# Quantification of Impacts of Colour on Affective Quality of Images

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The candidate confirms that the work submitted is her own and that appropriate credit has been given where reference has been made to the work of others.

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## Abstract

Most consumer images serve emotional functions as well as informational ones. The impression of an image can be affected not only by physical properties e.g. size, colour and media but also by the context of images, aesthetic properties and social/personal backgrounds of observers. However in traditional frameworks in image quality studies, the impacts of colour-appearance attributes on image quality have focused on maximising the informational functions of images, considering an image as a reproduced copy of a real scene. Thus, a new approach was adopted in this study in an attempt to investigate the emotional aspect of an image. The goal of this research is to study the impact of colour-appearance attributes of an image on emotional responses, and to develop quantitative models for predicting emotional response considering the context of the image. To achieve this goal, three sets of psychophysical and physiological experiments have been conducted.

First, the relationship between colour-appearance attributes and overall affective response to images was investigated for four different types of image contents. It was found that image colourfulness and lightness contrast had a consistent influence on these relationships for all types of images. The relationships between emotional responses of image pleasantness and excitement were significantly different between positive images and negative images. Accordingly, quantitative models of image pleasantness and excitement were developed as a function of image colourfulness and contrast separately for the two groups of images. Finally, models of image pleasantness and excitement for positive and negative images were developed as a linear equation based on models developed for each colour attribute.

The relationships between colour-appearance attributes and responses on colour-emotion scales, *active-passive, heavy-light* and *warm-cool,* were also studied for four different types of image content. Quantitative models of the three colour-emotion scales were developed as a function of colour attributes of images such as lightness, colourfulness and lightness contrast. As an application of using the colour-emotion model developed for images, the relationships between colour-emotion scales and image emotion were investigated and quantitative models of image pleasantness and excitement were developed as functions of three colour-emotion scales for two groups of images: positive and negative. The model performance based on the colour-emotion scales was compared with the performance of models based on the colour attributes. As a result, the latter model performed better than former.

The impact of image content and colour attributes of an image on emotional responses to images was investigated by measuring physiological responses to images which were compared with the psychophysical responses. It was found that the activities in skin conductance and heart rate showed significantly greater responses for the images with personal meanings and significances. For the effect of colour attributes in images, it was found that more chromatic images generated higher activity in skin conductance responses. It was also found that lower contrast images generated higher activity in corrugator EMG responses.

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# Chapter 1 Introduction

## 1.1 Background

Traditional approaches to evaluating the quality of colour image reproduction and to studying impact of colour-appearance attributes on image quality have focused on maximising the informational content of images, considering an image as a reproduced copy of a real scene. From this point of view, a number of definitions of image quality have been proposed, which involved concepts such as *fidelity, naturalness* and *usefulness.* (see Section 2.5.2) Colour plays a critical role especially in the evaluation of image *naturalness*. The most *widely-used* definition of *naturalness* is the extent to which the reproduced colours match the prototypical colours for critical objects such as skin, sky and grass (Yendrikhovskij *et al.*, 1999a). Therefore, the role of colour attributes (e.g. hue and colourfulness) in these concepts of image quality has been extensively studied (see Section 2.5.4.5) and a number of quantitative models (see Section 2.5.4.5).

Note, however, that most consumer images serve emotional functions as well as informational ones. As a copy of the real world, an image can provide a wide range of visual information about objects, their colours and the configuration and so on. On the other hand, an image also has emotional aspects which may play a significant role in quality evaluation, especially for consumer images (Norman 2004). As for other products, the impression of an image can be affected by many factors such as context, physical properties (e.g. size, colour and media; see section 2.5.4) and individual preferences regarding cultural background, gender, or personality.

Among these factors, one of the most critical factors is the context of images, which should be considered for enhancing the emotional impact. The content of a photographic image can be anything that exists in the real world, and its usage can be extremely wide. With the emotional function, images have long been used as emotional stimuli in experimental psychology. To provide a theoretical basis in this research area, a set of emotional pictures called the International Affective Picture System (aka IAPS; see Section 2.5.3) has been established. Many studies using the IAPS images as stimuli have found that the emotional responses largely depend on different image contents.

Moreover, an image can serve as visual records of experiences and memories for individuals and for specific groups of people for a moment of life. For example, people want to keep pictures of their family members in a frame on their desk or in their wallet not because they want to remember what their family members look like but because they enjoy the special feelings from looking at them and from having them close by. In other words, subject matter and personal aspects of images should be considered in quality estimation of images.

Thus, the present study aimed to investigate the role of colour in an image to control the emotional quality in association with contextual and personal properties. The result can be applied to existing imaging devices to perform affective judgement and to make the rendered image the most appropriate colour reproduction over the context of the image. To achieve this, the colour attributes of images need to be analysed and manipulated in such a way that a specific affective response to the images can be obtained. In the present study, the practical questions related to this application are: (a) how do we modify an image's colour characteristics in order to enhance its emotional impact? (b) are image emotion models derived from generic images applicable to personal ones?

To define and utilise the affective responses in a systematic way, two approaches were used to collect and to analyse the experimental data: dimensional models of emotions (see Section 2.4.2) and the "colour-emotion" models (see Section 2.4.5). Dimensional models of emotions were used to assess the overall emotional responses to images in association with context including image content and personal attachment to the images. Colour-emotion models help define the relationship between colours and reactive-level emotional responses determined by the configurations of colour stimuli. According to Ou *et al.*'s models (Ou, 2004a), all colour-emotions can be represented in a three-dimensional space defined by three independent axes, "colour activity", "colour weight" and "colour heat"; every single colour is located in this colour-emotion space and is defined by these three coordinates. It has been shown that the colour-emotion of any colour pair can be determined by a simple mean of the two emotion values of the two individual colours in that pair, which is called the "additivity of colour-emotion" (Ou, 2004b). Whether this additivity principle works for any complex images still remains to be seen, as an image includes millions of colour pixels. Nevertheless, having this model in relation with overall emotional responses for complex images will help modify an image's emotional impact more easily and more systematically. Thus, the present work focused on the following aspects: the relationship between overall emotional responses and colour-emotion responses, the relationship between the three factors of colour-emotion models in complex images, and the effects of colour attributes of an image on observer responses. These aspects were dealt with using psychophysical methods such as categorical judgement (see Section 2.4.3.1).

Emotional experiences involve several components including subjective feelings and physiological changes (see Section 2.4.3). Thus, physiological measurement and psychophysical methods were both used in the present research to obtain observer responses of different aspects. Although the results obtained from different components can sometimes be contradictory, such data will provide a deeper understanding of the impact of colour on affective responses to images than those based on only one component. The two types of measurements, psychophysical and physiological measurement, were compared in the present study, and the results discussed.

## 1.2 Objectives

The goals of the present study were to investigate the impact of the colour-appearance attributes of an image on the observer's emotional responses and to develop models for predicting the emotional responses considering the context of the image. Note that emotional responses may vary with the context of an image which is actually unlimited. In achieving these goals, specific objectives have been considered:

(a) To investigate the relationship between colour-appearance attributes and overall affective responses to images.

(b) To investigate the affective responses to images for different types of image contents including images having personal significance.

(c) To investigate the relationships between colour-appearance attributes and "colour-emotion" responses (see Section 2.4.5) for images, and between overall emotional responses and "colour-emotion" responses for complex images.

(d) To develop models for predicting overall affective responses to different types of images. The prediction will be based on colour-appearance attributes and "colour-emotion" values.

(d) To measure physiological responses to images and compare these with the psychophysical responses to images.

## 1.3 Thesis Outline

This thesis includes eight chapters as described below:

**Chapter 2 Literature Review**

In this chapter, studies in the literature relevant to the present research are reviewed, and divided into five subject areas: human visual system, colorimetry, colour-appearance models, emotional and affective quality of images. After this review, the scope of the present study is defined and the research hypotheses are provided.

### Chapter 3 Experimental Preparation

The experimental setup for this research are described in five sections: the specification of colour-measuring equipment, the colorimetric characteristics and characterisation models for the imaging devices used, the characteristics of physiological instruments and the experimental setups for the three experiments in this work. Statistical methods used for the data analysis are also described.

### Chapter 4 Experiment 1: Impacts of Colour-Appearance Attributes on Emotion for Printed Images Based on Psychophysical Method

This chapter describes the results from the psychophysical part of Experiment 1, which aimed to reveal the relationships between the colour-appearance attributes of images and overall emotional responses to images (also called "image emotion" in this thesis), in association with the contents of images. A set of quantitative models for predicting such relationships were accordingly developed as functions of colorimetric quantities with regards to the effect of image contents. The models are presented at the end of the chapter.

### Chapter 5 Experiment 2: Impacts of Colour-Appearance Attributes on Emotion for Displayed Images Based on Psychophysical Method

This chapter describes the results from Experiment 2 which aimed to investigate the relationships between the "colour-emotion factors" identified by Ou *et al.* (i.e. activity, weight and heat; see Section 2.4.5.2) for complex images and colorimetric quantities of images, and the relationships between the colour-emotion factors and overall emotional responses to images. A set of quantitative models for the three factors of colour-emotion and for overall image emotion were developed as functions of colorimetric quantities of images. Moreover, quantitative models of image emotion responses were developed as functions of three colour-emotion factors. Predictive performances of these models are compared in this chapter.

### Chapter 6 Comparison of Image-Emotion Models Developed for Different Media

This chapter compares the image-emotion models for pleasantness and excitement, as developed for printed and displayed images. Also presented are the combined models as functions of colour attributes of images.

**Chapter 7 Impacts of Colour-Appearance Attributes on Emotion Based on Physiological Method**

This chapter describes the results from the physiological part of Experiments 1 and 3. The aim of these measurements was to investigate the effect of colour attributes of images on emotional responses in terms of physiological reactions, and to find any differences in the effect of colour according to image content. The results described include the following: comparisons of physiological responses with the psychophysical data; the effects of image content on the physiological responses; and the effects of colour attributes on the physiological responses.

**Chapter 8 Conclusions**

This chapter summarises the major findings of the present study. Future work is also discussed.

## 1.4 Publications Based on this Work

The following publications were produced in the course of the present research.

- Joohee Jun, Li-Chen Ou, Boris Oicherman, Shuo-Ting Wei, Ronnier M. Luo, Hila Nachilieli, Carl Staelin. (2010) "Psychophysical and physiological measurement of image emotion", *IS&T's 18th Color Imaging Conference, San Antonio, Texas, USA:* 121-127.
- Joohee Jun, Li-Chen Ou, Ronnier M. Luo. (2011) "Extension of Colour-emotion Model for Complex Images", AIC 2011 Midterm Meeting, Zurich, Switzerland *(accepted).*
- Ou, L., Jun, J., Oicherman, B., Wei, S., Luo, M. R., Nachilieli, H., Staelin, C. "Affective quality of images assessed by psychophysical and psycho-physiological methods", Color Research and Application *(under review).*

# Chapter 2 Literature Review

The aims of this study are to understand the relationship between the colour characteristics of images and the emotional responses elicited by those images and to develop quantitative models of image emotion as functions of colorimetric quantities. This chapter reviews relevant literatures about colour, emotion, images and their relationship. It includes five main topics: an overview of the human visual system and colour perception in Section 2.1; an overview of CIE Colorimetry in Section 2.2; a discussion of colour-appearance attributes and the CIECAM02 model in Section 2.3; an overview of background theories about emotion studies in psychology and also studies related to the relationship between visual experiences and emotion in Section 2.4; an investigation of earlier studies related to image quality and emotional responses to images in order to reveal the important factors for affective image quality in Section 2.5.

## 2.1 Human Vision

Three elements of colour perceptions are the light, object and the eye which is part of the human visual system. The human visual system is one of the key elements required to see the colour of an object together with light and object. In this section, the structure of the eye and the procedure of colour perception are reviewed. The general reference used in this section is Fairchild's *Color-appearance Models* (Fairchild, 2005) and Lee's *Introduction to Color Imaging Science* (Lee, 2005).

### 2.1.1 Human Eye

The eye is a sensory organ which collects visual information from the outside world. Figure 2.1 shows a schematic diagram of the anatomical structure of the eye. The structure of the human eye can be analogous to a camera. The cornea and lens focus an image of the visual field on the retina. The retina, which is located at the back of the eye, acts like the image sensor or film of a camera. The cornea is a transparent outer surface which is the most important element for image-forming where the largest change in index of refraction in the eye's optical system exists between the curved surface and air at the interface. The lens is a flexible and layered structure which varies in refractive index. The iris is a sphincter muscle that controls pupil size. The retina is where the optical image formed by the eye is projected. It is located at the back of the eye and includes photosensitive cells of the visual system and circuit structure for initial signal processing and transmission. These cells are neurons, part of the central nervous system. The fovea, located on the retina, covers an area that subtends about 2° of visual field from the visual axis. The fovea has the best spatial and colour vision. Spatial acuity falls dramatically as the stimulus moves away from the fovea. The macular pigment is a yellow filter which protects the fovea by blocking short-wavelength light. Thus, together with the lens, influence inter-observer variability since their optical densities vary significantly from person to person. The optic nerve consists of axons of the ganglion cells which are the last level of neural processing in the retina. The information generated by photoreceptors is compressed and carried to fibres.

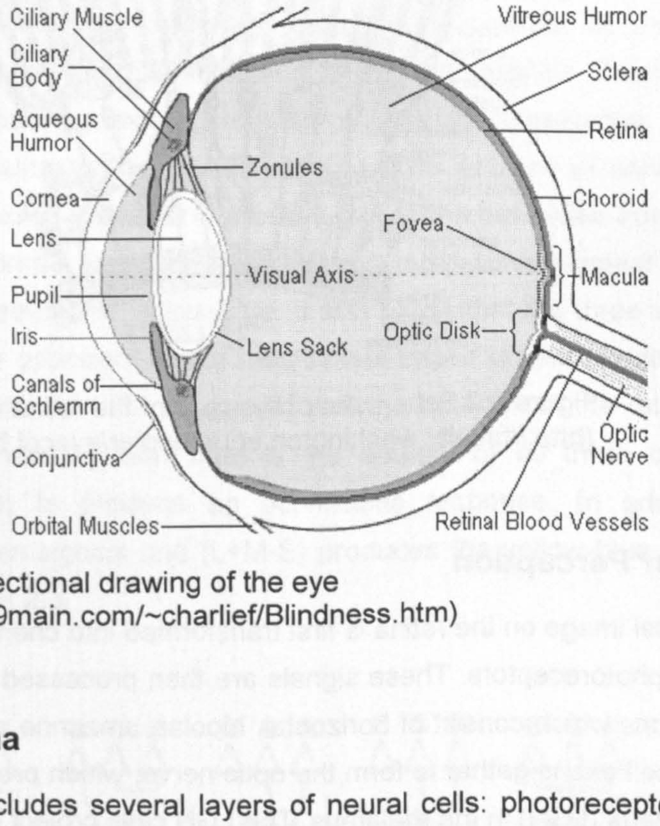



Figure 2.1 Cross-sectional drawing of the eye
(http://www.99main.com/~charlief/Blindness.htm)

## 2.1.2 The Retina

The retina includes several layers of neural cells: photoreceptors (rods and cones), bipolar cells and ganglion cells. The signals transmitted from the retina to higher levels of the brain via the ganglion cells are sophisticated combinations of the receptor signals. Each synapse between neural cells can effectively perform a mathematical operation such as adding, subtracting, multiplying and dividing additionally to the amplification, gain control and non-linearities which can appear within the neural cells.

The photoreceptor has two classes: rods and cones. Rods serve vision at low luminance levels while cones serve vision at higher luminance levels. When only rods are active, vision is referred to as *scotopic*. When only cones are active, vision is referred to as *photopic*. When both rods and cones are active, vision is referred to as *mesopic*.

While there is only one type of rod cells with a peak sensitivity at approximately 510nm, there are three types of cone cells: L, M and S. The LMS serve colour vision, whereas the rod system is incapable of colour vision. The S cones are relatively sparsely populated throughout the retina and completely absent from the most of the central area of the fovea. The relative proportion of the L:M:S cones is approximately 12:6:1. There are few rods present in the fovea whereas cone cells are highly concentrated in the fovea.

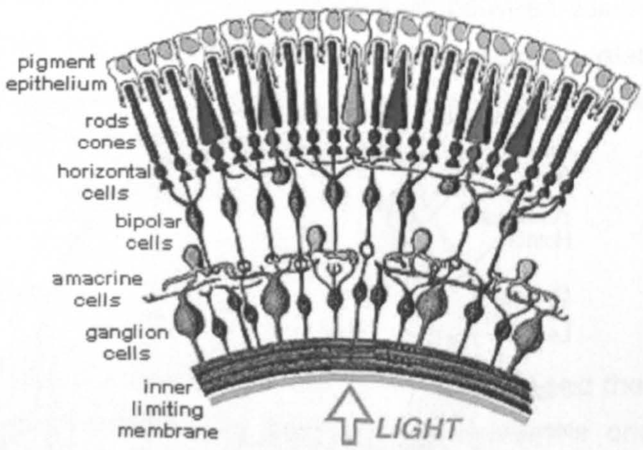



Figure 2.2 Schematic of the cells of the retina
(http://faculty.washington.edu/chudler/eyecol.html)

### 2.1.3 Colour Perception

The optical image on the retina is first transformed into chemical and electrical signals in the photoreceptors. These signals are then processed though a network of retinal neurons which consist of horizontal, bipolar, amacrine and ganglion cells. The ganglion cell axons gather to form the optic nerve, which projects to the lateral geniculate nucleus (LGN) in the thalamus. The LGN cells project onto visual area in the optical lobe of the cortex. In approximately 30 visual areas, cortical processing occurs and perception is achieved.

In the late 19$^{th}$ century, Palmer, Young and von Helmholtz claimed that we cannot have many types of colour sensors, one for each spectral composition, and they further proposed that we have three (Lee, 2005). Their theory of colour vision, based on direct sensor output from the three types of photoreceptor in the retina, is called trichromatic theory. Maxwell's demonstration, in which most colours we see can be reproduced by additively mixing three primary colours, supported trichromatic theory (Lee, 2005). Based on their work, trichromatic theory was proposed in which, it was assumed that a colour stimulus gives rise to signals formed by the three sets of receptors are transmitted to the brain to give rise to the perception of colour-appearance (see Section 2.3).

In 1878, Hering proposed an opponent-colours theory of vision as a result of many observations of colour-appearance phenomena. Hering reported that certain hues were never perceived together, for example reddish-green or yellowish blue. This phenomenon cannot be explained by trichromatic theory and led to him suggesting the opponent-colour theory. This theory assumes the existence of visual processes capable of generating neural signals of two opposite kinds, depending on the wavelength (Wyszecki, 1982).

Jameson (Jameson, et al., 1955) conducted hue-cancellation experiments and provided a method of quantifying opponent colours. In the experiments, observers were asked if the stimulus was reddish or greenish. Then another colour was added to cancel the existing reddish or greenish appearance. The same test was conducted using yellow and blue lights. The amount of cancellation colour used was taken as an indicator of the strength of the cancelled hue. Poirson *et al.* (1993) proposed three colour pathways determining colour-appearance which are white-black, red-green and yellow-blue. It was found that the three visual pathways explained well the opponent-colour mechanism based on the results from the hue-cancellation experiment. He suggested that the neurons of the retina encode the colour into opponent signals. That is the outputs of all three cone types are summed (L+M+S) to produce an achromatic response. In addition, (L-M+S) produces red-green signals and (L+M-S) produces the yellow-blue signals. This is illustrated in Figure 2.3.

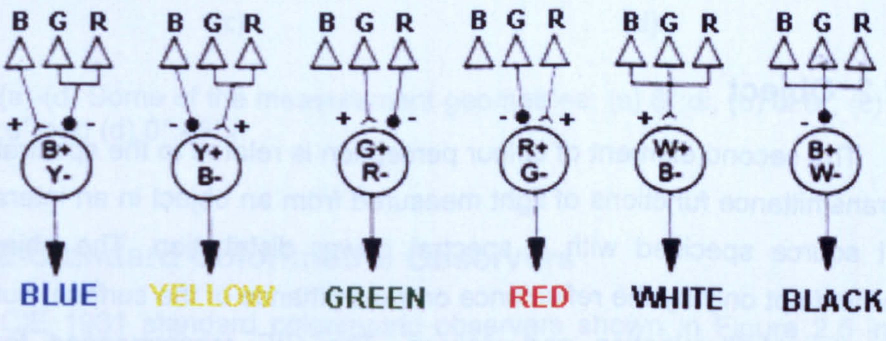



Figure 2.3 Schematic diagram for encoding cone signals into opponent-colour signals. RGB triangles represent LMS cone signals respectively. (http://faculty.washington.edu/chudler/eyecol.html)

## 2.2 CIE Colorimetry

The CIE colorimetry system (CIE, 2004) provides standard methods for specifying colour stimuli under controlled viewing conditions. The key components in colour perception, illumination, objects and standard observers are recommended by the system. This section describes how these components are specified and how they can be used together to specify a colour.

### 2.2.1 Light Source

A light source is defined by measuring its spectral power distribution curve (SPD), a function of wavelength across the visible spectrum. Spectral power is represented by spectral radiance ($W/sr/m^2/nm$), which is the emitted energy per unit time (power) per unit solid angle and per unit area measured in a given direction, at a point of a beam at each wavelength. A spectroradiometer is commonly used for measuring the SPD of a light source.

In 1931, the CIE recommended the use of three standard illuminants, known as illuminants A, B and C, representing incandescent light, direct sunlight and average daylight having the correlated colour temperatures (CCT) of about 2856, 4874 and 6774 K respectively. In 1963, the CIE recommended a series of D illuminants to meet the need of measuring colours that contain the ultra-violet region. The most *widely-used* D illuminants are D65 for surface colour industries and D50 for the graphic arts industry having CCT values of 6504 and 5003 K respectively. CIE F illuminants represent typical fluorescent light sources having CCT values ranging from 3000 K to 6430 K.

### 2.2.2 Object

The second element of colour perception is related to the spectral reflectance or transmittance functions of light measured from an object in an interaction with a light source specified with a spectral power distribution. The object colour is specified not only by the reflectance or transmittance of the surface, but also by the geometry of illumination and viewing. The CIE recommended four types of illumination and viewing geometries for reflectance measurement which are usually adopted in measuring instruments: diffuse/eight degree specular component included (di:8° or 8°:di), diffuse/eight degree specular component excluded (de:8° or 8°:de), diffuse/diffuse (d:d), diffuse/normal (d:0°), 45 annular/normal (45°a:0° or 0°:45°a), 45 directional/normal (45°x:0° or 0°:45°x). Figures 2.4 (a) to (d) show some of the measurement geometries.

In the di:8° geometry, the colour sample is illuminated from all angles by diffused light using an integrating sphere and viewed along an angle of around 8° from the normal direction to the surface. In the 8°:di geometry, the reverse geometry of di:8° which gives identical results, the sample is illuminated from an angle of around 8° from the normal direction and the reflected light is collected from all angles using an integrating sphere.

For the 45°x:0° geometry, the sample is illuminated at an angle of 45°±5° from the normal to the sample and measured at the normal direction. The reverse geometry 0°:45°x also gives identical results. The gloss in the sample should be excluded in both 45°x:0° and 0°:45°x geometries.

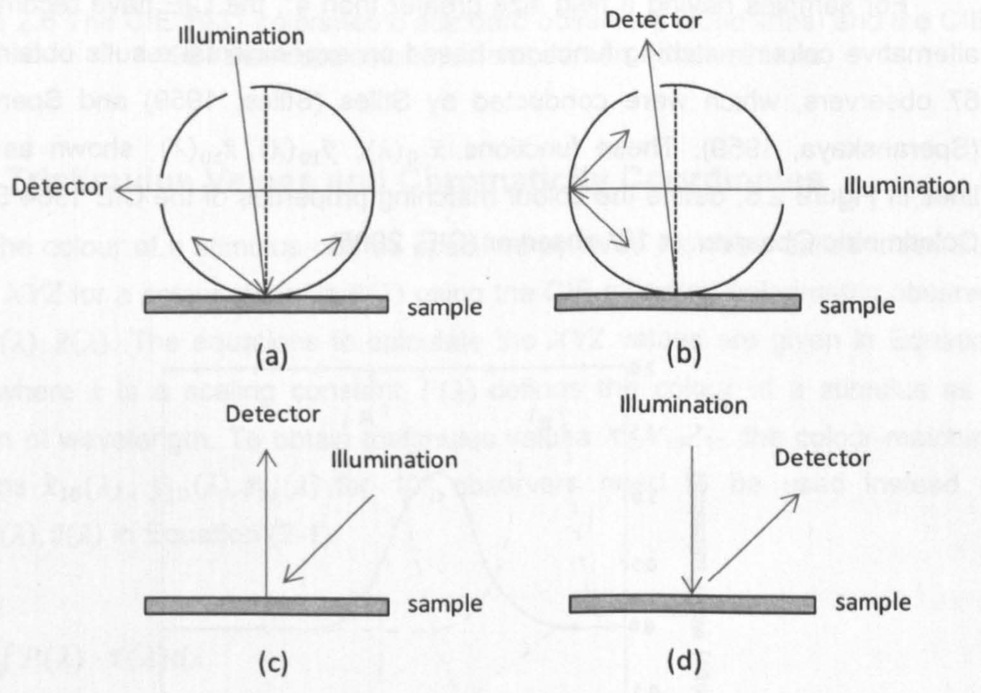



Figure 2.4(a)-(d) Some of the measurement geometries: (a) 8°:di, (b) di:8°, (c) 45°x:0° and (d) 0°:45°x

## 2.2.3 CIE Standard Colorimetric Observers

The CIE 1931 standard colorimetric observers shown in Figure 2.5 include three functions and were established from experimental results obtained from 17 observers conducted by Wright (Wright, 1929) and Guild (Guild, 1931). Each curve indicates the amount of the three RGB primaries required to match a unit amount of monochromatic test stimuli at each wavelength. The negative part of the curves indicates that the amount of the primaries had to be added to the monochromatic test stimuli for a match in both fields. This means that the wavelength is too saturated to be matched by the particular primaries. The negative tristimulus values adding to the test stimulus are to desaturate the test stimulus and bring it within the gamut of the primaries.

The standard colorimetric observer functions were then linearly transformed by a 3 × 3 matrix to $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ to avoid the negative part. These colour matching functions shown by solid lines in Figure 2.6 define the colour-matching properties of the CIE 1931 Standard Colorimetric Observer or 2° observer which serves for visual field sizes of 1° to 4°. These functions have no negative part and the areas under the three curves are equal because the tristimulus values of an equi-energy stimulus are the same. The Y tristimulus value is the summation of the relative photometric quantities (in unit of cd/m$^2$) of the RGB primaries.

For samples having a field size greater than 4°, the CIE have recommended alternative colour-matching functions based on experimental results obtained from 67 observers, which were conducted by Stiles (Stiles, 1959) and Speranskaya (Speranskaya, 1959). These functions, $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$, shown as dashed lines in Figure 2.6, define the colour matching properties of the CIE 1964 Standard Colorimetric Observer or 10° observer (CIE, 2005).

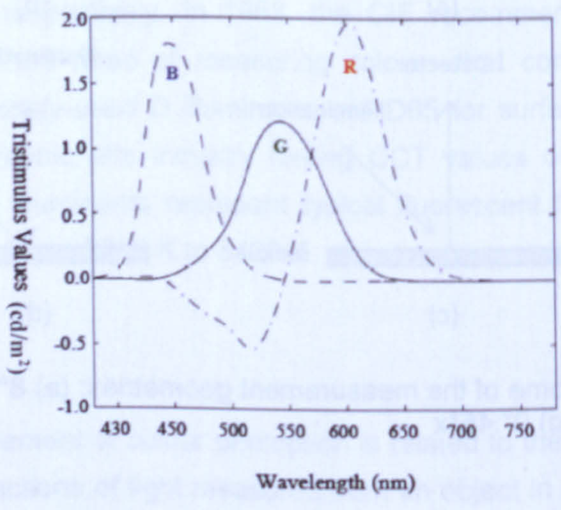



Figure 2.5 RGB colour-matching functions of the CIE 1931 standard observers

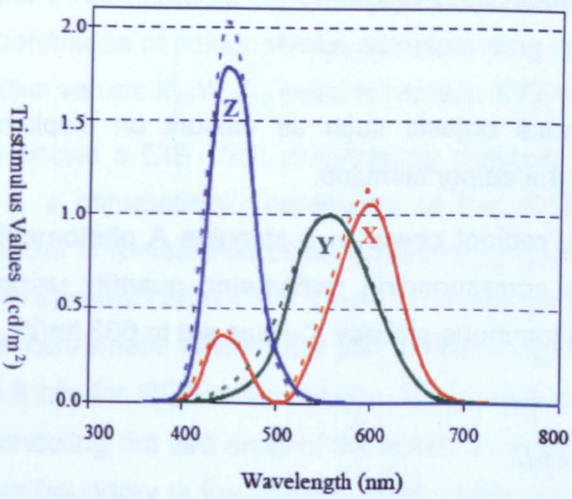



Figure 2.6 The CIE 1931 colorimetric standard observers (solid lines) and the CIE 1964 standard colorimetric observers (dashed lines)

### 2.2.4 Tristimulus Values and Chromaticity Coordinates

The colour of a stimulus can be specified by three numbers called tristimulus values *XYZ* for a colour stimulus $P(\lambda)$ using the CIE standard colorimetric observer $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$. The equations to calculate the *XYZ* values are given in Equation (2-1), where $k$ is a scaling constant, $P(\lambda)$ defines the colour of a stimulus as a function of wavelength. To obtain tristimulus values $X_{10}Y_{10}Z_{10}$, the colour-matching functions $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda), \bar{z}_{10}(\lambda)$ for 10° observers need to be used instead of $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ in Equation (2-1).

$$X = k \int P(\lambda) \cdot \bar{x}(\lambda) d\lambda$$
$$Y = k \int P(\lambda) \cdot \bar{y}(\lambda) d\lambda \qquad (2\text{-}1)$$
$$Z = k \int P(\lambda) \cdot \bar{z}(\lambda) d\lambda$$
$$k = \frac{100}{\int P(\lambda) \cdot \bar{y}(\lambda) d\lambda}$$

For a reflecting objects, the property of a colour stimulus, $P(\lambda)$ is defined by the product of the spectral reflectance, $R(\lambda)$ (or the spectral transmittance, $T(\lambda)$ for transmitting objects) and the spectral power distribution of the light source or illuminant $S(\lambda)$. Thus, for reflecting or transmitting objects, the colour property function is given in Equation (2-2).

$$P(\lambda) = R(\lambda) \cdot S(\lambda) \text{ or } P(\lambda) = T(\lambda) \cdot S(\lambda) \quad (2\text{-}2)$$

For self luminous objects such as colours on displays, $P(\lambda)$ defines the spectral radiance of the colour stimulus.

The amount of radiant power in a stimulus A photometric quantity could be calculated from the corresponding radiometric quantity using Equation (2-3), in which the maximum luminous efficacy *Km* was set to 683 lm/W.

$$\Phi_V = K_m \int_\lambda \Phi(\lambda) V(\lambda) d\lambda \quad (2\text{-}3)$$

where $\Phi_V$ is the photometric quantity corresponding to the radiometric quantity, $\Phi(\lambda)$. The $V(\lambda)$ is the CIE spectral luminous efficiency function for photopic vision, which corresponds to a weighted sum of the three cone sensitivity functions. The $Y$ tristimulus value is proportional to a photometric quantity as $\bar{y}(\lambda) = V(\lambda)$. The constant $k$ in Equation (2-1) is set equal to $K_m$, and so $Y$ is in photometric units. This $k$ value is also used for determining the $X$ and $Z$ tristimulus values in Equation (2-1).

In radiometric measurement, the amount of radiant power is measured using detectors which is equally sensitive to all wavelengths. In photometric measurement, measured quantity is based on the spectral luminous efficiency functions $V(\lambda)$ and $V'(\lambda)$ according to whether photopic or scotopic levels of illumination are involved. These functions are applied by filters which modify the spectral sensitivities close to the $V(\lambda)$ and $V'(\lambda)$.

Another way to represent tristimulus values XYZ is to use two-dimensional colour space called the CIE 1931 or 1964 chromaticity coordinates. The two coordinates in the 1931 CIE chromaticity diagram, *x* and *y*, can be calculated from the *XYZ* values using Equation (2-4).

$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z} \quad (2\text{-}4)$$
$$z = \frac{Z}{X+Y+Z}$$

where $x + y + z = 1$.

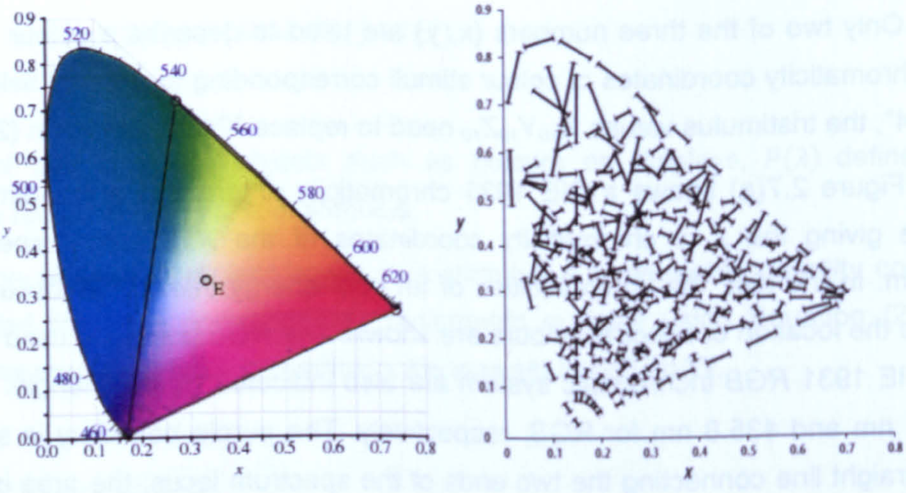
Only two of the three numbers (x, y) are used to describe a colour stimulus. For chromaticity coordinates of colour stimuli corresponding to a visual field greater than 4°, the tristimulus values $X_{10}Y_{10}Z_{10}$ need to replace XYZ in Equation (2-4).

Figure 2.7(a) shows a CIE 1931 chromaticity diagram in a two-dimensional space giving the *x*, *y* chromaticity coordinates of the *XYZ* colour specification system. In the plot, the chromaticities of an equi-energy stimulus (labelled E) and where the location of spectral colours are shown. The *RGB* primaries used to define the CIE 1931 *RGB* trichromatic system are also indicated by the triangle: 700 nm, 546.1 nm and 435.8 nm for RG*B*, respectively. The purple boundary is shown by the straight line connecting the two ends of the spectrum locus; the area inside the locus and the purple boundary is the domain of all visible colours. The area within the triangle formed by the three points of R, G and B primaries on the locus represents all colours that can be matched by additive mixtures of these three primaries. For the area outside the triangle, the additive mixture of two primaries can be matched with the additive mixture of the third primary and the target stimulus.

There is, however a well-known problem with the *xy* diagram (MacAdam, 1942): which is the diagram does not well represent the colour differences between the two pairs having the same perceived colour difference. In Figure 2.7 (b), each line represents perceptually the same proportion of colour difference according to the 1931 CIE standard colorimetric observer; however, it can be seen that the lengths of the vectors vary.

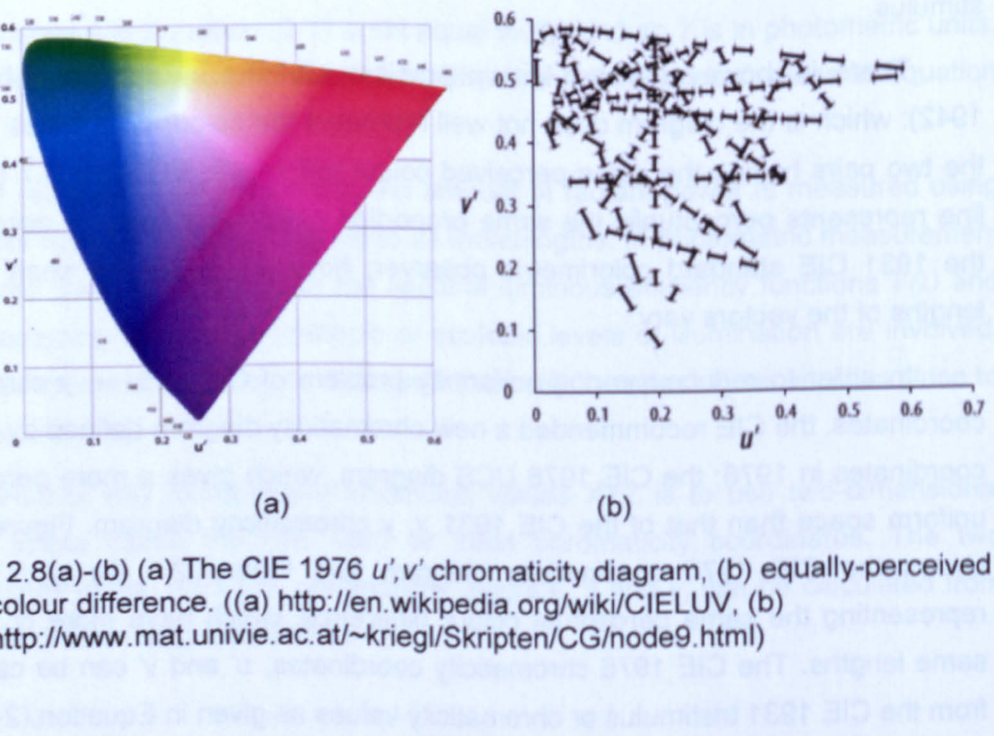
In order to reduce the non-uniformity problem of CIE 1931 *x*, *y* chromaticity coordinates, the CIE recommended a new chromaticity diagram defined by *u'* and *v'* coordinates in 1976: the CIE 1976 UCS diagram, which gives a more perceptually uniform space than that of the CIE 1931 *x*, *y* chromaticity diagram. Figure 2.8 (a) shows the CIE 1976 chromaticity diagram and Figure 2.8 (b) plots vectors representing the same perceptual colour difference, which have more or less the same lengths. The CIE 1976 chromaticity coordinates, *u'* and *v'* can be calculated from the CIE 1931 tristimulus or chromaticity values as given in Equation (2-5).

$$u' = \frac{4X}{X+15Y+3Z} = \frac{4x}{-2x+12y+3}, \quad v' = \frac{9Y}{X+15Y+3Z} = \frac{9y}{-2x+12y+3} \qquad (2\text{-}5)$$




(a) (b)

Figure 2.7(a)-(b) (a) The CIE 1931 *x*, *y* chromaticity diagram, (b) equally-perceived colour difference. ((a)http://en.wikipedia.org/wiki/CIE_1931_color_space, (b)http://www.mat.univie.ac.at/~kriegl/Skripten/CG/node9.html)




(a) (b)

Figure 2.8(a)-(b) (a) The CIE 1976 *u'*,*v'* chromaticity diagram, (b) equally-perceived colour difference. ((a) http://en.wikipedia.org/wiki/CIELUV, (b) http://www.mat.univie.ac.at/~kriegl/Skripten/CG/node9.html)

## 2.2.5 Uniform Colour Spaces

The CIELAB and CIELUV systems were the recommended uniform colour spaces for colour research and industry by the CIE (CIE, 1978). Both provide perceptually uniform spaces. The recommendation of these systems not only applies to the CIE 1931 standard colorimetric observer and its corresponding chromaticity coordinate system, but also to the CIE 1964 standard colorimetric observer and its corresponding chromaticity coordinate system. Both spaces are aimed to be used in comparisons of differences between object colours of the same size and shape, viewed in white to middle-grey surroundings, by an observer adapted to a field whose chromaticity is not too different from that of average daylight.

The CIELAB system, the most *widely-used* space, is defined by the three orthogonal dimensions of $L^*$, $a^*$ and $b^*$. In Figure 2.9, the vertical dimension L* represents the lightness, a* and b* represent the redness-greenness and yellowness-blueness perceptions of colours respectively. These dimensions are determined using Equation (2-6):

$$L^* = 116 \cdot f(\frac{Y}{Y_n}) - 16$$

$$a^* = 500 \cdot \left[ f(\frac{X}{X_n}) - f(\frac{Y}{Y_n}) \right] \qquad (2\text{-}6)$$

$$b^* = 200 \cdot \left[ f(\frac{Y}{Y_n}) - f(\frac{Z}{Z_n}) \right]$$

$$f(x) = \begin{cases} x^{1/3} & , x > \left(24/116\right)^3 \\ 841/108\, x + 16/116 & , x \le \left(24/116\right)^3 \end{cases}$$

$$C_{ab}^* = \sqrt{a^{*2} + b^{*2}}$$

$$h_{ab} = arctan\left(\frac{b^*}{a^*}\right)$$

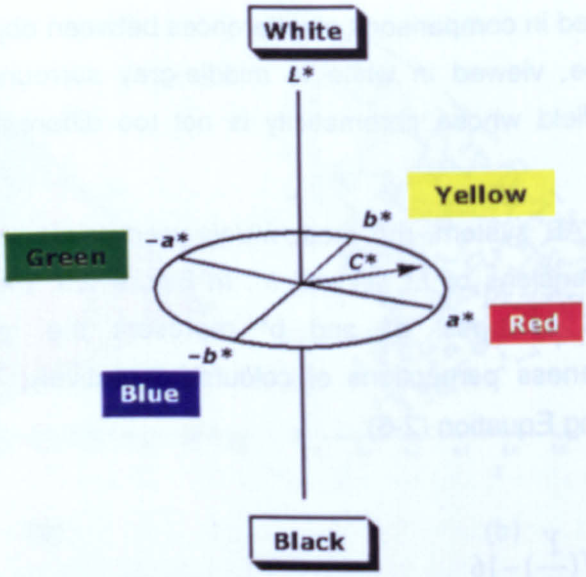



Figure 2.9 A three-dimentional representation of the CIELAB space (http://www.colour-journal.org/2007/1/5/07105article.htm).

$XYZ$ are the tristimulus values of a colour stimulus of interest and $X_nY_nZ_n$ are the tristimulus values of a reference white object. The reference white should be ideally a perfect reflecting diffuser illuminated by the same light source as for the colour stimulus of interest. In this case, $X_nY_nZ_n$ are the tristimulus values of the light source with $Y_n$ equal to 100. However, for practical measurements, the reference white stimulus is normally chosen as which has been calibrated against the perfect diffuser. The quantity $L^*$ in Equation (2-6) serves as the correlate of lightness. The quantity $C^*_{ab}$ serves as the correlate of chroma. The quantity $h_{ab}$ serves as the correlate of hue angle, which is useful for the numerical specification of hue. The angles are given in units of degrees using the following conventions: $0° < h_{ab} < 90°$ if $a^* > 0$ and $b^* > 0$; $90° < h_{ab} < 180°$ if $a^* < 0$ and $b^* > 0$; $180° < h_{ab} < 270°$ if $a^* < 0$ and $b^* < 0$; and $270° < h_{ab} < 360°$ if $a^* > 0$ and $b^* < 0$. The $a^*$ and $b^*$ values are referred to as colour coordinates representing the combined attributes of hue and chroma as in Equation (2-6).

The reverse transform from $L^*$, $a^*$ and $b^*$ to $XYZ$ is given in Equation (2-7):

$$X = \begin{cases} \frac{X_n}{7.787} \cdot \left( \frac{L^*}{116} + \frac{a^*}{500} \right) & \left( \frac{L^*}{116} + \frac{a^*}{500} \right) \le 7.787 \times 0.008856 \\ X_n \left( \frac{L^* + 16}{116} + \frac{a^*}{500} \right)^3 & \left( \frac{L^*}{116} + \frac{a^*}{500} \right) > 7.787 \times 0.008856 \end{cases}$$

$$Y = \begin{cases} \frac{Y_n}{7.787} \cdot \left( \frac{L^*}{116} \right) & \left( \frac{L^*}{116} \right) \le 7.787 \times 0.008856 \\ Y_n \left( \frac{L^* + 16}{116} \right)^3 & \left( \frac{L^*}{116} \right) > 7.787 \times 0.008856 \end{cases} \quad (2\text{-}7)$$

$$Z = \begin{cases} \frac{Z_n}{7.787} \cdot \left( \frac{L^*}{116} - \frac{b^*}{200} \right) & \left( \frac{L^*}{116} - \frac{b^*}{200} \right) \le 7.787 \times 0.008856 \\ Z_n \left( \frac{L^* + 16}{116} - \frac{b^*}{200} \right)^3 & \left( \frac{L^*}{116} - \frac{b^*}{200} \right) > 7.787 \times 0.008856 \end{cases}$$

Euclidean distance in CIELAB colour space represents the approximate magnitude of perceived colour difference between colour stimuli. Two equivalent equations describing CIELAB colour difference are given in Equation (2-8):

$$\Delta E^*_{ab} = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{1/2}$$

$$\Delta E^*_{ab} = (\Delta L^{*2} + \Delta C^{*2}_{ab} + \Delta H^{*2}_{ab})^{1/2} \quad (2\text{-}8)$$

where $\Delta H^{*2}_{ab} = 2\sqrt{C^*_{ab,1} \cdot C^*_{ab,2}} \cdot sin\,(\frac{\Delta h_{ab}}{2})$ is the hue difference; the indices 1 and 2 refer to the two colour stimuli of interest; $\Delta h_{ab}$ is the hue-angle difference between the two colour stimuli compared.

The CIELUV system also has three orthogonal dimensions. In Figure 2.10, the vertical dimension $L^*$ represents lightness; the two horizontal dimensions $u^*$ and $v^*$ represent the redness-greenness and yellowness-blueness perceptions of colours. The colour attributes of lightness, chroma, hue angle and saturation can be predicted by the CIELUV system using following formulae:

$$L^* = 116 \cdot f\left(\frac{Y}{Y_n}\right) - 16 \text{ for } x > 0.008856,$$

$$L^* = 903.3 \cdot \left(\frac{Y}{Y_n}\right) \qquad \text{for } x \leq 0.008856$$

$$u^* = 13L^*(u' - u'_n) \tag{2-9}$$

$$v^* = 13L^*(v' - v'_n)$$

$$C^*_{uv} = \sqrt{u^{*2} + v^{*2}}$$

$$s_{uv} = 13\sqrt{(u' - u'_n)^2 + (v' - v'_n)^2}$$

$$h_{uv} = \arctan(v^*/u^*)$$

where $u'$, $v'$ and $u'_n$, $v'_n$ are the chromaticity coordinates for the colour stimulus and for the reference white, respectively, determined using Equation (2-9).

