allocated, often being placed in the M hue category.

The expected population proportion for M tabs was 65.71% while the Trios found a proportion of 79.29% for M hues, or 111 M's allocated for 92 tab M's. M's were correctly allocated to M's 95.65% of the time and misallocated to R's 4.35% of the time. They were never misallocated to L's. This shows relatively high accuracy for an M being chosen as an M, but there is also a trend of other hues to be misallocated into the M category.

As a general rule, M hues will almost always be correctly identified as M hues, R hues will most likely be identified as R hues, but L hues will likely be misidentified as M hues.

In a study by Gomez, a dentist identified an L tab as an L tab only 14% of the time, an M as an M only 56.7% of the time, and an R as an R only 2.1% of the time versus the equivalent Trios results of 16.67% for L, 95.65% for M, and 70.83% for R, all seemingly equivalent to or higher than the dentist[49]. However, his study only relied upon the matches of a single observer and may therefore be prone to significant bias.

In a study by Paul, 3 evaluators chose the same Vita Classical shade only 26.6% of the time when given only 16 tab options, showing poor inter-evaluator consistency when compared to the high reproducibility of their computerized assessment[66]. The Trios was also consistent, so that precision was met even when accuracy was not. The best example of this is how the machine frequently mislabeled L hues as M hues. This is more beneficial than random error, because the dentist may accommodate for it with experience.

Chroma Matching Capacity

It is more difficult for humans and machines to reach a consensus on chroma than any other color characteristic[49]. Chroma is dependent on relative illumination, so that it is determined based off of the brightness of its surroundings[75]. Higher chroma tabs would reflect wavelengths of high saturation and brightness for its illumination, so that for a particular hue it would reflect wavelengths that compose that hue and absorb ones that desaturate that hue. Because there is less visual interference from accessory wavelengths, the tab would appear more vibrant[76]. It is unknown how an oscillating light source, of indeterminate wavelength composition, which either oscillates over space or time, would affect the chroma determination.

The Trios most accurately identified tabs of between 1.5-2.0 chroma. When tab chroma increased past this range, the Trios had a slight trend of overestimating chroma. When tab chroma decreased past this range, the Trios had a trend of underestimating chroma. According to Pop-Ciutrila, most natural central incisors in a population between 21-29 years old have chroma between 1-2[77]. This would suggest that if a natural central incisor was scanned with a true chroma of 1, the machine would have a tendency to underestimate the chroma, however, there is no tab value with chroma less than 1.0, so this is not possible. This lower-range deviance from the line is actually due to the machine consistently making an error for tabs of 0M2, where it would recognize the tabs as 0M1, instead. This indicates that bleach shades with a value of 0, where the tab is very bright, but a chroma of 2, where the tab is also moderately pure and intense (midway between grey and colorful), may be harder for the Trios to interpret. If the bleach shade 0M2 had not been included in scanning, the correlation between tab chroma and scan chroma would be even higher, and the range of most accurate assessment would be for tab chromas

between 1-2, which are coincident with the chromas most often seen in natural central incisors described above. The trend for choosing higher chromas than the tabs once tab chroma was above 2, is in contrast to human assessment, where dental students have a bias towards choosing lower chroma shades[78].

Because the Trios uses proprietary technology, it is unknown whether its color determination involves use of a spectrophotometer, colorimeter, digital assessment, or a combination of methods. What is more, not all devices within an instrument class function the same way. However, because the Trios has the option to take digital photos, it most likely utilizes a digital camera in some way.

The ability of digital technology to choose a particular chroma is dependent on the color space limits that are set[79]. Many electronics use color spaces which constrict the total amount of chromas possible, such as the Red Green Blue (aka RGB) color space which was developed by Microsoft and HP[79]. It has a limited chroma range like the range available on televisions and computer monitors. Many natural chromas would be outside the RGB range and may not be interpreted correctly if the software involved has RGB limits[79]. However, some digital color spaces have more chromas possible than with artists'pigment[76]. If digital assessment was utilized and tab chroma was outside the accepted range, the computer algorithm may have compressed the tab chroma information to "best-fit" into its parameters, creating error.

