Colour Difference Formulae: Past, Present and Future

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Introduction

The *Commission Internationale de l'Eclairage* (CIE) is responsible for the development of international colour standards. One important goal is to establish a colour difference formula that would provide objective colour decision-making to colour-using industries, i.e. a pass/fail decision based on a single number colour difference value (ΔE) from a standard, regardless of the colour of the standard. Over 40 colour difference formulae have been developed since the first CIE colorimetric system.[1] Table 1 lists most of them. The goal has been growing closer via the latest CIE recommendation, the CIEDE2000 formula.[2] This paper reviews the important development according to three different periods: before 1976 (the adoption of CIELAB and CIELUV [1]), between 1976 to 2001 (the recommendation of CIEDE2000) and after 2001. In the final period, new research areas have been identified and some recent results will be introduced.

The Formulae Developed Before 1976

Over twenty formulae were derived before 1976. They can be grouped into three families, i.e. those derived to fit MacAdam ellipses,[3] to fit the Munsell data,[4] to be linearly transformed from the CIE tristimulus colour space. The Munsell system was based on steps of equal visual perception. The spacing of the colour samples was intensively studied by the Optical Society of America and the CIE tristimulus values of ideally spaced samples were published in 1943.[4] It can be considered the earliest colour discrimination data and demonstrated the non-uniformity of the CIE XYZ system. The earlist Munsell based colour difference formulae is the Nickerson's index of fading[5] and the most successful formula in this family is ANLAB.[6] A series of cube root formulae were later derived to simplify the ANLAB formula which involves a cumbersome fifth-order polynomial function. This resulted in the CIELAB colour difference formula introduced in 1976.[1]

The MacAdam data[3] including 24 colour centres were studied using a split field visual colorimeter. This set of data also demonstrated the poor uniformity of the CIE XYZ system. Although a number of formulae were developed from the data, none of these formulae are widely used now because large differences have been found between the experimental results based on visual colorimeter and surface colours.

The formulae in the family of linear transformation from XYZ have been widely used for additive colour mixing such as that involving coloured lights and emissive phosphor displays. Some earlier formulae were developed including the CIE U*V*W* apace.[7] In 1976, it was refined to become CIELUV.[1]

CIELAB and CIELUV have been widely used, mainly because it is relatively easy to relate colours as seen with positions on the diagram. The ΔE values are calculations of the distance between the standard and sample in these spaces. They are used for industries concerned with subtractive mixture (surface colorant) and additive mixture of coloured light (TV), respectively.

The Formulae Developed Between 1976 and 2001

As mentioned in the last section, the formulae developed before 1976 were mainly derived to fit the Munsell and MacAdam data. The viewing conditions applied in these experiments are very different from those used in industries. With this in mind, many sets of experimental results were published. Most of them were conducted using large surface samples viewed under typical industrial viewing conditions. The medium to small colour-difference data sets show that CIELAB and CIELUV formulae do not accurately quantify small to medium size colour differences. Of these, the important data sets in terms of larger number of observers and sample pairs, smaller observer variations, are those accumulated by Luo and Rigg,[8] RIT-Dupont,[9] Kim and Nobbs,[10] Witt.[11] These data sets were used to develop more advanced formulae based on modifications to the CIELAB formula: *CMC(l:c),*[12] *BFD(l:c),*[13] CIE94.[14] (In general, one or two of these data sets were used to develop each formula.) All these formulae showed a much better improvement than

CIELAB in predicting the available data sets. However, detailed comparisons of these formulae reveal there are large discrepancies between their structures.

With this in mind, a CIE Technical Committee (TC) 1-47 on Hue and Lightness Dependent Correction to Industrial Colour Difference Evaluation was formed in 1998. After close collaboration between the TC members, a new formula, named CIEDE2000, was recommended by CIE in 2001. It includes five corrections to CIELAB: a lightness weighting function, a chroma weighting function, a hue weighting function, an interactive term between chroma and hue differences for improving the performance for blue colours, and a factor for re-scaling the CIELAB a^* scale for improving the performance for grey colours. The results showed that there is a considerable improvement from the more advanced formulae such as CIE94 or CMC to CIEDE2000 for all individual data sets.

Development Since 2001

As mentioned earlier, a very good colour difference formula, CIEDE2000 was developed. This great breakthrough is mainly due to the accumulation of many comprehensive and reliable data sets. However, new directions in colour difference research have been identified and described below.

- Almost all of the recent efforts have been spent on the modifications of CIELAB. CIE TC1-55 was formed to recommend a new perceptually uniform colour space from colour vision theories. Uniform colour spaces [15] based upon a colour appearance model such as CIECAM02 [16] could be an ideal solution.

- All colour difference formulae can only be used in a set of reference viewing conditions defined by the CIE.[14] It will be valuable to accumulate new data to investigate the visual effect due to variation of viewing parameters such as illuminant, coloured background, medium, physical size, colour difference magnitude, separation, texture, luminance level.[17,18] Subsequently, a formula capable of taking into account different viewing parameters can be derived.

- Almost all of the colour difference formulae were developed only to predict the colour difference between a pair of large single objects/patches. More and more applications require to predict colour differences between a pair of pictorial images. The current formula does not include necessary components to consider spatial variations for evaluating images. There is a need to develop a formula for this purpose.[19]

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Table 1 A list of most of the colour difference formulae.

Category of formulae	Munsell Data	MacAdam Data	Linear transfromation from XYZ	Other
Before 1976				
1935			Judd	
1936	Index of Fading			
1937			MacAdam	
1939	Balinkin			
1942			JHNBS	
1943	Munsell Renotation			
1944	ANLAB			
1946	Saunderson & Milner			
1951	Godlove			
1955				DIN
1958	Reilley cube root	Simon-Goodwin	Hunter LAB	
1963			CIEU*V*W*	
1965		Friele		
1967		FMC-I		
1969	Moton cube root			
1971	MLR	FMC-II		
1972	MCR			
1974	ΔEa			OSA
1976	CIELAB		CIELUV	
After 1976				
1978		FCM		
1980	JPC79	LABHNU		
1984	CMC	ATD		
1986		SVF		
1987	BFD			
1991	KC-III			
1995	CIE94			
1997	LCD			
1999	Kuehni			
2001	CIEDE2000	Oleari		