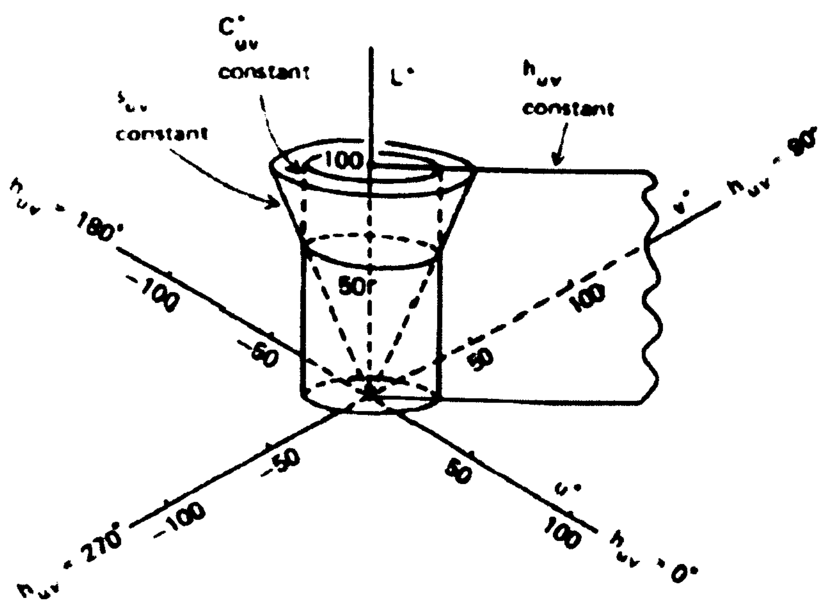



Figure 2.10 A three-dimensional representation of CIELUV space. (Hunt, 2004)

Colour-difference formulae in CIELUV system are defined similar to those in CIELAB system, as follows:

$$\Delta E^*_{uv} = (\Delta L^{*2} + \Delta u^{*2} + \Delta v^{*2})^{1/2} \tag{2-10}$$

$$\Delta E^*_{uv} = (\Delta L^{*2} + \Delta C^{*2}_{uv} + \Delta H^{*2}_{uv})^{1/2}$$

where $\Delta H_{uv}^{*2} = 2\sqrt{C_{uv,1}^{*} \cdot C_{uv,2}^{*}} \cdot sin\,(\frac{\Delta h_{uv}}{2})$; the indices 1 and 2 refer to the two colour stimuli of interest; $\Delta h_{uv}$ is the hue-angle difference between the two colour stimuli.

## 2.3 Colour-appearance

CIE colorimetry has provided effective ways to specify colours and colour differences of stimuli. This system works well under given viewing conditions; however, this constraint of a certain viewing conditions tends to limit its usage because diverse viewing conditions such as media, light sources, background colours, and luminance levels of surround lighting are involved when colours are applied in the real world. Therefore a colour-appearance model capable of predicting the appearance of colours under a wide range of viewing conditions has been developed. The CIE has defined the colour-appearance model as (CIE, 1998) "A colour-appearance model is any model that includes predictors of at least the relative colour-appearance attributes of lightness, chroma and hue." Many colour-appearance models have been proposed such as Hunt (Hunt, 1991), Nayatani (Nayatani, et al., 1997), RLAB (Fairchild, 1996), LLAB (Luo, 1996), CIECAM97s (CIE, 1998) and CIECAM02 (CIE, 2004). In this section, the important features of a colour-appearance model are reviewed based on CIECAM02, which is the latest system that the CIE has recommended.

### 2.3.1 Colour-Appearance Phenomena

The limitation of CIE colorimetry is that it only considers colour stimuli under a specific viewing condition. Colour-appearance in practice is affected by various viewing conditions including illumination, surround condition, background colour, size, shape texture and viewing geometry. Some of the colour-appearance phenomena are summarised in this section.

There are two phenomena related to the change of luminance level. The first one is the *Hunt effect* (Hunt, 1952). The Hunt effect can be summarised by the statement that the colourfulness of a given stimulus increases with luminance level. It implies that a typical outdoor scene appears much more colourful in bright sunlight than it does on a dull day. The second is the *Stevens effect* (Stevens, 1963). This states that as the luminance level increases, dark colours will appear darker and light colours will appear lighter.

When the chromaticity of a light source is changed, the colour of an object can be recognised with good consistency due to t he *chromatic adaptation*. This is achieved by the contraction of the pupil, changes in photoreceptor (cone and rod) responses, retinal pigment bleaching, changes in cellular activity and cortical changes (Kaiser, 1996). Several chromatic adaptation transform (CAT) models were developed to specify this phenomenon. The CMCCON97 transform, which is included in the CIECAM97s colour-appearance model (Luo, 1998) for chromatic adaptation transform and a revision of the CMCCAT97 named CMCCAT2000 (Li, 2002), was proposed by the CMC. But the current most *widely-used* transform CAT02, is included in CIECAM02 (CIE, 2004).

Colour-appearance can also be changed by different backgrounds. When background colour is changed, simultaneous contrast causes stimuli to shift in colour-appearance. The effect of simultaneous contrast from complex backgrounds on achromatic attributes also has been investigated (Fairchild, 1999; Lee, 2001) and the results revealed that the effect from complex backgrounds was very similar to that of uniform backgrounds when the latter is a linear integration of the former. This also explains why colour-appearance models derived from individual surface colour estimations also perform well for complex images.

Bartleson and Breneman (Bartleson, 1967) found that the perceived image contrast in colourfulness and brightness increased with increasing surround luminance level from dark, dim and average surrounds. This effect occurs because the dark surround of an image makes dark areas appear lighter while having little effect on light areas. This is an important colour-appearance phenomenon, especially for imaging and graphic arts industries, where it is often required to compare different media under quite different viewing conditions (Luo, 1998).

### 2.3.2 Colour-Appearance Attributes

The visual appearance of a colour stimulus can be described using terms such as brightness, lightness, colourfulness and hue, which are defined by the CIE as listed below (CIE, 1987).

*Brightness* is a visual perception according to which an area appears to exhibits more or less light. This is an open-ended scale with a zero origin defining the black. The brightness of a sample is affected by the luminance level of the light source. A surface colour illuminated by a higher luminance would appear brighter than the same surface illuminated by a lower luminance.

*Lightness* is the brightness of an area judged relative to the brightness of a similarly illuminated reference white. The lightness scale ranges from zero for black to 100 for white. The lightness of the background used may cause a change in the lightness of the sample. This is called the lightness contrast effect.

*Colourfulness* is the attribute of a visual sensation according to which an area appears to exhibit more or less chromatic content. This is an open-ended scale with a zero origin defining neutral colours. Similar to the brightness attribute, the colourfulness of a sample is also affected by luminance. A surface colour illuminated by a higher luminance would appear more colourful than the same surface illuminated by a lower luminance. This is known as the Hunt effect.

*Chroma* is the colourfulness of an area judged in proportion to the brightness of a similarly illuminated reference white. This is an open-ended scale with a zero origin representing neutral colours.

*Saturation* is the colourfulness of an area judged in proportion to its brightness. This scales ranges from zero representing neutral colours with an open end.

*Hue* is the attribute of a visual sensation according to which an area appears to be similar to one, or to proportion of two, of the perceived colours red, yellow, green and blue.

### 2.3.3 The Observing Fields

Viewing environments adjacent to a test stimulus can influence the appearance of the test stimulus. The surrounding area beyond the test stimulus in the visual field depends on the viewing distance and the size of the target stimulus. The visual angle can represent both the viewing distance and the size of the target stimulus. Although viewing environments contributing to colour-appearance phenomena are infinitely variable, attempts have been made to define five visual areas in the observing field (Hunt, 1991). The purpose was to provide a simplifyied definition of the viewing environment sufficient to make it feasible for modelling the spatial effects on colour-appearance. In this section, definitions of four visual components as shown in Figure 2.11 in the observing field are given, according to Hunt (Hunt, 1991; 1998).

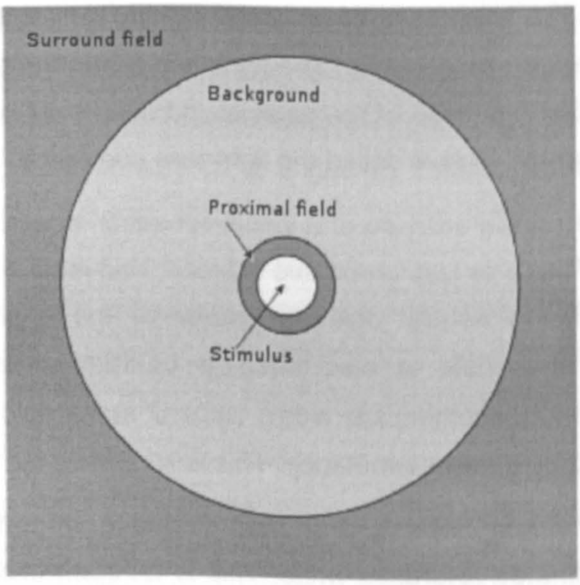



Figure 2.11 Components of the observing field (http://en.wikipedia.org/wiki/CIECAM02).

*Stimulus* is the colour element for which colour-appearance measurement is required. Typically a stimulus is a uniform patch of about 2° angular subtense. The reason for choosing a 2° visual angle for defining the stimulus can be found from the nature of the fovea that comprises approximately the central 1.5° diameter of the visual field.

*Proximal field* is the immediate environment of the colour element considered, extending typically for about 2° from the edge of the stimulus in all or most directions. It is normally specified to be equal to the background when the proximal field is not known.

*Background* is defined as the environment of the colour element considered, extending typically for approximately 10° from the edge of the proximal field in all or most directions. When the proximal field is the same as the background, the latter is regarded as extending from the edge of the colour element considered. The background is usually considered to be a neutral grey with 20 % luminance factor. For imaging applications, defining the background is difficult when the angular subtense of a target image is larger than 10°. In this case, the exact specification of the background is dependent on image content and the location of specific objects in the image, however, there is no standard guide for this ambiguous case.

*Surround* is the field beyond the background. The surround, for practical situations, can be considered to be the entire room in which viewing is taking place. The surround is referred to in categorical terms such as dark, dim or average for practical use of CIECAM02.

### 2.3.4 Colour-Appearance Model: CIECAM02

CIECAM02 (CIE, 2004), the colour-appearance model recommended by the CIE, consists mainly of three parts: a chromatic adaptation transform, a dynamic responses function and colour spaces formed by different combinations of colour-appearance attributes.

A chromatic adaptation transform is also to predict the tristimulus values of a corresponding colour from a reference viewing condition to another test viewing condition. The two colours from corresponding pairs have the same colour-appearance under two different illuminants. This transformation allows a colour-appearance model to predict the appearance of colours seen in different viewing conditions. The dynamic response functions allow prediction of the changes in response to stimuli under different lighting conditions across a wide range of luminance levels from very dark to very bright. The colour spaces used in the models are similar to the CIELAB space where chroma and hue are related to orthogonal coordinates of red-green and yellow-blue opponent signals and lightness is calculated in a non-linear way from an achromatic signal.

#### 2.3.4.1 Input and Output Data

The input data required in order to compute the colour-appearance attributes using CIECAM02 are listed in Table 2.2.

$Y_b$ is calculated from the luminance of the reference white in the test viewing condition divided by the luminance of the background on a percentage scale. $L_A$ is obtained by calculating $L_w Y_b/100$. For a self-luminous display to present test stimuli, 20% of the luminance of the reference white of the display can usually be regarded as $L_A$. When reflective test stimuli are assessed, 20% of the reference white illuminated by the light source in the test viewing condition is generally considered as $L_A$. The categorical terms for surround lighting levels- dark, dim and average- can be determined by calculating the surround ratio, $S_R$. This is the luminance of the surround white divided by the luminance of device white: an average surround for $0.2 \leq S_R < 1$; a dim surround for $0 < S_R < 0.2$ and a dark surround for $S_R \approx 0$.

Table 2.1 Parameters for different surround conditions in CIECAM02.

| Surround Condition | c | $N_c$ | $F$ |
|---|---|---|---|
| Average Surround | 0.69 | 1.0 | 1.0 |
| Dim Surround | 0.59 | 0.9 | 0.9 |
| Dark Surround | 0.525 | 0.8 | 0.8 |

Table 2.2 Input data for CIECAM02.

| Input Data | |
|---|---|
| Relative tristimulus values for the test stimulus in the test viewing conditions | $XYZ$ |
| Relative tristimulus vaues of the reference white in the test viewing conditions | $X_w Y_w Z_w$ |
| Tristimulus values of the reference white in the reference viewing conditions | $X_{wr} Y_{wr} Z_{wr}$=100 |
| Background luminance factor | $Y_b$ |
| Luminance of the test adapting field (cd/m$^2$) | $L_A=L_w Y_b/100$ |
| Surround parameters | $c$, $N_c$, $F$ |

### 2.3.4.2 Forward Model

The calculation steps to acquire the colour-appearance attribute values using CIECAM02 are described below.

Step 1: Calculate *RGB* responses using the CAT02 matrix.

$$\begin{pmatrix} R_w \\ G_w \\ B_w \end{pmatrix} = M_{CAT02} \begin{pmatrix} X_w \\ Y_w \\ Z_w \end{pmatrix}, \begin{pmatrix} R \\ G \\ B \end{pmatrix} = M_{CAT02} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}, \tag{2-11}$$

where the matrix $M_{CAT02}$ is the CAT02 matrix defined below.

$$M_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix}$$

Step 2: Compute the degree of adaptation factor, *D*, from $L_A$ ranging from one for complete adaptation to zero for no adaptation.

$$D = F[1 - \left(\frac{1}{3.6}\right) e^{\left(\frac{-La-42}{92}\right)}] \tag{2-12}$$

Step 3: Apply a *D* factor to obtain the corresponding cone responses $R_c G_c B_c$ for the reference viewing conditions.

$$\begin{pmatrix} R_c \\ G_c \\ B_c \end{pmatrix} = \begin{pmatrix} D_R R \\ D_G G \\ D_B B \end{pmatrix}, \quad \begin{pmatrix} R_{wc} \\ G_{wc} \\ B_{wc} \end{pmatrix} = \begin{pmatrix} D_R R_w \\ D_G G_w \\ D_B B_w \end{pmatrix} \tag{2-13}$$

$$D_R = Y_w D / R_w + 1 - D, \ D_G = Y_w D / G_w + 1 - D, \ D_B = Y_w D / B_w + 1 - D$$

Step 4: Calculate luminance level adaptation factor ($F_L$), chromatic background induction factor ($N_{cb}$) and brightness induction factor ($N_{bb}$).

$$F_L = 0.2k^4(5L_A) + 0.1(1-k^4)^2(5L_A)^{1/3}, \ \textit{where } k = 1/(5L_A+1).$$

$$n = Y_b / Y_w, \ z = 1.48 + \sqrt{n}, \ N_{bb} = 0.725(1/n)^{0.2}, \ N_{cb} = N_{bb} \tag{2-14}$$

Step 5: Calculate the adapted *RGB* responses from the $M_{CAT02}$ specification to Hunt-Pointer-Estevez fundamentals.

$$\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = M_{HPE} M_{CAT02}^{-1} \begin{pmatrix} R_c \\ G_c \\ B_c \end{pmatrix}, \quad \begin{pmatrix} R_w' \\ G_w' \\ B_w' \end{pmatrix} = M_{HPE} M_{CAT02}^{-1} \begin{pmatrix} R_{cw} \\ G_{cw} \\ B_{cw} \end{pmatrix}, \tag{2-15}$$

*where*

$$M_{CAT02}^{-1} = \begin{pmatrix} 1.096124 & -0.278869 & 0.182745 \\ 0.454369 & 0.473533 & 0.072098 \\ -0.009628 & -0.005698 & 1.015326 \end{pmatrix}$$

$$M_{HPE} = \begin{pmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 0.00000 \end{pmatrix}$$

Step 6: Calculate post-adaptation non-linearities for the sample $R'_a G'_a B'_a$ and for the adapted white $R'_{aw} G'_{aw} B'_{aw}$.

$$R_a' = 400(F_L R'/100)^{0.42} / [(F_L R'/100)^{0.42} + 27.13] + 0.1$$
$$G_a' = 400(F_L G'/100)^{0.42} / [(F_L G'/100)^{0.42} + 27.13] + 0.1$$
$$B_a' = 400(F_L B'/100)^{0.42} / [(F_L B'/100)^{0.42} + 27.13] + 0.1 \tag{2-16}$$

$$R'_{aw} = 400(F_L R'_w / 100)^{0.42} / [(F_L R'_w / 100)^{0.42} + 27.13] + 0.1$$
$$G'_{aw} = 400(F_L G'_w / 100)^{0.42} / [(F_L G'_w / 100)^{0.42} + 27.13] + 0.1$$
$$B'_{aw} = 400(F_L B'_w / 100)^{0.42} / [(F_L B'_w / 100)^{0.42} + 27.13] + 0.1 \qquad (2\text{-}17)$$

Step 7: Calculate the red-green (*a*) and yellow-blue (*b*) opponent correlates and hue angle (*h*).

Redness-Greenness: $a = R'_a - 12G'_a / 11 + B'_a / 11$ (2-18)

Yellowness-Blueness: $b = (R'_a + G'_a - 2B'_a) / 9$ (2-19)

Hue angle: $h = \tan^{-1}(b/a), \qquad 0 \le h \le 360$ (2-20)

Step 8: Calculate hue quadrature (*H*) and hue composition ($H_c$) using the following unique hue data.

Set $h' = \begin{cases} h + 360 & \text{if } h < h_1 \\ h & \text{otherwise} \end{cases}$

Choose a proper *i (i=1, 2, 3, 4 or 5)* so that $h_i \le h' \le h_{i+1}$.

$$e_t = \left[ \frac{\cos\left(h' \frac{\pi}{180} + 2\right) + 1}{4} + 0.7 \right] = \frac{1}{4}\left[ \cos\left(h' \frac{\pi}{180} + 2\right) + 2.8 \right]$$

$$e = \left( \frac{50000}{13} N_c N_{cb} \right) e_t \qquad (2\text{-}21)$$

$$H = H_i + i \frac{100[(h' - h_i) / e_i]}{\left[ (h' - h_i) / e_{i+1}(e_i + (h_{i+1} - h')) \right]} \qquad (2\text{-}22)$$

Table 2.3 Data to convert hue angles to hue quadrature, *H*

| | Red | Yellow | Green | Blue | Red |
|---|---|---|---|---|---|
| $i$ | 1 | 2 | 3 | 4 | 5 |
| $h_i$ | 20.14 | 90.00 | 164.25 | 237.53 | 380.14 |
| $e_i$ | 0.8 | 0.7 | 1.0 | 1.2 | 0.8 |
| $H_i$ | 0 | 100 | 200 | 300 | 400 |

Step 9: Calculate the achromatic signal of the stimulus under the reference viewing conditions and the reference white under the test viewing conditions.

$$A = [2R'_a + G'_a + B'_a/20 - 0.305]N_{bb}$$
$$A_w = [2R'_{aw} + G'_{aw} + B'_{aw}/20 - 0.305]N_{bb} \qquad (2\text{-}23)$$

Step 10: Calculate correlates of lightness (*J*), brightness (*Q*), chroma (*C*), colourfulness (*M*) and saturation (*s*).

$$J = 100(A/A_w)^{cz}, \text{ where } z = 1.48 + n^{0.5} \qquad (2\text{-}24)$$

$$Q = (4.0/c)(J/100)^{0.5}(A_w + 4.0)F_L^{0.25} \qquad (2\text{-}25)$$

$$t = \frac{e(a^2 + b^2)^{1/2}}{R'_a + G'_a + (21/20)B'_a} \qquad (2\text{-}26)$$

$$C = t^{0.9}(J/100)^{0.5}(1.64 - 0.29^n)^{0.73} \qquad (2\text{-}27)$$

$$M = CF_L^{0.25} \qquad (2\text{-}28)$$

$$s = 100(M/Q)^{0.5} \qquad (2\text{-}29)$$

#### 2.3.4.3 Inverse Model

Rstep 1:

If starting from Q, then J can be computed from

$$J = 6.25\left[\frac{cQ}{(A_w + 4)F_L^{0.25}}\right]^2 \qquad (2\text{-}30)$$

If starting from M, then C can be computed from

$$C = M / F_L^{0.25} \tag{2-31}$$

If starting from s, then C can be computed from

$$Q = (4.0/c)(J/100)^{0.5}(A_w + 4.0)F_L^{0.25}$$
$$C = (s/100)^2 Q / F_L^{0.25} \tag{2-32}$$

If starting from H or h,

$$h' = \frac{(H - H_i)(e_{i+1}h_i - e_i h_{i+1}) - 100 h_i e_{i+1}}{(H - H_i)(e_{i+1} - e_i) - 100 e_{i+1}} \tag{2-33}$$

Set $h = \begin{cases} h' - 360 \text{ if } h' > 360 \\ h' \quad \text{otherwise} \end{cases}$.

Rstep 2:

$$t = \left[ \frac{C}{\sqrt{J/100}(1.64 - 0.29^n)^{0.73}} \right]^{1/0.9} \tag{2-34}$$

$$e_t = \left[ \frac{\cos\left(h\frac{\pi}{180} + 2\right) + 1}{4} + 0.7 \right] = \frac{1}{4}\left[ \cos\left(h\frac{\pi}{180} + 2\right) + 2.8 \right] \tag{2-35}$$

$$e = \left( \frac{50000}{13} N_c N_{cb} \right) e_t \tag{2-36}$$

$$A = A_w (J/100)^{1/cz}$$
$$p_1 = e/t, \quad \text{if } t \neq 0$$
$$p_2 = (A/N_{bb}) + 0.305 \tag{2-37}$$
$$p_3 = 21/20$$

Rstep 3:

If $t = 0$, then $a = b = 0$ and go through to Rstep 4.

If $|\sin(h)| \geq |\cos(h)|$, then

$$p_4 = p_1 / \sin(h)$$

$$b = \frac{p_2(2 + p_3)(460/1403)}{p_4 + (2 + p_3)(220/1403)[\cos(h)/\sin(h)] - (27/1403) + p_3(6300/1403)} \tag{2-38}$$
$$a = b[\cos(h)/\sin(h)]$$

If $|\sin(h)| < |\cos(h)|$, then

$$
\begin{aligned}
p_5 &= p_1/\cos(h) \\
a &= \frac{p_2(2+p_3)(460/1403)}{p_5 + (2+p_3)(220/1403) - [(27/1403) + p_3(6300/1403)][\cos(h)/\sin(h)]} \\
b &= a[\sin(h)/\cos(h)]
\end{aligned}
\qquad (2\text{-}39)
$$

Rstep 4:

$$
\begin{pmatrix} R'_a \\ G'_a \\ B'_a \end{pmatrix} = \frac{1}{1403}\begin{pmatrix} 460 & 451 & 288 \\ 460 & -891 & -261 \\ 460 & -220 & -6300 \end{pmatrix}\begin{pmatrix} p_2 \\ a \\ b \end{pmatrix} \qquad (2\text{-}40)
$$

Rstep 5:

$$
\begin{aligned}
R' &= sign(R'_a - 0.1)\frac{100}{F_L}\left[\frac{27.13|R'_a - 0.1|}{400 - |R'_a - 0.1|}\right]^{1/0.42} \\
G' &= sign(G'_a - 0.1)\frac{100}{F_L}\left[\frac{27.13|G'_a - 0.1|}{400 - |G'_a - 0.1|}\right]^{1/0.42} \\
B' &= sign(B'_a - 0.1)\frac{100}{F_L}\left[\frac{27.13|B'_a - 0.1|}{400 - |B'_a - 0.1|}\right]^{1/0.42}
\end{aligned}
\qquad (2\text{-}41)
$$

$$
where\ sign(x) = \begin{cases} 1 & \text{if } x > 0 \\ 0 & \text{if } x = 0 \\ -1 & \text{if } x < 0 \end{cases}
$$

Rstep 6:

$$
\begin{pmatrix} R_c \\ G_c \\ B_c \end{pmatrix} = M_{CAT02}M_{HPE}^{-1}\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} \qquad (2\text{-}42)
$$

$$
where\ M^{-1}{}_{HPE} = \begin{pmatrix} 1.910197 & -1.112124 & 0.201908 \\ 0.370950 & 0.629054 & -0.000008 \\ 0.00000 & 0.00000 & 1.00000 \end{pmatrix}
$$

Rstep 7:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} R_c / D_R \\ G_c / D_G \\ B_c / D_B \end{pmatrix}, \text{where} \quad \begin{aligned} D_R &= \frac{Y_w D}{R_w} + 1 - D \\ D_G &= \frac{Y_w D}{G_w} + 1 - D \\ D_B &= \frac{Y_w D}{B_w} + 1 - D \end{aligned} \tag{2-43}$$

Rstep 8:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = M_{CAT02}^{-1} \begin{pmatrix} R \\ G \\ B \end{pmatrix} \tag{2-44}$$

### 2.3.4.4 Uniform Colour Spaces based on CIECAM02

The CIE colorimetry system described in Section 2.2 and the colour-appearance model described in Section 2.3 have the same purposes in their usage: the specification of colours, the evaluation of colour difference and the measurement of colour-appearance under various viewing conditions. To establish a colour-appearance model which satisfies all the three of these purposes, efforts to extend CIECAM02 to include the available colour difference data sets have been made (Li, 2003; Luo, 2006). The data sets comprise those for large-magnitude colour differences (LCD) and those for small-magnitude colour differences (SCD).

Three different colour spaces can be constructed by the combination of the attributes obtained from CIECAM02: lightness *J*, hue angle *h* and three correlates of chromatic content (chroma *C*, colourfulness *M* and saturation *s*).

a) $J$, $a_c$ and $b_c$

b) $J$, $a_M$ and $b_M$

c) $J$, $a_s$ and $b_s$

Among these three colour spaces, that derived using $J$, $a_M$ and $b_M$ was found to give the minimum and uniform error between the experimental and predicted colour difference for both the LCD and SCD data sets (Li, 2003). Therefore, *J* and *M* in CIECAM02 have been modified in order to give the best prediction of colour difference values for experimental results for all data sets available. The modified *J* and *M* are labelled as $J'$ and $M'$ in following equations.

$$J' = \frac{(1+100c_1)J}{1+c_1 J}$$

$$M' = (1/c_2)Ln(1+c_2 M) \quad (2\text{-}45)$$

$$\Delta E' = \sqrt{(\Delta J'/K_L)^2 + \Delta a'^2 + \Delta b'^2}$$

where $c_1$ and $c_2$ are constants and $K_L$ is a lightness parameter as given in Table 2.4.

Table 2.4 The three sets of coefficients for the three corresponding colour spaces.

| | CAM02-LCD | CAM02-SCD | CAM02-UCS |
|---|---|---|---|
| $K_L$, | 0.77 | 1.24 | 1.00 |
| $c_1$ | 0.007 | 0.007 | 0.007 |
| $c_2$ | 0.0053 | 0.0363 | 0.0228 |

A set of optimised values for $c_1$, $c_2$ and $K_L$ were determined for the three data sets: LCD, SCD and a combined set of LCD and SCD. The corresponding three colour spaces were constructed using these parameters for $J'$, $M'$ and $K_L$, and were named CAM02-LCD, CAM02-SCD and CAM02-UCS respectively.

The colour-difference formula in CAM02-UCS space showed good performance for predicting the LCD and SCD data, however it showed slightly worse performance than CAM02-LCD formula in predicting LCD data and CAM02-SCD formula in predicting SCD data. Therefore, the colour-difference formula in CAM02-UCS was suggested for use in applications involving small and large colour differences such as colour reproduction in the graphic arts industry and in evaluating colour differences under diverse viewing conditions by Luo (Luo, 2006).

## 2.4 Emotion

Emotions are complex phenomena as an essential part of our lives, relating to how we feel, how we behave and how we think. Emotions typically occur with subjective feelings, physiological changes, behavioural expressions and cognitions. Due to their multi-faceted nature, emotions have been studied in a number of different frameworks which have focused on one of the different components among those, however all of them present components comprising emotional experiences. Generally, emotions refer to the interaction between a person's internal and external world. For example, in the present study interactions between people and objects are the focus rather than those between people and people, or people to events/situations. Thus, the aim of this section is to investigate the theoretical background of relationship between emotion and the visual appearance of an image.

### 2.4.1 Theoretical Frameworks of Emotion Study

As mentioned above, emotional experiences accompany several components such as behaviour, thoughts, subjective feelings and bodily changes. In the study of emotions, different approaches to research have tended to focus on different component of emotion among these. Thus in contemporary studies on emotion, there are four general frameworks, that is evolutionary based on *Darwin's natural selection theory*, physiological based on the *James-Lange theory*, the cognitive and the social constructs (Cornelius, 1996; Fox, 2008). In this section, general ideas in the traditions are introduced.

One of the traditions of emotion is based on Darwin's theory of evolution and assumes that emotions are biologically given. He (Darwin, 1872) proposed that the evolution theory by *natural selection* applies not only to anatomic systems but also to the mind and the expressive behaviour of animals. It concluded that emotions are *adaptive* and help to communicate and to survive in the natural environment by organising an animal's behaviour. Darwin showed that many of emotional expressions were innate, not acquired by learning. His view has influenced many of the other theories in the research of emotion. Ekman's basic emotion theory has been proposed from this point of view. Ekman (1992) found that the facial expressions for six basic emotions are recognised similarly across cultures and languages through a set of experiment conducted in preliterate society in New Guinea and US. He named these six emotions "basic emotions" and these were "joy", distress", "anger", "fear", "surprise" and "disgust". He concluded that these basic emotions are universal and innate regardless of culture and language.

In this view, it is believed that emotional systems have evolved to help animals, including humans, adapt to the complex physical and social environments. The function of emotions is to initiate the immediate cooperation of the various processes of the body such as motor systems, physiological reactions and cognitive processes in order to deal with an urgent problem.

In addition to the evolutionary framework, there is a physiological framework proposed by James and Lange, called *James-Lange Theory* which assumes that emotions are the results of the perception of bodily changes. James and Lange (James, 1884; Lange , 1885 ) proposed that once people notice an event, then physiological reactions (called bodily changes) to an event occur, and the perception of these bodily changes is the emotion. These bodily changes are mostly related to the feedback from the *autonomic nervous system* (ANS), such as heart rate, muscle tension and blood pressure. This point of view on emotions was direct opposition to the commonsense viewpoint which considered that subjective feeling was the cause of the bodily changes.

In addition to the original James-Lange theory, Damasio (1999) proposed that the perception of various bodily changes can be the cause of emotional experience. He identified that these included biochemical and hormonal indicators of the body's internal state can be detected by specific parts of the brain. However, he argued that these changes in internal bodily state which can be detected by the brain are not necessarily accompanied by conscious awareness. This is quite different from the view of the original James-Lange theory in which emotions were regarded as conscious feeling states. A summary of this point of view is that emotions are fundamentally caused by a perception of changes in our internal bodily state.

Another tradition is the assumption that emotions are the results of cognitive appraisals. Cognition refers to internal mental states of the mind such as beliefs, desires and intentions which are the results of information processing coming through the senses. Arnold and Gasson (1954) proposed that emotion is "a felt tendency toward an object judged suitable and away from an object judged unsuitable, reinforced by specific bodily changes according to the type of emotion". The key idea in this view is that the judgement of the object determines the type of emotions and the bodily changes which are elicited. This judgement causing emotions links two sides: the object (event) and the person experiencing the object (event). Arnold called this judgement an *appraisal* and she also claimed that without appraisal there is no emotion as all emotions are initiated by a person's appraisal of the event which is experienced (Arnold 1960). She referred to appraisals as "direct, immediate, non-reflective, non-intellectual and automatic" judgements about the meaning of events. In this point of view, the key aspect is how to interpret the events rather than how the event itself influences the emotion which is elicited. Thus, the primary function of emotions in this view is to adjust the cognitive process to promote the priorities of a given emotion.

For the tradition of social constructs, it is assumed that emotions are socially constructed. Averill proposed that emotions are social constructions and can be understood only on a social level of analysis rather than as biological phenomena (Averill, 1980). From this point of view, emotions are acquired by learning when people are exposed to members within a given culture, and the function of emotion is to provide people with management ability according to demands of social roles in their culture (Averill, 1985). This is a very different approach from the other perspectives which gives much more meaning and significance to the social interaction between people.

## 2.4.2 Structural Models of Emotion

Many psychologists have accumulated knowledge of the structure of emotion and a number of structural models of emotion have been developed, which were mainly intended to represent similarities and/or dissimilarities between various emotions in a multi-dimensional framework. These models provide simple and systematic approaches to human emotions to be investigated related to the impact of colour in images. Therefore, some of the important models of emotion are reviewed in this section.

Russell (1980) suggested a two-dimensional model of emotion using a multi-dimensional scaling method, in which 28 emotion words were investigated: happy, delighted, excited, astonished, aroused, tense, alarmed, angry, afraid, annoyed, distressed, frustrated, miserable, sad, gloomy, depressed, bored, droopy, tired, sleepy, calm, relaxed, satisfied, at ease, content, serene, glad and pleased. The results showed that these terms were classified into two groups along with the two dimensions, which were "pleasure-displeasure" and "arousal-sleepiness", or just simply "*pleasure*" and "*arousal*". Figure 2.12 shows the two-dimensional structure of this model. The four quadrants resulted in by these two axes, the emotion concepts excitement, depression, distress and relaxation can be defined as combinations of the two dimensions "pleasure" and "arousal". For instance, "distress" can be defined as the combination of "low pleasure" and "high arousal" and "depression" as the combination of "low pleasure" and "low arousal". This implies that most emotions share these two primaries "pleasure" and "arousal".

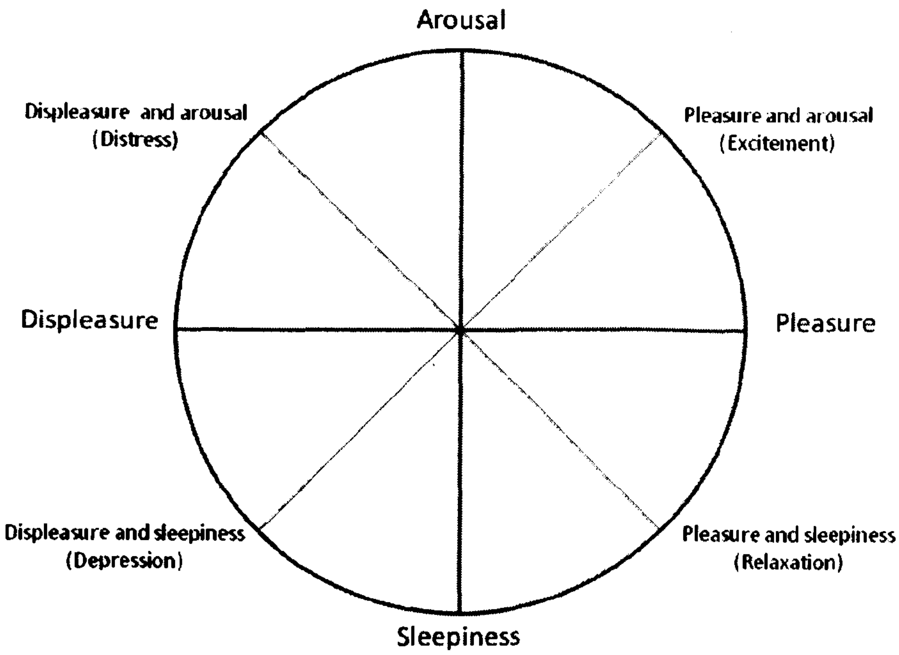



Figure 2.12 Two-dimensional emotion model proposed by Russell (1980) in which the dimensions are labelled "pleasure" and "arousal".

Watson and Tellegen (1985) also suggested a two-dimensional model of emotion from the results of several studies of the classification of emotion words. They claimed that "*positive*" and "*negative*" affects are the primary descriptors of emotional states rather than "pleasure" and "arousal". The "positive" factor represents "the extent to which a person avows a zest for life" and "negative" represents "the extent to which a person reports feeling upset or unpleasantly aroused." They emphasised that only the high end of each factor represents a state of emotion, whereas the low end of each dimension represents an *absence* of the emotional involvement. Figure 2.13 shows a two-dimensional emotion structure consisting of two axes: "positive" and negative" and four quadrants as combinations of two dimensions. Although this model based on two primary dimensions has a similar structure to Russell's model as pointed out by Watson and Tellegen themselves, they believed that their model is specifically useful for clinics as a way of describing and understanding psychopathology, especially in distinguishing anxiety from depression.

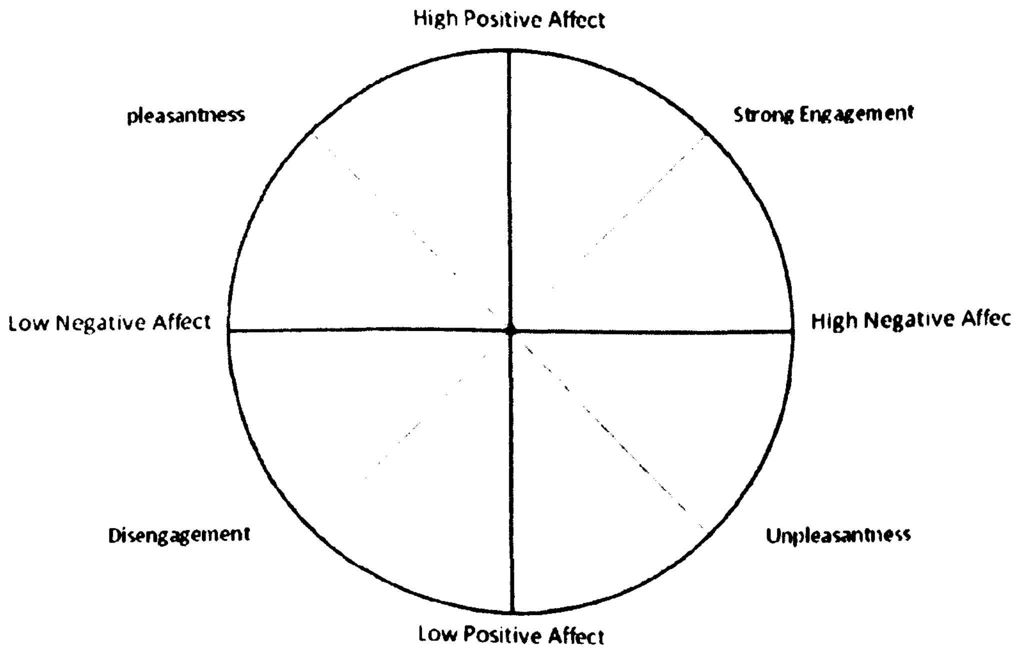



Figure 2.13 Two-dimensional model proposed by Watson and Tellegen (1985) in which the two dimensions are labelled as "positive" and "negative" affects.

Plutchik (2002) developed a three-dimensional model of emotion based on the eight primary emotions: fear, anger, sadness, joy, acceptance, disgust, anticipation and surprise identified in his study (Plutchik, 1980). He identified three characteristics of emotions as follows:

1) Emotions vary in intensity,

2) Emotions vary in their degree of similarity to one another and

3) Emotions express opposite bipolar feelings or actions.

Figure 2.14 shows the structure of this model with the vertical dimension representing for characteristics of intensity. The words adjacent each other in a circular plane in Figure 2.14 represent the similarity of the emotion. Bipolarity is represented by words located at the opposite point in a circular plane. Eight groups of emotions are from the eight primary emotions identified earlier in his study (Plutchik, 1980). He believed that the emotional state can be represented by the combination of several primary emotions, for example "joy" and "acceptance" could produce the mixed emotion of "love".

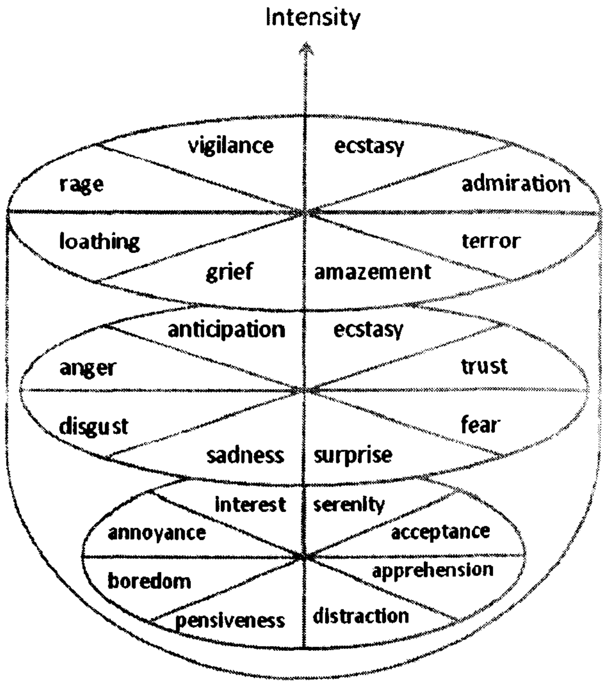



Figure 2.14 A three-dimensional model including eight primary emotions arranged as proposed by Plutchik (2002)

### 2.4.3 Measuring Emotion

As an emotional experience involves several components such as subjective feelings, physiological changes and behavioural expressions; measuring emotion can be performed by determining these correlates. In the present study, two different methods of measuring emotions were used: psychophysical methods for measuring the description of subjective feelings and the measurement of physiological changes. As general references for psychophysical methods, Fairchild's *Color Appearance Models* (Fairchild, 2005) and Engeldrum's *Psychometric Scaling* (Engeldrum, 2002) were used. For psycho-physiological methods, Fox's *Emotional Science* (Fox, 2008) and Stern's *Psychophysiologial Recording* (Stern, 2001) were used.

#### 2.4.3.1 Psychophysical methods

Psychophysics is defined as *a method to study the relationship between the physical measurements of stimuli and the sensation and perceptions that the stimuli evoke* (Fairchild 2005). Psychophysical experiments can be divided into two broad classes: threshold (or matching) experiments to measure visual sensitivity to small changes in stimuli and scaling experiments to investigate a relationship between the physical and perceptual magnitude of a stimulus (Fairchild 2005).

Stevens (1961) classified four types of measurement scales: nominal, ordinal, interval and ratio scales. A nominal scale introduces names or numbers to distinguish between stimuli. For example, the hue scale, red, yellow, and so on can be replaced by numbers corresponding to each hue category. However, those number are just labels and do not have any numerical properties. An ordinal scale is one in which stimuli are ranked in ascending or descending order regarding a particular attribute. However, it includes no distance information in between stimuli along the scale. Simple logical operations such as magnitude comparison can only be applied to an ordinal scale. For interval scale, the scale defines the difference between the amount of property measured by intervals between scale values. In this case, equal distances anywhere along the scale indicate the same difference in the property measured. In addition to the comparison of magnitude, simple arithmetic operations such as addition or subtraction can be performed on interval scales. A ratio scale is an interval scale which has a meaningful zero, representing no amount measured for the property.

One of the psychophysical scaling methods extensively used in the field of colour science is categorical judgment which measures the sensation magnitude on interval scales.

Categorical judgment is a method assigning test stimuli into pre-defined categories corresponding to the perceptual magnitude of the property. This method is particularly useful when the number of samples is large. The categories are defined assuming an equal interval between them and can be specified by numbers or text descriptions. The data collected from this method is an ordinal scale. Experimental data can be analysed using the mean category value method (Bartleson, 1984) or transferred onto an interval scale using *the Law of Categorical Judgement* (Torgerson, 1954). Torgerson's Law of Categorical Judgement states that the difference between a category boundary and the scale value of a stimulus is a random variable whose probability density function forms a normal distribution. The mean value of this distribution represents the difference between the category boundary and the stimulus scale value. This is expressed in Equation (2-46).

$$T_k - S_j = z_{jk}\sqrt{\sigma_j^2 + \sigma_k^2 - 2r_{jk}\sigma_j\sigma_k} \qquad (2\text{-}46)$$

where $T_k$ is the mean location of the $k$th category boundary; $S_j$ is the mean response to stimulus $j$; $\sigma_k$ is the discriminal dispersion of the $k$th category boundary; $\sigma_j$ is the discriminal dispersion of stimulus $j$; $r_{jk}$ is the coefficient of correlation between momentary positions of stimulus $j$ and category boundary $k$ on the scale; $z_{jk}$ is the normal deviate corresponding to the proportion of frequencies that stimulus $j$ is placed below boundary $k$.

In Condition D of Torgerson's Law of Categorical Judgement, all stimuli are assumed to have the same standard deviation among observations, i.e. $\sigma_j = \sigma_k = \sigma$, and that stimulus scale values are independent of category boundaries, i.e. $r_{jk} = 0$. Accordingly the value $T_k - S_j$ has a standard deviation of $\sigma\sqrt{2}$, which is a constant. Thus Equation 2-46 can be simplified to:

$$T_k - S_j = z_{jk}\sigma\sqrt{2} \tag{2-47}$$

where $\sigma$ is the common standard deviation for each stimulus and each category boundary.

### 2.4.3.2 Psycho-physiological Methods

Emotion also involves a range of physiological reactions such as increased heart rate and sweating in the hand when feelings of fear and anxiety are elicited. There are also less apparent reactions: internal changes such as various hormones may be released into the blood during the emotional experiences. These physiological changes are controlled by the autonomic nervous system (ANS), which is a complex network of fibres that extends throughout the body and transmits signals to the various organs over the body, muscles and glands. The ANS is involved with regulating the functioning of the body's internal environment through two main sections of the ANS: *the sympathetic ANS* controlling the effects related to arousal and *the parasympathetic ANS* controlling the effects which occur when we are resting. In this section, some of physiological measures of emotional reactions are described.

Facial electromyography (EMG) activity can provide subtle changes in facial muscle activity, as reactions to motivationally significant events. The activity of the muscles associated with frowning (*corrugator supercilii*) and smiling (*zygomatic*) have been used as measures of affective engagement in perception, imagery and anticipation.

The *corrugator supercilii* muscles, located above the eyebrows and between the eyes, are responsible for lowering and contraction of the brows. According to Ekman (1983), the muscle movements in this area are related to distress. According to Lang *et al.* (1993), significant contraction of the corrugator muscles tend to occur when viewing unpleasant pictures. Bradley *et al.* (Bradley, 2001) found that the corrugator muscle activity varied with the content of the stimulus pictures. They found that some unpleasant pictures, such as those depicting mutilation and contamination, elicited slightly larger EMG activity than other unpleasant stimuli. In this study, the smallest response from corrugators EMG was obtained for pleasant pictures such as of babies and families. These pictures tended to be rated quite high in the pleasure scale, but relatively low in the arousal scale. However, they found that the most arousing pleasant subjects, such as erotica and sports, did not prompt significant activity from the baseline.