Even if using the Munsell system, different areas of the color space have different maximum chroma limits because of the biological limitations of the human eye and the physics of color stimulation[80]. For example, violet hues have fewer chromas possible than yellow hues[80]. Some hue-value combinations can have upwards of 30 chromas[76], while most solid but vivid colors have about 8[80]. This lack of consistency across hue may account for why humans find

chroma so difficult to identify[49] and may make it more difficult for a software program to match correctly with its algorithm.

Clinical Implications

Results suggest that the Trios may be useful in a clinical setting. For dentists with normal color vision, one use would be to help verify a shade that has already been selected, especially if the arch was going to be scanned for preparation morphology anyway. Visual color matching combined with the use of digital cameras or spectrophotometers has been shown to improve the chances for successful shade matching[81]. Many dentists already use the Trios to take digital impressions, and only a few extra seconds are needed to yield color information about a specific tooth. Similarly, staff can easily be trained to use the scanner to make an initial color assessment, saving chair-time for the dentist by narrowing in the focus on color options that are already close to a match. In general, objective color assessment methods are also faster than subjective ones[71]. Finally, if trying to choose between two similar shades, the Trios may help make a final determination. A study showed that shade matching was improved with use of a spectrophotometer[82].

For color deficient dentists, the Trios may be especially useful. Instead of struggling with color tabs chair-side, which leads to loss of productivity and a decline in patient confidence, the color-blind dentist would have a more discreet and efficient method for 'guessing' the shade. The Trios would also help take some of the burden off of the dental assistant who is constantly called away from her other duties to help the dentist with the tabs.

The Trios, as a machine, also has several advantages over human assessment. Its judgements are objective and not prone to emotional or psychological biases[71]. The scanner head

acts as its own light source within the patient's mouth, so ambient operatory illumination, bib color, and wall color are less prone to skewing results[62]. Also, information about multiple teeth can be attained very rapidly. Although the midsections of tabs were evaluated in this study, in practice any part of the scanned tooth or even multiple parts of the same tooth may be selected and given a color assessment. Because the system can store both morphological and color information in a scan and send it directly to laboratories, the technician has access to more information than with traditional prescriptions.

Some pitfalls include large machine size, dependency on calibration success and frequency, need for the scanner head to be free of dust and scratches, need for additional training of personnel, and cost. It is probable that a busy dental practice would not calibrate the scanner before each session, as was done in this study. Therefore, additional errors may occur.

Even if a correct shade match is attained by the dentist, that does not mean the laboratory will be able to accurately reproduce the color. Most laboratories have their own set of shade reference tabs or porcelain shade stumps they use to assess color when making a prosthesis. Hue, value, and chroma exist on continuums in real life rather than discreet increments and are influenced by the surrounding lighting and individual perception[42]. Because of this, human shade matching is achieved by an anchoring and adjustment process, where the restoration being assessed is compared to reference stumps, which act as the anchor. For example, a restoration shade could be explained as less yellow than a shade tab or redder than the porcelain sample. Because the laboratory's anchors will never be exactly the same as the dentist's anchors, it would be very difficult for the technician to *exactly* match what the dentist had seen.

In addition, it's challenging to maintain the target color throughout the fabrication process. The number of porcelain firings, thickness of opaquer, thickness of dentin layer,

thickness of enamel layer, any fluorescence added, the translucency included, and glazing can alter the overall perception of shade and the way light reflects and refracts off of the restoration[83]. Any coping shine-through, visible metal collar, or visible abutment may also modify the final color from what was intended chairside[84, 85].

The porcelain system used is also important because many brands have different names or classifications for their colors and conversion charts may not be accurate. The Vita Omega 900 3D Master ceramic system is one of the only ceramic systems specifically fabricated to be used with the 3D Master classification[83]. If Vita's claim of interpolation were true for their porcelain, a technician using this system would have more predictable shade matching when shades were mixed and could produce mid-range colors more accurately. One study saw better color matching with the Omega 900 3D Master arrangement versus the Omega 900 organized by the Vitapan Classical system[83]. However, more research should be conducted to verify or discredit the claim of interpolation.