The *zygomatic muscles* are located from the cheek bone to near to the corner of the mouth. These muscle lift the corner of the mouth obliquely upwards and laterally to produce a smiling expression. This is important for the smile response and is related to happiness. Lang *et al.* (Lang, 1993; 1995) found that there is a strong positive correlation between activity in the zygomatic muscles and ratings of pleasure. In other words, activity in zygomatic muscle EMG increases as the ratings for pleasantness increases.

Skin conductance can be measured by applying a small electric current across the fingers to measure the resistance of the skin. The electrodermal activity (EDA) is closely related to eccrine sweat glands. Eccrine sweat glands are concentrated in the palms of the hands and soles of the feet, responding primarily to a mentally arousing stimulus, whereas other sweat glands respond mainly to increases in temperature (Stern, 2001).

Bradley *et al.* (2001) and Codispoti *et al.* (2007) found that images with arousing subjects such as erotica, threat or mutilation tended to prompt a large increase in skin conductance. Miler *et al.* (Miller, 2002) also found that physiological responses were enlarged when personally relevant scenes were involved in the imagination. Their results showed that skin conductance increased when people imagined pleasant or unpleasant events, compared to neutral images. Their results also showed that skin conductance, facial EMG with zygomatic muscle and heart rate responses evoke greater activities for personal than standard stimuli; however, no difference was found in corrugator EMG between personal and standard stimuli. They also found some differences in responses of subjective feelings which indicated that imagery of personal experiences were more arousing, vivid and interesting than standard imagery. Sabatinelli and Bradley (Sabatinelli, 2001; Bradley, 2005) reported that the anticipation of presenting a highly pleasant or unpleasant stimulus can also prompt large skin conductance changes.

Changes in heart rate are known to provide a good measure of changes in arousal. Early investigations exploring emotion in perception used heart rate as a function of differences in the level of pleasure, as this measure was considered critical in eliciting orienting or defence responses (Epstein, 1971; Turpin, 1983). It was consistently found that the heart rate decelerated when people viewed pictures of unpleasant events (Klorman, 1977; Hare 1971).

Lang *et al.*(1993) found that pictures rated as unpleasant typically generated bigger initial deceleration than pleasant or neutral pictures. Bradley *et al.* (Bradley, 2001) found that significant initial deceleration appeared for all kinds of unpleasant subjects, including both highly-arousing pictures (e.g. threat, mutilation) and relatively low arousing pictures (e.g. pollution and loss). They also found that highly-arousing pleasant pictures (e.g. erotica) generated significantly bigger initial deceleration than pleasant pictures which were rated lower in arousal. In other perceptual contexts such as video and sound, decelerative differences in cardiac responses between unpleasant arousing contents and neutral ones were also found by Palomba (2000) and Bradley *et al.* (2000), respectively.

It is known, however, that there are a number of difficulties in using heart rate as a measure of emotional state (Fox, 2008). Several physical factors such as posture, height and weight, and on individual's fitness level are known to have a significant influence on heart rate as well as the degree of variability in heart rate. Lang *et al.* (Lang 1990) found that heart rate also varies with different mental processes. They noted that heart rate tends to decelerate when external stimuli are given, it tends to accelerate when attempting to recall a memory.

Table 2.5 Factor loadings of dependent measures of emotional responses (Lang, 2000).

| | Lang *et al.* | | Cuthbert *et al.* | |
|---|---|---|---|---|
| Measure | Valence | Arousal | Valence | Arousal |
| Valence ratings | 0.86 | 0.00 | 0.89 | 0.07 |
| Corrugator EMG | -0.85 | 0.19 | -0.83 | -0.10 |
| Heart rate | 0.79 | -0.14 | 0.73 | -0.02 |
| Zygomatic EMG | 0.58 | 0.29 | - | - |
| Arousal ratings | 0.15 | 0.83 | -0.01 | 0.89 |
| Interest ratings | 0.45 | 0.77 | - | - |
| Viewing time | -0.27 | 0.76 | - | - |
| Skin conductance | -0.37 | 0.74 | 0.19 | 0.77 |

Table 2.5 summarises two main factors: valence and arousal extracted from a set of variables, including subjective and physiological responses to affective images in two studies by Lang *et al.* (Lang, 1993) and Curthbert *et al.* (1998). It

shows that valence has high loadings for pleasantness ratings, changes in heart rate and facial EMG. It also shows that arousal has high loadings for arousal ratings, skin conductance activity and overall viewing time. It should be noted that the cross-loading between factors is low, indicating that the two factors are significantly different.

### 2.4.4 Emotion Models Related to Visual Experience

Cupchik (1994) has proposed a model of emotion for aesthetic stimuli involving two levels of emotional response: *reactive* and *reflective*. The two levels of processing are associated with James's primary layer of emotion referring to subtle feelings such as pleasure and arousal and a secondary layer of emotion referring to coarse emotions such as happiness and sadness to aesthetic stimuli, respectively.

The reactive level represents the emotional response to the "configurations of features" in visual stimuli contributing to local visual effects of the aesthetic stimulus. The emotional responses are *bodily feelings* of pleasure and excitement or arousal. The reflective level represents the contribution of emotional responses to the "contextual meanings" in multilevel arts including syntactic and semantic information. The contextual meanings can generate global relations among aesthetic stimuli in the artwork. He suggested that the emotional experiences in the past may influence how viewers understand the meanings of aesthetic features in the artwork.

Ou *et al.* (2004a) extended the emotion model for a visual experience based on Cupchik's model of aesthetics. He assumed that Cupchik's theory can also apply to general visual experience. Thus, he proposed that emotional responses at the reactive level are determined directly by visual stimuli including the appearance of the object and its surroundings. Emotional responses at the reflective level result from a cognitive process the visual stimuli. This cognitive process interprets the visual stimuli into contextual meanings according to the appearance of the object and the context of the entire visual experience.

Norman (2004) has proposed three levels of interaction between people and products in product experience: visceral, behavioural and reflective. The visceral level makes initial judgements of what is good or bad, safe or dangerous, and sends appropriate signals to the motor system of the body and alerts the rest of the brain. This level of interaction is related to sensory stimuli such as visual appearance, touching and feeling as a start of affective processing followed by immediate emotional impact from conscious experience. The behavioural level is related to usability and performance. This level of interaction is not conscious, however it is influenced by the reflective level which involves conscious information, such as knowledge, memory and related experience. In other words, the behavioural level is influenced by the visceral and the reflective levels of interaction. The reflective level is placed at the highest level in the interaction process. This level depends on many factors in the various interactions among people, events, time and place rather than only between people and objects. This is also affected by knowledge, memory, experience, learning and social community. Norman suggested that the overall impression of the object is determined by the reflective level of interaction overriding the other two levels.

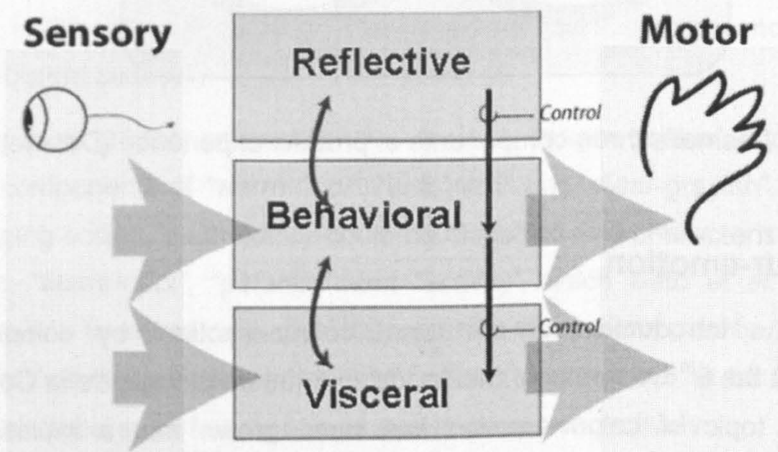



Figure 2.15 Norman's three levels of processing: Visceral, Behavioural and Reflective (Norman, 2004)

Desmet (2002; 2007) has proposed that product experience is a multi-faceted phenomenon that involves symptoms such as subjective feelings, behavioural reactions, expressive reactions and physiological reactions just like an emotional experience. He defined "product experience" as a change in core affect that is involved to human-product interaction". The core affect is a concept introduced by Russell (2003) in which the affect dimension was combined with physiological arousal into a circular two-dimensional model. Based on this definition, Desmet distinguished the three components of product experience as aesthetic pleasure, attribution of meaning and emotional response. The underlying process in product experience is that the entire set of affects is elicited by the interaction between user and a product. It includes the degree to which all our senses are gratified (aesthetic experience), the meanings we attach to the product (experience of meaning) and the feelings and emotions that are elicited (emotional experience). He emphasised that the hierarchical relationships between the emotional component and the other two are particularly important.

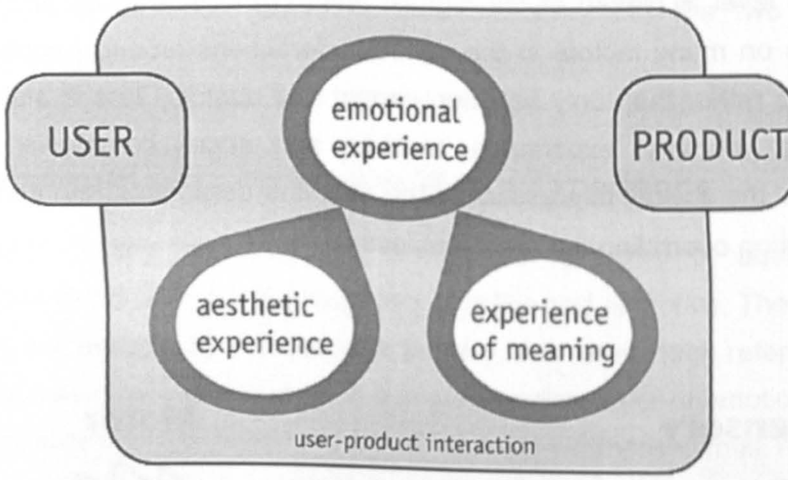



Figure 2.16 Desmet's three components of product experience (Desmet, 2007).

### 2.4.5 Colour-emotion

Since the introduction of the term "colour-emotion" by colour science researchers at the 8th Congress of the Association Internationale de la Coleur (AIC) in 1997, the topic of colour-emotion has been grown into a multidisciplinary research area focusing on the relationship between colour and emotions. In earlier studies, colour-emotion was referred as "colour meaning" (Osgood, 1957; Wright, 1962; Adams, 1973) and "colour image" (Kobayashi, 1981). The most *widely-used* definition is that colour-emotion is evoked by colours and that it can be expressed through words (Nobbs, 1997, Sato, 2001, Xin, 2000). Ou *et al.*(Ou, 2004a) used a more specific definition: *"Colour-emotion is the relationship between colour stimuli and the reactive-level of emotional responses which are determined by the configurations of colour stimuli in an entire visual experience"*. In this definition, the role of colour in the whole visual experience as the configurations of colour stimuli was pointed out. He investigated a number of word pairs to describe feelings from the configurations of colours such as "warm-cool" and "active-passive".

#### 2.4.5.1 Colour-emotion Scales

Most of the colour-emotion studies used pairs of adjective words (such as "warm-cool") as colour-emotion scales. Rating on semantic differential scales (Osgood, 1957) and accepting the factor analysis methods devised by Spearman (1904) are widely-used methods in colour-emotion studies.

Wright and Rainwater (1962) identified six principal component categories: happiness, showiness, forcefulness, warmth, elegance and calmness for 48 colour-emotion scales. They found some links between these components and the colour-appearance attributes hue, lightness and chroma. They also found that lightness and chroma showed larger influence on colour-emotion than hue.

Hogg (1969) identified four components -"impact", "usualness", "evaluation" and "warmth"- from 12 colour-emotion scales. The results showed that the "evaluation" component was closely related to "pleasant-unpleasant". "Impact" and "warmth" were related to chroma and hue, respectively.

Adams and Osgood (Adams, 1973) identified three universal components of "evaluation", "potency" and "activity" on colour-emotion from a set of experiments conducted in 23 different cultures. They reported that little difference was found between different cultures.

Kobayashi (1981) presented the "colour image scales" including three emotional components of "warm-cool", "soft-hard" and "clear-greyish". By using the colour imaging scales, each colour could be classified and characterised. The three component: "warm-cool", "potency" and "activity" which Sato *et al.* (Sato 2000) identified seem to agree with the Kobayashi's three components. Sato *et al.*'s components "warm-cool", "potency" and "activity" were found to be related to the three colour attributes of hue, lightness and chroma, respectively.

Ou *et al.* (2004a) have also identified three components of colour-emotion - "activity", "weight" and "heat"- in relation to chroma, lightness and hue, respectively.

Crozier (1996) suggested a reason for some common scales identified in many studies. That is, the colour-emotion scales used in these studies have been selected based on the three primary factors of semantic terms proposed by Osgood *et al.* (1957): "evaluative", "potency" and "activity".

### 2.4.5.2 Quantitative Models of Colour-emotion

In this section, quantitative models of colour-emotion for a single colour developed by Sato *et al.* (2000), Xin and Cheng (2000) and Ou *et al.* (2004a) are reviewed and presented in Table 2.6. The aim of these studies was focused on the development of quantitative equations to predict colour-emotion scale values using colour-appearance attributes such as lightness, chroma and hue. All of these models are based on the CIELAB colour space (see Section 2.2.5).

Sato proposed a set of colour-emotion models (Sato, 2000) to predict colour-emotion scale values for each scale (such as *warm-cool, heavy-light* and *weak-*

*strong)* with an assumption that there is always a colour which is warmest, heaviest and weakest. The idea to express colour-emotion numerically is that two colours having a large difference in colour-emotion also show a large colour difference from the most extreme colour (i.e. the warmest, heaviest and weakest colours). The equation proposed is shown in Equation (2-48):

$$CE = k_M + \sqrt{[k_L(L^* - L^*_0)]^2 + [k_A(a^* - a^*_0)]^2 + [k_B(b^* - b^*_0)]^2} \quad (2\text{-}48)$$

where $CE$ is the predicted value of colour-emotion for a test colour; $L^*$, $a^*$ and $b^*$ are the CIELAB coordinates of the test colour; $L_0^*$, $a_0^*$ and $b_0^*$ are the CIELAB coordinates of the reference colour; and $k_L$, $k_a$, $k_b$ and $k_M$ are constants. Equation (2-48) also can be converted to a form comprising two colour-appearance attributes: lightness and chroma as shown in Equation (2-49):

$$CE = k_M + \sqrt{[k_L(L^* - L^*_0)]^2 + [k_C(C^* - C^*_0)]^2} \quad (2\text{-}49)$$

where $L^*$ and $C^*$ are the CIELAB lightness and chroma for the test colour; $L_0^*$ and $C_0^*$ are the CIELAB lightness and chroma for the reference colour; and $k_L$, $k_C$ and $k_M$ are constants.

In order to consider the contribution of hue difference, Sato *et al.* added a hue-related variable, $(1-|h-h_0|/360°)$ into $C^*$, where $h$ and $h_0$ are the CIELAB hue angles of the test and the reference colours respect ively. Based on this idea, colour-emotion formulae were developed for 12 scales including "active-passive", "heavy-light" and "warm-cool". These are given in Table 2.6.

Xin and Cheng (Xin, 2000) also developed quantitative colour-emotion models using a multiple regression method assuming that the $L^*$, $C^*$ and $h$ colour-appearance attributes in CIELAB space were independent of each other. The formulae had following form:

$$CE = x_1 L^* + y_1 (C^*)^a + z_1 h + c_1 \quad (2\text{-}50)$$

where $CE$ is the predicted value of colour-emotion; $L^*$, $C^*$ and $h$ are CIELAB lightness, chroma and hue angle; $a$ is the exponents of chroma; $x_1$, $y_1$, $z_1$ and $c_1$ are constants. In their models, the entire range of hue angles was divided into two: 0° to 180° and 180° to 360° and equations for each range were proposed. Based on this form of equation, they developed colour-emotion models for 12 scales including "active-passive", "heavy-light" and "warm-cool" which are shown in Table 2.6.

Ou *et al.* (2004a) proposed a set of colour-emotion models for single colours. The main method used for model development was observing bubble charts which were useful to see not only the tendency between colour-emotion values and colour-appearance attributes in CIELAB space but also the relationship between any two attributes. Using these methods, they developed colour-emotion models for four colour-emotion scales, including "active-passive", "heavy-light" and "warm-cool", which are given in Table 2.6.

Table 2.6 Quantitative models of colour-emotion for single colour developed by Sato *et al.* (2000), Xin and Cheng (2000) and Ou *et al.* (2004a) in CIELAB space.

| Researcher | Colour-emotion | Models |
|---|---|---|
| Sato | Warm-cool | $WC = 3.5[cos(h - 50°) + 1]B - 80$ |
| | Heavy-light | $HL = -3.5L^* + 190$ |
| | Active-passive | $AP = \left\{[0.6(L^* - 50)]^2 + (4.6(1 - \frac{\Delta h_{290}}{360})C^*)^{1/2}\right\}^{1/2} - 115$ |
| | | $\Delta h_{290}$: hue angle difference from h=290, $0 \leq \Delta h_{290} \leq 180$ |
| | | $B = 2000\left(1 - \frac{\Delta h_{290}}{360}\right)C^*/[L^*(100-L^*)]$ |
| Xin and Cheng | Warm-cool | $WC_{0° \leq h_0 \leq 180°} = 0.154L^* + 39.378C^{*0.372} - 0.303h - 113.855$ |
| | | $WC_{180° \leq h_0 \leq 360°} = 0.355L^* + 23.476C^{*0.429} - 0.159(360° - h) - 105.710$ |
| | Heavy-light | $HL_{0° \leq h_0 \leq 180°} = -3.340L^* + 0.476C^* + 0.037h + 175.467$ |
| | | $HL_{180° \leq h_0 \leq 360°} = -3.477L^* - 0.264C^* + 0.072(360° - h) + 182.866$ |
| | Active-passive | $AP_{0° \leq h_0 \leq 180°} = -0.296L^* + 3.162C^{*0.931} - 0.073 - 68.835$ |
| | | $AP_{180° \leq h_0 \leq 360°} = -0.120L^* + 4.385C^{*0.864} + 0.032(360° - h) - 84.791$ |
| Ou | Warm-cool | $WC = -0.5 + 0.02C^{*1.07}\cos(h - 50°)$ |
| | Heavy-light | $HL = -1.8 + 0.04(100 - L^*) + 0.45\cos(h - 100°)$ |
| | Active-passive | $AP = -2.1 + 0.06\left[(L^* - 50)^2 + (a^* - 3)^2 + (\frac{b^* - 17}{1.4})^2\right]^{1/2}$ |

### 2.4.5.3 Colour-emotion for Colour Combinations

Hogg (1969) investigated 12 colour-emotion scales for colour pairs and identified four underlying factors: "active-potency", "evaluative", "emotional tone" and "usual/obvious". He found that "active-potency" was correlated with both lightness and chroma difference. He also found that the "evaluative" factor was correlated with hue. "Emotional tone" was found to be correlated with hue difference and "usual/obvious" showed a complex correlation with all three colour-appearance attributes. In this study, he also investigated the relationship between emotions for single colours and colour pairs. He found that colour-emotion values for two colour combination for "warm-cool" and "strong-weak" had a high correlation with the arithmetic means of the colour-emotion scores for each colour in the pair. This suggests an "additive" relationship between single-colour and colour-combination emotions which can be described by the following formula:

$$E = \frac{E_1 + E_2}{2} \qquad (2\text{-}51)$$

where $E$ is the intensity of a colour-emotion for a colour pair of two colours (1 and 2); $E_1$ and $E_2$ are the intensities for colour-emotions for individual colours.

As an extension to their colour-emotion models for single colours, Ou *et al.* (2004b) investigated the colour-emotion factors for colour pairs and the relationship between emotions for single colour and colour pairs for these factors. They identified three colour-emotion factors for colour pairs which were identical for single colour-emotions: *colour activity* comprising "fresh-stale", "clean-dirty", "modern-classical" and "active-passive"; *colour weight* comprising "tense-relaxed", "hard-soft" and "heavy-light"; *colour heat* defined by "warm-cool". They also found that the additive relationship between single colours and colour combinations was conserved in all the three factors.

Wang *et al.* (2007) investigated the additive relationship between colour-emotions for three-colour combinations using the three scales "active-passive", "heavy-light" and "warm-cool". They also studied the influence of area proportion on colour-combination emotions. Thirty colour combinations (each including three constituent colours), generated randomly by 35 colours, were used as the stimuli in the experiment. For each of the 30 colour combinations, they setup seven different area ratios in sizes for each constituent colour as experimental stimuli, including (4:1:4), (3:1:3), (2:1:2), (1:1:1), (1:2:1), (1:3:1) and (1:4:1). They assumed that the additive relationship for two-colour combinations described in Equation (2-51) can be extended for the three-colour combinations where the constituent colours share the same size as shown in Equation (2-52). They also assumed that for three-colour combinations, the contribution of each constituent colour to the emotion value of an entire combination was proportional to the size of that colour area, as described in Equation (2-53).

$$E = \frac{E_1 + E_2 + E_3}{3} \tag{2-52}$$

$$E = \frac{a_1 E_1 + a_2 E_2 + a_3 E_3}{a_1 + a_2 + a_3} \tag{2-53}$$

where $E$ represents the colour-emotion value for an entire colour combination; $E_1$, $E_2$ and $E_3$ represent colour-emotion values for the three constituent colours in that combination; $a_1$, $a_2$ and $a_3$ represent the area for each of the three colours. They found that the additive relationship was also conserved for three-colour combinations; however, the effect of area proportion was significant only for specific colour combinations exhibiting a high colour-emotion difference value between the colour-emotion value for the colour in the middle of the combination and colour-emotion values for those on the two sides within that combination. The colour-emotion difference is defined in Equation (2-54).

$$\Delta CE = \left| E_2 - \frac{(E_1 + E_3)}{2} \right| \tag{2-54}$$

They also found that this effect was particularly significant for the "heavy-light" scale.

## 2.5 Affective Quality of Images

### 2.5.1 Frameworks in the study of Image Quality

As imaging devices have become more widespread, understanding image appearance and developing image quality models have been one of the main research subjects in the colour-imaging field. Thus, many studies have been done to understand the perception of image appearance and to develop an empirical image appearance model which is applicable to specifying image appearance and subjective image quality.

The present study focuses on an investigation of the relationship between the colour characteristics of images and the emotional responses elicited by those images. Thus in this section, studies related to identifying important attributes for image appearance and models for image preference will be reviewed.

### 2.5.2 Definition of Image Quality

Although image quality has been defined by many researchers, there is no unified agreement on this as it cannot be simply defined. This section introduces some of the definitions of the quality of image reproductions which are relevant to the present study.

Janssen *et al.* (1997) proposed a definition of image quality as "the quality of an image is the degree to which the image is both useful and natural. The usefulness of an image is defined to be the precision of the visual representation of the image, and the naturalness of an image is defined as the degree of correspondence between the visual representation of the image and knowledge of reality as stored in memory." This concept suggested two important steps assessing usefulness and naturalness to determine image quality in the context of the human visuo-cognitive system. First, observers obtain visual information from the scenes presented on imaging devices and then an internal representation is constructed. Second, the information is appraised by referring to internal memory. The first step is referring to the usefulness of an image which indicates the extent to which the image is representative of the real world. The second step is referring to the naturalness of an image.

Yendrikhovskij (2002) proposed a concept of image quality comprising three attributes which adds an additional attribute, *fidelity*, to Janssen *et al.*'s concept. He proposed that the overall quality of an image can be predicted as the weighted sum of the three attributes and different types of image may need different weights on each attribute as shown in Figure 2.17. He defined these three attributes as follows:

*Fidelity* – the degree of apparent match of the reproduced image to the external reference.

*Usefulness* – the degree of apparent suitability of the reproduced image to satisfy the corresponding task.

*Naturalness* – the degree of apparent match between the reproduced image and an internal reference.

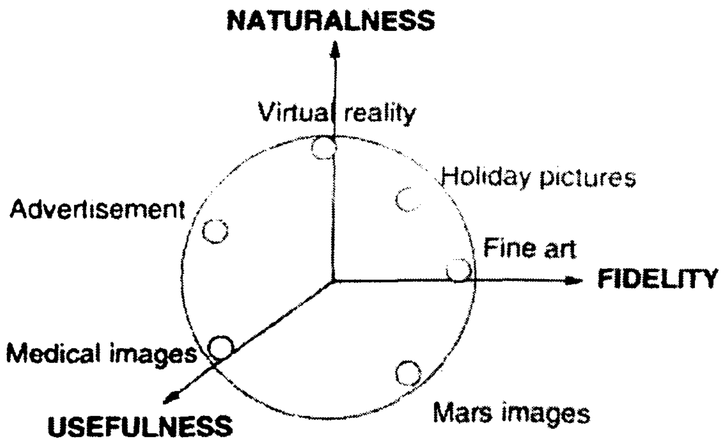



Figure 2.17 Usage of the FUN dimensions on the quality of different image applications (Yendrikhovskij, 1999a)

Keelan *et al.* (2002) proposed that the nature of the attributes contributing to image quality can be classified into four categories: personal, aesthetic, artifactual and preferential attributes. The personal attribute refers to the relationship between the observer and the subject of the image. The aesthetic attribute refers to the artistic characteristics of image. The artifactual attribute indicates a degradation of quality when apparent defects are introduced by imaging systems. Finally, the preferential attributes, for example contrast and colour tone, are always discernable in an image and have an optimal position that usually depends on both the tastes of the observer and the contents of the scene. Regarding these four attributes, he suggested a working definition of image quality as "The quality of an image is defined to be an impression of its merit or excellence, as perceived by an observer neither associated with the act of photography, nor closely involved with the subject matter depicted." In this definition, he excluded those attributes related subject matter which may be very subjective and so have a great influence when the image has personal meaning or attachment to observers. However recently, the general usage of images has been extremely wide and is largely expanding toward many applications such as personal blogs and personal photo albums. In these applications, images definitely include personal values and special meanings to those. As the subject matter and personal aspects of images are highly associated with emotional responses, the attributes related to subjects and personal meaning need to be studied.

In addition, some other attributes named as preference and image appeal, have been studied in elsewhere (Savakis, 2000; Calabria, 2003a; 2003b, Koh, 2006) in which the definitions of these attributes were mainly about the quality colours in the images.

## 2.5.3 Image and Emotion

It has long been recognised in experimental psychology that aesthetic and emotional responses to images are highly personal and are greatly affected by personal preferences (O'hare, 1976). Many researchers have consistently found that emotions can be measured and quantified and that relationships can be set up between the physical properties of the image and emotion.

Many studies investigating the emotional responses to images used one of the most widely-used stimulus sets, known as the International Affective Picture System (IAPS, 2005), which is a set of static images containing various subjects including people, animals, nature, various objects, events and scenes. It samples as broadly as possible the range of visual representations in the world. This system includes calibrated emotional stimuli (956 pictures in 2008 divided into 16 sets of pictures) that can serve as a measurement standard analogous to those used in physical metrics in research on emotion. The pictures in IAPS that evoke the most emotion depict human agents, activities and events. Over half of the pictures in IAPS depict people engaged in positive, neutral or negative activities.

By using the stimuli in this system, it has been demonstrated that each of the two independent dimensions of emotion- valence (pleasantness) and arousal (excitation)- can be characterised by a particular physiological measurement (see Section 2.4.3.2). However, there have been only a few attempts to establish a relationship between image properties and affective response. Bernat *et al.* (Bernat 2006) reported a correlation between image theme and all physiological measures of emotion for themes including erotic, adventure, victim and threat. He used the term "affective intensity", suggesting that a continuous scale can be established between image content and emotion. Another aspect of image emotions studied by Codispoti and De Cesarei (Codispoti, 2007) is related to viewing geometry. In their result, skin conductance measurements were found to be linearly related to image size, suggesting a link between the image size and arousal.

The term *affective imaging* was introduced by Fedorovskaya *et al.* (Fedorovskaya, 2001). In the study, they attempted to investigate the use of affective characteristics of images. They measured the affective responses to selected images in verbal and physiological ways in order to test whether the responses could be predicted by selecting an appropriate emotional content. They found that the choice of image content can influence affective responses. However, no further studies have been done, which adopt the enhancement of image characteristics to enable the affective quality of images to meet a pre-defined state.

## 2.5.4 Factors Affecting Image Emotion

### 2.5.4.1 Image Content

In this study, image content mainly refers to the contents of the scene which can be described using a range of keywords to illustrate the image such as family, picnic and so on. Engeldrum (2002) suggested that the "contextual" factors of image content may have a significant effect on perceived image quality and preference due to factors such as spatial configuration of the elements and/or objects, a few critical colours of skin tones, grass and sky and emotional involvement of the observer in the test image.

Regarding image content and its impact on image appeal, Savakis *et al.* (2000) conducted an experiment on the human estimation of image appeal, where 11 participants were asked to rank pictures 0 to 100 in 30 groups of images based on the relative appeal within their group and comment on the factors that influenced their assessments. They defined image appeal as the interest that a picture generates when viewed by third-party observers. Based on observers' responses, the comments were compiled in terms of attributes which may contribute in a positive or negative manner towards the emphasis image score. A frequency index is associated with each of the attributes and is incremented or decremented every time a positive or negative attribute is mentioned by one of the participants. They found that attributes can be divided into four groups: people, composition/subject, quality measures and duplicate (or redundant). Amongst these four attributes, more emphasis tended to be placed on those related to composition/subject and people than on quality measures and duplicate. The study suggested that image appeal related to these attributes can be influenced by changing objective measures such as image colourfulness, lightness and sharpness.

Kim *et al.* (2008) studied changes in the psychological dimensions that evaluate the image quality of still images on TV accounting for the various levels of the TV's physical controls (e.g. contrast, brightness, hue (tint), saturation (colour), correlated colour temperature and gamma). They collected a large number of adjectives describing five different categories of scenes shown on TV: news, history drama, sports, soap drama, and documentaries. The result of factor analysis on all of the psychophysical data showed that there were slight differences in psychological dimensions according to each scene as shown in Table 2.7. Psychological dimensions can be roughly divided into three categories: SSE (scene-specific emotion), Sensation, and Pleasant-Unpleasantness. They also performed psychophysical experiments where observers were asked to evaluate the image quality of five scenes with variations in their colour characteristics, using the scales shown in Table 2.7. The physical controls of a TV having three to five levels were used to produce pictures having various image characteristics. In the results, changes in the colour due to changes in the levels of each control showed that each scene had different effects on the psychological dimensions. Maximisation of dynamic range was, in particular, found also to maximise all of the psychological reactions studied for all scenes. Changes in saturation and hue led to different reactions in the three psychological dimensions for all scenes. Changes in gamma and correlated colour temperature resulted in weak reactions of psychological dimensions, and the reaction varied according to the scene.

Table 2.7 Psychological dimensions & adjectives (Kim, 2008).

| TV Scene | News | Documentary | Sports | Soap Drama | History Drama |
|---|---|---|---|---|---|
| SSE | Calm<br>Simple<br>Live<br>Natural<br>Sophisticated | Approaching<br>Live<br>Strong<br>Intense<br>Cool<br>Dynamic | Active<br>Strong<br>Live<br>Dynamic | Intense<br>Splendid<br>Sensuous<br>Active<br>Stimulus | Strong<br>Courageous<br>Dynamic<br>Tense<br>Live |
| Sensation | Refined<br>Colourful<br>Bright<br>Vivid | Soft<br>Natural<br>Abundant<br>Vivid | Colourful<br>Vivid<br>Bright | Bright<br>Vivid<br>Refined | Colourful<br>Attractive<br>Bright<br>Vivid |
| Pleasant-Unpleasant | Stimulus<br>Dynamic | - | Soft<br>Natural<br>Harmonic | Natural<br>Soft<br>Delicate | Soft<br>Natural<br>Harmonic |

IAPS classifies all images in the system into three values based on a three-dimensional emotion space. It is theoretically based on the three-dimensional structure of emotion proposed by Russell and Mehrabian (Russell, 1977). The two primary dimensions were "valence" (i.e. pleas ant vs. unpleasant) and "arousal" (calming vs exciting). The third dimension was called "dominance" or "control". Several studies (Bradley, 2001; Codispoti, 2007) have shown that the distribution of emotions in the space of the first two dimensions (pleasure vs arousal) tends to have a "boomerang" shape as shown in Figure 2.18. This graph indicates that if a picture is regarded as highly pleasant or as highly unpleasant, its arousal rating is also high; pictures that are rated as neutral (on the pleasantness scale) tend to be rated low in arousal.

By using the stimuli in this system, physiological measurements have been *widely-used* and many correlations between physiological measures and the degree of image pleasantness and level of arousal are observed (Cuthbert, 1998). Many other studies have shown that the physiological responses to image stimuli are related to a set of specific measures referring to the level of pleasantness and arousal (see Section 2.4.3.2).

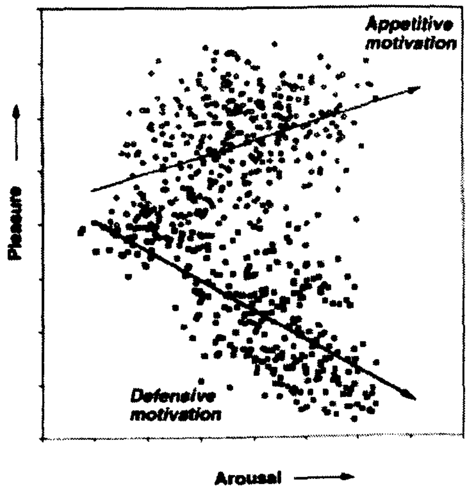



Figure 2.18 Plot of pictures from the International Affective Picture System on the basis of their mean pleasure (*y*-axis) and arousal (*x*-axis) ratings. Each point in the plot represents the ratings for a picture (Bradley, 2001).

### 2.5.4.2 Image Size

Sánchez-Navarro *et al.* (Sánchez-Navarro, 2006) studied the influence of both the emotional subject and the physical characteristics of affective stimuli on physiological and cognitive indices (verbal reactions) of the emotional response. They used 54 pictures from IAPS, including unpleasant, neutral, and pleasant subjects, and used two picture sizes as experimental conditions (120 × 90 cm (visual angle: 33.4° x 25.4°) and 52 × 42 cm (visual angle: 14.8° x 12.0°)) with a 2m viewing distance. Sixty-one observers were randomly assigned to each experimental condition. The skin conductance response, heart rate, free viewing time, and picture valence and arousal ratings were recorded. In their result, the affective subject of the image had an effect on all records; however, image size had no effect on emotional responses.

Nevertheless, Codispoti *et al.* (Codispoti, 2007) obtained experimental results showing some size effects on their physiological measurements. In their study, changes in emotion were measured while participants viewed pictures presented in small (visual angle: 2.62° x 1.96°), medium (6.99° x 5.22°), and large (20.96° x 15.66°) sizes and varying in affective picture subject. Emotional modulation of skin conductance was absent for the smallest stimuli and increased linearly for the medium and largest stimulus sizes. However, the affective modulation of heart rate and corrugator muscle (used when frowning- see Section 2.4.3.2) activity were not influenced by picture size.

#### 2.5.4.3 Previous Experience

As mentioned in Section 2.4.3.2, Miler *et al.* (2002) found that the personal relevance of the emotional stimuli may have influence on emotional response. They observed that skin conductance increased when people imagined pleasant or unpleasant events, compared to neutral images and also that such responses were enlarged when personally relevant scenes were involved in the imagination.

There are also other studies which found that the relation between two stimuli presented may have influence on emotional response. Procter *et al.* (2003) argued that if there was a strong association between two sequential stimuli, the subject tended to respond faster than when the previous stimuli was unfamiliar. Codispoti *et al.* (2007) found that measured autonomic responses (skin conductance and heart rate change) were more rapid for replicated stimulus. These findings imply that observers will react differently to images they have seen before.

#### 2.5.4.4 Colour

Bradley *et al.* (2001) explored the effect of colour on a viewer's response to pictures and examined whether colour can influence the affective responses to specific picture subjects such as mutilation. In this experiment, they selected 18 different contents from IAPS including 8 pleasant, 2 neutral and 8 unpleasant contents and four images for each content. Of the 95 observers, 47 were asked to view these pictures displayed in colour, and the rest viewed in grey scale. They measured the affective responses obtained in two different ways (verbal reports and physiological measurements). These tended to be similar, regardless of whether the pictures were presented in colour or greyscale. The results also showed that the manipulation of picture colour did not have any significant effect on emotions verbally reported in terms of pleasant, neutral and unpleasant contents. Thus, they concluded that the colour of an image had no observable impact on the pattern of measured affective responses.

Nevertheless, other studies have demonstrated that colour had an effect on the psychophysical responses of emotion. Hekkert and van Wieringen (Hekkert, 1996) examined the reactions to paintings which were presented with and without colour. They found that removing colour from paintings decreased liking for the average viewer. As an extension to this work, Pozella *et al.* (2005) investigated the effects of colours on 20 digitised art paintings which varied in their subject (portraits vs. landscapes) and style (modern vs. traditional), selected from the collection of the National Gallery of Art in Washington, D.C. In the experiments they conducted, 30 out of 60 observers viewed these pictures in colour and the rest in grey. Observers were asked to rate on twelve seven-point scales: 1. Simple-complex, 2. Displeasing-pleasing, 3. Uninteresting-interesting, 4. Ugly-beautiful, 5. Weak-powerful, 6. Passive-active, 7. Unbalanced-balanced, 8. Clear-indefinite, 9. No pleasure-extreme pleasure, 10. No discomfort-extreme discomfort, 11.Relaxed-tense, and 12.Drowsy-alert. The results showed that the two image subjects (portraits vs. landscapes) had different effects of image colour on the viewers' affective responses. For portraits, removing colour from the image increased the perceived pleasantness and beauty. In contrast, removing colour from the landscape images reduced perceived beauty.

### 2.5.4.5 Image Appearance Attributes

Many studies have identified important image appearance attributes influencing the image quality judgement. In this section, some of these studies are reviewed.

Bech *et al.* (1996) studied large numbers of attributes which had effects on image quality assessment. As a result, they identified eleven attributes as primary factors of image quality through a large questionnaire asking engineers working Philips and Bang and Olufsen to list all words relevant to image quality. Those were sharpness, contrast, transition between areas, rendering of lines, rendering of details, movement blur, details in light parts, details in dark parts, ratio between light and dark parts, rendering of contours and rendering of depth.

Yendrikhovskij *et al.* (1999b) have studied the effect of brightness and chroma on image quality assessment. They modelled image quality judgments (*IQ*) as a combination of brightness rendering (*B*) and chromatic rendering (*C*) judgments with different weights: $IQ = w_1B + w_2C$.

Hirai *et al.* (2006) used 13 pairs of adjectives to compare image quality between two different types of display, LCD and PDP: "soft-hard", "w arm-cool", "colourful-sober", "light-dark", "fine-coarse", "brilliant-cloudy", "stereoscopic-plane", "real-virtual", "prefer-dislike", "impressive-poor", "heavy-light", "natural-artificial", and "smooth-rough". This was a unique attempt that applied a set of word pairs representing affective responses to the evaluation of image quality.

Kwak *et al.* (2006) extended the determination of preferred colours for natural familiar objects into satisfactory reproduction of point colours, e.g. a sports car with a strong red colour.

Boust *et al.* (2004) attempted to relate memory colours of familiar objects to preferred image reproduction. Eight images were provided to experts who were asked to modify the images until the images looked "preferred". They produced several intermediate versions of the enhanced image, which were relevant to important steps in the improvement of image quality. Generally, the first step for the experts was to segment an image into several interesting zones in order to enhance them. These zones mainly corresponded to familiar objects, for example skin tones, sky, grass and tree. Thus, the colours belonging to skin, sky and grass in the enhanced versions of the target images were compared with the memory-colour data set of those provided by Yendrikhovskij *et al.* (1999). The main results from this comparison are summarised as follows.

(1) the experts tended to use the whole dynamic range and gamut available for enhancing images. As the experts changed lightness information in the target images, the shifts occurring in the colours of skin, sky and grass seldom matched the memory-colour data set.

(2) The colours of skin, sky and grass in the enhanced target images did not seem to exactly fall inside the ellipses of the memory-colour data set in the *u'v'* chromaticity domain.

(3) Some images that were perceived to have degraded image preference had a high percentage of memory colours.

They concluded that one important element used to judge an image was the coherence of the whole colour distribution, which should make the whole scene at least natural and plausible.

Based on previous literature, three important attributes - naturalness, contrast and colourfulness- are reviewed in next section for the present study.

#### 2.5.4.5.1 Image Naturalness

Many researchers (Rider, 1996; Fedorovskaya, 1997; Janssen, 1997; Yendrikhovskij, 1999a; Hunt, 2004) have proposed that naturalness is one of the important image appearance attributes for image quality evaluation. Hunt (Hunt 2004) claimed that naturalness can be assessed by the mental recollection of the colour sensations previously experienced - so called *memory colour*- when looking at objects similar to those being appraised.

Yendrikhovskij *et al.* (1999a) proposed a process of naturalness judgement which assumed that the process was based on two steps of comparison. In the process, they assumed three representations of colour: reproduced object colours, apparent object colours and prototypical object colours. The reproduced object colour is an area of the reproduction corresponding to light coming from an object surface and contains points of different colours. The object colour can be represented by a statistical description such as mean colour. The apparent colour is the perceived version of the reproduced colour and may not be the same due to the influence of viewing conditions. They proposed that the key process of the naturalness judgement is the comparison between apparent object colour and prototypical object colour. In this study, they demonstrated the process using memory colours of grass, skin and sky to specify image naturalness. They manipulated two test images in terms of hue and chroma. A naturalness index was devised and computed by means of a Gaussian function of the differences between the average saturation ($s_{uv}$) values of the manipulated images and the saturation of a set of natural images for each of the grass, skin and sky areas. They found that the images manipulated by such changes led to a systematic reduction in perceived image naturalness, i.e. changing hue produces a more unnatural image appearance than only varying chroma or lightness.

Janssen *et al.* (2000) also used the memory colours of grass, skin and sky to predict image naturalness by computing the degree of matches in the three dimensions, $Y$, $u'$ and $v'$ between an image considered and a set of natural images. Both researchers demonstrated that the naturalness of an entire image could be determined from the naturalness predictions for the grass, skin and sky areas of the image. However, the validity of this result is dependent on the characteristics of the set of natural images in which the memory colour information for grass, skin and sky was extracted.

Choi *et al.* (2008) proposed an image quality model in the form of a linear function of three attributes: image naturalness, image colourfulness and image contrast. The naturalness model was defined as a function of colourfulness, sharpness and reproduction of shadow detail. In the naturalness model, the colourfulness predictors were calculated as ratios of the colourfulness attributes in CAM02-UCS M' for each of the original and manipulated images to that of the original image. The scale values for original and manipulated images were also divided by that of the original image. The corresponding trend for image naturalness vs. image colourfulness is a skewed bell-shape function given in Equation (2-55).

$$N_C = \exp\left[3.68 - \frac{3.71}{x} - 3.70\ln(x)\right] \quad (2\text{-}55)$$

where x is the compute image colourfulness ratio in CAM02-UCS. The reproduction of shadow detail was defined as the ratio of the number of pixels having the lightness J' in CAM02-UCS less than 30. The curve also had skewed bell-shaped function and was defined by a function given in Equation (2-56).

$$N_{RSD} = \exp\left[1.60 - \frac{0.31}{x} - 0.33\ln(x)\right] \quad (2\text{-}56)$$

where x is the ratio of the number of pixels having J' less than 30. Image sharpness was defined as the ratio of the pixel-based colour difference computed at 128X96 image resolution. The proposed function is shown in Equation (2-57).

$$N_S = \exp\left[28.48 - \frac{28.54}{x} - 28.82\ln(x)\right] \quad (2\text{-}57)$$

where x is the pixel-based colour-difference ratio at 128X96 image resolution computed in CAM02-UCS space. Based on these three predictors, they proposed a naturalness model as a function of the three as shown in Equation (2-58).

$$N = 0.53N_{RSD} + 0.83N_C + 0.54N_S - 0.85 \quad (2\text{-}58)$$

An image quality model was also proposed as defined in Equation (2-59). This is a function of image naturalness, colourfulness and contrast which are collected scale values.

$$IQ = 0.40IQ(contrast) + 0.50IQ(colourfulness) + 0.72N - 0.53 \quad (2\text{-}59)$$

In this equation, IQ(contrast) is defined in Equation (2-60).

$$IQ(contrast) = \exp[7.73 - 7.80/x - 7.13\ln(x)] \quad (2\text{-}60)$$

where x is the predicted perceived image contrast. IQ(colourfulness) is defined in Equation (2-61).

$$IQ(\text{colourfulness}) = \exp[0.80 - 0.92/x - 0.44\ln(x)] \quad (2\text{-}61)$$

where x is the predicted perceived image colourfulness.

Koh *et al.* (2006; 2008) proposed that the perceived quality of a colour image has two dimensions: one of preference, i.e. the degree to which the colour of the digital videos most pleases the viewer, and one of naturalness, i.e. the degree to which the colour of the digital video is considered the most lifelike or natural. They studied the relationship between preference and naturalness when the chroma and lightness of the colour varied. Preference and naturalness scores increased to a maximum and then decreased as the mean chroma and lightness of the videos increased. The mean chroma at which preference is at a maximum is greater than the mean chroma at which naturalness is at a maximum. Maximum preference and naturalness scores, however, occurred at similar mean lightness values.

2.5.4.5.2 Image Colourfulness

Fedorovskaya *et al.* (1997) proposed that the colourfulness of an image is the main attribute underlying image quality and naturalness. In this study, the relationship between image colourfulness and perceptual quality in terms of image quality and naturalness was explored. The variation in colourfulness was generated in two different ways: by adding or subtracting the same amount of chroma to or from the chroma value of each pixel; by multiplying a constant to the chroma value of each pixel. As a result, a perceived colourfulness model was proposed in the form given in Equation (2-62).

$$\text{Colourfulness} = w_1 \cdot \text{average chroma} + w_2 \cdot \text{standard deviation of chroma} + w_3 \quad (2\text{-}62)$$

The three weighting parameters $w_1$, $w_2$ and $w_3$, were dependent on image content and four equations corresponding to the four test images used were reported in this study. In their study, the four test images manipulated only in the chroma domain were assessed by observers in terms of image colourfulness. They also found that the colourfulness enhancement (about 1.03 times to the original chroma in average for all images) resulted in higher perceived quality, however further increase led to a reduction in quality. They concluded that this was due to the resulting decrease in naturalness as the result also showed that perceived quality was strongly related to naturalness. The results showed that the optimal values of chroma for maximum quality were dependent on image content and that the relationship between the colourfulness and perceived quality was also dependent on image content.