Lastly, the technician's preferences, experience, and eyesight can differ, and on any given day, the quality of the restorations may change.

5. SUMMARY AND CONCLUSIONS

Summary and Future Direction

Despite the promising results of this paper, as with any emerging technology, caution and critical analysis should be employed before dismissing conventional methods. More studies are needed to verify findings, and in vivo analysis should be incorporated, if possible. The Trios is a helpful adjunct for dental shade matching, especially for value determination. However, the final assessment should be made by the dentist and confirmed by the patient.

Conclusions

1. The Trios had a total shade matching success rate similar to or better than human assessment
2. The Trios had a value matching success rate of 99.29%, and reported value was highly correlated to tab value.
3. The Trios had a chroma matching success rate of 77.86%, and reported chroma was highly correlated to tab chroma.
4. M hues will almost always be correctly identified as M hues, R hues will most likely be identified as R hues, but L hues will likely be misidentified as M hues.

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APPENDIX

RAW DATA

Tab Value	Tab Hue	Tab Chroma	Shade Tab	Scan	100% Match?	Value Match?	Hue Match?	Chroma Match?	Value Reading	Hue Reading	Chroma Reading
0	M	2	0M2	0M1	1	0	0	1	0	M	1
1	M	2	1M2	1M2	0	0	0	0	1	M	2
2	M	2	2M2	2M2	0	0	0	0	2	M	2
3	M	2	3M2	3M2	0	0	0	0	3	M	2
4	M	2	4M2	4M2	0	0	0	0	4	M	2
5	M	2	5M2	5M2	0	0	0	0	5	M	2
0	M	1	0M1	0M1	0	0	0	0	0	M	1
0	M	2	0M2*	0M2	0	0	0	0	0	M	2
0	M	3	0M3	0M3	0	0	0	0	0	M	3
1	M	1	1M1	1M1	0	0	0	0	1	M	1
1	M	2	1M2*	1M2	0	0	0	0	1	M	2
2	M	1	2M1	2M1	0	0	0	0	2	M	1
2	L	1.5	2L1.5	2M2	1	0	1	1	2	M	2
2	R	1.5	2R1.5	2R1.5	0	0	0	0	2	R	1.5
2	M	2	2M2*	2M2	0	0	0	0	2	M	2
2	L	2.5	2L2.5	2M3	1	0	1	1	2	M	3
2	R	2.5	2R2.5	2M3	1	0	1	1	2	M	3
2	M	3	2M3	2M3	0	0	0	0	2	M	3
3	M	1	3M1	3M1	0	0	0	0	3	M	1
3	L	1.5	3L1.5	3M2	1	0	1	1	3	M	2
3	R	1.5	3R1.5	3R1.5	0	0	0	0	3	R	1.5
3	M	2	3M2*	3M2	0	0	0	0	3	M	2
3	L	2.5	3L2.5	3M3	1	0	1	1	3	M	3
3	R	2.5	3R2.5	3M3	1	0	1	1	3	M	3
3	M	3	3M3	3M3	0	0	0	0	3	M	3
4	M	1	4M1	4M1	0	0	0	0	4	M	1
4	L	1.5	4L1.5	4M2	1	0	1	1	4	M	2
4	R	1.5	4R1.5	4R1.5	0	0	0	0	4	R	1.5
4	M	2	4M2*	4M2	0	0	0	0	4	M	2
4	L	2.5	4L2.5	4M3	1	0	1	1	4	M	3
4	R	2.5	4R2.5	4R2.5	0	0	0	0	4	R	2.5
4	M	3	4M3	4M3	0	0	0	0	4	M	3
5	M	1	5M1	5M1	0	0	0	0	5	M	1
5	M	2	5M2*	5M2	0	0	0	0	5	M	2
5	M	3	5M3	5M3	0	0	0	0	5	M	3
0	M	2	0M2	0M1	1	0	0	1	0	M	1
1	M	2	1M2	1M2	0	0	0	0	1	M	2
2	M	2	2M2	2M2	0	0	0	0	2	M	2
3	M	2	3M2	3M2	0	0	0	0	3	M	2
4	M	2	4M2	4M2	0	0	0	0	4	M	2
5	M	2	5M2	5M2	0	0	0	0	5	M	2
0	M	1	0M1	0M1	0	0	0	0	0	M	1
0	M	2	0M2*	0M2	0	0	0	0	0	M	2
0	M	3	0M3	0M3	0	0	0	0	0	M	3
1	M	1	1M1	1M1	0	0	0	0	1	M	1
1	M	2	1M2*	1M2	0	0	0	0	1	M	2
2	M	1	2M1	2M1	0	0	0	0	2	M	1
2	L	1.5	2L1.5	2R1.5	1	0	1	0	2	R	1.5
2	R	1.5	2R1.5	2R1.5	0	0	0	0	2	R	1.5
2	M	2	2M2*	2M2	0	0	0	0	2	M	2
2	L	2.5	2L2.5	2M3	1	0	1	1	2	M	3
2	R	2.5	2R2.5	2M3	1	0	1	1	2	M	3
2	M	3	2M3	2M3	0	0	0	0	2	M	3
3	M	1	3M1	3M1	0	0	0	0	3	M	1
3	L	1.5	3L1.5	3M2	1	0	1	1	3	M	2
3	R	1.5	3R1.5	3R1.5	0	0	0	0	3	R	1.5
3	M	2	3M2*	3M2	0	0	0	0	3	M	2
3	L	2.5	3L2.5	3M3	1	0	1	1	3	M	3
3	R	2.5	3R2.5	3M3	1	0	1	1	3	M	3
3	M	3	3M3	3M3	0	0	0	0	3	M	3
4	M	1	4M1	4M1	0	0	0	0	4	M	1
4	L	1.5	4L1.5	4L1.5	0	0	0	0	4	L	1.5
4	R	1.5	4R1.5	4R1.5	0	0	0	0	4	R	1.5
4	M	2	4M2*	4M2	0	0	0	0	4	M	2
4	L	2.5	4L2.5	4L2.5	0	0	0	0	4	L	2.5
4	R	2.5	4R2.5	4R2.5	0	0	0	0	4	R	2.5
4	M	3	4M3	4M3	0	0	0	0	4	M	3
5	M	1	5M1	5M1	0	0	0	0	5	M	1
5	M	2	5M2*	5M2	0	0	0	0	5	M	2
5	M	3	5M3	5M3	0	0	0	0	5	M	3