2.5.4.5.3 Image Contrast

Contrast for a simple periodic pattern such as a sinusoidal grating is generally defined using the Michelson contrast (Michelson, 1962) equation (2-63).

$$C = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \qquad (2\text{-}63)$$

where $L_{max}$ and $L_{min}$ are the maximum and minimum luminance values in the pattern. The values range from 0 to 1. This can be also used for a larger area such as an image which is the perceived appearance. It has been reported that the changes in contrast measured by this definition relate well to the perceived contrast of the display (EIA, 1987). Contrast can also be described by contrast ratio (CR), which is the ratio of the luminance of the bright area ($L_{max}$) to that of the dark area ($L_{min}$) as shown in Equation (2-64) (ANSI, 1977).

$$CR = \frac{L_{min}}{L_{max}} \qquad (2\text{-}64)$$

This is a common methods used to describe display contrast which refers to dynamic range. It is greater than zero, which represents no visible difference between the compared colours.

Calabria *et al.* (Calabria, 2003a) found that there tended to be significant differences in perceived image contrast between colour images and their corresponding achromatic versions. Then, he (Calabria, 2003b) studied the perceived contrast in colour images and proposed an empirical model of perceived contrast as a function of image lightness, chroma and sharpness information. He found that his model, named Single Image Contrast (SIP) tended to depend on image content. The relationship between perceived image contrast and each of the three predictors was modelled as a linear function with different weights. For lightness and chroma, the standard deviation of lightness ($K_L$) and chroma ($K_C$) values for all pixels in an image were used as modelling parameters. For sharpness information, the standard deviation of the lightness in the high-frequency filtered image was used. Then an image-dependent model was developed, as shown in Equation (2-65).

$$SIPk = -1.505 = 0.131K_c + 0.151K_L + 666.216K_s \quad (2\text{-}65)$$

$$\Delta SIPk = SIP_{K_i} - SIP_{K_j} \quad (2\text{-}66)$$

An image-independent model was also proposed as shown in Equation (2-66), by defining the contrast difference obtained between two images (*i* and *j*) which have the same content but are different in lightness, chroma and sharpness.

## 2.6 Summary

The aim of this study is to clarify the relationship between the colour characteristics of images and emotional responses to them and to develop quantitative models of image emotion as functions of colorimetric quantities. According to this aim, this chapter has reviewed topics related to the present study.

In sections 2.1 to 2.3, basic information in the field of colour science field related to the human visual system, colorimetry and CIECAM02 colour-appearance model was reviewed.

As reviewed in Section 2.4, emotion is a complex process which includes several components: cognition which interprets the meanings of the emotional event, physiological responses which are controlled by ANS system including the brain, subjective feelings and behavioural reactions. Structural models of emotion which can be used to describe the subjective feelings towards the emotional stimuli and methods to measure the emotional responses of subjective feelings and physiological responses were reviewed.

In Section 2.4, emotion models for visual experiences were also reviewed. According to Cupchik's aesthetic model (Cupchik, 1994), subjective feelings can be divided into two levels: *reactive* and *reflective*. These two levels of emotional responses seem to correspond to *visceral* and *reflective* levels in Norman's model (Norman 2004). Ou *et al.* (2004a) adopted this concept which defines two levels of emotional responses to define the responses of colour-emotion. The colour-emotion model is related to one of the main focuses of the present study, which describes the interaction between colour, which is one of the most important characteristics of an image, and emotion. Considering the interaction between images and emotion, which is the main focus in the present study, both levels of emotional responses may contribute to the emotional responses as images typically contain not only visual properties such as the configuration of colours, various objects, but also possess special meaning to observers. Thus, studies related to these properties of images were reviewed in Section 2.5.

Considering the several definitions of image quality described in Section 2.5, there is a main difference found between the approaches to defining the subjective responses in image quality studies and those in product design studies. The approaches in image quality tend to restrict the possible reactions to simply a question of good or bad; However, as mentioned above, images typically contain not only visual properties such as configuration of colours and various objects, but can also possess special meaning to observers. Moreover, several factors of images (see Section 2.5.4) can influence the affective responses to images, e.g. image content, size, previous experience or personal meaning and image appearance attributes including colour characteristics.

According to the findings from the review, the scope of the present study was determined as described below.

To investigate the affective response to images, Russell's two-dimensional model of emotion was to be used (Russell, 2003) using psychophysical methods. An alternative method for measuring observer responses would be adopted, making use of a number of physiological measuring instruments. The results from these two methods would then be compared.

The relationship between image emotion scales used in the study (including pleasantness and excitement) would be examined. Regarding the modelling of image emotion scales, this study would focus on the colour characteristics of images, image content and personal value. It should be noted, however, that many other factors of observer characteristics may also be influential (e.g. cultural background, gender or personality). These factors can be considered in future work.

This study would also test the colour-emotion models developed by Ou *et al.* (2004a) to see whether they could also be applied to complex images. Then, the relationship between overall emotional responses and colour-emotion responses and also the relationship between the three factors of the colour-emotion model for complex images and colour attributes of images will be investigated. Thus, models for the relationship between colour-emotion scales (e.g. warm/cool) and image emotion scales (e.g. pleasant/unpleasant) would then be developed.

On the basis of the literature survey and the scope of this study, a number of hypotheses have been set out as described below:

(a) Image emotion scales as investigated in this study (i.e. pleasant-unpleasant, exciting-calming, like-dislike, natural-unnatural and appealing-unappealing) can be divided into two groups in line with Russell's (Russell 2003) two-dimensional model of emotion in general terms.

(b) The affective responses to images will be different for different types of image contents. Four types of image contents are to be tested in this study: positive, negative, neutral and personal.

(c) Ou *et al.*'s (2004a) colour-emotion models (e.g. warm/cool) will work well in predicting the affective responses to complex images, making use of the additivity theory of colour-emotion (Ou 2004b).

(d) Psychophysical responses to images will agree well with the corresponding physiological responses.

# Chapter 3  Experimental Preparation

The aims of the present study were to clarify the relationship between the colour characteristics of images and the emotional responses elicited by those images and also to develop quantitative models of image emotion as functions of colorimetric quantities considering effect of image content. In the present study, the emotional responses were investigated using two different approaches. One was "image emotion" in which the subjective affective quality of images was described using real emotion terms considering overall effect of colour and content. To measure the responses of image emotion, not only psychophysical methods but also physiological methods were applied as sometimes emotions are presented by bodily changes. The other approach was "colour-emotion" (see Section 2.4.5), which mainly considered colours in images to describe configurations of colour for reactive-level emotional responses.

To achieve these aims, two psychophysical and two physiological experiments were conducted, as summarised in Table 3.1. Experiment 1 investigated the relationship between the colour-appearance attributes of images and emotional responses elicited by those images in order to find any differences in these relationships according to image content. In this experiment, semantic classification of image contents was considered according to two criteria: the level of pleasantness and the level of personal attachment. Five scales were used to investigate image emotion including *pleasant-unpleasant, exciting-calming, like-dislike, natural-unnatural* and *appealing-unappealing*. Physiological signals from heart rate, facial muscle movement and skin conductance for physiological responses were also taken. Experiment 2 investigated the relationship between the colour attributes of images and colour-emotion for complex images and also the relationship between colour-emotion of images and image emotion. Six emotion scales were used including: *pleasant-unpleasant, exciting-calming, like-dislike, active-passive, heavy-light* and *warm-cool*. Experiment 3 was designed to investigate the effect of colour reproduction in terms of chroma and contrast on emotional responses presented through physiological signals. This experiment focused on reducing the number of presentations of the same stimuli in order to maximise the reactivity of emotional activation to the stimuli. Thus, the experiment was divided into two parts to examine the effect of the chromatic characteristics and contrast of images on physiological responses separately. Details of specific experimental setups such as selection of images, colour rendering of images, emotion scales used, observers, viewing condition and procedures will be discussed in Section 3.4 in this chapter.

In this chapter, the general experimental setup for this research are described in five sections: the specification of colour-measuring equipment, the colorimetric characteristics and characterisation model of the imaging device used, the characteristics of physiological instruments used and experimental setups for four experiments in this work. Additionally, the statistical methods used for the data analysis will be discussed.

Table 3.1 Outlines of experimental conditions consisting of methods of measurement, imaging device used, number of original test images and their aims.

| Experiment | Method of measuring emotional responses | Imaging Device | Stimuli |
|---|---|---|---|
| 1 | Psychophysics<br>5 scales (*pleasant-unpleasant, exciting-calming, like-dislike, natural-unnatural* and *appealing-unappealing)* | Prints | 10 test images<br>(4 *a-priori* subjects) |
| | Physiology<br>Skin conductance, heart rate and facial EMG | Prints | 10 test images<br>(4 *a-priori* subjects) |
| 2 | Psychophysics<br>6 scales (*pleasant-unpleasant, exciting-calming, like-dislike, active-passive, heavy-light* and *warm-cool)* | Display | 12 test images<br>(4 *a-priori* subjects) |
| 3 | Physiology<br>Skin conductance, heart rate and facial EMG | Display | 37 test images<br>(4 *a-priori* subjects) |

## 3.1 Colour-Measuring Equipments

In this study, two colour-measuring instruments were mainly used to determine the tristimulus values of the stimuli and viewing conditions for the experiments: a Minolta CS-1000 tele-spectroradiometer and a GretagMacbeth Spectrolino Spectrophotometer. The CS-1000 was used for display evaluation, to develop the device characterisation model in Experiments 2, 3 and to specify the viewing condition in Experiment 1. The Spectrolino spectrophotometer was used to measure colour patches for characterising the printer used in Experiment 1.

### 3.1.1 Minolta CS-1000 Tele-Spectroradiometer

#### 3.1.1.1 Specification

A Minolta CS-1000 tele-spectroradiometer (TSR), shown in Figure 3.1, was used to measure XYZ tristimulus values for a series of uniform colour patches presented on the LCD display used in Experiments 2 and 3. These values were used to evaluate display characteristics and to develop the characterisation models for the display. The tristimulus values of a white tile under the same lighting condition as used in Experiment 1 were measured. It records spectral power distribution data in the range of 380-780 nm with 1 nm intervals. The colour-matching functions to convert measured SPD to XYZ values used were the CIE 1931 standard colorimetric observer. The specifications of the CS-1000 TSR used are given in Table 3.2.

Figure 3.1 Colour-measuring instrument: Minolta CS-1000

Table 3.2 Specification of CS-1000 tele-spectroradiometer (Minolta, 2010)

| | |
|---|---|
| Measurement Functions | (1) Radiance<br>(2) With software:<br>Chromaticity (2°- and 10° observer),<br>Luminance, Colour temperature etc. |
| Wavelength Range | 380 - 780 nm |
| Bandwidth | 5 nm |
| Wavelength Resolution | 0.9 nm/pixel |
| Wavelength Precision | ±0.3 nm (median wavelength: 546.1 nm Hg lamp) |
| Angle of measurement | 1° |
| Measurement Range of Luminance | 0.01 – 80,000 cd/m$^2$ (For illuminant A) |
| Accuracy (for illuminant A) | (1) Luminance: ±2% ±1digit<br>(2) Chromaticity: x:±0.0015, y:±0.001 |
| Repeatability (for illuminant A) | (1) Luminance: ±0.1% ±1digit<br>(2) Chromaticity: ±0.0002 |

### 3.1.1.2 Reliability of CS-1000 Tele-Spectroradiometer

Physical uncertainty in measurement can be caused by fluctuations in the measurements made by the CS-1000 TSR and by the display where stimuli were presented. This section reports the performance of the TSR in terms of accuracy and repeatability.

To verify the spectral accuracy of the CS-1000 TSR, a Bentham CL-Hg light source was measured using a Bentham tele-spectroradiometer. The CL-Hg lamp had peaks at specific wavelengths due to electron transitions inside the mercury atom. The most prominent of these include 253.65, 296.73, 365.02, 404.66, 435.83, 546.08, 576.96 and 579.07 nm according to "Wavelengths and Transition Probabilities for Atoms and Atomic Ions, Part I. Wavelengths" NIST reference NSRDS-NBS 68. The measured peaks of the light source were 364.5, 403.8, 435.3, 545.5, 576.4 and 578.4 nm as shown in Figure 3.2 which suggests that the measured data deviate within around 0.5 nm from the corresponding reference data. Spectral accuracy of the CS-1000 TSR was examined by measuring red and yellow LEDs and comparing the results to those measured by Bentham tele-spectroradiometer. The difference of peak values between the two instruments was found to be within 2 nm (see Figure 3.3).

The luminance accuracy was also assessed by measuring a tungsten light source in an integrating sphere (Bentham SRS8Q Spectral Radiance/Luminance Standard). The results are shown in Figure 3.4. The measured $x$ and $y$ chromaticity values were 0.4732 and 0.4172, respectively. Reference data provided by Bentham Instruments and traceable to the NPL standard were 0.4718 and 0.4157 for x and y values respectively. Chromaticity difference between two instruments was within 0.015 units.

The above measurements were carried out in July in 2008 by Dr. Peter Rhodes at the Colour and Imaging Group in the Department of Colour Science at the University of Leeds.

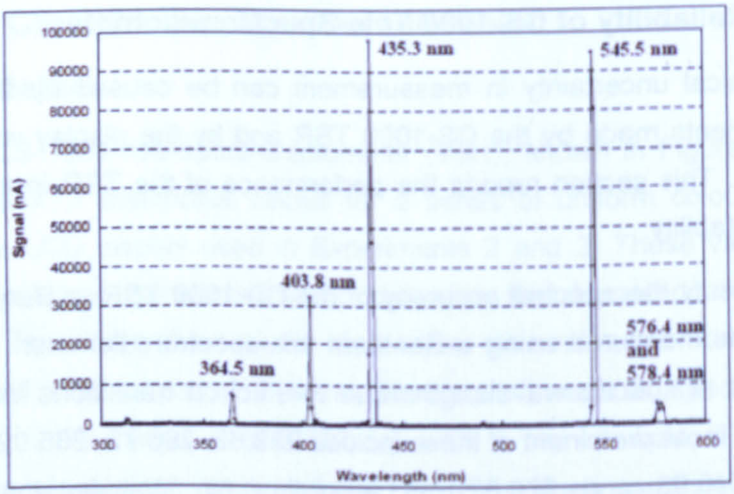



Figure 3.2 Measurement result of CL-Hg line source using Bentham TSR

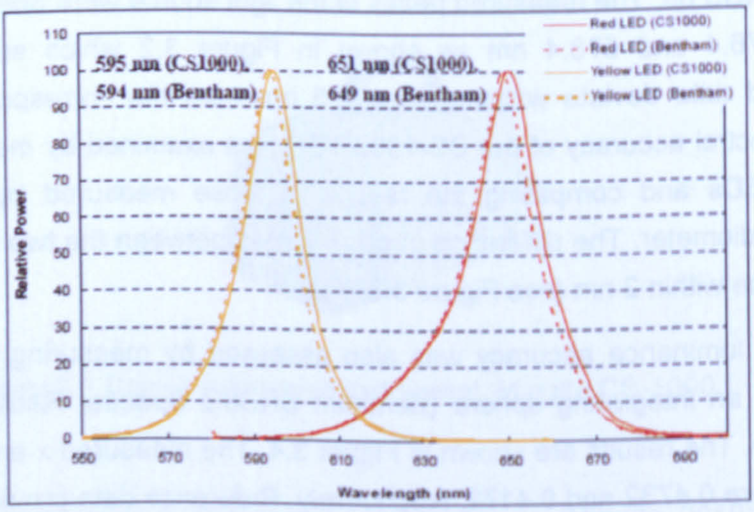



Figure 3.3 Measurement result of red and yellow LEDs using both TSRs

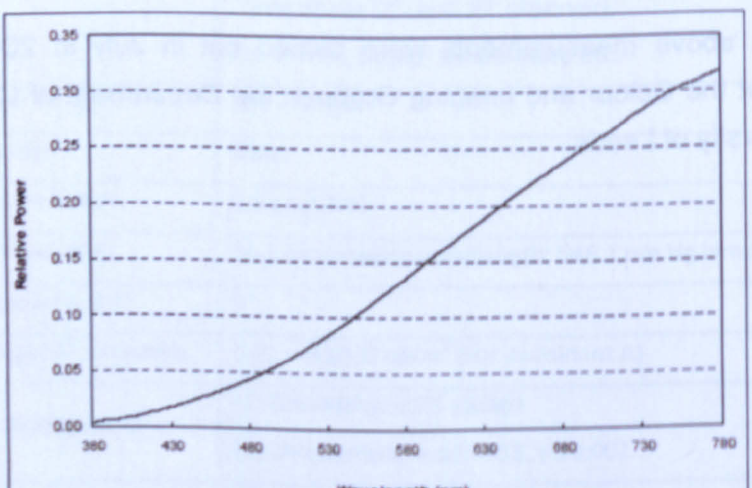



Figure 3.4 Measurement result of SRS8Q standard using CS-1000 TSR

Repeatability of CS-1000 TSR was also examined by measuring the SRS8Q standard integrating sphere five times in 30 minutes with a tungsten light source inside the sphere. Table 3.3 shows the resulting XYZ data and their colour differences ($\Delta E^*_{ab}$) from the mean XYZ. From the table, it can be seen that the TSR is highly repeatable, i.e. having very small $\Delta E^*_{ab}$ values.

Table 3.3 Repeatability measurement of the CS-1000 TSR

| Measurement | X | Y | Z | $\Delta E^*_{ab}$ |
|---|---|---|---|---|
| 1st | 97.81 | 86.07 | 24.89 | 0.10 |
| 2nd | 97.83 | 86.09 | 24.89 | 0.13 |
| 3rd | 97.81 | 86.06 | 24.81 | 0.06 |
| 4th | 97.81 | 86.06 | 24.87 | 0.06 |
| 5th | 97.80 | 86.05 | 24.81 | 0.10 |
| Mean | 97.81 | 86.07 | 24.85 | |

### 3.1.2 GretagMacbeth Spectrolino Spectrophotometer

A GretagMacbeth Spectrolino spectrophotometer, shown in Figure 3.5, was used to measure XYZ tristimulus values of the chart colours used for printer characterisation in Experiment 1. It could measure the colours of charts with grid layout automatically. Table 3.4 summarises its specification. In the present study, the measurement mode was fixed to "Reflection" and the settings for illumination and observers were fixed to CIE illuminant D65 and the CIE 1931 standard colorimetric observer.

Figure 3.5 Colour-measuring instrument: GretagMacbeth Spectrolino Spectrophotometer

Table 3.4 Specification of GretagMacbeth Spectrolino Spectrophotometer (www.gain.com.tw/archives/Spectrolino_en.pdf)

| | |
|---|---|
| Wavelength Range | 380 -730 nm |
| Wavelength Resolution | 10 nm |
| Measurement Modes | Reflection, Emission, Transmission |
| Measurement Geometry(Reflection) | 45/0 ring optic |
| Measurement Aperture | 4 mm |
| Light Source | Gas-filled tungsten, type A illumination |
| Physical Filters | D65 (approximately daylight) Pol (polarised) and No (neutral, incandescent lamp light A) |
| Illuminant Type | D50, D65, A, C, D30...D300, F1...F12 |
| Standard Observers | 2°, 10° |
| Inter Instrument Agreement | Typically 0.3 $\Delta E^*_{ab}$ (D50, 2°) average based on 12 BCRA tiles<br>Maximally 0.8 $\Delta E^*_{ab}$ (D50, 2°) on 12 BCRA tiles |
| Short-term Repeatability | 0.03 $\Delta E^*_{ab}$ (D50, 2°) (mean value of 10 experiments referring to the warm up time and repeatability) |

Table 3.5 The accuracy of Spectrolino in $\Delta E^*_{ab}$ unit.

| Colour | | | Spectrolino | | | Measured | | | |
|---|---|---|---|---|---|---|---|---|---|
| HUE | VALUE | CHROMA | L* | a* | b* | L* | a* | b* | $\Delta E^*_{ab}$ |
| 2.5R | 7 | 8 | 72.5 | 35.5 | 14.0 | 71.8 | 34.8 | 13.9 | 1.00 |
| 10YR | 5 | 2 | 51.5 | 4.2 | 12.2 | 51.1 | 3.7 | 11.8 | 0.79 |
| 10YR | 9 | 2 | 91.6 | 3.1 | 15.7 | 90.5 | 2.9 | 15.1 | 1.27 |
| 5Y | 4 | 4 | 41.8 | 1.8 | 27.5 | 41.8 | 0.9 | 27.9 | 1.04 |
| 2.5GY | 8 | 8 | 81.4 | -18.5 | 56.1 | 80.5 | -19.0 | 54.2 | 2.16 |
| 5G | 6 | 4 | 62.4 | -22.4 | 9.0 | 61.6 | -22.4 | 8.0 | 1.28 |
| 2.5BG | 7 | 6 | 73.0 | -33.1 | 2.9 | 71.7 | -32.4 | 1.5 | 2.01 |
| 2.5BG | 8 | 4 | 82.0 | -18.1 | -7.2 | 80.4 | -17.3 | -8.4 | 2.17 |
| 10B | 4 | 6 | 41.4 | -9.8 | -22.9 | 40.7 | -8.9 | -23.5 | 1.32 |
| 5P | 3 | 4 | 30.8 | 13.8 | -14.9 | 30.7 | 13.8 | -14.7 | 0.25 |
| 5RP | 3 | 2 | 30.9 | 9.6 | -2.3 | 30.6 | 9.8 | -2.2 | 0.36 |
| 5PB | 6 | 10 | 62.6 | -1.0 | -36.9 | 61.4 | 0.1 | -37.3 | 1.65 |
| | | | | | | | mean | | 1.28 |
| | | | | | | | max | | 2.17 |
| | | | | | | | median | | 1.28 |

Accuracy of measurement of Spectrolino was examined by comparing the measured Lab values in CLELAB space for 12 Munsell colour patches with those measured by a GretagMacbeth ColorEye Spectrophotometer. The colour difference for each colour was calculated in $\Delta E^*_{ab}$ and summarised in Table 3.5. The average $\Delta E^*_{ab}$ was 1.28 and the maximum was 2.17$\Delta E^*_{ab}$. This colour difference may be due to the different geometry which is used by the two instruments, however, the performance is acceptable which is within 1.3$\Delta E^*_{ab}$.

## 3.2 Characteristics of the Imaging Device

A liquid crystal display (LCD) and an ink-jet printer were used to reproduce image stimuli throughout this study (see Table 3.1) to compare the emotional impact of images regarding rendering of colour properties and image subjects obtained from different media. In this section, the characteristics of two imaging devices and the way those have been used in this study will be described.

### 3.2.1 Characteristics of Display

A 40" (diagonal screen size) LCD TV screen, *SAMSUNG LE40F71BX*, having full HD pixel format (1920x1080 pixel resolution) was used as the display for a series of experiments using displayed images in this study. It had an aspect ratio of 16:9 and is capable of addressing 10 bits of colour depth levels per each channel, although only eight bits per channel were used in this study. The light sources in the backlight of LCD were cold cathode fluorescent lamps (CCFL). In this section, the colorimetric characteristics and development of the characterisation model for the display will be illustrated. All measurements were performed on a square colour patch (pixel size: 200X200) located in the centre of the display with a grey having RGB equal to (128,128,128) background using the TSR in a darkened room.

#### 3.2.1.1 Four Parameters for Display Setting

Four controls were adjusted to manually setup the LCD screen and "standard mode" was used for measuring display characteristics, as listed in Table 3.6. To find the relationship between these controls and the colour reproduction characteristics of the display, tone reproduction curves at various settings were investigated as described in this section.

Table 3.6 Settings parameters for the LCD display and their ranges

| Controls | Standard Setting | Range |
|---|---|---|
| Contrast | 80 | 0-100 |
| Brightness | 50 | 0-100 |
| Colour | 50 | 0-100 |
| Tone | Cool 1 | warm2 / warm1 / normal / cool1 / cool2 |

#### 3.2.1.1.1 Contrast Control

Figure 3.6 shows the tone reproduction curves for five different grey input levels at different contrast settings. In these measurements, brightness, colour and tone were fixed at 60, 50 and Cool1, respectively. The result showed that as the contrast setting value was increased without changing other parameters, gamma values of the tone reproduction curve (TRC) are decreased. And it also showed that increasing contrast values strongly affects to the slope of the TRC. Thus it was verified that the function of the contrast control is to increase the slope between the brightest and darkest colours.

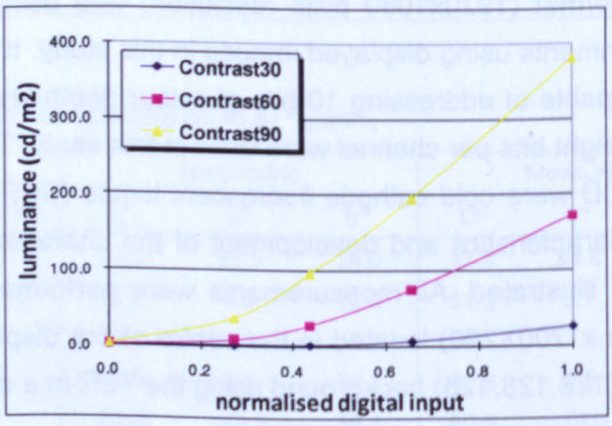



Figure 3.6 Tone reproduction curves at different values of contrast control

Table 3.7 Gamma values for neutral TRC and contrast ratio at different contrast settings

| Contrast Settings | 30 | 60 | 90 |
|---|---|---|---|
| Grey γ | 3.67 | 2.15 | 1.70 |
| Contrast Ratio | 50:1 | 166:1 | 177:1 |

For each of the three cases, the gamma values for the neutral TRC and contrast ratio (white luminance/black luminance) were computed as listed in Table 3.7. This showed that the contrast ratio increased as with contrast setting.

3.2.1.1.2 Brightness Control

Figure 3.7 shows the tone reproduction curves for five different grey input levels at different brightness settings. In these measurements, contrast, colour and tone were fixed at 60, 50 and cool1, respectively. The results showed that as the brightness setting was increased without changing other parameters, TRC gamma values decreased. It also showed that increasing brightness changed the intercepts, not the slope of the TRC. Thus it was verified that the function of the brightness control is to adjust the overall luminance of the LCD.

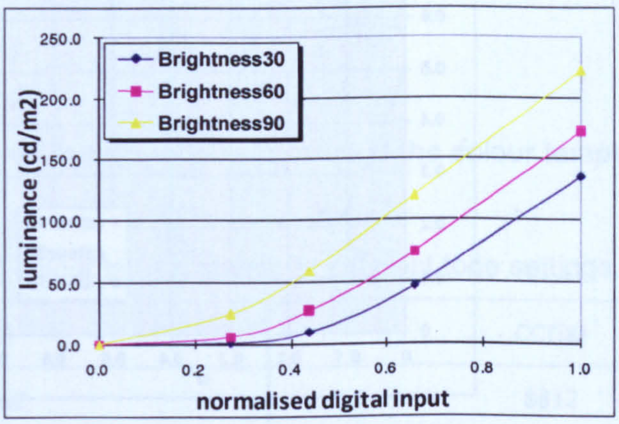



Figure 3.7 Tone reproduction curves at different brightness settings

For each of the three cases, the gamma values for neutral TRC and contrast ratio (white luminance/black luminance) were computed as listed in Table 3.8. This shows that the contrast ratio increased as brightness settings decreased. It seems that the contrast ratio is at its highest between 30 and 60.

Table 3.8 Gamma values for neutral TRC and contrast ratios at different brightness settings

| Brightness Settings | 30 | 60 | 90 |
|---|---|---|---|
| Grey γ | 2.80 | 2.15 | 1.60 |
| Contrast Ratio | 179:1 | 166:1 | 80:1 |

3.2.1.1.3 Colour Control

Figure 3.8 shows the chromaticity coordinates of the RGB primaries as the colour control is changes. As the colour setting is increased, it can be seen that colours on the screen become more and more saturated. However, as shown in Figure 3.8, there are negligible changes in colour gamut as the colour values were increased. In these measurements, contrast, brightness and tone were fixed at 60, 60 and Cool1, respectively.

Table 3.9 gives CIE 1976 *u'v'* values for the maximum red, green, and blue input signals and the computed gamut at different colour settings. When considering the computed actual gamut area, the gamut was largest at colour setting 50.

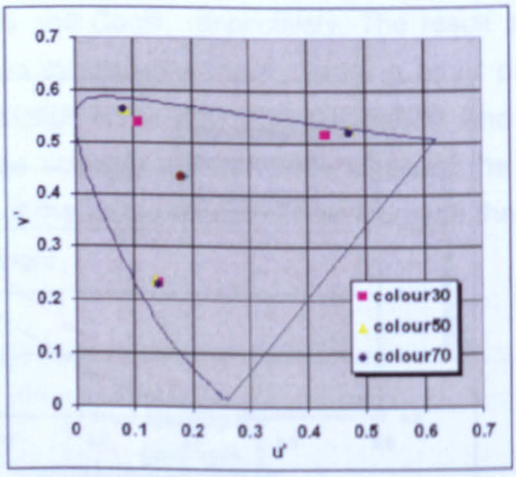



Figure 3.8 Colour gamut at different colour settings

Table 3.9 Gamma values for neutral TRC and contrast ratio at different colour settings

| Colour Setting | 30 | | 50 | | 70 | |
|---|---|---|---|---|---|---|
| | *u'* | *v'* | *u'* | *v'* | *u'* | *v'* |
| Red | 0.4729 | 0.523 | 0.4721 | 0.5218 | 0.4605 | 0.5203 |
| Green | 0.0822 | 0.5639 | 0.0818 | 0.5635 | 0.0928 | 0.5544 |
| Blue | 0.1362 | 0.2417 | 0.1407 | 0.2305 | 0.1426 | 0.2267 |
| Gamut | 0.0525 | | 0.0571 | | 0.0556 | |

When changing the colour settings, there were no changes in the gamma value for the neutral TRC (it remained at 2.15). However, when considering TRC for the red, green and blue channels separately, the gamma values for each channel decreased as the colour setting increased.

Table 3.10 Gamma values for neutral and RGB TRCs at different colour settings.

| Colour Setting | 30 | 50 | 70 |
|---|---|---|---|
| Grey γ | 2.15 | 2.15 | 2.15 |
| R γ | 2.54 | 2.16 | 1.75 |
| G γ | 2.4 | 2.25 | 1.9 |
| B γ | 2.7 | 2.22 | 1.56 |

3.2.1.1.4 Tone Control

Changing the tone settings affects correlated the colour temperature of white as given in Table 3.11.

Table 3.11 Correlated colour temperatures for different tone settings

| Tone | CCT(K) |
|---|---|
| warm2 | 8812 |
| warm1 | 9531 |
| normal | 9598 |
| cool1 | 12142 |
| cool2 | 14985 |

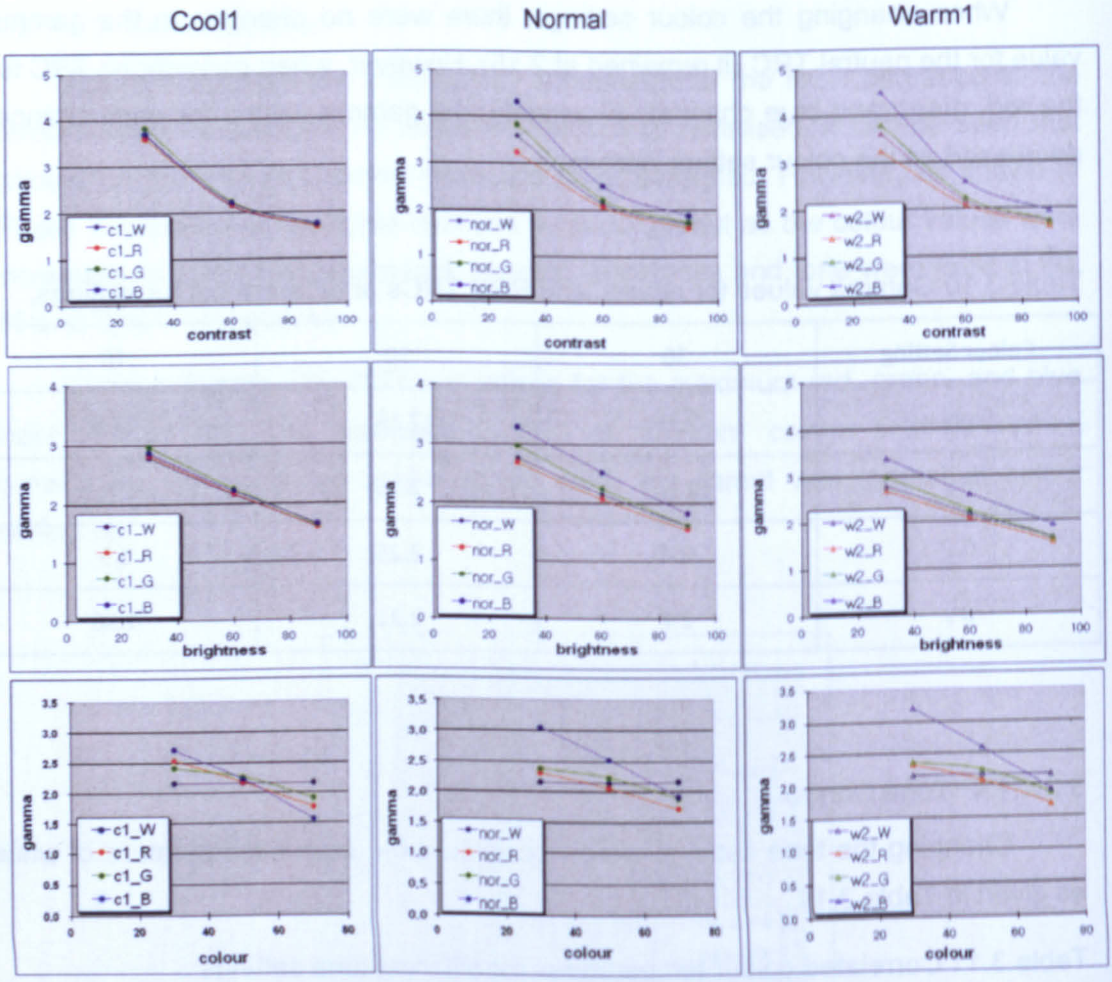



Figure 3.9 Changes in gamma for different tone settings: cool1 (left), normal (centre) and warm1 (right); at different contrast settings (top); at different brightness (middle); and at different colour settings (bottom).

At three different tone settings (cool1, normal and warm1), gamma variation due to changes in the other three parameters were investigated. Figure 3.9 shows changes in gamma values for red, green, and blue channels as a result of varying three other parameters (contrast, brightness, and colour controls) at three different tone settings. As investigated in the preceding sections, gamma values behave in exactly the same way when the other three parameters change. Considering changes in gamma values for each channel, while gamma for grey TRC does not change with the tone setting, gamma for each RGB channel does. These are common phenomena as the three parameters change. Thus it can be concluded that the tone changes are accomplished by changing the RGB channel gamma, mostly the blue channel.

#### 3.2.1.2 Temporal Stability

The CCFL lamps in the backlight of an LCD require a certain period of time to stabilise in terms of their luminance. This stabilisation time was examined by measuring luminance for the centre position of the screen showing a full white pattern. The CS-1000 (see Section 3.1.1) was used to measure continuously over a two-hour period at one-minute intervals. The results are given in Figure 3.10 which shows the colour difference between the initial and subsequent measurements against the time. The result shows that colour change in luminance level increases after turning on and then reaches a sufficiently stable level after about 80 minutes. Hence, all experiments including instrument measurement and visual assessment were carried out after about 80 minutes from turning on.

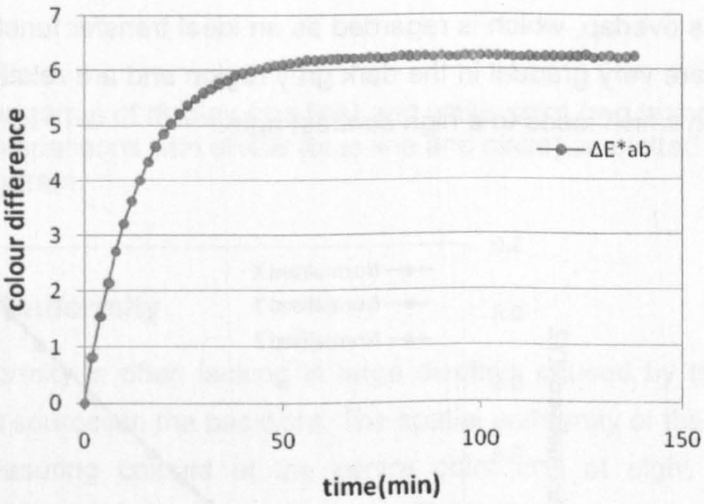



Figure 3.10 Test results of stabilisation time for the LCD used

#### 3.2.1.3 Repeatability

Repeatability of the display was examined by measuring 64 test colours with the combinations of 0, 85, 170 and 255 for each RGB channel. These were a set of colours used to test performance of the characterisation model for this display (section 3.2.1.7). Table 3.12 illustrates measurement results in terms of $\Delta E^*_{ab}$ computed between the first measurement and the following measurements. The overall average colour difference is $0.89\Delta E^*_{ab}$ over the two-week period. This difference may be caused by both the display and the measuring device.

Table 3.12 Average colour differences of 64 colours for repeatability of colour reproduction.

| Time interval | | 4 hours | 2 weeks |
|---|---|---|---|
| Colour difference ($\Delta E^*_{ab}$) | Average | 0.42 | 0.89 |
| | Std. deviation | 0.14 | 0.39 |

### 3.2.1.4 Tone Reproduction Curve

The tone reproduction curve, which represents the relationship between digital input and the corresponding output, evaluated by measuring 19 steps of neutral colours with RGB values equally divided from 0 to 255. The relationships between digital inputs and normalised XYZ values for outputs are shown in Figure 3.11. All three curves overlap, which is regarded as an ideal transfer function. The slopes of the curves are very gradual in the dark grey region and are relatively steeper in the bright region which leads to a high contrast ratio.

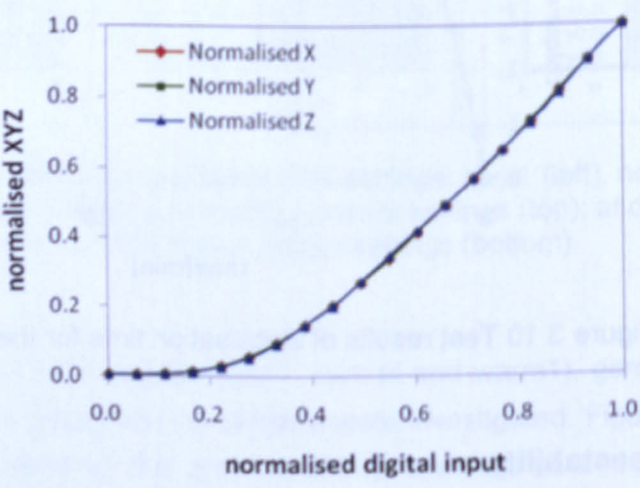



Figure 3.11 Tone reproduction curves of the LCD display, normalised XYZ (red, green and blue respectively) vs. RGB input values.

### 3.2.1.5 Colour Gamut

Colour gamut is the range of colours that can be achieved on a given colour reproduction medium under a specified set of viewing conditions. The colour coordinates of the display RGB primaries were measured under dark surround conditions and plotted on the *u'v'*-diagram in Figure 3.12. The gamut of the 40" display was found to be larger than sRGB especially in the red and green regions, whereas it was a little smaller in the blue region. This white point of the display was used throughout the display evaluation.

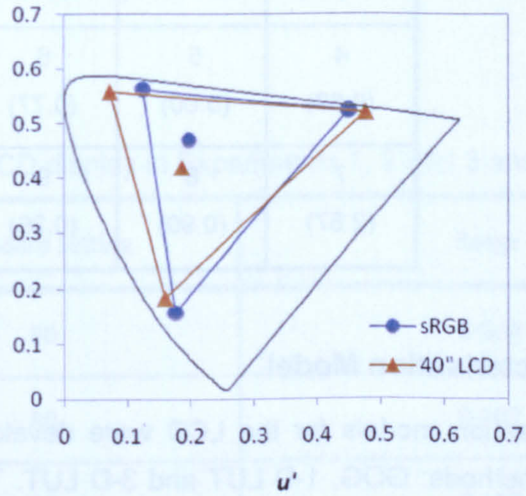



Figure 3.12 Colour gamut of display (red line) and white point (red triangle in the centre) in comparisons with sRGB (blue line and circle) as plotted on a CIE 1976 u'v' diagram.

### 3.2.1.6 Spatial Uniformity

Spatial uniformity is often lacking in large displays caused by the geometry and shape of light sources in the backlight. The spatial uniformity of the display was assessed by measuring colours at the centre point and at eight surrounding positions for the full white pattern illustrated in Table 3.13. Colour differences in terms of $\Delta E^*_{ab}$ were then calculated between the centre and eight positions shown in Table 3.13. The average colour difference for the eight surrounding points was 1.55$\Delta E^*_{ab}$. The smallest difference was 0.67$\Delta E^*_{ab}$ found in the middle of the vertical direction and the maximum was 3.36$\Delta E^*_{ab}$ located at upper left corner.

Table 3.13 Nine points used for uniformity measurement and result of spatial uniformity in terms of $\Delta E^*_{ab}$.

| | | |
|---|---|---|
| 1 (3.36) | 2 (2.73) | 3 (2.01) |
| 4 (0.67) | 5 (0.00) | 6 (0.77) |
| 7 (2.57) | 8 (0.90) | 9 (0.96) |

### 3.2.1.7 Characterisation Model

Characterisation models for the LCD were developed and compared using three different methods: GOG, 1-D LUT and 3-D LUT. To build the GOG and 1-D LUT models, 52 neutral colours with equal intervals from 0 to 255 were measured and used as a training set. For the 3-D LUT model, 125 colours (5x5x5 RGB input values with 0, 64, 128, 192, and 255 for each RGB channel) were used as the training set.

The performance of each method was compared by computing the colour difference between measured and predicted values for 64 test colours (4x4x4 RGB input values with 0, 75, 180, and 255 for each RGB channel) in $\Delta E^*_{ab}$ units. The resulting $\Delta E^*_{ab}$ values are listed in Table 3.14 in terms of mean, median, standard deviation, and maximum values. The results showed that the 3D LUT method gave the best predictions compared with the other models in terms of mean, and median colour difference. However, the 3-D LUT method showed the worst accuracy in terms of standard deviation and maximum values. Although the shape of the tone reproduction curves appeared very similar to a power function, the GOG model did not give the best accuracy. Among GOG and 1D LUT, they displayed very similar performances although 1D LUT was slightly more accurate than GOG in terms of average and median $\Delta E^*_{ab}$. Therefore, the 1-D LUT model was selected and used for the colour manipulation of image stimuli in subsequent experiments.

Table 3.14 Predictive performance of characterisation models in terms of $\Delta E^*_{ab}$.

| $\Delta E^*_{ab}$ | *GOG* | *1D LUT* | *3D LUT* |
|---|---|---|---|
| **Average** | 4.87 | 4.71 | 3.89 |
| **Median** | 5.07 | 4.86 | 3.49 |
| **Std.** | 2.94 | 2.94 | 3.29 |
| **Max** | 10.35 | 10.37 | 11.17 |

For Experiment 2 using the LCD display, the display setting was changed to make the white point of the display from 9000K close to D65 for the convenience of making ICC profiles for the printer. The final chromaticity coordinates were (x, y) = (0.3121, 0.3317). The changed settings for four display controls are given in Table 3.15.

Table 3.15 Settings for the LCD display in Experiments 1, 2 and 3 and their ranges.

| Controls | Standard Setting | Range |
|---|---|---|
| Contrast | 80 | 0-100 |
| Brightness | 80 | 0-100 |
| Colour | 50 | 0-100 |
| Tone | Warm2 | Warm2/ Warm1/ Normal/ Cool1/ Cool2 |

The characterisation models for this setting of the display were developed using 1-D LUT. To build this model, 52 neutral colours from RGB 0 to 255 with equal intervals of 5 were measured and used as a training set. The resulting colour difference between measured and predicted values for 64 test colours in CIELAB $\Delta E^*_{ab}$ units are listed in Table 3.16 in terms of median, standard deviation, and maximum values. The 64 test colours were the combinations of 0, 85, 170 and 255 for each RGB channel. This model was used for conversion between RGB to XYZ during image manipulation in Experiments 1, 2 and 3.

Table 3.16 Performance of characterisation models for Experiments 1, 2 and 3

| $\Delta E^*_{ab}$ | *1D LUT* |
|---|---|
| **Median** | 6.49 |
| **Std. deviation** | 3.23 |
| **Max** | 14.89 |

### 3.2.2 Printer Characterisation

#### 3.2.2.1 Specification

An HP Designjet Z3200 printer was used to reproduce image stimuli for Experiment 1, as will be described in Chapter 4. Its specification and performance for colour accuracy and repeatability specified by the manufacturer are given in Table 3.17. As it uses 12 inks as listed in Table 3.17, this printer has a much larger colour gamut compared to typical CMYK printers. A spectrophotometer is built inside the printer which enables it easily to calibrate and make an ICC colour management profile. From Table 3.17, it can be seen that the printer has good colour accuracy, high-quality inks and light fastness.

Table 3.17 Specification and performance for colour accuracy and repeatability of printer used in Experiment 1. (HP, 2010)

| | |
|---|---|
| Model | HP Designjet Z3200 Photo Printer |
| Ink colours | 12: blue, green, magenta, chromatic red, yellow, grey, photo black, matte black, light cyan, light grey, light magenta, gloss enhancer |
| Print resolution | Up to 2400 x 1200 dpi |
| Colour accuracy | Median < 1.6 $\Delta E_{2000}$, 95% of colours < 2.8 $\Delta E_{2000}$<br>(ICC absolute colorimetric accuracy on HP Proofing Matte paper) |
| Short term colour stability | Less than 1 $\Delta E_{2000}$ in less than 5 minutes<br>(with HP Premium Instant Dry Photo Satin media, right after calibration) |
| Print-to-print repeatability | Average < 0.5 $\Delta E_{2000}$, 95% of colours < 1.4 $\Delta E_{2000}$<br>(with HP Premium Instant Dry Photo Satin paper, right after calibration) |
| Maximum Optical Density | 4L*min/2.5D<br>(with HP premium Instant Dry Photo Gloss Media) |
| Light Fastness | Approximately 200 years fade resistance |

In the present study, the HP Premium Instant-dry Satin Photo Paper (HP part number Q7996A) was used. The reflectance curves of the paper with and without UV are shown in Figure 3.13. The two curves are almost the same across the visible range from 400nm to 700 nm. This indicates that the paper had very little florescent property.

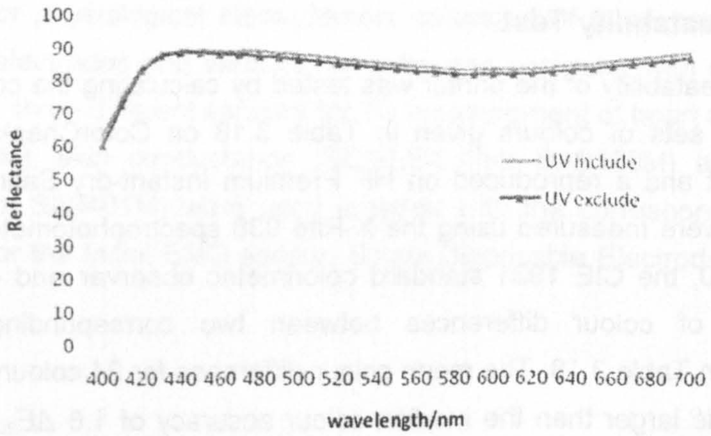



Figure 3.13 Reflectance of the paper used for Experiment 1 with UV included and excluded. (Guo, 2009)

Table 3.18 Summary of printer repeatability for 11 colours.

| | Target | | | Measured | | | |
|---|---|---|---|---|---|---|---|
| | L* | a* | b* | L* | a* | b* | $\Delta E_{2000}$ |
| dark skin | 37.50 | 16.30 | 17.65 | 39.76 | 16.45 | 18.95 | 2.11 |
| light skin | 66.92 | 18.06 | 19.64 | 67.62 | 18.24 | 20.13 | 0.62 |
| blue sky | 50.17 | -4.59 | -20.97 | 50.73 | -2.43 | -21.93 | 2.08 |
| foliage | 41.82 | -15.20 | 22.71 | 42.74 | -14.86 | 23.52 | 1.00 |
| blue flower | 55.87 | 9.14 | -23.29 | 57.37 | 8.96 | -23.54 | 1.42 |
| bluish green | 70.32 | -31.05 | -0.30 | 71.38 | -29.47 | -1.91 | 1.55 |
| orange | 63.96 | 34.10 | 62.75 | 65.27 | 34.08 | 64.88 | 1.32 |
| purplish blue | 39.45 | 8.50 | -40.46 | 40.20 | 10.01 | -40.64 | 1.21 |
| moderate red | 52.31 | 48.53 | 20.88 | 54.28 | 47.90 | 23.58 | 2.49 |
| purple | 30.49 | 22.43 | -18.32 | 31.42 | 24.09 | -18.22 | 1.18 |
| yellow green | 70.43 | -21.60 | 55.52 | 70.93 | -21.36 | 53.39 | 0.75 |
| orange yellow | 72.64 | 18.44 | 68.17 | 73.35 | 18.78 | 69.10 | 0.58 |
| blue | 29.77 | 14.69 | -50.48 | 30.74 | 14.94 | -50.71 | 0.76 |
| green | 54.34 | -40.10 | 31.79 | 54.68 | -40.02 | 31.91 | 0.33 |
| red | 43.22 | 56.15 | 30.80 | 44.39 | 56.35 | 31.81 | 1.19 |
| yellow | 83.09 | 3.01 | 80.77 | 82.31 | 3.98 | 80.31 | 0.78 |
| magenta | 52.32 | 49.73 | -10.90 | 54.26 | 47.59 | -11.42 | 2.04 |
| cyan | 50.42 | -28.74 | -28.26 | 50.44 | -27.08 | -29.46 | 1.07 |
| white | 94.05 | 0.17 | 3.81 | 92.69 | -1.67 | 1.77 | 3.35 |
| neutral 8 | 80.56 | 0.08 | 1.35 | 81.99 | -0.78 | -0.15 | 2.16 |
| neutral 6.5 | 66.38 | -0.45 | 1.26 | 67.76 | -0.45 | -1.08 | 2.55 |
| neutral 5 | 51.20 | -0.69 | 0.64 | 52.05 | -0.18 | -1.31 | 2.22 |
| neutral 3.5 | 35.49 | -0.56 | 0.24 | 35.97 | 0.19 | -1.56 | 2.10 |
| black | 20.95 | 0.52 | 0.71 | 21.13 | 0.69 | 0.04 | 0.72 |
| | | | | | **mean** | | **1.48** |
| | | | | | **max** | | **3.35** |
| | | | | | **median** | | **1.27** |

#### 3.2.2.2 Repeatability Test

The repeatability of the printer was tested by calculating the colour difference between two sets of colours given in Table 3.18 on ColorChecker 24 chart: a physical chart and a reproduced on HP Premium Instant-dry Satin Photo Paper. The colours were measured using the X-Rite 938 spectrophotometer with the CIE illuminant D50, the CIE 1931 standard colorimetric observer and 45/0 geometry. The results of colour differences between two corresponding colours are summarised in Table 3.18. The mean colour difference for 24 colours is 1.93 $\Delta E_{2000}$ which is a little larger than the median colour accuracy of 1.6 $\Delta E_{2000}$ as shown in Table 3.17. The maximum colour difference was 3.35$\Delta E_{2000}$ which is a little larger than the 95% of colour accuracy of 2.8$\Delta E_{2000}$. The performance of the profile seemed reasonable to typical ICC profile performances in excess of 2.5$\Delta E^*_{ab}$ for many printers. The measurements were carried out in April in 2009 by Dr. Peter Rhodes at the Colour and Imaging Group in the Department of Colour Science at the University of Leeds.

#### 3.2.2.3 Characterisation of Printer: ICC Profiles

To match printed stimuli with those shown on the LCD display having a peak white close to D65, ICC profiles were generated for the display as input device and for the printer as output device using GretagMacbeth ProfileMaker (GretagMacbeth, 2005) colour management software. For the printer profile, an electronic colour chart included in the printer itself was printed out on HP Premium Instant-dry Satin Photo Paper (see Section 3.2.2.1). Then all the colours were measured using the GretagMacbeth Spectrolino spectrophotometer (see Section 3.1.2). The measured XYZ values were used to enter into the profiler software to generate an output profile. For the LCD display, 52 measured grey levels from 0 to 255 were input into the profiler software to generate an input profile for the LCD display. Finally, the generated ICC profiling were applied to images using Adobe Photoshop for all the images to be printed. The experimental images were then printed onto the HP Premium Instant-dry Satin Photo Paper at a resolution of 200 dpi.

## 3.3 Physiological Instrument (Thought Technology, 2007)

### 3.3.1 Specification

For physiological measurement in the experiments, Thought Technology's ProComp5 Infinity (SA7525) and Physiology Suite software were used. The instruments for physiological measurement consisted of three parts as shown in Figure 3.13: electrodes and sensors, encoder and computer with software. In the present study, three different sensors for the measurement of heart rate (BVP/FLEX Pro: SA9308M), skin conductance (SC/FLEX Pro: SA9309M) and facial EMG (MyoScan-Pro: SA9401M) were used together with the corresponding electrodes were used. For the facial EMG sensor, Single Disposable Electrodes (T3404) was used.

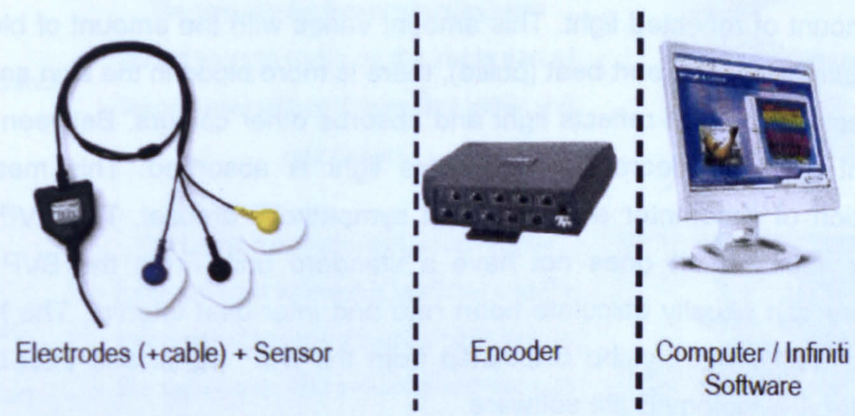



Figure 3.14 Three parts of the physiological instrument for measuring facial EMG.

The ProComp5 Infiniti encoder is a five-channel, multi-modality device for real-time computerised physiological and data acquisition. It has five protected pin sensor inputs with two channels sampled at 2048 samples/sec and three channels sampled at 256 samples/sec. The sensors pass signals to the host computer via the microprocessor-controlled ProComp5 Infiniti encoder unit.

Facial Electro-Myography (EMG) measures muscle activity by detecting and amplifying the small electrical impulses that are generated by muscle fibres when they contract. Since all the muscle fibres located in the recording area of the sensor contract at different rates, the signal detected by the sensor is a constantly varying difference of potential between its positive and negative electrodes. The number of muscle fibres that are involved during any given contraction depends on the force required to perform the movement. Because of this, the intensity of the resulting electrical signal is proportional to the strength of contraction. The MyoScan sensor's active range is from 10 to 500 Hz. It can record EMG signals from zero up to 2000 microvolts (μV).

Skin conductance is a measure of the skin's ability to conduct electricity. A tiny electrical voltage is applied through two electrodes, usually strapped to two fingers of one hand, in order to establish an electric circuit where the participant becomes a variable resistor. The real-time variation in conductance, which is the inverse of the resistance, is calculated in the software. SC indicates changes in the sympathetic nervous system. As a person becomes more or less stressed, the skin's conductance increases or decreases proportionally. The standard measurement unit for conductance is called Siemens. Normal readings, for skin conductance in a relaxed state are around 2 μS but readings can vary greatly with environmental factors and skin type.

The BVP sensor bounces infra-red light against a skin surface and measures the amount of reflected light. This amount varies with the amount of blood present in the skin. At each heart beat (pulse), there is more blood in the skin and more light is reflected as blood reflects light and absorbs other colours. Between pulses, the amount of blood decreases and more light is absorbed. This measure is an indication of vasomotor activity and of sympathetic arousal. The BVP signal is a relative measure. It does not have a standard unit. From the BVP signal, the software can usually calculate heart rate and inter-beat interval. The heart rate in units of beats/min can be calculated from the BVP signal and inter-beat interval using the Physiology Suite software.

Three sensors were placed on each observer's body. The sensor recording heart rate was placed on the inside of the first joint of the middle finger of the left hand or right hand for left-handed observers. The sensor recording skin conductance includes two electrodes placed on the inside part of second joint of two fingers, the index and ring finger. The sensor recording facial EMG has three electrodes (with different cord colours), each corresponding to signal (blue), reference (yellow), and ground (black). An extended cable of three electrodes were used which made it more convenient to attach the face. Among the three sensors, the signal electrode was placed on the forehead right above left eyebrow and the reference electrode was placed right next to the signal one. The ground electrode was attached to the non-hairy part of skin right below the left ear. Table 3.19 summarises the placement of sensors. After all sensors had been placed on the observer's body, they were connected to the corresponding channel of the encoder which links the sensors to the computer.

Table 3.19 Guide for the placement of sensors to measure heart rate, skin conductance and facial EMG with photos of each sensor worn on the body.

| Sensor | Part of body | Examples |
|---|---|---|
| Heart Rate | Placed on the inside part of the first joint of the middle finger of left hand (right hand for left-handed observers). An elastic band was used to make a more secure fit. |  |
| Skin Conductance | The two conductive electrodes were placed so as to touch on the inside part of second joint of two fingers (the index and ring finger). |  |
| Facial EMG (Corrugator) | The signal electrode was placed on the forehead right above left eyebrow and the reference electrode attached right next to the signal one. The ground electrode was attached to the non-hairy part of skin right below the left ear. |  |

## 3.3.2 Performance of Physiological Instruments

The purpose of using physiological instruments is to measure and investigate the effect of image colour attributes on emotional responses in terms of physiological reactions. In physiological recordings, the magnitude of the responses for a specific sensor may have a certain range of signal; however, it also can vary greatly depending on individuals. For reliable results, stability and repeatability are more important than the accuracy of the measurement because what we measure is the changes in the physiological responses evoked by the effect of image colour attributes on emotional responses, not on the absolute values. Thus in this section, the reliability of the physiological instruments is examined to ensure the performance of instruments.

### 3.3.2.1 Facial EMG Sensor

The repeatability of the EMG sensor was examined by applying a comparable amount of electric voltage to the sensor which can be generated by muscle contraction of the human body. The range of the electricity which can be produced by muscle contraction is from zero up to 0.4 mV (Thought Technology, 2007). Thus a static voltage of 0.4mV was applied between the positive (blue) and negative (yellow) electrodes of the EMG sensor and the signal coming into the ProComp5 encoder was recorded for about 1 min. Figure 3.15 shows the recorded pattern of the signal for 1min. The y-axis of the graph is microvolts and the x-axis is time. As seen in the graph, the response remained reliable and stable in between 6.5 and 7.5 microvolts for most of the measurement time. However, it was also found that the sensor is very sensitive to the changes in surrounding electric field which can also be caused by the movement of sensor and other electric equipment. In this case, it is difficult to distinguish whether peaks shown in the pattern originated from the changes in the voltage which are generated from muscle contraction. Thus, this property of the sensor tends to weaken the reliability of using the facial EMG data.

### 3.3.2.2 Skin Conductance Sensor

The repeatability of the skin conductance sensor was examined by measuring the electricity through a resistance which is of a comparable amount to that of the human skin at a relaxed state. The range of the resistance of human skin at a relaxed state is up to 10MΩ (Thought Technology, 2007). Thus resistances having 10 to 10M Ω were connected between the two electrodes of the sensor and the signal coming into the ProComp5 encoder was recorded for about 1 min. Figures 3.16 (a)-(d) show the recorded patterns of the signal for the resistance of 10, 25k, 1M and 10MΩ for about 1min. The y-axis of the graph is microsiemens and the x-axis is time. As seen in the graph, the conductance remained reliable and stable over the measurement time for all four different resistors. Also, it was found that the sensor was not affected by the changes in surrounding fields. Thus, it can be expected that this sensor will give reliable results for the changes in skin conductance due to the visual stimulus.

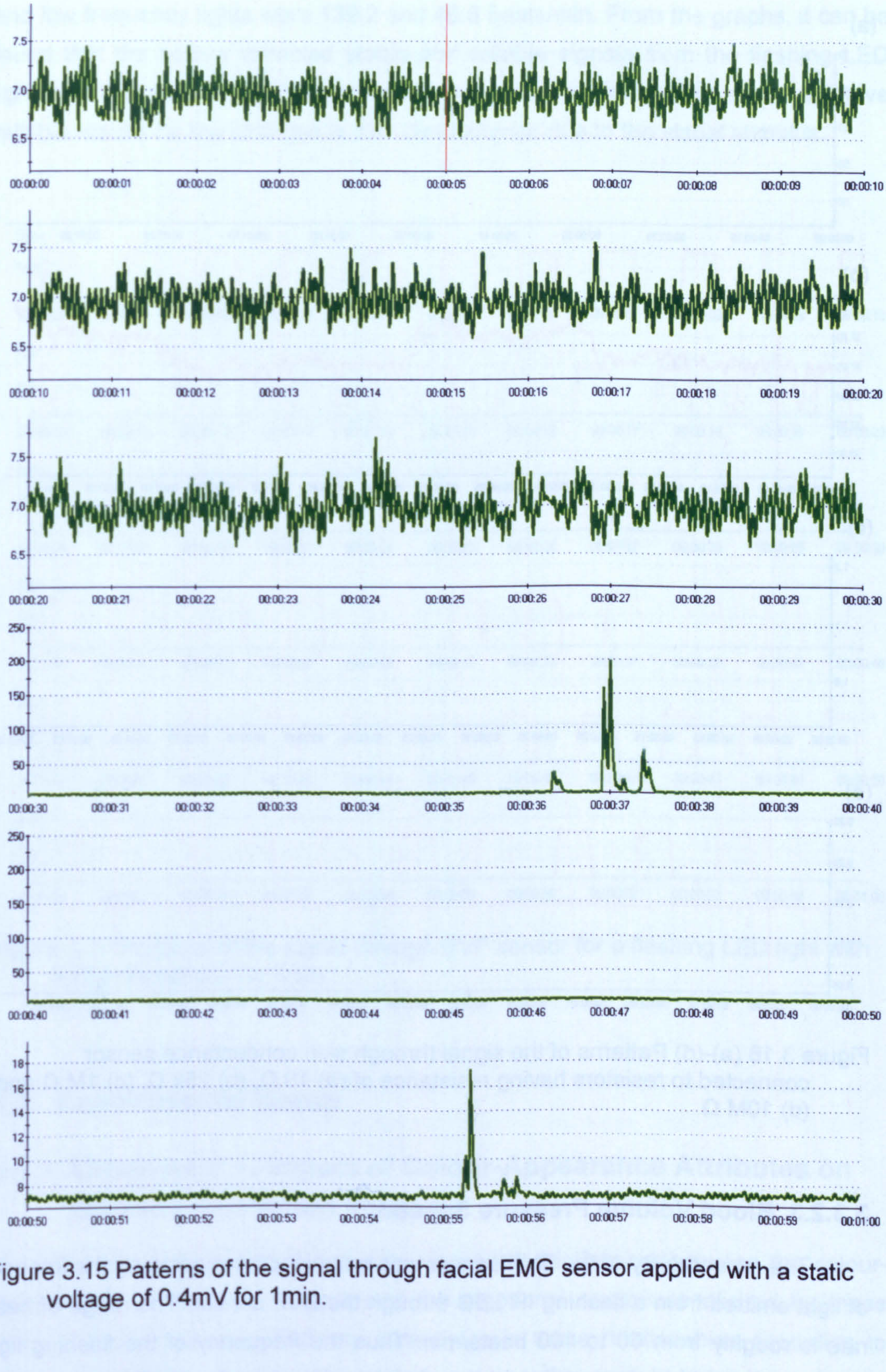



Figure 3.15 Patterns of the signal through facial EMG sensor applied with a static voltage of 0.4mV for 1min.

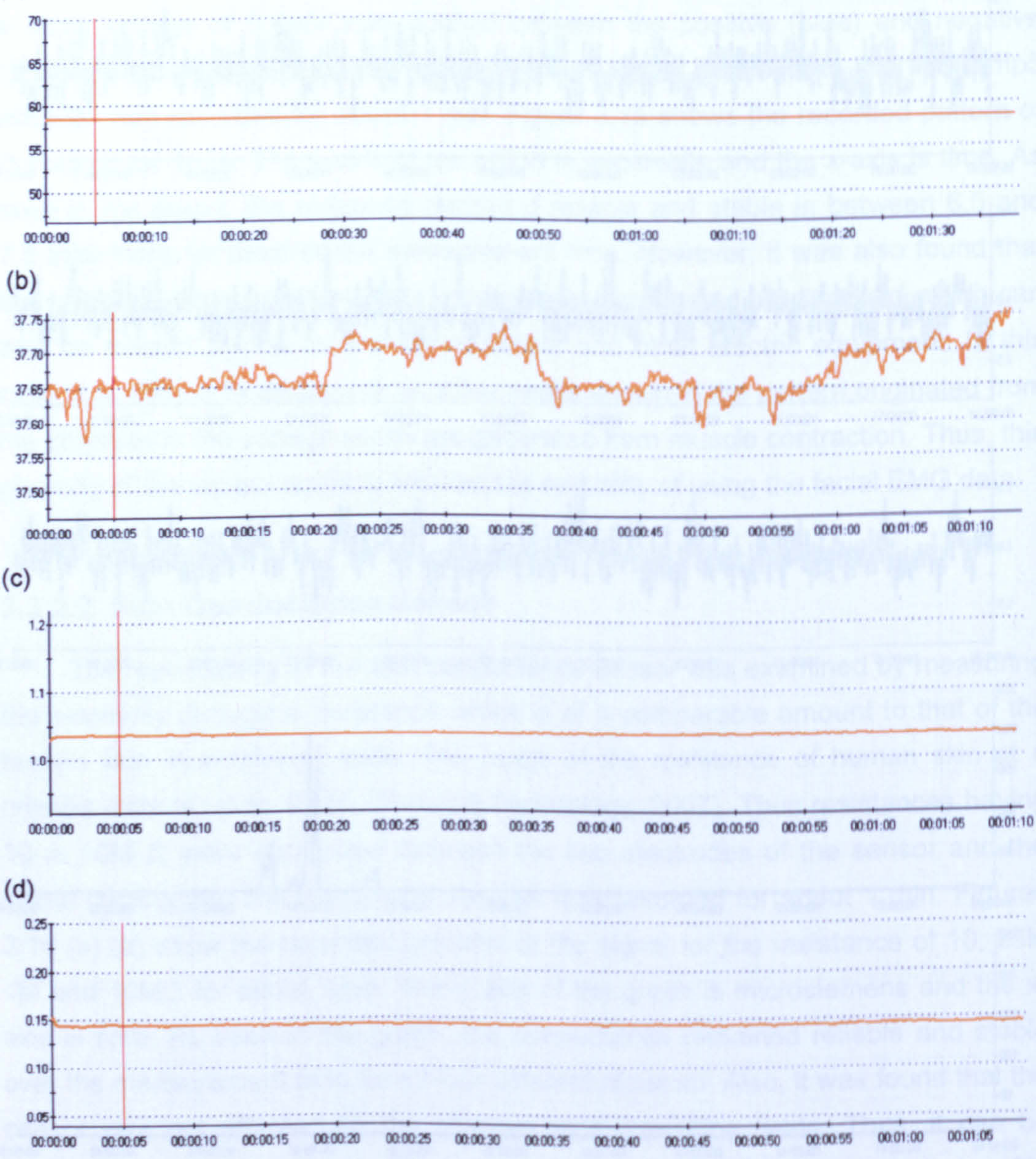
(a)
(b)
(c)
(d)


Figure 3.16 (a)-(d) Patterns of the signal through skin conductance sensor connected to resistors having resistance of (a) 10 Ω, (b) 25k Ω, (c) 1M Ω and (d) 10M Ω.

### 3.3.2.3 Blood Volume Pressure Sensor

The repeatability of the BVP sensor was examined by measuring the intensity of light emitted from a flashing IR LED through the BVP sensor. The range of heart rate is roughly from 60 to 100 beats/min. Thus the frequency of the flashing light was adjusted within the range and the signal coming into the ProComp5 encoder was recorded for about 1 min. Figures 3.17 and 3.18 show the recorded pattern of blood volume pulse for the signals having a frequency for about 1min. The y-axis of the graph is microsiemens and the x-axis is time. The mean heart rate for the high and low frequency lights were 139.2 and 46.6 beats/min. From the graphs, it can be found that the sensor detected stable and reliable signals from the flashing LED light over the measurement time. Thus, it can be expected that this sensor will give reliable results for the changes in skin conductance due to the visual stimulus.

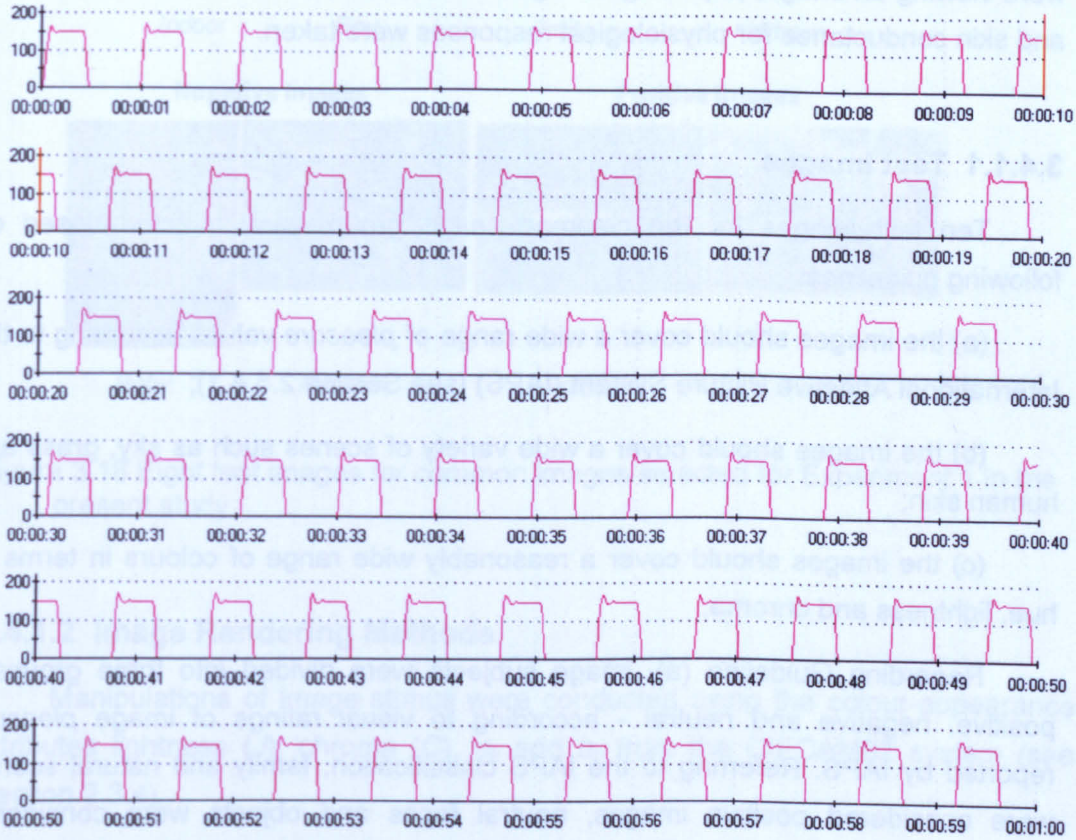



Figure 3.17 Patterns of the signal through BVP sensor for a flashing LED light with a high frequency for 1min.

## 3.4 Experimental Setup

### 3.4.1 Experiment 1: Impact of Colour-Appearance Attributes on Emotion for Printed Images

The aim of Experiment 1 was to reveal the relationship between the colour-appearance attributes of images and the emotional responses elicited by those images. It also aimed to find any differences in these relationships according to image content including not only positive and negative ones but also those having personal attachment. It also includes the development of quantitative models of image emotion as functions of colorimetric quantities with regards to the effect of image content.

To achieve these objectives, a set of psychophysical and physiological experiments was designed. In this experiment, 29 observers participated to assess 178 original and rendered images manipulated in terms of lightness contrast, chroma and tone according to five emotion scales: *pleasant-unpleasant, exciting-calming, like-dislike, natural-unnatural* and *appealing-unappealing*. While observers were viewing an image, physiological signals of heart rate, facial muscle movement and skin conductance for physiological responses were taken.

#### 3.4.1.1 Test Images

Ten test images for the common image group were selected based on following guidelines:

(a) the images should cover a wide range of *pleasure* values according to the International Affective Picture System (IAPS) (see Section 2.5.4.1);

(b) the images should cover a wide variety of scenes such as sky, grass and human skin;

(c) the images should cover a reasonably wide range of colours in terms of hue, lightness and chroma.

Regarding Guideline (a), image subjects were divided into three groups - positive, negative and neutral - according to visual ratings of image *pleasure* reported by IAPS. Referring to the IAPS classification, family and natural scenes were considered positive images, neutral faces and objects were considered neutral, and photos of a crying baby and rubbish were considered negative. The images are in Figure 3.15. These common images were shown to all observers for their visual assessment. The source of the eight original common images are as follows: "Family" and "Boy" purchased from corbis.com; "Rubbish" and "Baby" from the IAPS system (see Section 2.5.4.1); "Horses" and "Indoor" from HP Labs; "Fruits" and "Harbour" from the SHIPP (Standard High Precision Picture) collection of sRGB sample images produced by the Institute of Image Electronics Engineers of Japan.

To collect test images having personal emotional attachment, each observer was asked to provide two of their own photos in which their families, friends and/or they appeared. These personal images were only shown to the one who provided them for the visual assessment.

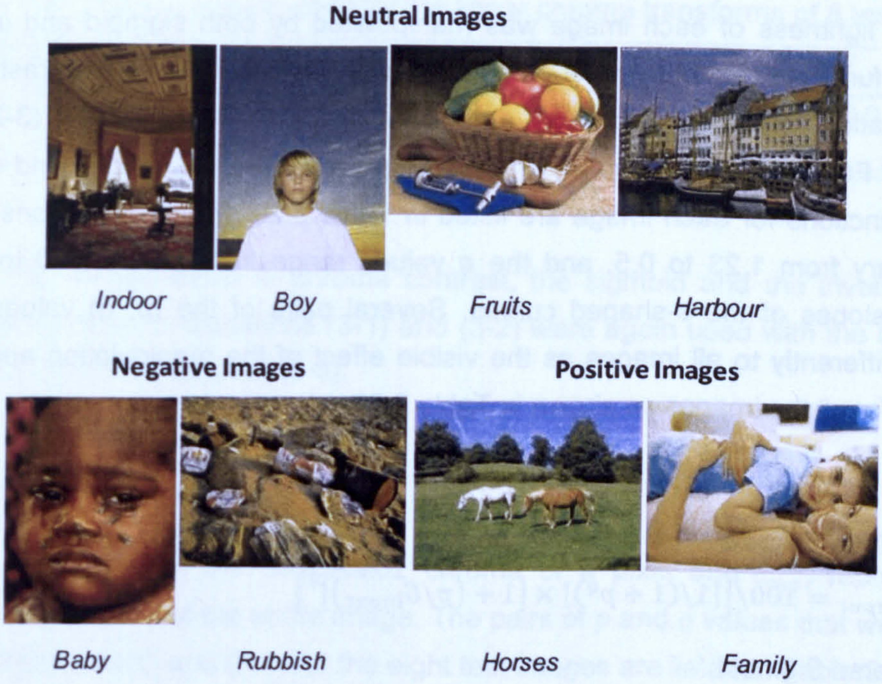



Figure 3.18 Eight test images for common images selected for Experiment 1 in the present study

### 3.4.1.2 Image Rendering Methods

Manipulations of image stimuli were conducted using the colour-appearance attributes lightness ($J$), chroma ($C$), $a_c$ and $b_c$ from the CIECAM02 system (see Section 2.3.4).

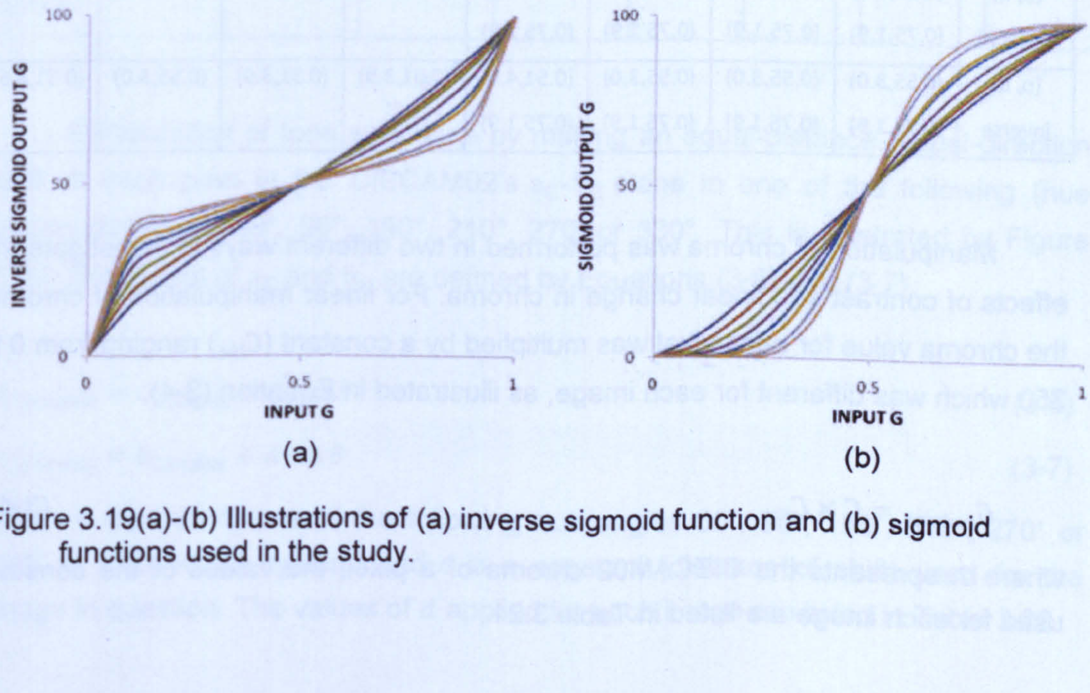



Figure 3.19(a)-(b) Illustrations of (a) inverse sigmoid function and (b) sigmoid functions used in the study.

The lightness of each image was manipulated by both sigmoid and inverse sigmoid functions pixel-by-pixel to investigate the effect of contrast. The transformations for these functions are given in Equations (3-1) and (3-2) and illustrated Figures 3.19 (a) and (b). In these equations, the values of $p$ and $q$ used in both functions for each image are listed in Table 3.20. In both equations, the $p$ values vary from 1.23 to 0.5, and the $q$ values range from 1.45 to 7.0 to make different slopes of the s-shaped curves. Several pairs of the (p, q) values were applied differently to all images as the visible effect of the manipulation appeared different for all the images as shown in Table 3.20.

Sigmoid:

$$G_{output} = 100/\{[1/(1+p^q)] \times [1+(p/G_{input})]^q\} \tag{3-1}$$

Inverse Sigmoid:

$$G_{output} = 100p\{[1-G_{input}/(1+p^q)]/[G_{input}/(1+p^q)]\}^{-1/q} \tag{3-2}$$

in which

$$G_{input} = J/100 \tag{3-3}$$

where $J$ represents the CIECAM02 lightness of a pixel.

Table 3.20 The $p$ and $q$ values used in both the sigmoid and inverse sigmoid functions for lightness manipulation

| image | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| (p, q) Sigmoid | (0.55,3.0) (0.75,1.9) | (0.51,3.9) (0.75,1.9) | (0.51,3.9) (0.75 1.9) | (0.51,4.5) (0.75 1.9) | (0.51,3.9) | (0.51,3.9) | (0.51,3.9) | (0.5,7.0) |
| (p, q) inverse | (0.55,3.0) (0.75,1.9) | (0.55,3.0) (0.75,1.9) | (0.55,3.0) (0.75,1.9) | (0.51,4.5) (0.75,1.9) | (0.51,3.9) | (0.51,3.9) | (0.55,3.0) | (0.51,4.5) |

Manipulation of chroma was performed in two different ways to investigate the effects of contrast and linear change in chroma. For linear manipulation of chroma, the chroma value for each pixel was multiplied by a constant ($C_{lin}$) ranging from 0 to 350 which was different for each image, as illustrated in Equation (3-4).

$$G_{output} = C \times C_{lin} \tag{3-4}$$

where $C$ represents the CIECAM02 chroma of a pixel; the values of the constant used for each image are listed in Table 3.21.

Table 3.21 The $C_{lin}$ values used for the linear chroma transforms of 8 test images.

| image | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| $C_{lin}$ | 0, 0.75, 1.5,2.5 | 0, 0.75, 1.5, 2.0 | 0, 0.75, 1.5, 2.0 | 0, 0.5, 1.75, 2.5 | 0, 2.5 | 0, 2.5 | 0, 2.0 | 0, 2.5 |

For manipulations in chroma contrast, the sigmoid and the inverse sigmoid functions shown in Equations (3-1) and (3-2) were again used with the definition of $G_{output}$ shown in Equation (3-5):

$$G_{input} = C/C_{max} \tag{3-5}$$

where $C$ represents the CIECAM02 chroma of a pixel and $C_{max}$ represents the maximum chroma of the entire image. The pairs of $p$ and $q$ values that were applied to Equations (3-1) and (3-2) for the eight test images are listed in Table 3.22.

Table 3.22 The $p$ and $q$ values used in both the sigmoid and inverse sigmoid functions for the non-linear chroma transform

| image | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| (p, q) Sigmoid | (0.5,7.0) (0.55,3.0) | (0.5,7.0) (0.55,3.0) | (0.5,7.0) (0.55,3.0) | (0.5,7.0) (0.63,2.35) | (0.5,7.0) | (0.5,7.0) | (0.51,4.5) | (0.51,4.5) |
| (p, q) Inverse Sigmoid | (0.5,7.0) (0.63,2.35) | (0.51,3.9) (0.63,2.35) | (0.51,3.9) (0.63,2.35) | (0.5,7.0) (0.55,3.0) | (0.5,6.0) | (0.5,7.0) | (0.5,6.0) | (0.51,4.5) |

Manipulation of tone was done by making an equal-distance, equal-direction shift of each pixel in the CIECAM02's $a_C$-$b_C$ plane in one of the following (hue angle) directions: 30°, 90°, 150°, 210°, 270° or 330°. This is illustrated by Figure 3.20. The output of $a_C$ and $b_C$ are defined by Equations (3-6) and (3-7).

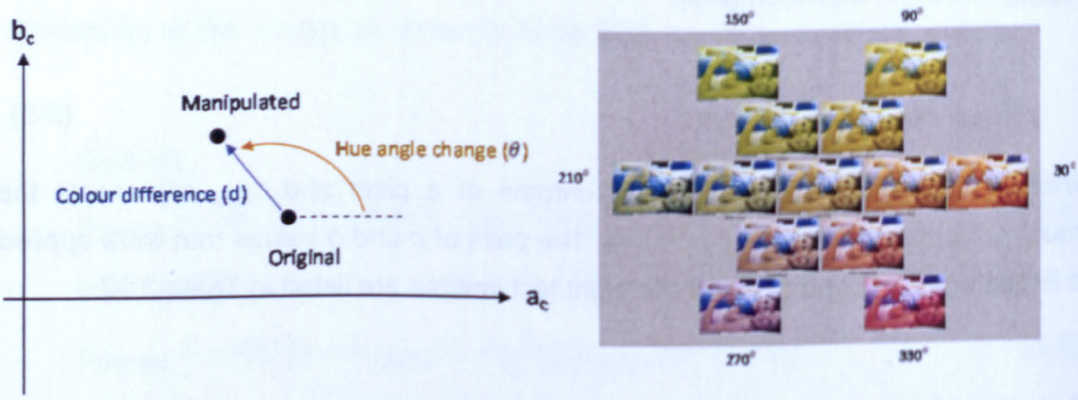
$$a_{C,output} = a_{C,input} + d\cos\theta \tag{3-6}$$

$$b_{C,output} = b_{C,input} + d\sin\theta \tag{3-7}$$

where $\theta$ represents one of the following hue angles 30°, 90°, 150°, 210°, 270° or 330° in CIECAM02 system; and $d$ is a constant (distance of shift) used for the image in question. The values of $d$ applied for each image are listed in Table 3.23.

Table 3.23 The values of $d$ applied for each image in the $a_c$ and $b_c$ transforms for tone manipulation.

| image | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| $d$ | 20 | 10 | 10 | 10 | 30 | 20 | 20 | 20 |
| | 40 | 20 | 20 | 20 | | | | |




(a) (b)

Figure 3.20 Illustration of tone manipulation: (a) the relationship between the original and the tone-manipulated images; (b) examples of tone-manipulated images.

Table 3.24 Summary of the number of original and manipulated images with number of rendering parameters used in Experiment 1.

| | Neutral | Positive | Negative | Personal | |
|---|---|---|---|---|---|
| No. of original images | 4 | 2 | 2 | 2 | 10 |
| Rendering parameters (No. of levels) | Contrast (4)<br>Chroma (4)<br>Chroma (4)<br>Tone (12) | Contrast (2)<br>Chroma (2)<br>Chroma (2)<br>Tone (6) | Contrast (2)<br>Chroma (2)<br>Chroma (2)<br>Tone (6) | Contrast (2)<br>Chroma (2)<br>Chroma (2)<br>Tone (6) | |
| No. of manipulated images | 24×4 = 96 | 12×2 = 24 | 12×2 = 24 | 12×2 = 24 | 168 |
| Total | | | | | 178 |

In summary, 24 manipulation methods were applied to render each neutral image's colour characteristics in terms of lightness, chroma and tone. To compare the results from neutral images with those from images having emotional content, 12 manipulation methods were applied to vary the colour characteristics of emotional stimuli including positive, negative and personal images. In total, 178 rendered images were reproduced including eight original test images for eight test images. The summary of the number of original and manipulated images with number of rendering parameters used in Experiment 1 is given in Table 3.24.

#### 3.4.1.3 Reproduction of Experimental Images

All original images were converted to have the same pixel resolution of 1024 x 768. The RGB signals of each image were converted into XYZ using a characterisation model for the LCD display described in Section 3.2.1.7, and then transformed to CIECAM02 (see Section 2.3.4) for image manipulations. After ICC profiles for the printer and display developed in Section 3.2 were applied to images, they were reproduced on 6" x 4" prints using a HP Designjet Z3200 printer and HP Premium Satin Photo Paper (see Section 3.2.2). Each print was surrounded by a 0.5 cm white frame and presented against an A5-size black card as the background. The final appearance of the image prepared is given in Figure 3.21.

Figure 3.21 An example of a final version of image stimuli prepared for Experiment 1.

#### 3.4.1.4 Evaluation of Colour Rendering of Printed Images

Performance evaluation of the whole reproduction process was conducted using the image stimuli printed for experiments, including many other manipulated versions as will be described in this section. First, the RGB values of the images were transformed to XYZ using the characterisation model for the LCD display, and then transformed to CIECAM02. Then, several versions of the manipulated images were generated according to the transform functions for each attributes of CIECAM02 as described in Section 3.4.1.2, and then converted back to XYZ then RGB. Finally, ICC profiles for the LCD display and printer were applied for printing.

As mentioned in the previous section, image stimuli were collected in electronic forms with RGB values for each pixel and finally presented in printed version in Experiment 2. It is important to ensure that accurate colours were maintained in the course of image reproduction while several transformations were applied. Therefore, the colour difference between predicted target colours in each manipulated version of images and output colours finally reproduced as prints through a series of transformations are examined in this section.

To do this, two locations on each print of ten common images were selected as shown in Figure 3.22. The XYZ values at each point were measured for all original and manipulated versions using an X-Rite portable Spectrophotometer with a setting of Illuminant D65 and 2° observer. Then, the predicted target colours from image manipulation were calculated by converting the measured XYZ values to CIECAM02 attributes in terms of $J$, $a_c$ and $b_c$ then transformed using the image manipulation functions for each attribute as described in Section 3.4.1.2. The measured XYZ values for output colours of manipulated images were then converted to CIECAM02 attributes in terms of $J$, $a_c$ and $b_c$ for comparison with target colours. The XYZ of the reference white used for the conversion was also measured for the white paper on which images were printed and the values were (80.05, 84.66, 94.82).

The colour difference between target colours and output colours was computed using a colour-difference formula in the CIECAM02 colour space using $J$, $a_c$ and $b_c$ as given in Equation (3-8).

$$\Delta E_{CIECAM02} = \sqrt{\Delta J^2 + \Delta a_c^2 + \Delta b_c^2} \quad (3\text{-}8)$$

The mean colour difference values between target colours and output colours at each point in all manipulated versions of eight images are listed in Table 3.25.

The colour difference between target colour and output colours was found to be the largest for the images manipulated by non-linear transforms of chroma and smallest for images manipulated by non-linear transforms of lightness. Among 16 points in eight images, the colour difference value at Point 2 in Image 2 was found to be the smallest and Point 1 in Image 4 the largest. It should be noted that these colour differences include errors from ICC profiles of LCD display and printer and also the error from characterisation model for LCD display.


Figure 3.22 Location of the two points in the eight common images where colour was measured for comparison.

Table 3.25 Mean colour-differences between target colours and output colours at each of the two points in all manipulated images in terms of $\Delta E_{CIECAM02}$ for four manipulations. (TONE: tone manipulation; CNL:chroma non-linear manipulation, CL: chroma linear manipulation and JNL: lightness non-linear manipulation.)

| Image | Point | TONE | CNL | CL | JNL | Mean |
|---|---|---|---|---|---|---|
| 1 | 1 | 12.14 | 9.09 | 4.11 | 0.75 | 6.52 |
| | 2 | 11.78 | 8.87 | 5.60 | 0.37 | 6.65 |
| 2 | 1 | 3.49 | 1.33 | 1.06 | 0.75 | 1.66 |
| | 2 | 5.66 | 9.33 | 4.30 | 1.09 | 5.09 |
| 3 | 1 | 7.49 | 25.42 | 3.68 | 1.45 | 9.51 |
| | 2 | 5.26 | 11.78 | 7.26 | 2.03 | 6.58 |
| 4 | 1 | 5.43 | 18.94 | 19.73 | 1.46 | 11.39 |
| | 2 | 3.54 | 11.77 | 3.36 | 1.08 | 4.94 |
| 5 | 1 | 6.17 | 3.11 | 0.73 | 1.03 | 2.76 |
| | 2 | 6.96 | 5.21 | 2.00 | 1.41 | 3.90 |
| 6 | 1 | 3.46 | 9.44 | 9.70 | 0.76 | 5.84 |
| | 2 | 16.41 | 12.84 | 9.36 | 4.62 | 10.81 |
| 7 | 1 | 7.72 | 6.76 | 9.61 | 0.56 | 6.16 |
| | 2 | 3.47 | 5.45 | 6.61 | 1.23 | 4.19 |
| 8 | 1 | 6.29 | 3.66 | 9.32 | 1.76 | 5.26 |
| | 2 | 5.27 | 4.29 | 2.10 | 1.52 | 3.29 |
| | **Mean** | **6.91** | **9.20** | **6.16** | **1.37** | **5.91** |

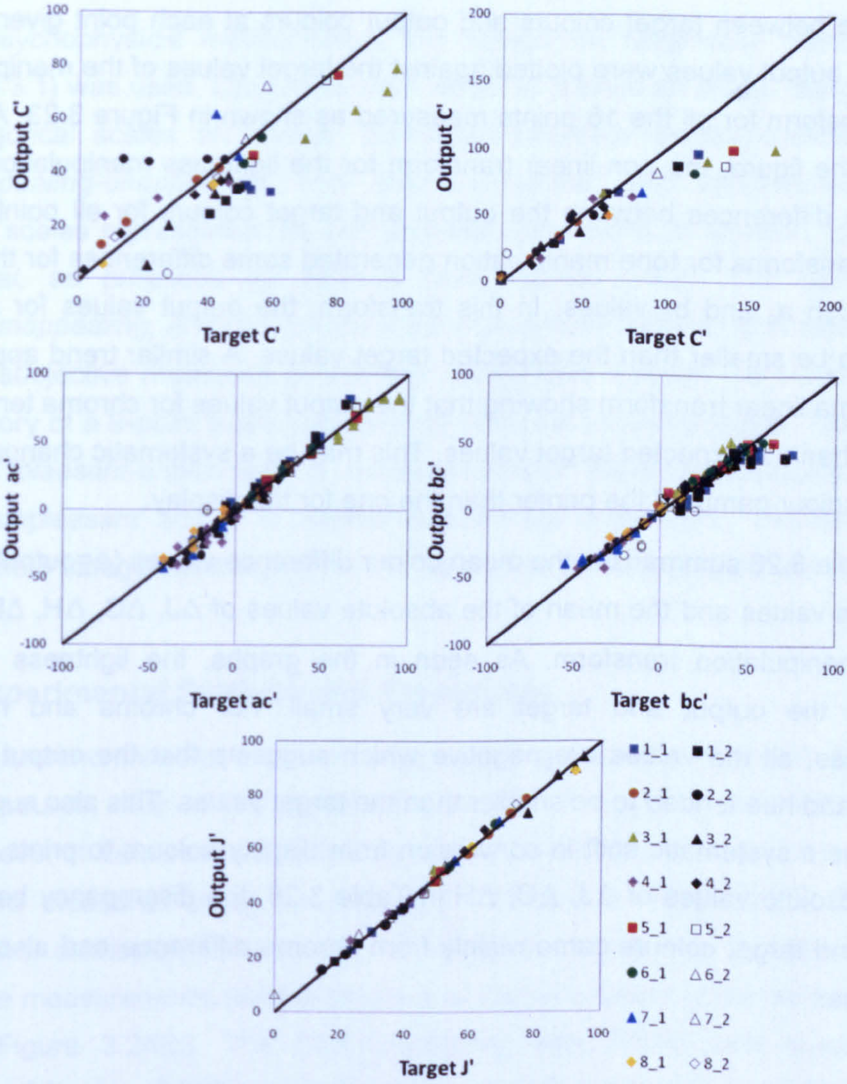



Figure 3.23 The output values plotted against the target values of the manipulation parameters for the chroma non-linear transform (top left); chroma linear transform (top right); $a_c$ and $b_c$ transforms for tone manipulation (centre); lightness transform (bottom).