Tab Value	Tab Hue	Tab Chroma	Shade Tab	Scan	100% Match?	Value Match?	Hue Match?	Chroma Match?	Value Reading	Hue Reading	Chroma Reading
0	M	2	0M2	0M1	1	0	0	1	0	M	1
1	M	2	1M2	1M2	0	0	0	0	1	M	2
2	M	2	2M2	2M2	0	0	0	0	2	M	2
3	M	2	3M2	3M2	0	0	0	0	3	M	2
4	M	2	4M2	4R2.5	1	0	1	1	4	R	2.5
5	M	2	5M2	5M2	0	0	0	0	5	M	2
0	M	1	0M1	0M1	0	0	0	0	0	M	1
0	M	2	0M2*	0M2	0	0	0	0	0	M	2
0	M	3	0M3	0M3	0	0	0	0	0	M	3
1	M	1	1M1	1M1	0	0	0	0	1	M	1
1	M	2	1M2*	1M2	0	0	0	0	1	M	2
2	M	1	2M1	2M1	0	0	0	0	2	M	1
2	L	1.5	2L1.5	2R1.5	1	0	1	0	2	R	1.5
2	R	1.5	2R1.5	2R1.5	0	0	0	0	2	R	1.5
2	M	2	2M2*	2R2.5	1	0	1	1	2	R	2.5
2	L	2.5	2L2.5	2M3	1	0	1	1	2	M	3
2	R	2.5	2R2.5	2M3	1	0	1	1	2	M	3
2	M	3	2M3	2M3	0	0	0	0	2	M	3
3	M	1	3M1	3M1	0	0	0	0	3	M	1
3	L	1.5	3L1.5	3M2	1	0	1	1	3	M	2
3	R	1.5	3R1.5	3R1.5	0	0	0	0	3	R	1.5
3	M	2	3M2*	3M2	0	0	0	0	3	M	2
3	L	2.5	3L2.5	3M3	1	0	1	1	3	M	3
3	R	2.5	3R2.5	3R2.5	0	0	0	0	3	R	2.5
3	M	3	3M3	3M3	0	0	0	0	3	M	3
4	M	1	4M1	4M1	0	0	0	0	4	M	1
4	L	1.5	4L1.5	4L1.5	0	0	0	0	4	L	1.5
4	R	1.5	4R1.5	4R1.5	0	0	0	0	4	R	1.5
4	M	2	4M2*	4M2	0	0	0	0	4	M	2
4	L	2.5	4L2.5	4M3	1	0	1	1	4	M	3
4	R	2.5	4R2.5	4R2.5	0	0	0	0	4	R	2.5
4	M	3	4M3	4M3	0	0	0	0	4	M	3
5	M	1	5M1	5M1	0	0	0	0	5	M	1
5	M	2	5M2*	5M2	0	0	0	0	5	M	2
5	M	3	5M3	5M3	0	0	0	0	5	M	3
0	M	2	0M2	0M1	1	0	0	1	0	M	1
1	M	2	1M2	1M2	0	0	0	0	1	M	2
2	M	2	2M2	2M2	0	0	0	0	2	M	2
3	M	2	3M2	3M2	0	0	0	0	3	M	2
4	M	2	4M2	4R2.5	1	0	1	1	4	R	2.5
5	M	2	5M2	5M2	0	0	0	0	5	M	2
0	M	1	0M1	0M1	0	0	0	0	0	M	1
0	M	2	0M2*	0M2	0	0	0	0	0	M	2
0	M	3	0M3	0M3	0	0	0	0	0	M	3
1	M	1	1M1	1M1	0	0	0	0	1	M	1
1	M	2	1M2*	1M2	0	0	0	0	1	M	2
2	M	1	2M1	2M1	0	0	0	0	2	M	1
2	L	1.5	2L1.5	2R1.5	1	0	1	0	2	R	1.5
2	R	1.5	2R1.5	2R1.5	0	0	0	0	2	R	1.5
2	M	2	2M2*	2R2.5	1	0	1	1	2	R	2.5
2	L	2.5	2L2.5	2M3	1	0	1	1	2	M	3
2	R	2.5	2R2.5	2M3	1	0	1	1	2	M	3
2	M	3	2M3	2M3	0	0	0	0	2	M	3
3	M	1	3M1	3M1	0	0	0	0	3	M	1
3	L	1.5	3L1.5	4R1.5	1	1	1	0	4	R	1.5
3	R	1.5	3R1.5	3R1.5	0	0	0	0	3	R	1.5
3	M	2	3M2*	3M2	0	0	0	0	3	M	2
3	L	2.5	3L2.5	3M3	1	0	1	1	3	M	3
3	R	2.5	3R2.5	3M3	1	0	1	1	3	M	3
3	M	3	3M3	3M3	0	0	0	0	3	M	3
4	M	1	4M1	4M1	0	0	0	0	4	M	1
4	L	1.5	4L1.5	4L1.5	0	0	0	0	4	L	1.5
4	R	1.5	4R1.5	4R1.5	0	0	0	0	4	R	1.5
4	M	2	4M2*	4M2	0	0	0	0	4	M	2
4	L	2.5	4L2.5	4M3	1	0	1	1	4	M	3
4	R	2.5	4R2.5	4R2.5	0	0	0	0	4	R	2.5
4	M	3	4M3	4M3	0	0	0	0	4	M	3
5	M	1	5M1	5M1	0	0	0	0	5	M	1
5	M	2	5M2*	5M2	0	0	0	0	5	M	2
5	M	3	5M3	5M3	0	0	0	0	5	M	3