Table 3.26 Mean values of ΔJ, ΔC, ΔH (left) and the mean of the absolute values of ΔJ, ΔC, ΔH, $\Delta E_{CIECAM02}$ (right) for each image manipulation transform.

| transform | ΔJ | ΔC | ΔH | \|ΔJ\| | \|ΔC\| | \|ΔH\| | $\Delta E_{CIECAM02}$ |
|---|---|---|---|---|---|---|---|
| HUE | -0.21 | -0.79 | -1.22 | 1.16 | 4.51 | 4.29 | 7.12 |
| CNL | 0.42 | -4.22 | -2.46 | 1.12 | 10.31 | 3.48 | 11.59 |
| CL | 0.45 | -6.15 | -3.17 | 1.85 | 9.43 | 5.46 | 12.21 |
| JNL | 0.13 | 0.24 | -1.26 | 1.29 | 2.32 | 2.72 | 4.41 |
| **mean** | **0.20** | **-2.73** | **-2.03** | **1.35** | **6.64** | **3.99** | **8.83** |

To find the reason why some of the points showed quite larger colour difference between target colours and output colours at each point given in Table 3.25, the output values were plotted against the target values of the manipulation of each transform for all the 16 points measured as shown in Figure 3.23. As can be seen in the figure, the non-linear transform for the lightness manipulation showed very little differences between the output and target colours for all points. The $a_c$ and $b_c$ transforms for tone manipulation generated some differences for the colours having high $a_c$ and $b_c$ values. In this transform, the output values for $a_c$ and $b_c$ tended to be smaller than the expected target values. A similar trend appeared for the chroma linear transform showing that the output values for chroma tended to be smaller than the expected target values. This may be a systematic change from the smaller colour gamut of the printer than the one for the display.

Table 3.26 summarises the mean colour difference values (Δ=output – target), the mean values and the mean of the absolute values of ΔJ, ΔC, ΔH, ΔE for each image manipulation transform. As seen in the graphs, the lightness difference between the output and target are very small. For chroma and hue angle differences, all the values are negative which suggests that the output values of chroma and hue tended to be smaller than the target values. This also supports that there was a systematic shift in conversion from display colours to prints. From the mean absolute values of ΔJ, ΔC, ΔH in Table 3.26, the discrepancy between the output and target colours came mainly from chroma difference and also from hue difference.

### 3.4.1.5 Observers

A total of twenty-nine observers, including twenty Chinese and nine British aged from 19 to 35 (all studying at the University of Leeds) participated in the experiment, as summarised in Table 3.27. All observers passed the Ishihara Color Test (Ishihara, 1985) for colour deficiency before starting the experiment.

Table 3.27 Summary of the distribution of observers participating in the experiment.

| | **Male** | **Female** | **All** |
|---|---|---|---|
| **British** | 1 | 8 | 9 |
| **Chinese** | 8 | 12 | 20 |
| **Total** | 9 | 20 | 29 |

#### 3.4.1.6 Categorical Judgement Scales for Image Emotion

For psychophysical measurement, the categorical judgement method (see Section 2.4.3.1) was used. Observers were asked to assess an image using five 9-point categorical scales as follows: *pleasant-unpleasant, exciting-calming, like-dislike, appealing-unappealing, and natural-unnatural.* The *pleasantness* and *excitement* scales represented the two principal dimensions of emotion, *pleasure* and *arousal,* as proposed by Russell (see Section 2.4.2). The *like-dislike, appealing-unappealing, and natural-unnatural* scales have been used in many other studies as subjective measures of affective quality (see Section 2.5.1 and 2.5.2). Each category of a 9-point scale was labelled using verbal descriptions. Taking the example of *pleasant-unpleasant*, '9' corresponded to 'extremely pleasant', '1' to 'extremely unpleasant' and '5' to 'neither pleasant nor unpleasant'. The definitions of each of the 9 categories are given in the instructions shown in Appendix A.

#### 3.4.1.7 Experimental Settings and Procedures

The experiment was carried out using a viewing cabinet with a D65 simulator as the light source, situated in a darkened room with viewing geometry of 0/45. The luminance level of illumination and the colour around the light source of the viewing cabinet were measured using the CS-1000 TSR and a white $BaSO_4$ tile. The spectral power distribution is shown in Figure 3.24(a), which was determined from the white tile measurements divided by the spectral reflectance of the tile measured shown in Figure 3.24(b). The CCT of lighting was 6219K with chromaticity coordinates of (x, y) = (0.3172, 0.3376) and the level of luminance was 279.9cd/$m^2$. The luminance of the background grey was 90.7cd/$m^2$ and the surround was average condition.

Each observer was presented with 178 images including 26 repeats, one at a time. After a 5-second break during which the observer did not see any stimuli, each image was shown for a viewing period of 10 seconds, followed by a session of answering five questions on a questionnaire (question period). Then a 10-30 sec break was given before next cycle was started. The purpose of this rest period was to avoid carrying influence over from the previous stimuli. The prints were presented individually in the viewing cabinet.

For physiological measurement, heart rate, skin conductance and facial EMG were recorded throughout the whole session. Three sensors were placed on each observer's body according to the placement guide mentioned in Section 3.3. After all sensors were put on the observer's body, they were connected to the corresponding channel of the encoder which links sensors with the computer. The instructions given to observers prior to the experiment are shown in Appendix A.

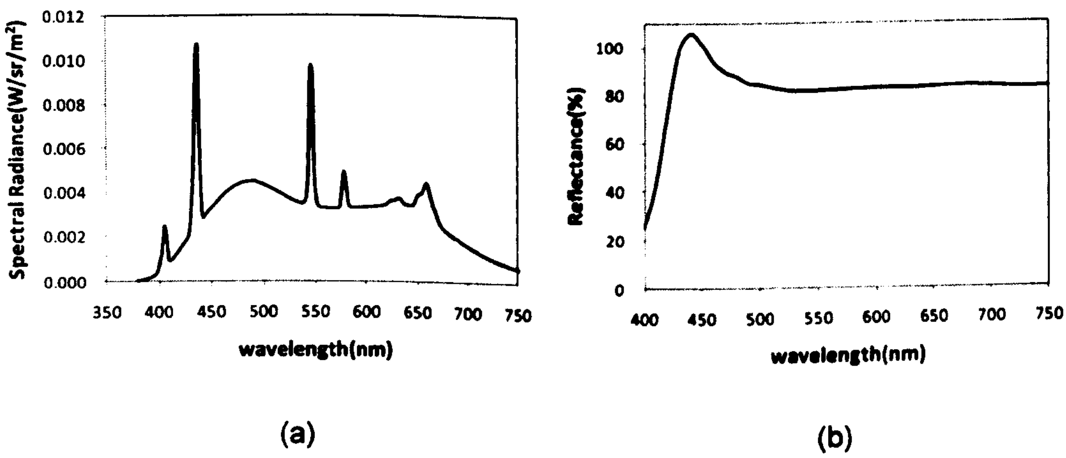



Figure 3.24(a)-(b) (a) SPD of the illumination of the viewing cabinet; (b) reflectance of the white tile used to measure (a)

### 3.4.2 Experiment 2: Impact of Colour-Appearance Attributes on Colour-emotion and Image Emotion for Displayed Images

The aim of this experiment was to investigate the relationship between colour attributes of images on a display and colour-emotion scales of *warm-cool*, *light-heavy* and *active-passive* and also to develop quantitative models of colour-emotion as functions of colorimetric quantities for image stimuli. Moreover, the aim of this experiment includes the development models of image pleasantness and excitement in terms of colour-emotion scales of images and the comparison of the two models derived from Experiments 1 and 2.

To achieve these aims, a series of psychophysical experiments was carried out. In the experiment, 17 observers were asked to assess 253 original and rendered images manipulated in terms of lightness, lightness contrast, chroma and tone on six emotion scales including *pleasant-unpleasant*, *exciting-calming*, *like-dislike*, *active-passive*, *heavy-light* and *warm-cool*.

#### 3.4.2.1 Test Image

Ten test images, including eight common and two personal images per observer, were selected based on the guidelines introduced in Section 3.4.1.1. An additional intent regarding guideline (a) included was that images should cover a wide range of arousal values according to the IAPS results. According to IAPS (see Section 2.5.4.1) results, very highly arousing stimuli contained contents such as mutilation, death (highly arousing and unpleasant) and erotica (highly arousing and pleasant). However, very arousing stimuli were excluded for safety reasons. Instead, adventure, baby and couple were selected as positive images; a roach, dead animal and injured human added to negative. The nine original test images for the common category are given in Figure 3.25.

The source of the nine original common images are as follows: "Family" and "Boy" were purchased from corbis.com; "Rubbish" and "Baby" are from the IAPS system (see Section 2.5.4.1); "Harbour" and "Fruits" are from the SHIPP (Standard High Precision Picture) collection of sRGB sample images produced by the Institute of Image Electronics Engineers of Japan; and the other six images were downloaded from the Flickr website with permission under Creative Commons 2.0 Attribution license copyright.

To collect personal images, a portrait of each observer was taken with a fixed background indoor scene to limit the background which was not controllable for those used in Experiment 1. Personal images were only shown to the observer who provided them for the visual assessment.

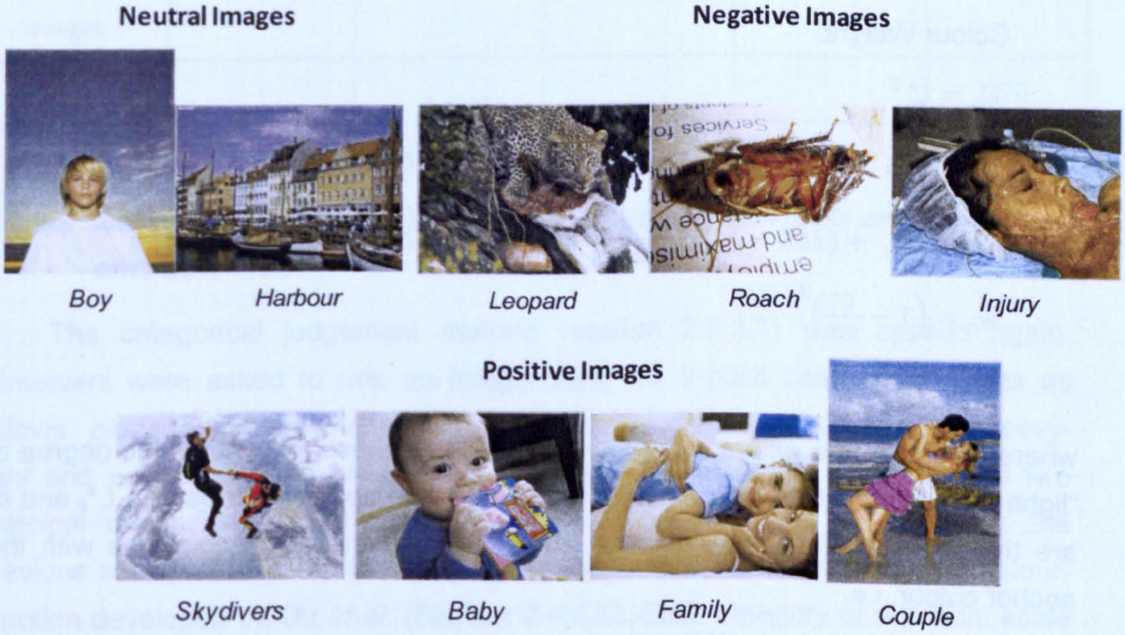



Figure 3.25 Ten test images for common category selected for Experiment 2.

### 3.4.2.2 Image Rendering Methods

Manipulation of image stimuli was conducted using three colour-appearance attributes lightness (*J*), chroma (*C*) and tone ($a_C$ and $b_C$) in the CIECAM02 system as described in Section 3.4.1.2. For each original image, 18 rendered images were produced having six different levels of lightness (*J*), chroma (*C*) and tone ($a_C$ and $b_C$).

Additional manipulation regarding image activity and weight were done using an Adobe Photoshop plug-in developed by HP Labs using Equations (3-9) and (3-10) which were based on Ou *et al.*'s original colour-emotion model (see Section 2.4.5.2).

Colour Activity:

$$\begin{aligned} L_a^* &= L_o^*(1 + ks) + 50 \\ a_a^* &= a_o^*(1 + ks) + 3 \\ b_a^* &= b_o^*(1 + ks/1.4) + 17 \end{aligned} \tag{3-9}$$

where *k* controls the extent of "activity" or "inactivity"; *s* controls the direction of the shift and is equal to either +1 for enhancing or to -1 for reducing the activity. $L^*_o$, $a^*_o$ and $b^*_o$ are the pixel's CIELAB coordinates, shifted so that the origin coincides with the anchor colour, i.e. $L_o^* = L^* - 50$; $a_o^* = a^* - 3$; $b_o^* = b^* - 17$.

Colour Weight:

$$L_a^* = L_o^{*\,\gamma}$$

$$h_a = \begin{cases} h_o + h_o \frac{(180 - h_o)}{180} w_c k + 100, & h_o \leq 180 \\ h_o + (360 - h_o)\frac{(h_o - 180)}{180} w_c k + 100, & h_o > 180 \end{cases} \tag{3-10}$$

$$w_c = \left(1 - \frac{C^*}{150}\right)^3$$

where *k* controls the extent of "yellowness" or "bluishness"; $\gamma$ controls the degree of "lightness" with positive values for lighter colours and negative for darker. $L^*_o$ and $h_o$ are the pixel's CIELAB coordinates, shifted so that the origin coincides with the anchor colour, i.e.

$$L_o^* = 100 - L^*;\ h_o = 100 - h \tag{3-12}$$

For each original image, 8 rendered images were reproduced having four different levels of activity and weight.

In summary, 26 manipulation methods were applied to render image colour characteristics in terms of lightness, chroma, tone, colour activity and colour weight. In total, 270 rendered images were reproduced (including original images) from ten test images. The summary of the number of original and manipulated images with number of rendering parameters used in Experiment 2 is given in Table 3.28.

Table 3.28 Summary of number of original and manipulated images with the number of rendering parameters used in Experiment 2.

| | Neutral | Positive | Negative | Personal | |
|---|---|---|---|---|---|
| No. of original images | 2 | 4 | 3 | 1 | 10 |
| Rendering parameters (No. of levels) | Contrast (6)<br>Chroma (6)<br>Tone (6)<br>Activity (4)<br>Weight (4) | Contrast (6)<br>Chroma (6)<br>Tone (6)<br>Activity (4)<br>Weight (4) | Contrast (6)<br>Chroma (6)<br>Tone (6)<br>Activity (4)<br>Weight (4) | Contrast (6)<br>Chroma (6)<br>Tone (6)<br>Activity (4)<br>Weight (4) | |
| No. of manipulated images | 26×2 = 52 | 26×4 = 104 | 26×3 = 78 | 26×1 = 26 | 260 |
| Total | | | | | 270 |

### 3.4.2.3 Categorical Judgement Scales for Image Emotion and Colour-emotion

The categorical judgement method (section 2.4.3.1) was applied again. Observers were asked to rate an image using six 9-point categorical scales as follows: *pleasant-unpleasant, exciting-calming, like-dislike, active-passive, heavy-light* and *warm-cool*. The *pleasantness* and *excitement* scales represent the two principal dimensions of emotion, *pleasure* and *arousal,* as mentioned in the previous section. The other three scales correspond to the three factors of colour-emotion developed by Ou *et al.* (Section 2.4.5.2). Each category of a 9-point scale was also labelled using verbal descriptions. Taking the example of *pleasant-unpleasant*, '9' corresponded to 'extremely pleasant', '1' to 'extremely unpleasant' and '5' to 'neither pleasant nor unpleasant'.

### 3.4.2.4 Observers

A total of 17 observers, including 1 European, 4 Chinese and 12 Korean aged from 19 to 51, participated in the experiment, as summarised in Table 3.29. All observers had passed the Ishihara test for colour deficiency before starting the experiment.

Table 3.29 Summary of the numbers of observers participating in the experiment

| | Male | Female | All |
|---|---|---|---|
| **European** | 0 | 1 | 1 |
| **Korean** | 5 | 7 | 12 |
| **Chinese** | 4 | 0 | 4 |
| **Total** | 9 | 8 | 17 |

### 3.4.2.5 Experimental Settings and Procedures

Each image, in total 300 including 30 repeats, was presented in random order on a 40" LCD display (see Section 3.2.1) having a grey background with RGB = (128, 128, 128) in a darkened room. Observers were asked to assess six emotional attributes based on 9-category scales by clicking one of the numbered buttons on the screen. The experiments consisted of four sessions. For each session observers rated the images presented. The viewing distance was 1.3m from the surface of the display, where the size of images presented on the display corresponded to a visual field of 22°(h) x 15°(v). The stimulus presented on the display is shown in Figure 3.27. The instructions provided to observers prior beginning the experiment are given in Appendix B.

Figure 3.27 The display layout used for Experiment 2.

### 3.4.3 Experiment 3: Physiological Responses on Chroma and Contrast of Images

#### 3.4.3.1 Test images

The aim of this experiment was to investigate the effect of colour reproduction in terms of chroma and contrast on emotional responses presented through physiological signals. The design of this experiment focused on limiting the number of presentations of the same stimuli to as few as possible to maximise the reactivity of emotional arousal to emotional stimuli. Therefore, the experiment was divided into two parts to examine the effect of chromatic characteristics and contrast of images on physiological responses, separately. Thus images for the two parts of the experiment were selected separately.

The subjects of images were divided into four *a-priori* categories including positive, neutral, negative and personal; the former three categories were collectively called "common images". For the personal images, those included in Experiment 2 were again used. For the common images which included the three *a-priori* categories, six images for each category were selected separately for the two parts of experiment according to the guideline introduced in Sections 3.4.1.1 and 3.4.2.1. The original test images are given in Figures 3.28 and 3.29. The sources of these images are mainly from the Flickr website with permission under Creative Commons 2.0 Attribution license copyright. The addresses for each image are given in Appendix D.

Figure 3.28 The 18 test images selected to investigate the chromatic effect of images in Experiment 3 ( top row: negative; middle: neutral; bottom: positive).

Figure 3.29 The 18 test images selected to investigate the contrast effect of images in Experiment 3 (top row: negative; middle: neutral; bottom: positive).

### 3.4.3.2 Image Rendering Methods

Manipulations of image stimuli were conducted using two colour-appearance attributes lightness (*J*) and chroma (*C*) from the CIECAM02 system as described in Section 3.3.1.2. For chroma manipulation, only achromatic versions of each original image were generated. For contrast manipulation, an inverse sigmoid function was applied to each of original images to represent an effect of reduced contrast.

In total, 76 rendered images including 38 original images (18 in Figure 3.28, 18 in Figure 3.29 and two personal images) were reproduced including original images for 38 test images as given in Table 3.30.

Table 3.30 Summary of number of original and manipulated images with the number of rendering parameters used in Experiment 3.

| | Neutral | | Positive | | Negative | | Personal | | |
|---|---|---|---|---|---|---|---|---|---|
| No. of original images | 6 | 6 | 6 | 6 | 6 | 6 | 1 | 1 | 38 |
| Rendering parameters (No. of levels) | Chroma (1) | Contrast (1) | Chroma (1) | Contrast (1) | Chroma (1) | Contrast (1) | Chroma (1) | Contrast (1) | |
| No. of manipulated images | 6 | 6 | 6 | 6 | 6 | 6 | 1 | 1 | 38 |
| Total | | | | | | | | | 76 |

### 3.4.3.3 Experimental Settings and Procedures

A total of 18 observers including 1 European, 4 Chinese and 13 Korean aged from 19 to 51 participated in the experiment as summarised in Table 3.31. All observers passed the Ishihara test for colour deficiency before starting the experiment.

Each image of the 76 images was presented on a 40" LCD display (see Section 3.2.1) in darken room in random order. Observers were asked to sit in front of the display at a viewing distance of 1.3m wearing sensors to measure heart rate, skin conductance and facial EMG. After the sensors were placed on an observer's body, their task was to focus their eyes on the images presented whilst staying still for whole experimental session. The instructions for this task were given as in Appendix C. Each image was presented for 10 sec followed by a 10-30 sec break before the next cycle.

Table 3.31 Summary of the number of observers participating in the experiment.

| | Male | Female | All |
|---|---|---|---|
| European | 0 | 1 | 1 |
| Korean | 5 | 8 | 13 |
| Chinese | 4 | 0 | 4 |
| Total | 9 | 9 | 18 |

## 3.5 Statistical Methods

The data collected from the psychophysical experiments were first transformed into scale values averaged over all observer responses for each stimulus and for each scale to represent the visual results. The visual results were analysed using correlation coefficients, root mean square and principal component analysis. This section describes the statistical measures that were used to analyse the experimental data. Cohen's "*Statistical power analysis for the behavioral sciences*" (Cohen, 1988) and Lewis' "*Statistics Explained*" (Lewis & Traill, 1999) were used as the general reference in this section.

### 3.5.1 Root Mean Square

Root mean square (RMS), as given in Equation (3-11), indicates the extent to which two data sets agree with each other.

$$RMS = \sqrt{\frac{\sum (x_i - y_i)^2}{N}} \qquad (3\text{-}11)$$

where $x_i$ and $y_i$ are values of two data sets for specific sample $i$ and N is the number of test images. Note that RMS is equivalent to standard deviation when $y_i$ is equal to the mean value of $x_i$.

The minimum value of RMS is 0, indicating perfect agreement between the two data sets. Although the maximum value depends on the range of both data sets, larger RMS values indicate less agreement regardless of the maximum value.

In the present study, RMS was used to reveal the level of repeatability and accuracy in the visual results for individual observer.

### 3.5.2 Correlation Coefficient

The Pearson product-moment correlation coefficient (also called Pearson correlation coefficient) indicates the strength and direction of a linear relationship between two sets of data.

The correlation coefficient is defined in Equation (3-12):

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\left[\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2\right]^{1/2}} \qquad (3\text{-}12)$$

where $x_i$ and $y_i$ are individual values of two data sets for stimulus $i$; $\bar{x}$ and $\bar{y}$ are the mean values of the two data sets.

The correlation coefficient is defined only if both of the standard deviations are finite and non-zero. The coefficients range from -1.0 to 1.0, where -1.0 represents a perfect negative correlation and 1.0 a perfect positive correlation. The value of zero indicates a non-linear relationship between the two data sets.

Cohen suggested the interpretations for correlations in psychophysical research as shown in Table 3.32; however, the plot of the two data sets needs be examined together with the interpretation of correlation coefficients because a perfect positive correlation does not indicate a perfect agreement between two data sets. For a perfect agreement between two data sets, all the data points should be located on the 45° line.

Table 3.32 The interpretation of a correlation coefficient.

| Extent of Correlation | Negative | Positive |
|---|---|---|
| Small | -0.29 to -0.10 | 0.10 to 0.29 |
| Medium | -0.49 to -0.30 | 0.30 to 0.49 |
| Large | -0.50 to -1.00 | 0.50 to 1.00 |

In the present study, the correlation coefficient $r$ was used as a measure of linear correlation between a pair of data sets and applied to all experiments to determine correlation between experimental data.

The square value of the correlation coefficient $r$ (called as the coefficient of determination) $R^2$ is a measure of the fraction of the total variance of a data set that can be explained by the variance of another data set. In the present study, $R^2$ was used to measure the performance of prediction of the models developed. The $R^2$ values range from 0 to 1: 0 indicates that none of the variance of the visual data is accounted for by the model and 1 indicates that the visual data can be determined perfectly by the model.

The correlation coefficient can be also used to examine the significance of each predictor in models developed. This can be done by comparing two correlation coefficients for a data set of visual results: one for the complete model which includes all the predictors and the other for the incomplete model which includes one variable excluded from the complete model. If all predictors are significant in prediction, the correlation coefficients for any of the incomplete models and visual data will have significantly smaller values than for the original data. The procedure is given below.

a) Generate several incomplete models from the original one by taking away each of the predictors.

b) Calculate the correlation coefficients values ($r_1 \ldots r_n$) for each of the incomplete models and for the complete model.

c) To compare $r_1$ and $r_2$, find $Z_1$ and $Z_2$ corresponding to $r_1$ and $r_2$ according to Equation (3-13).

$$Z_n = \frac{1}{2} Ln\left(\frac{1+r_n}{1-r_n}\right) \qquad (3\text{-}13)$$

d) The null hypothesis is that the population coefficients are equal, i.e. $H_0$: $\rho_1 - \rho_2 = 0$.

The alternative hypothesis $H_1$ is usually one of the two:

(i) $\rho_1 - \rho_2 \neq 0$ (two-tailed) or

(ii) $\rho_1 - \rho_2 > 0$ or $\rho_1 - \rho_2 < 0$ (both one-tailed).

e) Choose a level of significance and read the critical value from the normal table ($Z_c$=1.96 for 95% with a two-tailed test and 1.64 for 95% with a one-tailed test).

f) Calculate the test statistics using Equation (3-14):

$$z = \frac{Z_1 - Z_2}{\sigma}\text{, where } \sigma = \sqrt{\frac{1}{n_1 - 3} + \frac{1}{n_2 - 3}} \qquad (3\text{-}14)$$

g) If $|Z| > Z_c$, reject the null hypothesis.

If the test result shows that the correlation coefficient for an incomplete model is significantly smaller than the one for the complete model, the predictor excluded from the complete model is significant for prediction. In the present study, this method was applied to examine the significance of each predictor in the emotion models developed in Chapter 6.

### 3.5.3 Principal Component Analysis

Principal component analysis (PCA) is a method to simplify multidimensional data sets to smaller numbers of dimensions for analysis by removing some highly-correlated variables from the data sets and replacing them with a smaller number of independent variables. This is used to identify the underlying criteria that explain the correlations between the variables.

The extraction of principal components begins by determining the *eigenvectors* and *eigenvalues* of a covariance matrix. Eigenvectors and eigenvalues are defined as the solution to Equation (3-15):

$$\mathbf{A}\mathbf{v}_k = \lambda_k \mathbf{v}_k \quad (k=1\ldots n) \tag{3-15}$$

where $\mathbf{A}$ is a real and symmetric matrix of size nxn, $\mathbf{v}_k$ are eigenvectors of the matrix $\mathbf{A}$ and $\lambda_k$ are the associated eigenvalues. Usually, a few components can account for most of the variation and these components can be used to replace the original variables.

In the present study, $\mathbf{A}$ is the covariance matrix of experimental data (averaged scale values) for a set of semantic scales. The output from PCA is the classification results of semantic scales in terms of *component loadings*, that is the correlation coefficients between semantic scales and the principal components extracted. These methods were applied to reveal the inter-relationships between semantic scales used in all the psychophysical experiments.

## 3.6 Summary

In the present study, two psychophysical and two physiological experiments were conducted. The aims and specific setups for each experiment including test images, image rendering methods, semantic differential scales to measure the emotional responses, observers, viewing conditions and procedures were described. The general settings applied to the experiments were also illustrated. These included the specification and performance of the TSR and spectrophotometer used; the colorimetric characteristics and characterisation methods of display and printer used and the characteristics of the physiological instruments used to measure heart rate, skin conductance and facial EMG. Finally, the statistical methods applied to analyse the visual results were explained. These include root mean square (R MS) for evaluation of observer variation, Pearson correlation coefficient r for investigation of the linear relationship between two sets of data, the coefficient of determination $R^2$, a measure of the performance of prediction of the models developed, the significance test of each predictor in models using correlation coefficients and principal component analysis methods (PCA) used to identify the underlying interrelation between semantic scales.

# Chapter 4 Experiment 1: Impact of Colour-Appearance Attributes on Emotion for Printed Images Based on Psychophysical Method

The aim of this experiment was to reveal the relationship between colour-appearance attributes of images and emotional responses evoked by images and also to find any differences in these relationships according to image content (not only including positive and negative ones but also those having personal attachment). It includes the development of quantitative models of image emotion as functions of colorimetric quantities with regards to the effect of image content.

To achieve these objectives, a set of psychophysical and physiological experiments were designed and performed. In this chapter, only the results from the psychophysical experiments will be discussed. Analyses for the physiology results will be discussed in Chapter 7. In the psychophysical part of Experiment 1, 29 observers (9 British and 20 Chinese) were asked to assess 178 original and manipulated images in terms of five emotion scales: *pleasant-unpleasant, exciting-calming, like-dislike, natural-unnatural* and *appealing-unappealing*. Image manipulation methods were described in Section 3.4.1.2.

The experimental data were transformed into average scores for four subgroups of observers: female, male, British and Chinese. This chapter describes the results for following topics: cultural difference and gender difference, comparison of emotion scales, influence of image subject and quantification of the relationship between colour characteristics and image emotion scales.

## 4.1 Observer Variability

Observer variability was investigated to test the performance of observers who took part in this experiment in two different ways: accuracy and repeatability. The statistical measure used to represent variation was RMS (Root Mean Square) as defined in Section 3.5.1.

### 4.1.1 Observer Accuracy (Inter-observer Variability)

Observer accuracy indicates how the visual result of individual observer varies against the mean of all observers' results. The RMS values can be seen as the distance between the individual visual results and the mean values of each emotion scale for the group. The smaller the RMS value, the smaller distance and higher the accuracy.

Table 4.1 summarises observer accuracy for two gender groups and cultural groups in terms of mean RMS for the group. *Exciting-calming* shows the highest accuracy for British and Chinese groups as well as for male and female groups.

Natural-unnatural shows the poorest in terms of group mean. The accuracy for British and Chinese groups were found to be similar for all scales. The accuracy values in female and male groups were also found to be similar. The overall accuracy value of 1.35 indicates reasonable levels of observer accuracy for this experiment.

Table 4.1 Inter-observer variability in terms of RMS

| | pleasant-unpleasant | exciting-calming | natural-unnatural | like-dislike | appealing-unappealing | mean |
|---|---|---|---|---|---|---|
| British | 1.28 | 1.17 | 1.52 | 1.39 | 1.43 | 1.36 |
| Chinese | 1.20 | 1.11 | 1.48 | 1.39 | 1.50 | 1.34 |
| Female | 1.22 | 1.11 | 1.48 | 1.37 | 1.45 | 1.33 |
| Male | 1.24 | 1.17 | 1.52 | 1.42 | 1.53 | 1.38 |
| **mean** | 1.23 | 1.14 | 1.50 | 1.39 | 1.48 | 1.35 |

### 4.1.2 Observer Repeatability (Intra-observer Variability)

Observer repeatability indicates how repeatable the result is for each individual observer. The RMS values can be seen as the variation between first and second response for the same image for an individual. The smaller the RMS value, the smaller the variation and more likely the responses is repeatable. Table 4.2 summarises RMS values for the two gender groups and cultural groups in terms of mean RMS for the group. *Pleasant-unpleasant* shows the highest repeatability and *like-dislike* the lowest. Differences between repeatability values for the British and Chinese groups are found for all scales, with a value of 0.25 RMS units on average. A difference between female and male groups is also found for all scales, with a mean value of 0.29 RMS units.

Table 4.2 Intra-observer variability in terms of RMS

| | pleasant-unpleasant | exciting-calming | natural-unnatural | like-dislike | appealing-unappealing | mean |
|---|---|---|---|---|---|---|
| British | 1.41 | 1.50 | 1.69 | 1.64 | 1.40 | 1.53 |
| Chinese | 1.66 | 1.72 | 1.82 | 1.89 | 1.82 | 1.78 |
| Female | 1.67 | 1.76 | 1.86 | 1.87 | 1.78 | 1.79 |
| Male | 1.35 | 1.41 | 1.60 | 1.68 | 1.49 | 1.50 |
| **mean** | 1.52 | 1.60 | 1.74 | 1.77 | 1.62 | 1.65 |

## 4.2 Cultural and Gender Differences

The responses for five emotion scales by British and Chinese observer groups were compared using Pearson's correlation coefficient (R) (see Section 3.5.2) to investigate cultural differences. To exclude any gender effects, the comparison was conducted using only the data from female observers. The numbers of observers in both groups used in the comparison were 8 for British and 12 for Chinese. As shown in Figure 4.1, the results show high correlation, with correlation coefficients ranging from 0.74 to 0.86 between two observer groups except for *exciting-calming,* which has a correlation coefficient of 0.53. However, there is a reasonable agreement between British and Chinese groups as the data points are aligned close to the 45° line.

For further investigation of the cultural differences, the method of principal component analysis (PCA) (see Section 3.5.3) was applied to clarify the interrelationship of five emotion scales for each of two observer groups. The components extracted from British and Chinese groups are listed in Table 4.3 (a) to (b). In both observer groups, five emotion scales were classified into two subgroups accounting for 90.58% and 91.95% of the total variance for responses of British and Chinese groups, respectively. The two subgroups were labelled component 1 and component 2. For both subgroups, four scales *like-dislike, pleasant-unpleasant, appealing-unappealing,* and *natural-unnatural* were combined into component 1, while *exciting-calming* were regarded as component 2. This indicates that British and Chinese groups have a very similar underlying structure of their emotional responses to images for female observers. However, the number of observers for the data used in this comparison might be too small to have a concrete conclusion and further study will be needed to do so.

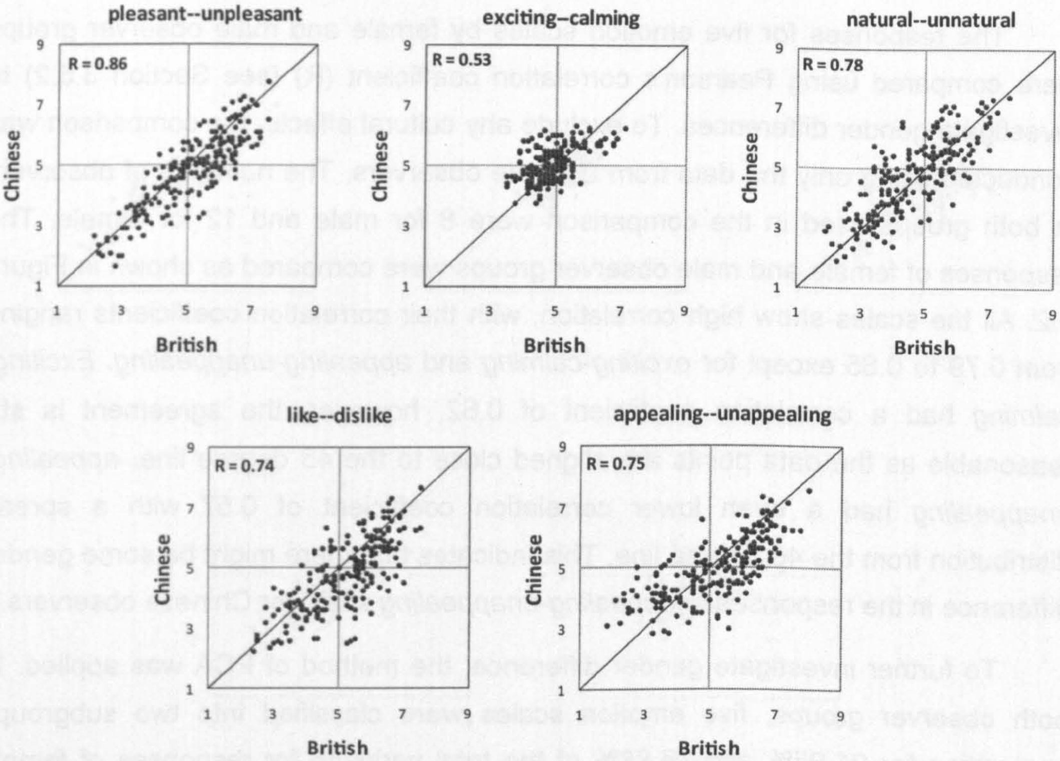



Figure 4.1 Comparisons of emotion responses between British and Chinese female observers.

Table 4.3 Comparisons of emotion responses between British and Chinese female observers; (a) British observers, (b) Chinese observers.

(a)

| | component 1 | component 2 |
|---|---|---|
| % of variance | 68.56 | 22.02 |
| like-dislike | **0.975** | 0.077 |
| appealing-unappealing | **0.974** | 0.102 |
| pleasant-unpleasant | **0.971** | 0.068 |
| natural-unnatural | **0.764** | -0.374 |
| exciting-calming | 0.051 | **0.970** |

(b)

| | component 1 | component 2 |
|---|---|---|
| % of variance | 69.30 | 22.65 |
| like-dislike | **0.982** | 0.109 |
| appealing-unappealing | **0.935** | 0.294 |
| pleasant-unpleasant | **0.902** | 0.214 |
| natural-unnatural | **0.896** | -0.140 |
| exciting-calming | 0.097 | **0.984** |

The responses for five emotion scales by female and male observer groups were compared using Pearson's correlation coefficient (R) (see Section 3.5.2) to investigate gender differences. To exclude any cultural effects, the comparison was conducted using only the data from Chinese observers. The numbers of observers in both groups used in the comparison were 8 for male and 12 for female. The responses of female and male observer groups were compared as shown in Figure 4.2. All the scales show high correlation, with their correlation coefficients ranging from 0.79 to 0.85 except for *exciting-calming* and *appealing-unappealing*. *Exciting-calming* had a correlation coefficient of 0.62, however, the agreement is still reasonable as the data points are aligned close to the 45 degree line. *appealing-unappealing* had a even lower correlation coefficient of 0.57 with a spread distribution from the 45 degree line. This indicates that there might be some gender difference in the responses to *appealing-unappealing* scale for Chinese observers.

To further investigate gender difference, the method of PCA was applied. In both observer groups, five emotion scales were classified into two subgroups accounting for 91.95% and 86.88% of the total variance for responses of female and male groups, respectively. The two subgroups were labelled component 1 and component 2. In both groups, two principal components - component 1 comprising four scales of *like-dislike, pleasant-unpleasant, appealing-unappealing*, and *natural-unnatural* and component 2 accounting for *exciting-calming* - were extracted as shown in Table 4.4(a)-(b). This suggests that the underlying structures for the five emotion scales are almost the same for female and male observers. However, note that the component scores were very close with 0.683 for component 1 and 0.682 for component 2 for two subgroups for *appealing-unappealing* scale in the result from male observers. This indicates that the scale was regarded to include the property of component 2 for Chinese male observers. Thus, further study will be needed to have a concrete conclusion with a sufficient number of observers.

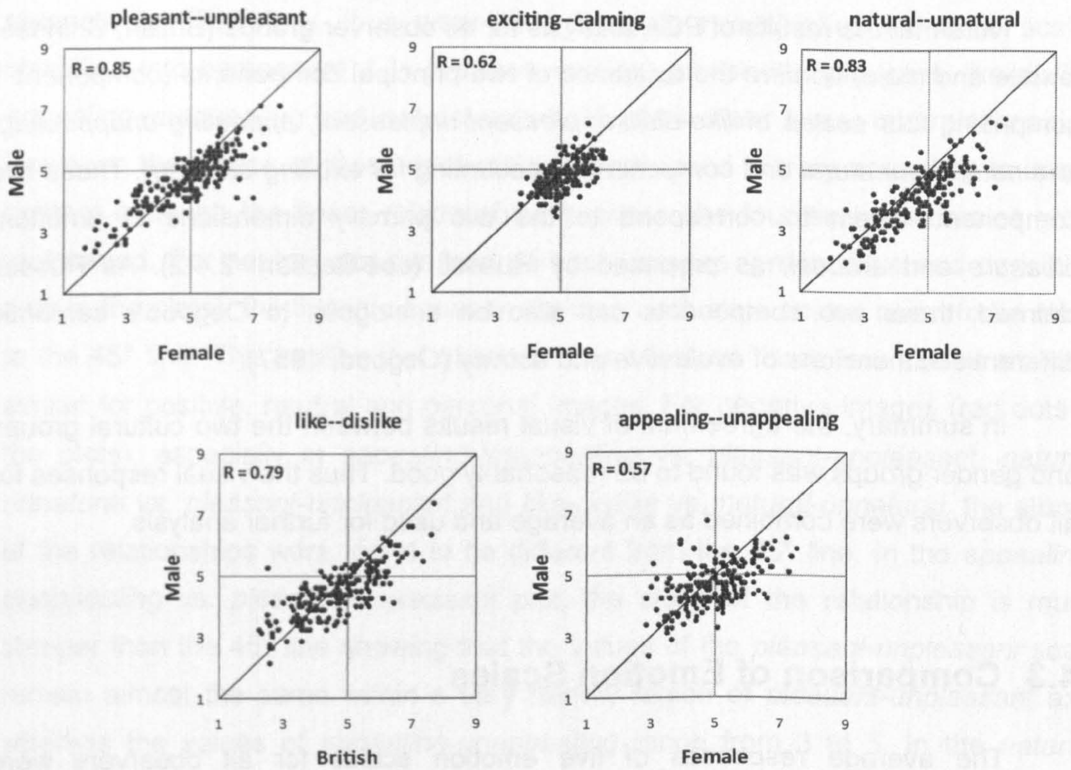



Figure 4.2 Comparisons of emotion responses between Chinese female and male observers.

Table 4.4 Comparisons of emotion responses between Chinese female and male observers; (a) Female Observers, (b) Male Observers.

(a)

| | component 1 | component 2 |
|---|---|---|
| % of variance | 69.30 | 22.65 |
| like-dislike | **0.982** | 0.109 |
| appealing-unappealing | **0.935** | 0.294 |
| pleasant-unpleasant | **0.902** | 0.214 |
| natural-unnatural | **0.896** | -0.140 |
| exciting-calming | 0.097 | **0.984** |

(b)

| | component 1 | component 2 |
|---|---|---|
| % of variance | 59.51 | 27.37 |
| like-dislike | **0.963** | 0.163 |
| pleasant-unpleasant | **0.893** | -0.046 |
| natural-unnatural | **0.885** | 0.089 |
| appealing-unappealing | **0.683** | 0.628 |
| exciting-calming | -0.029 | **0.968** |

Note that the results of PCA analysis for all observer groups (British, Chinese, female and male) confirm the existence of two principal components (component 1 comprising four scales of *like-dislike, pleasant-unpleasant, appealing-unappealing,* and *natural-unnatural* and component 2 accounting for *exciting-calming*). These two components seem to correspond to the two primary dimensions of emotion, *pleasure* and *arousal,* as proposed by Russell (see Section 2.4.2). As Russell claimed, these two components can also be analogous to Osgood's semantic differential dimensions of *evaluative* and *activity* (Osgood, 1957).

In summary, the agreement of visual results between the two cultural groups and gender groups was found to be reasonably good. Thus the visual responses for all observers were combined as an average and used for further analysis.

## 4.3 Comparison of Emotion Scales

The average responses of five emotion scales for all observers were compared to that of each scale using scatter plots Figure 4.3 and Pearson's correlation coefficient to reveal the interrelationship. The relationship between *pleasant-unpleasant* and *exciting-calming* illustrates a 'boomerang shape' distribution between the two primary dimensions of emotion - pleasure (*pleasant-unpleasant*) and arousal (*exciting-calming*) - with two wings towards the highly exciting regions, which is consistent with previous studies using IAPS pictures (see Section 2.5.4.1). This indicates that an image rated as highly pleasant or as highly unpleasant was also rated as highly exciting; images which judged to be neutral on the pleasantness scale were found to score low in arousal. However, comparing the shape of this distribution to those presented in Lang and Bradley's studies (see Section 2.5.4.1), the two wings extending towards highly exciting corners do not seem to be so distinct and there seem to be missing points in those regions. This might be because of extremely arousing image contents that are very pleasant or unpleasant pictures (such as a dead body, mutilation, or sexual erotica) are excluded as stimuli in this experiment.

Overall, the *exciting-calming* scale shows low correlation with the other four scales, having correlation coefficients less than 0.25. *Pleasant-unpleasant* is very highly correlated with *like-dislike* and *appealing-unappealing,* having correlation coefficients of 0.95 and 0.93, respectively. *Like-dislike* is also very highly correlated with *appealing-unappealing,* having a correlation coefficient of 0.95. *Natural-unnatural* also shows high correlation with *pleasant-unpleasant, like-dislike* and *appealing-unappealing,* having correlation coefficients of 0.71, 0.83 and 0.79, respectively. Therefore, it is clear that these four evaluative semantic scales classified into component 1 in previous section- *pleasant-unpleasant, like-dislike, appealing-unappealing* and *natural-unnatural-* show clear linear interrelationships. However, the slopes of those relationships were found to vary according to image content although the linear relationships between the four semantic scales were maintained. For neutral, positive and personal images (green, blue and dark blue dots in the plots), the linearity between the four evaluative scales seem to be close to the 45° line. This implies that observer responses on these four scales are very similar for positive, neutral and personal images. For negative images (red dots in the plots), especially in *appealing-unappealing* vs. *pleasant-unpleasant*, *natural-unnatural* vs. *pleasant-unpleasant* and *like-dislike* vs. *natural-unnatural*, the slopes of the relationships were found to be different from the 45° line. In the *appealing-unappealing* vs. *pleasant-unpleasant* plot, the slope of the relationship is much steeper than the 45° line showing that the values of the *pleasant-unpleasant* scale remain almost the same within a very narrow region of *pleasant-unpleasant* axis whereas the values of *appealing-unappealing* range from 3 to 5. In the *natural-unnatural* vs. *pleasant-unpleasant* plot, the values of *pleasant-unpleasant* scale vary only within a very narrow region of the *pleasant-unpleasant* axis whereas the values of *natural-unnatural* range from 2.5 to 5.5. Similarly in the *like-dislike* vs. *natural-unnatural* plot, the values of the *like-dislike* scale vary within a relatively shorter range than for the *natural-unnatural* scale. This indicates that some extent of *unpleasantness* for negative image content would be regarded natural or appealing. In addition, some extent of *disliking* for negative images would also be regarded natural.

Scatter plots of the relative scale values between original and manipulated images show the interrelationship between the five scales much clearer, as shown in Figure 4.4. In the plots, the *exciting-calming* scale shows low correlation with the other four scales. The four evaluative scales illustrate clear linear relationships between each scale for all categories of images; however, it can be noted that responses for negative images (in red dots), vary in relatively smaller range of scales than for the other categories of images. This indicates that emotional responses for negative images are less affected by changes in colour attributes. This will be described in further detail in the following section.

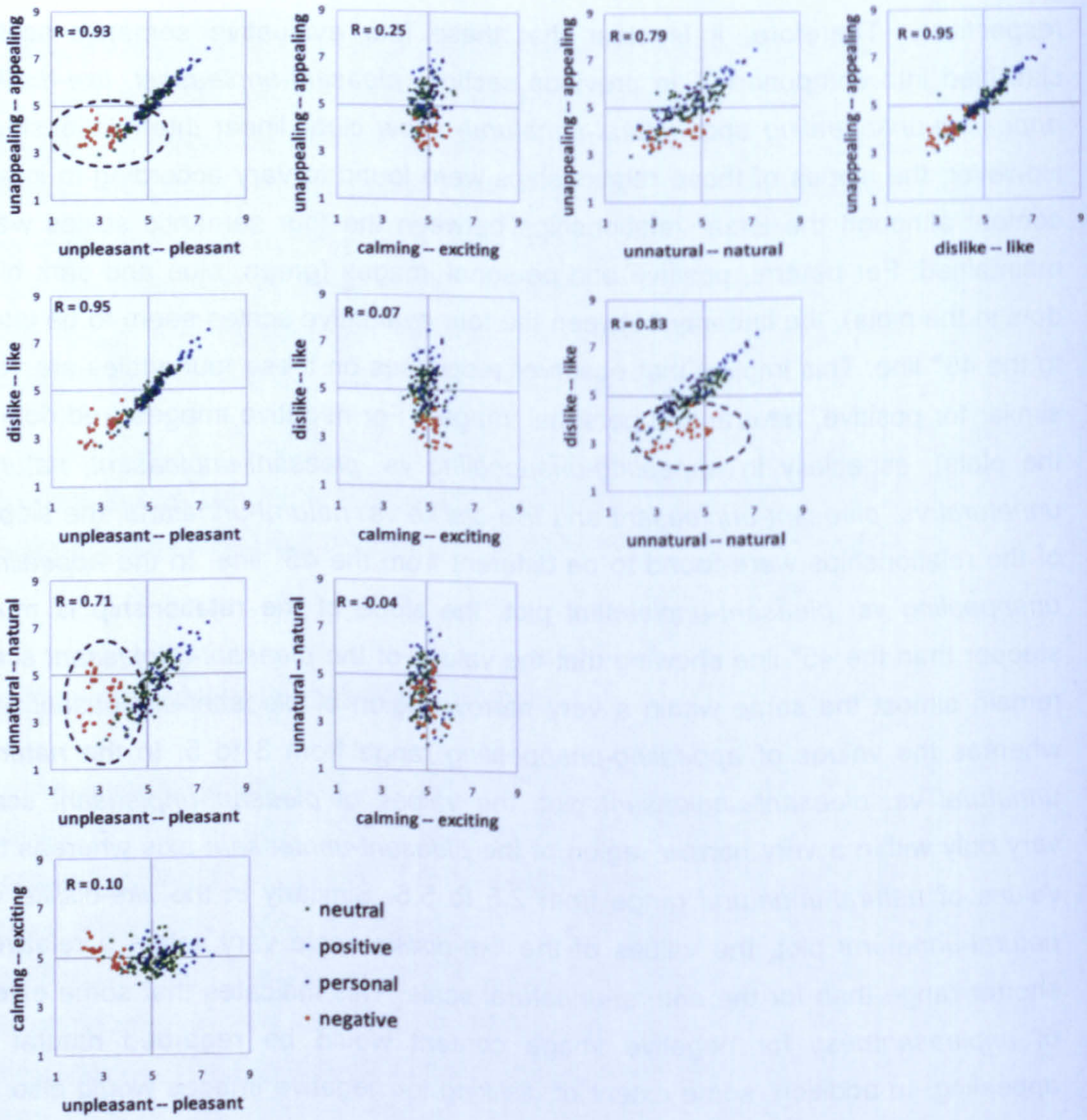



Figure 4.3 Comparisons of the observer responses between the five semantic scales across all image subjects and all observers based on absolute scale values.

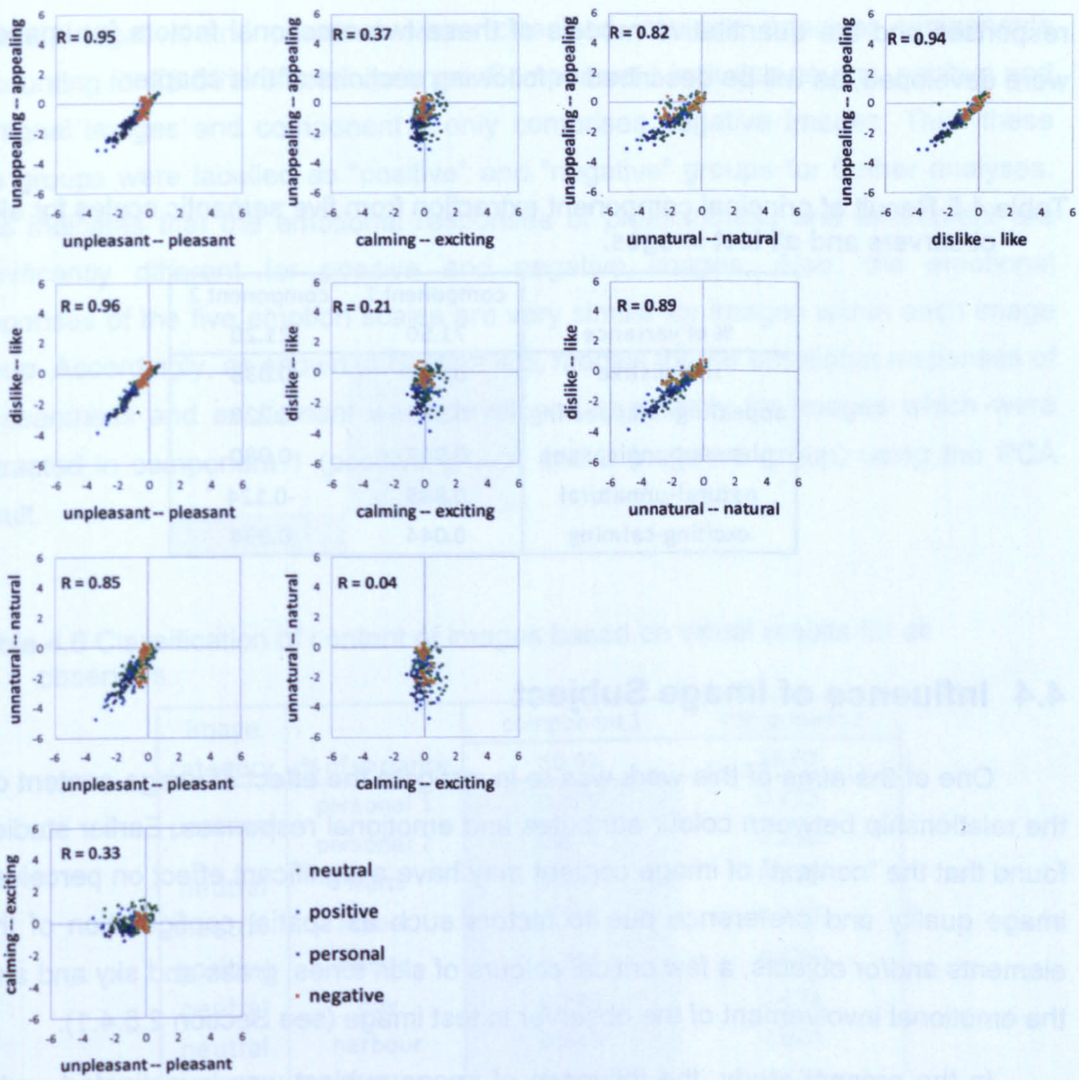



Figure 4.4 Comparisons of the observer responses between the five semantic scales across all image subjects and all observers based on the relative scale values between original and manipulated images.

PCA analysis was applied to check the underlying structures of all observers' responses and the result is shown in Table 4.5. Similar to the results for cultural and gender difference (see Section 4.2), two principal components of *pleasure* and *arousal* were maintained for the result of all observers accounting for 71.5% and 21.2% of total variance for components 1 (*pleasure*) and 2 (*arousal*), respectively. This result supports the hypothesis that the four scales- *pleasant-unpleasant, like-dislike, appealing-unappealing* and *natural-unnatural-* are highly associated with each other and that *exciting-calming* is independent of all the other scales. As mentioned in the previous section, these two components seem to correspond to *pleasure* and *arousal* as proposed by Russell (see Section 2.4.2) and the semantic differential dimensions of *evaluative* and *activity* by Osgood (see Section 2.4.5.1). In the present study, further analysis was carried out on these two factors of responses and the quantitative models of these two emotional factors for images were developed, as will be described in following sections of this chapter.

Table 4.5 Result of principal component extraction from five semantic scales for all observers and all test images.

| | component 1 | component 2 |
|---|---|---|
| % of variance | 71.50 | 21.20 |
| like-dislike | **0.987** | 0.038 |
| appealing-unappealing | **0.959** | 0.220 |
| pleasant-unpleasant | **0.947** | 0.080 |
| natural-unnatural | **0.885** | -0.124 |
| exciting-calming | 0.044 | **0.994** |

## 4.4 Influence of Image Subject

One of the aims of this work was to investigate the effect of image content on the relationship between colour attributes and emotional responses. Earlier studies found that the "context" of image content may have a significant effect on perceived image quality and preference due to factors such as spatial configuration of the elements and/or objects, a few critical colours of skin tones, grass and sky and also the emotional involvement of the observer in test image (see Section 2.5.4.1).

In the present study, the influence of image subject was investigated under two assumptions. These were that (1) emotional responses were affected by the level of image pleasantness and (2) the responses were affected by the personal values of images to the observers. According to the first assumption, images were selected by three *a-priori* categories according to the level of pleasantness (based on the image content): positive, neutral and negative groups (see Section 3.4.1.1). Additionally, images provided by the observers (i.e. photos of the observer's family members or friends) were included in the experiment to investigate the effect of personal attachment to images. The result was then compared with common images, i.e. the "generic images" that had no personal values to those observers.

The influence of image subject on the emotional responses were analysed to find any statistical similarity between image groups. To do this, PCA was applied to group images showing similar trends among the four *a-priori* categories (neutral, positive, negative and personal). As a result, the responses of emotional responses were found to be significantly affected by the level of pleasantness of image content rather than by the personal values of images to observers. Table 4.6 shows that ten images used in this experiment -including four *a-priori* categories of positive, neutral, negative and personal- were classified into two principal components accounting for 78.69% of total variance. Component 1 includes neutral, positive and personal images and component 2 only comprises negative images. Thus these two groups were labelled as "positive" and "negative" groups for further analyses. This indicates that the emotional responses of *pleasantness* and *excitement* are significantly different for positive and negative images. Also, the emotional responses of the five emotion scales are very similar for images within each image group. Accordingly, as shown in Section 4.5, models for the emotional responses of *pleasantness* and *excitement* were developed separately for images which were extracted in component 1 (positive group) and 2 (negative group) using the PCA result.

Table 4.6 Classification of content of images based on visual results for all observers.

| Image category | | component 1 | component 2 |
|---|---|---|---|
| | % of variance | 50.02 | 28.67 |
| personal | personal 1 | **0.889** | 0.315 |
| | personal 2 | **0.874** | 0.338 |
| neutral | fruits | **0.855** | 0.229 |
| neutral | indoor | **0.795** | 0.320 |
| positive | horses | **0.784** | 0.474 |
| neutral | boy | **0.726** | 0.432 |
| neutral | harbour | **0.645** | 0.620 |
| positive | family | **0.600** | 0.517 |
| negative | rubbish | 0.257 | **0.861** |
| | baby | 0.319 | **0.833** |

## 4.5 Quantification of Image Emotion

One of the aims in this chapter is to develop models of emotion factors in terms of factors for complex images as a function of colour attributes of images such as colourfulness and lightness contrast. From results of the inter-relationship between scales studied in Section 4.3, two emotional components were extracted: *pleasantness* and *excitement*. These two factors of emotion were found to have different underlying structures for "positive" and "negative" images depending on the pleasantness levels of images as discussed in Section 4.4. As will be described in this section, quantitative models of two emotion factors for images, *pleasantness* and *excitement,* were developed for "positive" and "negative" image groups. Then within positive image group, the influence of personal values of images to observers on the relationship between colour attributes of images and emotional responses were compared for personal and common images.

Image colourfulness was determined by the median colourfulness in CAM02-UCS (see Section 2.3.4.4) for the image. Image contrast was determined using the standard deviation of image lightness in CAM02-UCS. It was found that these two colour attributes had a clearer relationship with the visual results expressed by the relative difference between the original and manipulated, than those of the absolute scale values. It seems that the relative difference serves as a normalisation process to minimise the image dependency problem.

### 4.5.1 Pleasant-Unpleasant

To investigate the relationship between pleasantness responses and colour attributes of images, the pleasantness responses obtained for 10 images were averaged at each manipulation level within each *a-priori* category. Then, according to the results concluded from Section 4.4, the average values for four categories were divided into two subgroups of "positive" (including positive, neutral and personal images) and "negative" (including negative images only).

Figure 4.5 (a) shows changes in pleasantness responses plotted against the colour attributes of images colourfulness for "positive" group including positive (empty square symbols in the plot), neutral (crosses) and personal (empty triangles) among the four *a-priori* categories. Overall, Figure 4.5 (a) shows that as image colourfulness increases or decreases, the pleasantness for positive images decreases significantly. Neutral and positive images show very similar trends in the extent of changes to pleasantness responses according to colourfulness changes. Personal images show a slightly sharper trend than the others, however this does not seem to be a large difference. That is, when the colourfulness is rendered (either making it higher or lower), the positive image is regarded as less pleasant than the original.

As shown in Figure 4.5 (b), the changes in lightness contrast also result in lower value for pleasantness, whether the lightness contrast increases or decreases for the positive group of images. Very similar trends were seen for all three categories of images: neutral (solid diamonds), positive (solid squares) and personal (solid triangles).

Similar results can be found in previous studies studied by Fedorovskaya *et al.* (1997) and Calabria *et al.* (2003a). Fedorovskaya (1997) reported that original images were found to be ranked as the most, or the second most, preferred depending on images among many other manipulated versions in terms of chroma in the scale of image quality and naturalness. Calabria (2003a) studied the image preference of various manipulated versions in terms of chroma by multiplying by a scalar from 0 to 1.2 with a 0.2 interval. The results showed that the original level of chroma multiplied by scalar 1 appeared to be the most preferred image among many versions for pictorial images. This study also showed that the original images contrast were found to be ranked as the most or the second most preferred images depending on images among many other manipulated versions in terms of lightness. From the results of previous studies and the present study, it might be believed that colour reproduction schemes such as chroma and lightness contrast renderings for "positive" images tend to reduce pleasant feelings. Note that "positive" includes three categories of images and these include most of images which can be found in our daily lives.

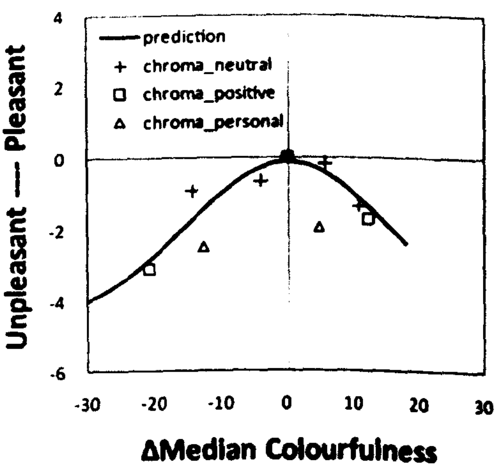
Regarding the result which is the original images were always most preferred and any changes in colourfulness and contrast always lead to decrease of image pleasantness, there is an issue which needs to be pointed out. In the present study, 8 original images were selected according to several criteria in order to cover a wide range of pleasantness level, a wide variety of scenes such as sky, grass and human skins, and a reasonably wide range of colours in terms of hue, lightness and chroma. In addition, there was one more criterion which is a reasonably high level of image quality. The purpose of this criterion was to help observers focus on the affective quality rather than the image quality itself so that observers' responses can be independent from the image quality. Thus, all the original images were well-balanced in colour and almost at the highest quality which can be achieved for them. Then, these images were modified in terms of one of image colour attributes through several manipulation functions. In the manipulation process, it is possible that the colour balance and image quality could get worse than for the original as only one attribute were rendered. Also for the rendering of colour attributes, the level of change in each attribute was large enough to be perceived easily and to stimulate the emotional reactions, however, it should not be so large to generate significant defects. However, the degradation in image quality can be also caused by the large changes in colour attributes.

Another possibility for the most preferred results for original images could be due to the symmetric manipul ations of colour attributes f rom the original. This indicates that the original image is always in the middle in the magnitude of the manipulated attributes. It always tends to be an average as an optimised version in manipulation of an attributes.

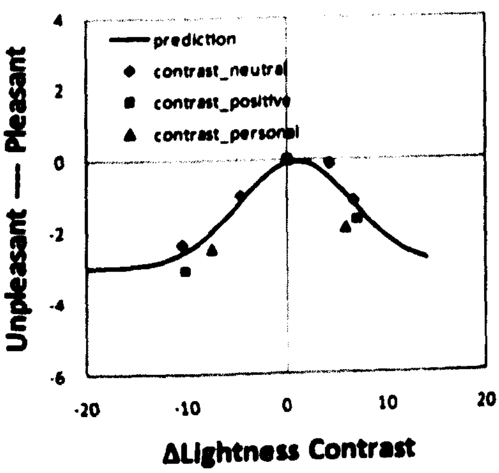
The relationship shown in Figure 4.5(a), the change in image pleasantness ($\Delta P$) for positive images, was modelled as a function of the change in image colourfulness using the *Log Normal Distribution Function* (Limpert, 2001) for best fit of experimental data that showed skewed bell-shaped curves. Although various other functions were tried, this fitted the trend of data well and was easily adjusted to fit the shape of the data. The model is given in Equation (4-1):

$$\Delta P(\Delta M) = k_0 + \frac{k_1}{\sigma\sqrt{2\pi}(k_2\Delta M - k_3)} e^{\frac{-[ln(k_2\Delta M - k_3) - \mu]^2}{2\sigma^2}} \qquad (4\text{-}1)$$

where $\Delta M$ is the change in image colourfulness values from an original image to the manipulated version; $\mu$ and $\sigma$ are shape parameters; $k_1$ is the amplitude of the distribution curve; $k_3$ is a location parameter; and $k_0$ and $k_2$ are constants. This equation was also used to model the relationship between pleasantness and contrast based on the data for images manipulated in terms of contrast. These coefficients were optimised for the best fit of experimental data separately for positive images manipulated in terms of colourfulness and contrast. Table 4.7(a) shows the coefficients optimised for models in Equation (4-1) to predict pleasantness. These models were found to determine the experimental data of image pleasantness to the extent of 80% and 94% for colourfulness and contrast manipulated images, respectively. Note that these $R^2$ values were computed for two separate data sets of chroma and lightness contrast manipulations.




(a)




(b)

Figure 4.5(a)-(b) Changes in image pleasantness plotted against changes in image colourfulness(a) and lightness contrast(b) together with the model prediction for each relationship in the positive group of images, including neutral ((a) crosses;(b) diamonds), positive ((a) empty squares; (b) solid squares) and personal((a) empty triangles; (b) solid triangles) images.

Figures 4.6(a) and (b) show changes in image pleasantness responses plotted against the colour attributes of image colourfulness and lightness contrast for the "negative" group of images. For images with negative content, decreasing image colourfulness results in higher pleasantness, whereas the effect of increasing colourfulness is similar for "positive" images, as shown in Figure 4.6 (a). However, the extent of change in pleasantness is not as significant as for positive images. As shown in Figure 4.6 (b), the increase in lightness contrast also results in lower pleasantness for negative images; however, the magnitude of this is smaller than for positive images. This suggests that adjusting unpleasant feelings for negative images though changes in colourfulness and contrast seems to be relatively more difficult than for positive images. The result shows the possibility of enhancing the pleasantness of negative images by making them less colourful; however, to confirm these trends on negative images, further experiments need to be conducted as only three variations of each colour attributes in terms of colourfulness and contrast were studied in this experiment.

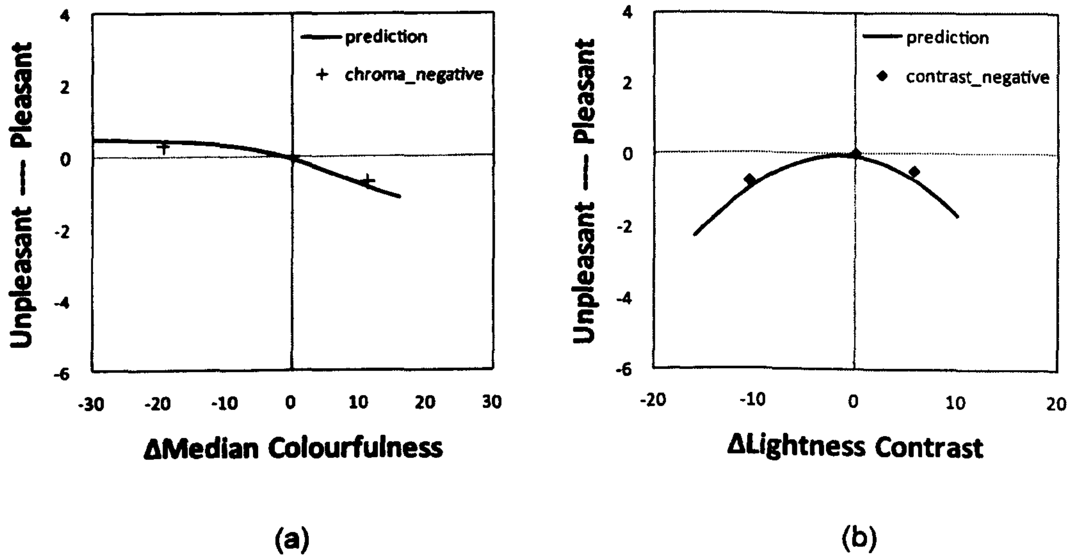



Figure 4.6(a)-(b) Changes in image pleasantness plotted against changes in image colourfulness (a) and lightness contrast (b) together with the model prediction for each relationship in the negative group.

Models of pleasantness for negative images as a function of each colour attribute were also developed. For the relationship between pleasantness and colourfulness, the *Boltzmann Distribution Function* showed the best fit to experimental data that followed inverted S-shaped curves. The model is given in Equation (4-2).

$$\Delta P(\Delta M) = k_0 + (k_1 - k_0) \times \left(1 + e^{\frac{(\Delta M - k_2)}{\alpha}}\right)^{-1} \quad (4\text{-}2)$$

where $\Delta M$ is the change in image colourfulness from an original image to the manipulated version; and $k_0$ to $k_2$ are constants. These coefficients were optimised to best fit the experimental data for negative images manipulated in terms of colourfulness. For the model as a function of contrast, Equation (4-1) was used and all coefficients were optimised for the best fit. Table 4.7(b) shows the coefficients optimised for these models in Equations (4-1) and (4-2) for predicting pleasantness for negative images. These models were found to determine 99% and 100% of the variance in the experimental data of pleasantness for colourfulness and contrast manipulated images, respectively.

Table 4.7(a)-(b) Coefficients of the image pleasantness models shown in Equations (4-1) and (4-2) as functions of colourfulness and lightness contrast for (a) positive and (b) negative images.

(a)

| | $k_0$ | $k_1$ | $k_2$ | $k_3$ | $\mu$ | $\sigma$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|---|---|
| $\Delta P(\Delta M)$ | -4.70 | 5.10 | -0.03 | -1389.75 | 7.23688 | 0.00032 | 0.80 | 0.00 |
| $\Delta P(\Delta CO)$ | -3.05 | 2.74 | -0.06 | -1390.48 | 7.23736 | 0.00026 | 0.94 | 0.00 |

(b)

| | $k_0$ | $k_1$ | $k_2$ | $\alpha$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|
| $\Delta P(\Delta M)$ | 0.50 | -1.63 | 7.58 | 7.39 | 0.99 | 0.08 |

| | $k_0$ | $k_1$ | $k_2$ | $k_3$ | $\mu$ | $\sigma$ | $R^2$ | |
|---|---|---|---|---|---|---|---|---|
| $\Delta P(\Delta CO)$ | -12.88 | 121.41 | -0.16 | -54.21 | 4.003 | 0.069 | 1.00 | 0.04 |

### 4.5.2 Exciting-Calming

The relationship between excitement responses and the colour attributes of images was investigated in similar way to pleasantness responses. The excitement responses obtained for 10 images were averaged for each manipulation level within each *a-priori* category. Then the average values for the four categories were divided into two subgroups of "positive" (including positive, neutral and personal images) and "negative" (including negative images).

Figure 4.7 (a) shows changes in the image excitement responses plotted against image colourfulness for the positive group of images including positive (empty squares), neutral (crosses) and personal (empty triangles) among the four *a-priori* categories. Overall, the plot shows that the excitement for positive images increases significantly as image colourfulness increases and decreases as colourfulness decreases. This trend exhibits a slightly different slope in the trend for each *a-priori* group, however the differences do not seem to be significant.

Figure 4.7 (b) shows changes in image excitement responses plotted against the colour attributes of lightness contrast for the positive group of images including positive (solid squares), neutral (solid diamonds) and personal (solid triangles) among the four *a-priori* categories. The plot shows that the excitement values for neutral and positive images among the three categories increase as image colourfulness increases and decrease as colourfulness decreases. The trend for the personal group appears to be quite different, although the extent of difference is not significantly large. The excitement value for personal images falls whether lightness contrast increases or decreases. In either direction, when contrast varies (either getting higher or lower), the personal image was regarded as more calming whereas the other images were regarded as more exciting.

This might be because personal images tend to always be regarded as an "extremely positive" subject no matter how colour attributes are reproduced. Note that the relationship between *pleasant-unpleasant* and *exciting-calming* was described as a 'boomerang shape' distribution in Section 4.3. This indicates that highly-pleasant or highly-unpleasant stimuli also tended to be regarded as highly exciting and images which were scored as neutral on the pleasantness scale are found to be low on the exciting scale. In other words, highly-pleasant stimuli tend to show a positive correlation with excitement and negative stimuli tend to show negative correlation with excitement. This implies that the relationship between the two scales for highly-pleasant stimuli could follow similar trends with regards to changes in colour attributes. As seen in Figures 4.8(a) and (b), the positive correlation between pleasantness and excitement for personal images (dark blue dots in Figure 4.8(b)) tend to show much clearer positive correlation than for neutral and positive images shown in Figure 4.8(a).

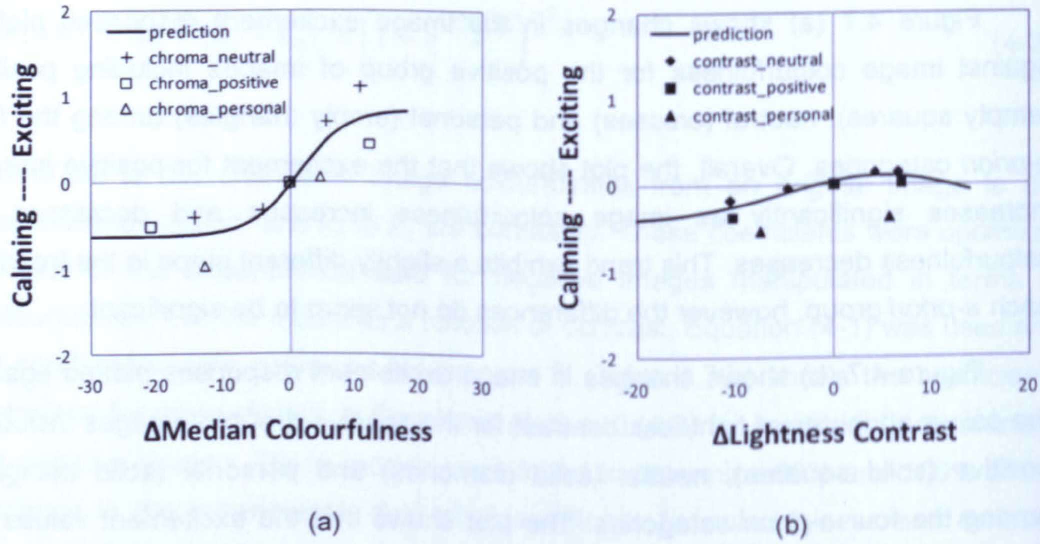



Figure 4.7(a)-(b) Changes in image excitement plotted against changes in image colourfulness(a) and lightness contrast(b) together with the model prediction for each relationship for the positive group of images including neutral ((a) crosses;(b) diamonds), positive ((a) empty; (b) solid squares) and personal((a) empty; (b) solid triangles) images.

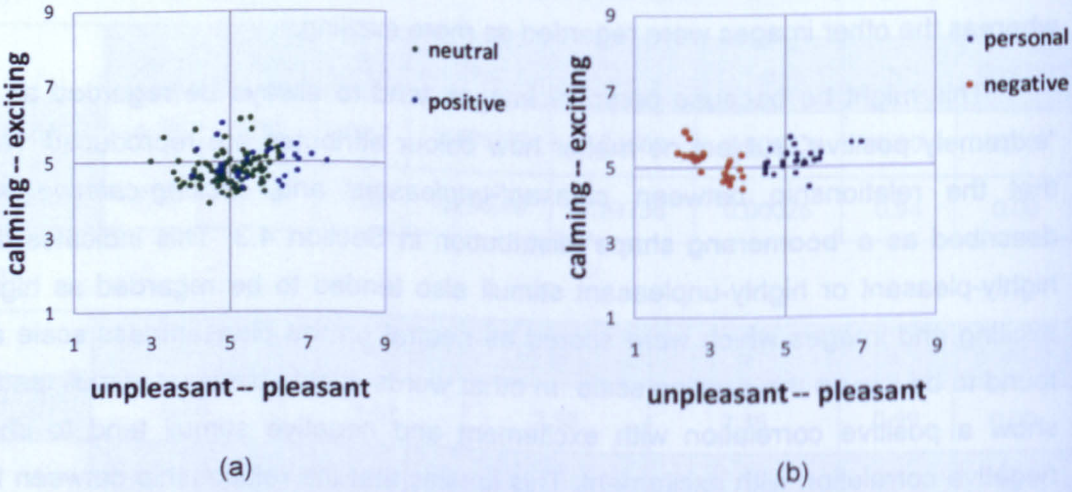



Figure 4.8(a)-(b) Relationship between *pleasant-unpleasant* and *exciting-calming* scales values for (a) neutral and positive images and for (b) personal and negative images.

This result suggests that the exciting feelings of positive images excluding personal images can be enhanced by rendering images with increased colourfulness and contrast. However for personal images, it seems difficult to expect an enhancement in emotional response by rendering colour attributes. To be certain of this conclusion on personal images, further experiments are needed as only three levels of colourfulness and contrast were studied in this experiment.

A model of image excitement ($\Delta E$) for positive images as a function of colourfulness was developed using the structure of Equation (4-2) but the coefficients were determined using data sets of "excitement" responses for images manipulated in colourfulness. The relationship between excitement and contrast was modelled using Equation (4-1) and coefficients were optimised for the best fit to data sets for contrast manipulations. Table 4.8(a) shows the coefficients found for the colourfulness and contrast models which determined 91% and 62% of variance in experimental data image pleasantness for colourfulness and contrast manipulated images, respectively.

Figures 4.9(a) to (b) show changes in image excitement plotted against the colour attributes of images colourfulness and lightness contrast for negative images. As shown in Figure 4.9(a), decreasing image colourfulness results in significantly lower excitement and increasing colourfulness makes images more exciting than the original. As shown in Figure 4.9(b), increasing image contrast results in higher excitement for negative images. This implies that the excitement of negative images can be enhanced by increasing both colourfulness and contrast. Also, for negative images models of image excitement as a function of colourfulness and contrast were developed using Equation (4-2). Table 4.8(b) shows the coefficients optimised for each model and these were found to determine the data to the extent of 100% for both sets manipulated in colourfulness and contrast.

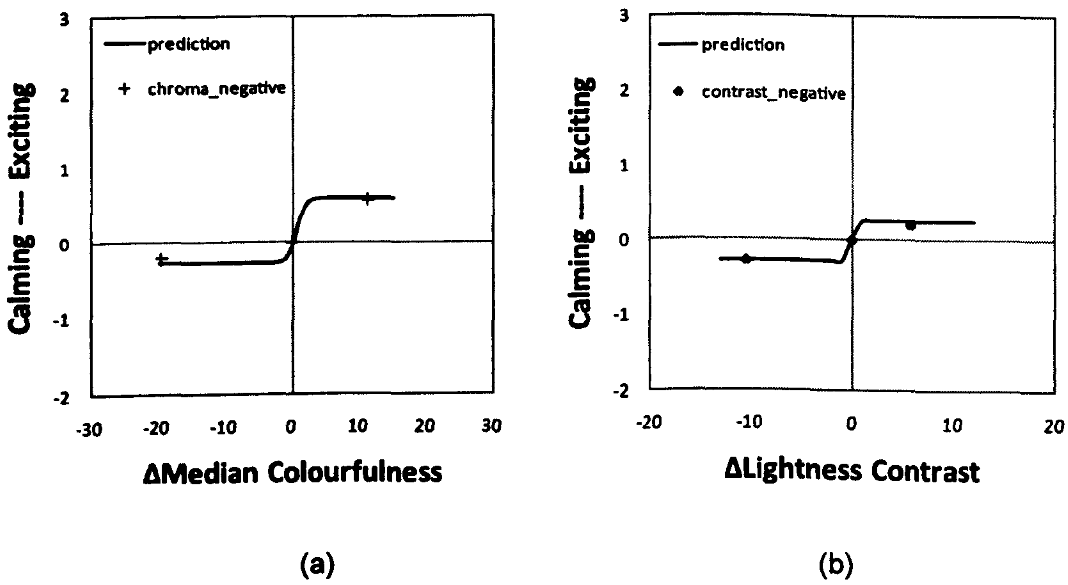



Figure 4.9(a)-(b) Changes in image excitement plotted against changes in image colourfulness (a) and lightness contrast (b) together with the model prediction for each relationship in both the positive group of images and negative group of images.

Table 4.8(a)-(b) Coefficients of image excitement model used in Equation (4-1) and (4-2) as a function of colourfulness and image contrast for (a) positive images and (b) negative images.

(a)

| | $k_0$ | $k_1$ | $k_2$ | $\alpha$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|
| $\Delta E(\Delta M)$ | -0.63 | 0.84 | 1.37 | 3.64 | 0.91 | 0.00 |

| | $k_0$ | $k_1$ | $k_2$ | $k_3$ | $\mu$ | $\sigma$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|---|---|
| $\Delta E(\Delta CO)$ | -0.44 | 2.204 | -0.164 | -1390.37 | 7.23673 | 0.00120 | 0.62 | 0.04 |

(b)

| | $k_0$ | $k_1$ | $k_2$ | $\alpha$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|
| $\Delta E(\Delta M)$ | -0.28 | 0.60 | 0.58 | 0.62 | 1.00 | 0.00 |
| $\Delta E(\Delta CO)$ | -0.29 | 0.26 | -0.05 | 0.14 | 1.00 | 0.00 |

Finally, models of image pleasantness and excitement for positive and negative images were developed as a linear function of colourfulness (M) and contrast (CO) as shown in Table 4.9. The performance of each model was tested for the entire data set including all images manipulated in terms of colourfulness and contrast. Pleasantness models were found to determine 88% and 97% of variance in the data set for positive and negative images respectively. *P(ΔM)* and *P(ΔCO)* for positive images are defined by Equation (4-1) with coefficients given in Table 4.7(a). *P(ΔM)* and *P(ΔCO)* for negative images are also defined by Equations (4-2) and (4-1) respectively with coefficients shown in Table 4.7(b). The excitement models determined the 66% and 96% of variance in date set for positive and negative images respectively. *E(ΔM)* and *E(ΔCO)* for positive images are defined by Equations (4-2) and (4-1) respectively with coefficients shown in Table 4.8(a). *E(ΔM)* and *E(ΔCO)* for negative images are also defined by Equation (4-2) with coefficients provided in Table 4.8(b). P-values shown in the table indicate that the agreement between model prediction and the data point are statistically significant at a significance level of 0.05.

Note that the relationships between image emotions and two image colour attributes were investigated independently. Thus, cross terms of image colourfulness and contrast for inter-relationship between image emotions and two image colour attributes could be added to the equations shown in Table 4.9 for more robust performance of the models and this could one of the future works.

Table 4.9 Predictive models for image pleasantness and excitement developed as a linear equation based on the relationship with colour attributes of colourfulness (*M*) and contrast (*CO*).

| Image Emotion Models (colour attributes) | | | $R^2$ | p-value |
|---|---|---|---|---|
| Pleasantness | positive | $\Delta Pleasantness(M, CO) = 0.78*P(\Delta M) + 0.93*P(\Delta CO)$ | 0.88 | 0.00 |
| | negative | $\Delta Pleasantness(M, CO) = 0.77*P(\Delta M) + 1.16*P(\Delta CO)$ | 0.97 | 0.00 |
| Excitement | positive | $\Delta Excitement(M, CO) = 0.64*E(\Delta M) + 1.32*E(\Delta CO)$ | 0.66 | 0.00 |
| | negative | $\Delta Excitement(M, CO) = 0.73*E(\Delta M) + 1.00*E(\Delta CO)$ | 0.96 | 0.00 |

## 4.6 Summary

The aim of this experiment was to investigate the relationship between the colour attributes of images and the emotional responses elicited by those images, and also to develop quantitative models of image emotion as functions of colorimetric quantities with regards to the effect of image content.

First of all, the inter- and intra-observer variability values were compared between genders and between cultures. It was found that all observer groups had similar levels of observer accuracy and repeatability. As a result of comparisons in emotional responses between genders and cultures, it was found that all observer groups share the same underlying structures of emotional responses for images. Principal component analysis was used to investigate the underlying structure between emotion scales. Two components were extracted from all observer groups which are: *like-dislike, pleasant-unpleasant, natural-unnatural* and *appealing-unappealing,* which are related to the *evaluative* factor proposed by Osgood, and *exciting–calming which is* related to Osgood's *activity* factor.

The influence of image subject on emotional response was investigated by applying the method of principal component analysis to emotion scales to find any similarity between images used in the experiment. As a result, the responses of image emotion were significantly different for the positive group which included positive, neutral and personal images and for the negative group. Personal values seemed to affect the emotional responses of pleasantness and excitement to images; however the effect on psychophysical responses did not seem to be significant. Thus, emotion models for pleasantness and excitement were developed separately for the data set corresponding to positive and negative images.

The relationships between emotional responses for all images used in the experiment and colour attributes were explored and quantitative models were developed as a function of the colour attributes of images. As a result, pleasantness can be enhanced for negative images by decreasing colourfulness, whereas pleasantness for positive images cannot be enhanced by changing the colour attributes studied. Image excitement can be enhanced by increasing colourfulness and contrast for both positive and negative images. Finally, models of image pleasantness and excitement for positive and negative images were developed as linear equations based on the models developed for each colour attribute.

# Chapter 5 Experiment 2: Impact of Colour-Appearance Attributes on Colour-emotion and Image Emotion for Displayed Images

In Chapter 4 covering the results of Experiment 1, the relationships between the responses of image emotions to four different contents of printed images and colour attributes were explored and quantitative models for image pleasantness and excitement were developed as a function of colourfulness and lightness contrast for positive and negative image groups. Using these models, image pleasantness can be enhanced only for negative images by decreasing colourfulness, whereas image pleasantness for positive images cannot be enhanced by changing the colour attributes studied. In addition, image excitement can be enhanced by increasing colourfulness and contrast for both positive and negative images.

As mentioned in Section 1.1, two approaches to defining and utilising the affective responses in a systematic way were introduced: "image emotion" (see Section 2.4.2) and "colour-emotion" (see Section 2.4.5). The concept of "image emotion" was used to describe the overall emotional responses to images in association with their context regarding content and personal attachment. The concept of "colour-emotion" was used to define the relationship between colours and reactive-level emotional responses determined by the configurations of colour stimuli as its original definition with regards an easy and systematic way to utilise the image emotion models which developed in previous chapter in practice.

In this chapter, the results from Experiment 2, which focused on investigating colour-emotion responses for complex images, are described. Quantitative models of colour-emotion for images will be developed as a function of colour-appearance attributes. The performance of the colour-emotion models reviewed in Section 2.4.5.2 and the additivity principle (see Section 2.4.5.3) will be tested for image stimuli. Finally, the aim of this experiment was to investigate the relationship between the colour attributes of images and the colour-emotion scales of activity, weight and heat it was also aimed at developing quantitative models of colour-emotion as functions of colorimetric quantities for image stimuli.

To achieve these objectives, a second psychophysical experiment was carried out. In this experiment, 17 observers (1 European, 4 Chinese and 12 Korean) were asked to assess 208 original and rendered images manipulated in terms of lightness contrast and colourfulness on six emotion scales including *pleasant-unpleasant, exciting-calming, like-dislike, active-passive, heavy-light* and *warm-cool.*

The experimental data were transformed into averaged scores for five groups of observers: female, male, European, Korean and Chinese. As will be shown in this chapter, these data were analysed for the following investigations: cultural difference and gender difference, comparison of emotion scales, influence of image subject, and quantification of image emotion as well as colour-emotion scales.

## 5.1 Observer Variability

Observer variability in Experiment 2 was investigated to examine the performance of observers who have participated in this experiment in two different ways: accuracy and repeatability. RMS (see Section 3.5.1) was used again to represent variation in observer responses.

### 5.1.1 Observer Accuracy (Inter-observer Variability)

Table 5.1 summarises RMS values of observer accuracy for two cultural groups except for European as there was only one European observer and two gender groups in terms of mean RMS for the group.

For the Korean group, *pleasant-unpleasant* among the six scales showed the highest accuracy with an RMS value of 1.20. For Chinese group, *like-dislike* showed the highest accuracy with RMS values of 1.28. *Exciting-calming* showed the poorest accuracy, with an RMS value of 1.67 for the Korean group. For the Chinese group, *warm-cool* showed the poorest accuracy with an RMS of 1.46. Comparing the two gender groups, *pleasant-unpleasant* showed the highest with RMS values of 1.22 and 1.19 respectively for female and male groups. The scales showing the poorest accuracy were *active-passive* with an RMS value of 1.64 for female and *exciting-calming* with an RMS value of 1.56 for male. In terms of the mean value for each scale, *pleasant-unpleasant* showed the highest accuracy with an RMS value of 1.20 whereas *exciting-calming* showed the poorest accuracy with an RMS value of 1.59.

Although there seemed to be some differences in accuracy between scales and between culture and gender groups, the results suggest that the accuracy of all observer groups was similar for each scale; the mean accuracy of 1.40 over all observer groups indicates a reasonable level of accuracy for observer responses regarding the magnitude of the 9-point scale.

Table 5.1 Inter-observer variability in terms of RMS

| | active-passive | light-heavy | warm-cool | like-dislike | pleasant-unpleasant | exciting-calming | mean |
|---|---|---|---|---|---|---|---|
| Korean | 1.56 | 1.40 | 1.53 | 1.29 | 1.20 | 1.67 | 1.44 |
| Chinese | 1.26 | 1.17 | 1.46 | 1.20 | 1.28 | 1.35 | 1.29 |
| Female | 1.64 | 1.33 | 1.56 | 1.26 | 1.22 | 1.62 | 1.44 |
| Male | 1.39 | 1.34 | 1.48 | 1.24 | 1.19 | 1.56 | 1.37 |
| **mean** | 1.49 | 1.34 | 1.51 | 1.27 | 1.22 | 1.59 | 1.40 |

### 5.1.2 Observer Repeatability (Intra-observer Variability)

Table 5.2 summarises the RMS values of observer repeatability for two gender groups and two cultural groups - Chinese and Korean - in terms of mean RMS for the group.

For the two groups, *pleasant-unpleasant* showed the highest repeatability with RMS values of 1.21 and 1.10 respectively for Korean and Chinese. *Warm-cool* showed the poorest repeatability with an RMS value of 1.67 for the Korean group. For the Chinese group, *active-passive* showed the poorest repeatability with an RMS of 1.60. Comparing the two gender groups, *pleasant-unpleasant* showed the highest repeatability with RMS values of 1.10 and 1.23 respectively for female and male groups. The scales showing the poorest repeatability was *warm-cool* with an RMS value of 1.67 for female and *active-passive* with an RMS value of 1.64 for male. In terms of mean value for each scale, *pleasant-unpleasant* was the highest with an RMS value of 1.17, whereas *warm-cool* showed the poorest repeatability with an RMS value of 1.60.

Although there seemed to be some difference in repeatability between scales and between culture and gender groups, these results suggest that the repeatability of all observer groups was similar for each scale. The mean accuracy value of 1.40 over all observer groups indicates a reasonable level of repeatability for observers' responses regarding the magnitude of the 9-point scale.

Table 5.2 Intra-observer variability in terms of RMS.

| | active-passive | light-heavy | warm-cool | like-dislike | pleasant-unpleasant | exciting-calming | mean |
|---|---|---|---|---|---|---|---|
| Korean | 1.50 | 1.47 | 1.67 | 1.30 | 1.21 | 1.45 | 1.43 |
| Chinese | 1.60 | 1.19 | 1.47 | 1.24 | 1.10 | 1.44 | 1.34 |
| Female | 1.33 | 1.39 | 1.67 | 1.18 | 1.10 | 1.48 | 1.36 |
| Male | 1.64 | 1.45 | 1.53 | 1.32 | 1.23 | 1.43 | 1.43 |
| **mean** | 1.52 | 1.40 | 1.62 | 1.28 | 1.18 | 1.45 | 1.41 |

## 5.2 Cultural and Gender Differences

The responses for the six emotion scales by Korean and Chinese male observer groups were compared to investigate the cultural differences between the two groups using Pearson's correlation coefficient (see Section 3.5.2). To exclude any gender effects, observer responses were compared using only the data from male observers. The numbers of observers in both groups used in the comparison were 5 for Korean and 4 for Chinese. As shown in Figure 5.1, the results indicated very good agreement for *pleasant-unpleasant, like-dislike* and *active-passive* with correlation coefficients ranging from 0.71 to 0.88. Responses for *light-heavy* and *exciting-calming* also show good agreement between the two observer groups, with correlation coefficients of 0.59 and 0.53. The largest variation w as found from responses for *warm-cool,* with a correlation coefficient of 0.22 indicating that there were cultural differences between the two groups.

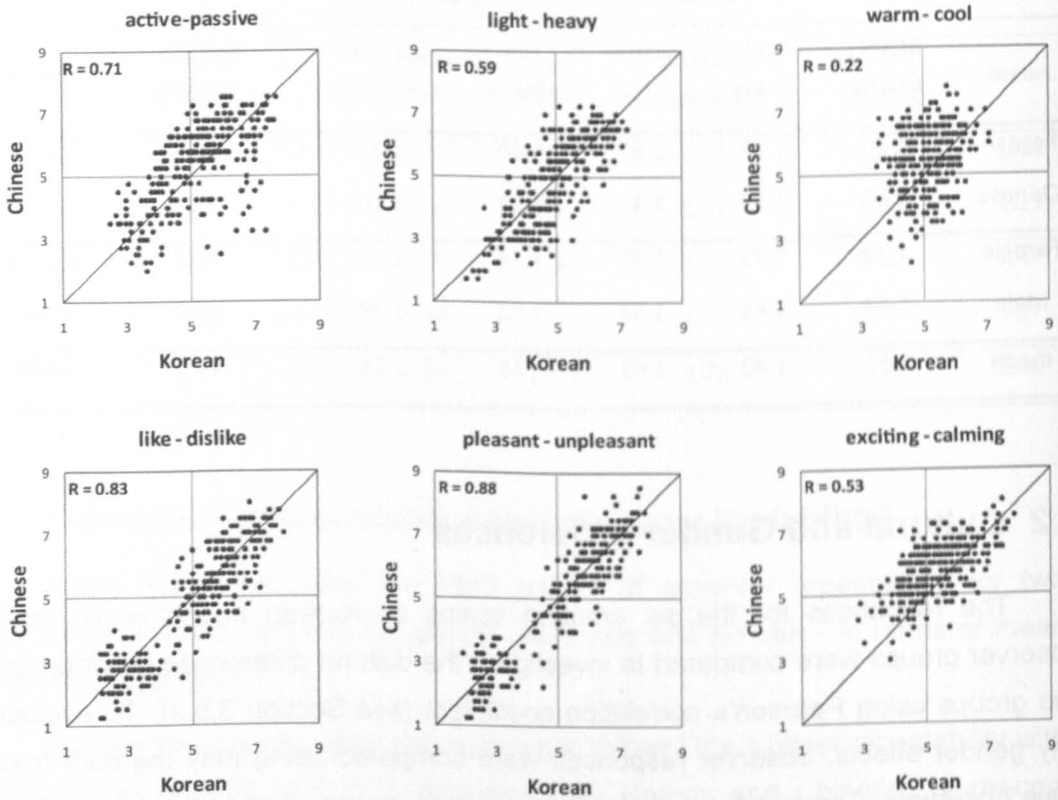



Figure 5.1 Comparisons of emotion responses between Korean and Chinese male observers.

Table 5.3(a)-(b) Component loadings for (a) Korean and (b) Chinese observers.

(a)

| % of variance | component 1<br>55.30 | component 2<br>21.99 |
|---|---|---|
| like-dislike | **0.937** | 0.042 |
| pleasant-unpleasant | **0.925** | 0.076 |
| active-passive | **0.911** | 0.113 |
| light-heavy | **0.727** | 0.528 |
| exciting-calming | **0.474** | 0.383 |
| warm-cool | -0.004 | **0.935** |

(b)

| % of variance | component 1<br>59.04 | component 2<br>28.65 |
|---|---|---|
| like-dislike | **0.959** | 0.219 |
| pleasant-unpleasant | **0.957** | 0.223 |
| light-heavy | **0.950** | -0.070 |
| active-passive | **0.875** | 0.336 |
| warm-cool | 0.126 | **0.883** |
| exciting-calming | 0.150 | **0.851** |

To further investigate cultural difference, the method of principal component analysis (PCA) (see Section 3.5.3) was applied to clarify the interrelationship of six emotion scales for each of two observer groups. The components extracted from the Korean and Chinese groups are listed in Tables 5.3(a) and (b). For both groups, the six emotion scales were classified into two principal components accounting for 77.29% and 87.69% of total variances for responses of Korean and Chinese groups respectively. As a result, both groups showed high component loadings on *like-dislike, pleasant-unpleasant* and *light-heavy* in component 1; *warm-cool* in component 2. *Exciting-calming* was grouped into component 1 for Korean and component 2 for Chinese. This suggests that Korean and Chinese observers share a similar underlying structure of colour-emotional responses for images, although *exciting-calming* was grouped into different components in the two groups.

To explore the underlying structures of colour-emotion for images between Korean and Chinese groups, a component plot was drawn for each group based on the component loadings listed in Table 5.3. The results are shown in Figures 5.2(a) and (b) for Korean and Chinese respectively. In both diagrams, the six emotion words are located in two-dimensional space formed by the two principal components. In both plots, all emotion words are located in similar positions except for "exciting".

In the Korean results, "exciting" is located close to "active", "like" and "pleasant". In the Chinese result, "active" is located close to "warm". This implies that Chinese observers are more likely to feel excited about warm images and that Korean are likely to prefer exciting images. However, the number of observers used for the comparison was small, further study will be needed to conclude a concrete culture effect with sufficient number of observers.

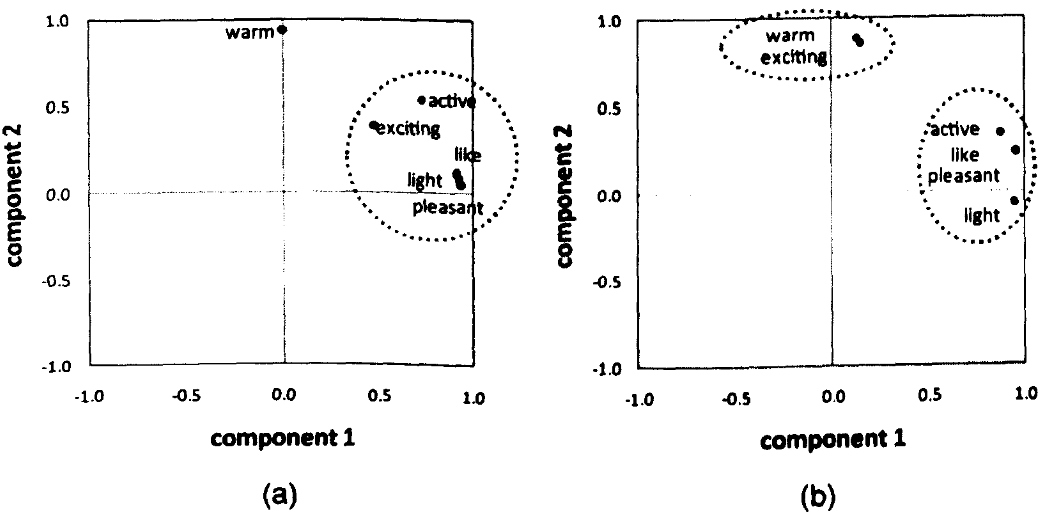



Figure 5.2(a)-(b) Component plot of colour-emotion responses from the (a) Korean and (b) Chinese male observers.

The responses of male and female observers are compared in Figure 5.3. To exclude any cultural effects, the comparison was conducted using only the data from Korean observers. The numbers of observers in both groups used in the comparison were 5 for male and 7 for female. The results show good agreement for *active-passive, pleasant-unpleasant* and *like-dislike* with correlation coefficients from 0.74 to 0.88. Responses for *light-heavy* and *exciting-calming* also show good agreement between the two groups, with correlation coefficients of 0.50 and 0.56. The largest difference was found from responses for *warm-cool* with a correlation coefficient of 0.37 suggesting that the two observer groups had a difference for *warm-cool*.

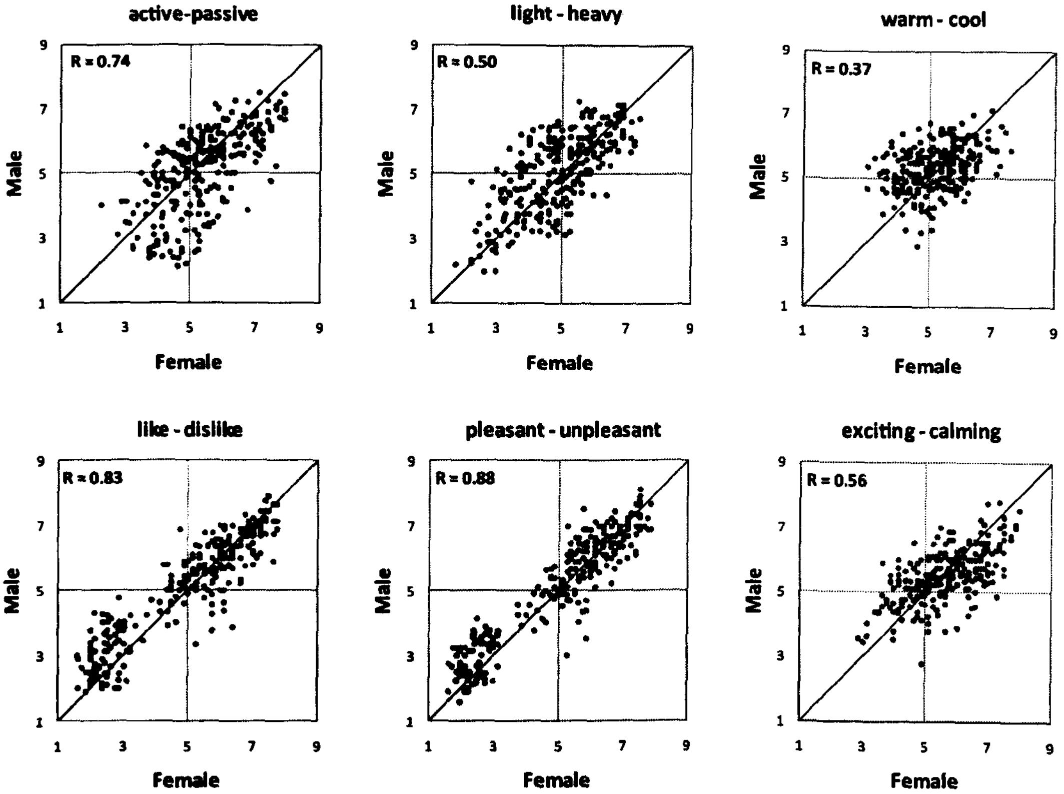



Figure 5.3 Comparisons of emotion responses between Korean female and male observers.

To fu rther investigate this difference, PCA was again used to clarify the interrelationship between the six emotion scales for each of the two observer groups. The components extracted from female and male observers are listed in Table 5.4(a)-(b). For both groups, six emotion scales were classified into two principal components, taking account of 78.16% and 77.29% of the total variances in responses by female and male observers respectively. In the results, both groups show high component loadings on *like-dislike, pleasant-unpleasant* and *light-heavy* in component 1; *exciting-calming* in component 2. This suggests that female and male observers share a similar underlying structure of colour-emotional response for images, although *active-passive* and *warm-cool* were classified into different components in the two groups' results.

To compare the underlying structures of colour-emotion for images between female and male observers, a component plot was drawn again for each group based on the loadings listed in Tables 5.4(a)-(b). The results are shown in Figures 5.4(a) and (b) for female and male observers respectively. In both plots, all emotion words are placed in similar positions except "active" and "warm".

In the female results, "active" is located close to "exciting"; and "warm" is in the opposite direction. In the male results, "active" and "exciting" are found to be located close to "like", "pleasant" and "light". This implies that female observers tend to feel excited with active images and prefer cool images. Also, males tend to prefer active and exciting images. However, the number of observers used for the comparison was small again, further study is required to conclude a concrete gender effect with sufficient number of observers.

Table 5.4 Component loadings for (a) Korean female and (b) Korean male observers.

(a)

| | component 1 | component 2 |
|---|---|---|
| % of variance | 46.46 | 31.70 |
| like-dislike | **0.939** | 0.080 |
| pleasant-unpleasant | **0.937** | 0.115 |
| light-heavy | **0.818** | -0.269 |
| warm-cool | **-0.508** | -0.287 |
| exciting-calming | -0.162 | **0.944** |
| active-passive | 0.273 | **0.915** |

(b)

| | component 1 | component 2 |
|---|---|---|
| % of variance | 55.30 | 21.99 |
| like-dislike | **0.937** | 0.042 |
| pleasant-unpleasant | **0.925** | 0.076 |
| active-passive | **0.911** | 0.113 |
| light-heavy | **0.727** | 0.528 |
| exciting-calming | **0.474** | 0.383 |
| warm-cool | -0.004 | **0.935** |

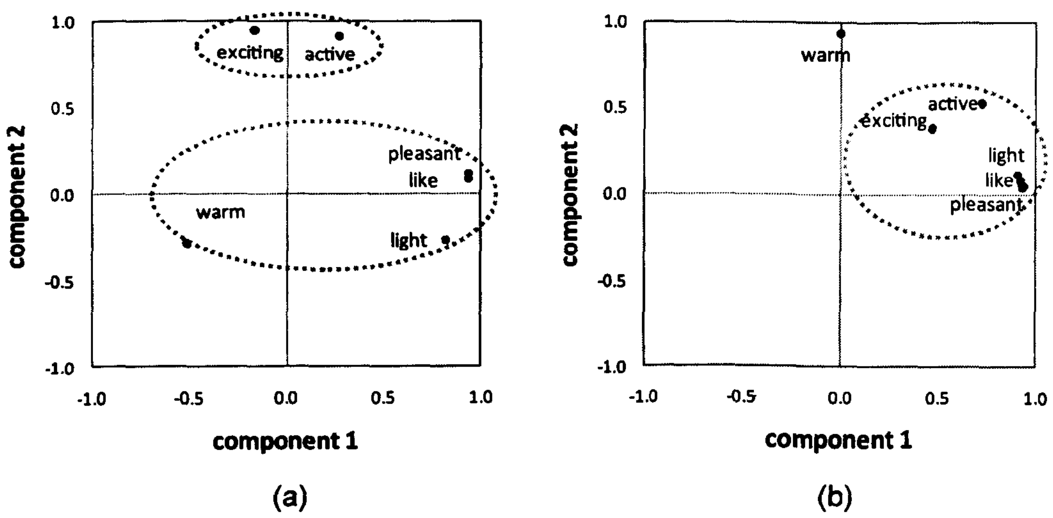



Figure 5.4 (a)-(b) Component plots of colour-emotion responses by the Korean (a) female and (b) male observers.

## 5.3 Relationship between Colour-Emotion and Image Emotion

Colour-emotion (see Section 2.4.5) and image emotion (see Section 2.5.3) actually share the same basis in that they are founded on the three primary factors introduced by Osgood (Osgood, 1957); i.e. evaluative, potency and activity factors. According to the three-factor theory of emotion proposed by Russell, pleasantness and arousal correspond to two factors: evaluative and activity (Russell, 1977). The existing colour-emotion models (see Section 2.4.5.2) developed by Ou *et al.*, Sato *et al.* and Xin *et al.* also share two of the three factors, colour activity and heat corresponding to activity factor and colour weight corresponding to potency factor. (Ou, 2004a)

To investigate the inter-relationship between colour-emotion and image emotion scales for image stimuli based on underlying primary factors, PCA was applied to classify responses of all the observers on the six emotion scales. The results shown in Table 5.5, indicate that two principal components extracted from the six emotion scales accounted for 78.38% of total variance in the experimental data. These two components were: component 1, comprising *like-dislike, pleasant-unpleasant* and *light-heavy*; and component 2, comprising *exciting–calming* and *warm-cool.* This implies that colour-emotion and image emotion for image stimuli are actually based on two primary factors from the three primary factors *evaluative, potency* and *activity*. These could be evaluative and activity factors corresponding to components 1 and 2 respectively. This is different to Ou's classification where *light-heavy* and *active-passive* were classified into potency and activity factor (Ou, 2004a). The *light-heavy* scale showed very high correlation with component 1 with a loading value of 0.889 (Table 5.5) and it was consistently classified into component 1 in the results based on the responses of different observer groups including Korean, Chinese, male and female. Accordingly, the *light-heavy* scale tends to be closely related evaluative factor for image stimuli. On the other hand, the *active-passive* scale showed high correlation with component 1 with a loading value of 0.737; it also showed some degree of correlation with component 2, however, with a loading value of 0.584 as shown in Table 5.5. It was classified into component 1 in the results based on responses of Korean and female groups, and classified into component 2 in the results based on responses of Chinese and male groups. This indicates that the *active-passive* scale has both evaluative and arousing properties, and this can be presented differently in different observer groups. The relationship between colour-emotion and image emotion will be discussed with regard to the influence of colour attributes in more detail in Section 5.5.

Table 5.5 Principal component matrices (component loadings) for all observers.

| | component 1 | component 2 |
|---|---|---|
| % of variance | 54.39 | 23.99 |
| like-dislike | **0.970** | -0.035 |
| pleasant-unpleasant | **0.969** | -0.021 |
| light-heavy | **0.889** | -0.162 |
| active-passive | **0.737** | 0.584 |
| exciting-calming | 0.127 | **0.926** |
| warm-cool | -0.189 | **0.462** |

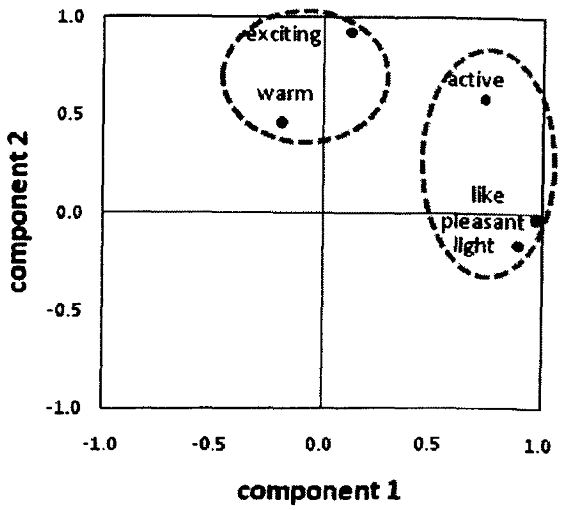



Figure 5.5 Component plots of colour-emotion for images from all observers.

## 5.4 Influence of Image Subject

To investigate the influence of image subject on emotional response, PCA was applied to each emotion scale to group images showing statistically similar trends. As a result, the responses of image emotion were significantly affected by the image content whereas the responses of colour-emotion were not.

For the two image emotion scales of *pleasant-unpleasant* and *exciting-calming* as shown in Tables 5.6(a)-(b), ten images (including four image subjects of positive, neutral, negative and personal) were classified into two principal components accounting for 75.46% and 77.13% of the total variances in responses of *pleasantness* and *excitement* respectively. Looking at those images comprising component 1, it was found that they included neutral, positive and personal images whereas component 2 only included negative images. Thus these two groups were labelled "positive" and "negative" in further analyses. This indicates that the emotional responses of *pleasantness* and *excitement* were significantly different for positive and negative images. It also indicates that the emotional responses of *pleasantness* and *excitement* were very similar for images within each image group. This agrees with the results of the influence of image content for printed images (shown in Table 4.6 in Section 4.4) which indicated that only two groups of image categories were significantly differentiated, as shown in Table 4.6. Thus, models for the image emotions of *pleasantness* and *excitement* were developed separately for images in component group 1 and 2. These two groups were labelled "positive" and "negative" groups in further analyses.

For the colour-emotion scales *active-passive, light-heavy* and *warm-cool* shown in Tables 5.7(a)-(c), one principal component was extracted for the ten images (which included positive, neutral, negative and personal images), accounting for 74.03%, 79.56% and 70.25% of the total variance for the responses *active-passive, heavy-light* and *warm-cool* respectively. This indicates that the emotional responses of three colour-emotion scales were very similar for all images used in this experiment. Thus, models for three factors of colour-emotion- *active-passive, heavy-light* and *warm-cool-* were developed for all images.

Table 5.6(a)-(b) Dependency of image emotion scales on image content: results of Principal Component Analysis for responses of (a) *pleasant-unpleasant* and (b) *calming-exciting*.

(a)

| | Pleasant-Unpleasant | component 1 | component 2 |
|---|---|---|---|
| | % of variance | 55.86 | 19.6 |
| positive | Baby | 0.942 | -0.106 |
| neutral | Harbour | 0.931 | 0.008 |
| personal | Personal | 0.904 | -0.013 |
| neutral | Boy | 0.882 | 0.013 |
| positive | Couple | 0.869 | 0.188 |
| positive | Family | 0.852 | 0.163 |
| positive | Skydivers | 0.825 | -0.143 |
| negative | Roach | 0.220 | 0.874 |
| neagtive | Injury | -0.159 | 0.809 |
| neagtive | Leopard | 0.001 | 0.670 |

(b)

| | Exciting-Calming | component 1 | component 2 |
|---|---|---|---|
| | % of variance | 45.24 | 31.89 |
| positive | Family | 0.900 | 0.198 |
| personal | Personal | 0.898 | 0.152 |
| neutral | Harbour | 0.835 | 0.468 |
| positive | Couple | 0.784 | 0.459 |
| positive | Baby | 0.727 | 0.508 |
| neutral | Boy | 0.626 | 0.626 |
| positive | Skydivers | 0.613 | 0.417 |
| negative | Roach | 0.187 | 0.834 |
| negative | Injury | 0.235 | 0.819 |
| negative | Leopard | 0.456 | 0.712 |

Table 5.7(a)-(c) Dependency of colour-emotion scales of images on image content: results of Principal Component Analysis for responses of (a) *active-passive* (b) *light-heavy* and (c) *warm-cool.*

(a)

| | Active-Passive | component 1 |
|---|---|---|
| | % of variance | 74.03 |
| positive | Family | 0.947 |
| neutral | Harbour | 0.940 |
| positive | Couple | 0.930 |
| personal | Personal | 0.916 |
| positive | Skydivers | 0.888 |
| positive | Baby | 0.869 |
| neutral | Boy | 0.849 |
| negative | Roach | 0.834 |
| neagtive | Leopard | 0.758 |
| negative | Injury | 0.619 |

(b)

| | Light-Heavy | component 1 |
|---|---|---|
| | % of variance | 79.56 |
| personal | Personal | 0.969 |
| neutral | Boy | 0.967 |
| positive | Couple | 0.936 |
| positive | Family | 0.923 |
| positive | Baby | 0.915 |
| neutral | Harbour | 0.889 |
| negative | Injury | 0.880 |
| negative | Roach | 0.849 |
| positive | Skydivers | 0.787 |
| negative | Leopard | 0.784 |

(c)

| | Warm-Cool | component 1 |
|---|---|---|
| | % of variance | 70.25 |
| negative | Roach | 0.953 |
| neutral | Harbour | 0.936 |
| personal | Personal | 0.903 |
| positive | Baby | 0.835 |
| positive | Family | 0.827 |
| neutral | Boy | 0.820 |
| negative | Injury | 0.793 |
| positive | Couple | 0.771 |
| negative | Leopard | 0.764 |
| negative | Skydivers | 0.749 |

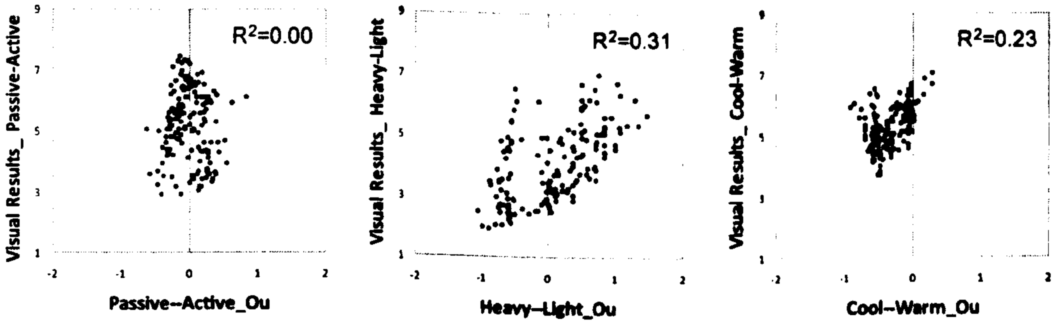
## 5.5 Testing the Colour-Emotion Models

In this section, colour-emotion models for single colour developed by Sato *et al.*, Xin *et al.* and Ou *et al.* (see Table 2.6 in Section 2.4.5.2) were tested against the visual results obtained from Experiment 2.

The test results predicted by the current colour-emotion models were computed by assuming that the additivity principle of colour-emotion for colour combinations also applied to images. Thus, the test results for each scale of colour-emotion were computed by taking the average of individual pixel scale values over the entire image. Then, the test results computed for each image were plotted against the visual results obtained for that image for *active-passive*, *heavy-light* and *warm-cool*.

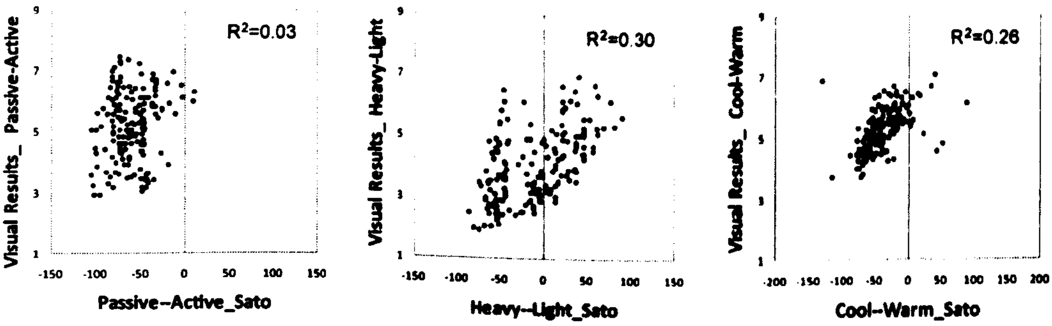
Figures 5.6 to 5.8 shows the test results predicted by the three sets of colour-emotion models developed by Ou *et al.*, Sato *et al.* and Xin *et al.* plotted against the visual results obtained from Experiment 2. The agreement between the predicted and the visual results are represented by $R^2$ for each scale. From the plots and the $R^2$ values, the agreement between the test results and the visual results was the poorest for the *active-passive* scale with $R^2$ values less than 0.1. For the *heavy-light* scale, the plots tend to show very similar trends in their predictive results. The agreement between the test results and the visual results has an overall linear relationship and seems to be reasonable for the "heavy" region; however, it tends to spread out over the "light" region. Each model's prediction for *heavy-light* responses by Ou et. al, Sato et al. and Xin et al. were not as poor as those for the *active-passive* scale, with $R^2$ values of 0.31, 0.30 and 031 respectively. For *warm-cool* scale, the prediction by Sato et. al's model seems reasonabley good as the plots show some linear trend with an $R^2$ of 0.35. The prediction by Xin *et al.*'s model also shows some extent of linear relationships with $R^2$ values of 0.26. The prediction by Ou *et al.*'s model did not present any linear trend between the test results and the visual results in the plot, although it had the similar $R^2$ value with Xin's prediction.

In summary, the test results of colour-emotion models for single colours with an assumption colour-emotion additivity for colour combinations also applied to an image showed some extent of agreement for colour-emotion responses for images, especially for the *heavy-light* and *warm-cool* scales. However, it still seem to be needed to develop a colour emotion model for complex images in different way. Thus, the relationship between the colour-appearance attributes of images and colour-emotion responses was discussed and a set of colour-emotion models for colour images will be developed in the next section.



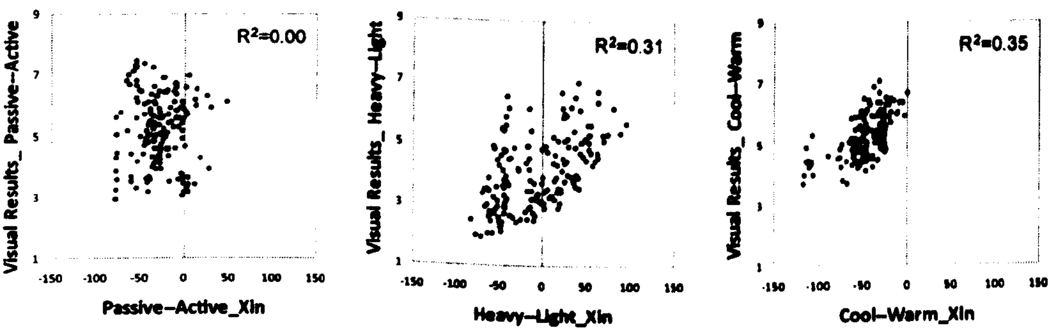

(a) (b) (c)

Figure 5.6 (a)-(c) Visual results for (a) colour activity, (b) colour weight and (c) colour heat plotted against Ou et al.'s (see Section 2.4.5.2) colour-emotion model predictions.




(a) (b) (c)

Figure 5.7 (a)-(c) Visual results for (a) colour activity, (b) colour weight and (c) colour heat plotted against Sato *et al.*'s (see Section 2.4.5.2) colour-emotion model predictions.




(a) (b) (c)

Figure 5.8 (a)-(c) Visual results for (a) colour activity, (b) colour weight and (c) colour heat plotted against Xin *et al.*'s (see Section 2.4.5.2) colour-emotion model predictions.

## 5.6 Modelling Colour-Emotion Scales

One of the aims in this chapter is to describe how colour-emotion models for complex images were developed as functions of colour attributes of images such as lightness, colourfulness and lightness contrast. These models are to be used to modify images to acquire a pre-defined emotional quality by which images affect people so as to induce them into the corresponding emotional state. Three scales of colour-emotion factors were modelled as functions of colourfulness, lightness contrast and light first and one combined model for each scale was developed.

Image colourfulness and lightness were determined by the median colourfulness and lightness in CAM02-UCS (Section 2.3.4.4) for the image in question. Image contrast was determined from the standard deviation of image lightness in CAM02-UCS.

### 5.6.1 Active – Passive

To investigate the relationship between *active-passive* responses and colour attributes of images, the scale values obtained for 10 images were averaged for each manipulation level over all image categories using the results concluded from the influence of the image subjects on colour-emotion responses described Section 5.4.

Figures 5.9 (a) to (c) show changes in responses on the *active-passive* scale plotted against the three image colour attributes colourfulness, lightness contrast and lightness. The 17 data points in the plots represent the original image and 16 manipulated images with different symbols for each manipulation of chroma (crosses), contrast (solid squares) and lightness (empty circles).

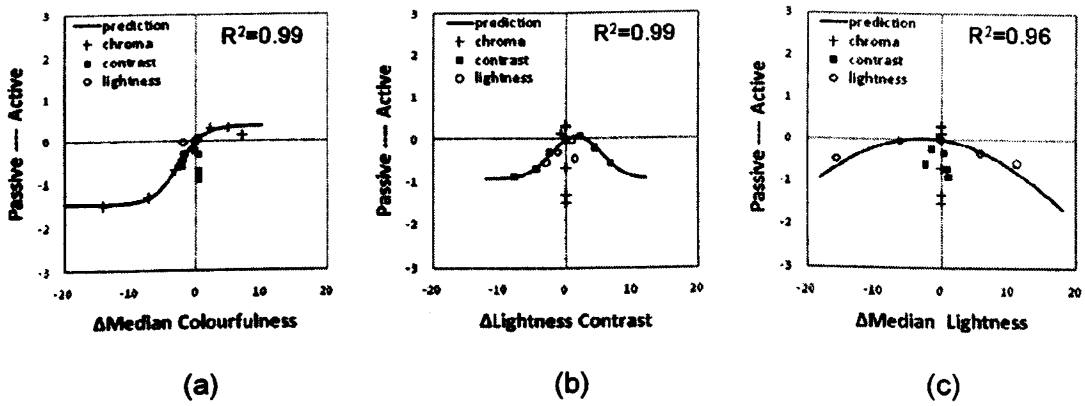



Figure 5.9 (a)-(c) Changes in active-passive responses plotted against changes in (a) image colourfulness,(b) lightness contrast and (c) lightness with the predictive models for each relationship (crosses for chroma manipulation; solid squares for contrast manipulation; empty circles for lightness manipulation).

Table 5.8 (a)-(b) Coefficients used in Equation (5-1) as a function of (a) colourfulness and coefficients in Equation (5-2) as a function of (b) image contrast and lightness for colour activity.

(a)

| | $k_0$ | $k_1$ | $k_2$ | $\alpha$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|
| $\Delta Activity\ (\Delta M)$ | 0.35 | -1.47 | -2.63 | 1.83 | 0.99 | 0.00 |

(b)

| | $k_0$ | $k_1$ | $k_2$ | $k_3$ | $\mu$ | $\sigma$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|---|---|
| $\Delta Activity\ (\Delta CO)$ | -0.932 | 1.024 | -0.110 | -1390.663 | 7.237411 | 0.000288 | 0.99 | 0.00 |
| $\Delta Activity\ (\Delta J)$ | -8.401 | 3.293 | -0.005 | -1390.472 | 7.237408 | 0.000112 | 0.96 | 0.00 |

The colour activity for images ($\Delta Activity$) was modelled based on the data for images manipulated in terms of colourfulness as a function of the change in image colourfulness using the *Boltzmann Distribution Function* for best fit of the experimental data that followed S-shaped curves. The model is given in Equation (5-1):

$$\Delta Activity\ (\Delta M) = k_0 + (k_1 - k_0) \times \left(1 + e^{\frac{(\Delta M - k_2)}{\alpha}}\right)^{-1} \quad (5\text{-}1)$$

where $\Delta M$ is the change in image colourfulness values from an original image to the manipulated version; and $k_0$ to $k_2$ are constants. The relationship between colour activity and image contrast was modelled based on the data for images manipulated in terms of image contrast using the *Log Normal Distribution Function* (Limpert, 2001) for best fit of the experimental data that showed skewed bell-shaped curves. The model is given in Equation (5-2):

$$\Delta Activity\ (\Delta CO) = k_0 + \frac{k_1}{\sigma\sqrt{2\pi}(k_2 \Delta CO - k_3)} e^{\frac{-[\ln(k_2 \Delta CO - k_3) - \mu]^2}{2\sigma^2}} \quad (5\text{-}2)$$

where $\Delta CO$ is the change in image contrast values from an original image to the manipulated version; $\mu$ and $\sigma$ are the shape parameters; $k_1$ is the amplitude of the distribution curve; $k_3$ is the location parameter; and $k_0$ and $k_2$ are constants. This equation was also used to model the relationship between colour activity and image lightness based on the data for images manipulated in terms of lightness with a different set of coefficients. Table 5.8 shows coefficients optimised to fit the experimental data in Equations (5-1) to (5-2) and $R^2$ with p-value for each model. $R^2$ indicates the extent of percentage to determine the each experimental data set. The

$R^2$ value for each model was calculated only based on the data points which were affected by the particular manipulation. The $R^2$ and p-values for each model indicate that the goodness of fit for each model was significantly good at a significance level of 0.05.

As shown in Figure 5.9 (a), colour activity for images has a higher value when image colourfulness increases and a lower value as image colourfulness decreases. This indicates that more colourful image colours make them more active overall. This has been found in the colour-emotion responses for *active-passive* scale for single colours studied by Ou *et al.* (Ou, 2004). They found that less colourful colours located in the central area of CIELAB space tended to have lower scores for the *active-passive* scale than those in the outer part. According to the finding in his study, the *active-passive* scale value of a colour was modelled by colour difference from medium grey at $L^*$=50. Another model was built in Ou's study in which the activity score is predicted by the colour difference between the colour and a muddy yellow with ($L^*$, $a^*$, $b^*$) = (50, 3, 17). However, this second model was derived based on results of responses using four emotion scales - active-passive, fresh-stale, clean-dirty and modern-classical - labelled as colour activity factors for single colours.

Figure 5.9 (b) shows that the relationship between the colour activity of images and lightness contrast increases slightly as image contrast increases. Any significant increase or decrease in image contrast results in a lower colour activity. This might be caused by the effect of contrast rendering which applied sigmoid and inverse sigmoid functions to the lightness values of original images. The effect of reducing contrast by applying an inverse sigmoid function tends to flatten out the mid-tone range of the tone reproduction curve so as to make dark regions of images lighter and lighter parts darker. This means that the overall tone of images tends towards medium grey as contrast decreases. Medium grey was found to be the least active colour in Ou's results for single colour-emotion.

On the other hand, the effect of enhancing contrast by applying sigmoid functions is to make dark regions of images even darker and lighter parts lighter. Some extent of increase in contrast can emphasise the information of the image but further increases make the image become too dark to distinguish details in dark regions. Figure 5.10 show the changes in median image lightness plotted against the changes in lightness contrast. As seen in the plot, the median lightness decreases as image contrast increases. This indicates that the greater the increase in contrast, the darker the where image becomes and leading to a loss of information. When this loss becomes to be great because of too low lightness, the viewer may feel that the image is unlikely to be a real scene. This may be the reason that a large increase in contrast makes the image less active.

Figure 5.9 (c) also shows that any change in image lightness (either increases or decreases) result in lower colour activity. However, the variation of the changes in the y-axis seems to be rather small. The data points for lightness manipulation (empty circles) seem to be closely located to the prediction curve in both Figures 5.9 (a) and (b). Thus, the changes in active-passive responses for the images may be well explained by only colourfulness and contrast attributes.

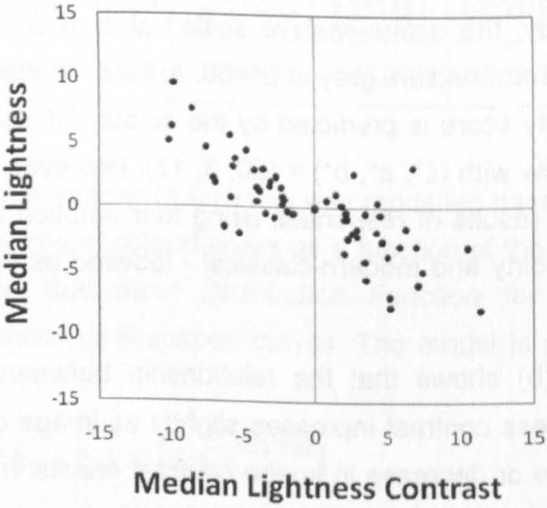



Figure 5.10 The relationship between image contrast and median lightness for images rendered in terms of lightness contrast.

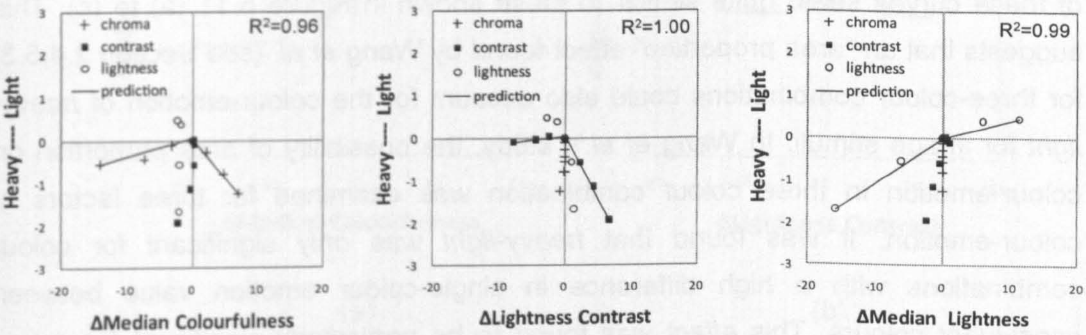
### 5.6.2 Heavy – Light

Figures 5.11 (a) to (c) show changes in heavy-light responses plotted against the three attributes colourfulness, lightness contrast and lightness. The 17 data points in the plots represent the original and 16 manipulated images using different symbols for each manipulation of chroma (crosses), contrast (solid squares) and lightness (empty circles).

A model of colour weight for images ($\Delta Weight$) was constructed based on the data for images manipulated in terms of colourfulness as a function of the change in image colourfulness using the bi-linear function defined by Equation (5-3). The relationship between colour weight and image contrast was modelled based on the data for images manipulated in terms of image contrast also using Equation (5-3). This equation was also applied to model the relationship between colour weight and image lightness based on the data for images manipulated in terms of lightness with a different set of coefficients. Tables 5.9 shows coefficients optimised to fit the experimental data and $R^2$ with p-values for each model. The $R^2$ and p-values for each model indicate that the goodness of fit for each model was significantly good at a significance level of 0.05.

$$\Delta Weight(\Delta M) = k_0 + k_1 \cdot \Delta M \quad (5\text{-}3)$$

where $\Delta M$ is the change in image colourfulness values from an original image to the manipulated version; and $k_0$ to $k_1$ are constants.



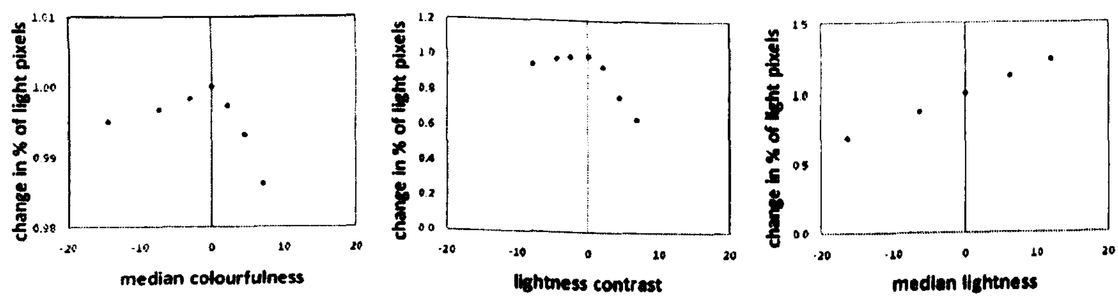

(a) (b) (c)

Figure 5.11 (a)-(c) Changes in colour weight plotted against changes in image (a) colourfulness, (b) lightness contrast and (c) lightness with the predictive models for each relationship (crosses for chroma manipulation; solid squares for contrast manipulation; empty circles for lightness manipulation).

Table 5.9 Coefficients used in Equation (5-3) as a function of colourfulness, contrast and lightness for colour weight.

| | $k_0$ | $k_1$ | $R^2$ | p-value |
|---|---|---|---|---|
| $\Delta Weight\ (\Delta M)$ | 0.043 ($\Delta M > 0$)<br>0.031 ($\Delta M < 0$) | 0.058 ($\Delta M > 0$)<br>-0.181 ($\Delta M < 0$) | 0.96 | 0.00 |
| $\Delta Weight\ (\Delta CO)$ | 0.043 ($\Delta CO > 0$)<br>0.031 ($\Delta CO < 0$) | 0.058 ($\Delta CO > 0$)<br>-0.181 ($\Delta CO < 0$) | 1.00 | 0.00 |
| $\Delta Weight\ (\Delta J)$ | 0.043 ($\Delta J > 0$)<br>0.031 ($\Delta J < 0$) | 0.058 ($\Delta J > 0$)<br>-0.181 ($\Delta J < 0$) | 0.99 | 0.00 |

Figure 5.11 (a) shows that any change in image colourfulness (either increases or decreases) results in lower colour weight. For further investigation, the effect of the area proportion (Wang *et al.*: see Section 2.4.5.3) on colour-emotion responses for colour combinations was examined to determine whether this could be applied to images. Thus, the population of "light" pixels in each images were computed for each image using Ou *et al.*'s *heavy-light* model (see Section 2.4.5.2) for single colour-emotion. A "light" pixel was defined as being when the scale value for that pixel is greater than 0. Figures 5.12 (a)-(c) show the changes in percentage of "light" pixels averaged over 10 test images (including positive, neutral and negative subjects) plotted against the changes in colour attributes manipulated in terms of median colourfulness, lightness contrast and median lightness. The trends of these curves seem quite similar to those shown in Figure 5.11 (a) to (c). This suggests that an "area proportion" effect found by Wang *et al.* (see Section 2.4.5.3) for three-colour combinations could also account for the colour-emotion of *heavy-light* for image stimuli. In Wang *et al.*'s study, the possibility of area proportion on colour-emotion in three colour combination was examined for three factors of colour-emotion. It was found that *heavy-light* was only significant for colour combinations with a high difference in single-colour emotion value between constituent colours. This effect was found to be particularly significant for colour weight. The area proportion in a three-colour combination could be regarded as analogous to the number of pixels which appear to have a specific range of colour grouped in a adjacent area in an image.

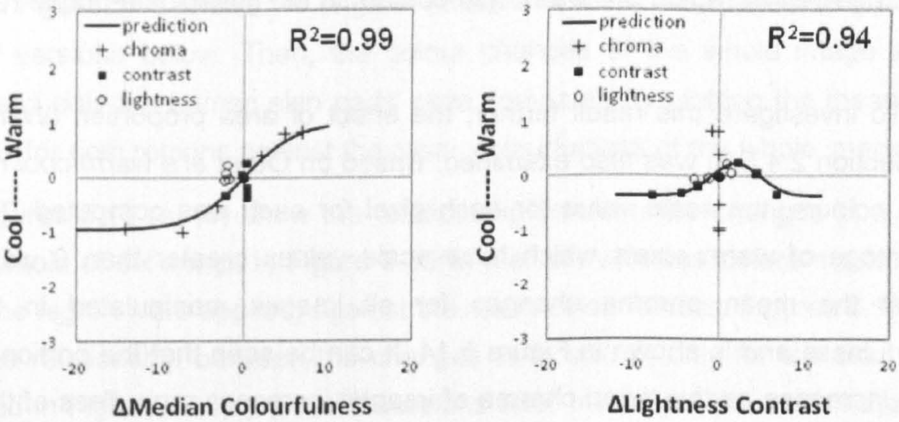



(a) (b) (c)

Figure 5.12 (a)-(c) Changes in % of "light" pixels regarding its single-colour-emotion averaged over images used in the experiment plotted against the changes in colour attributes in terms of (a) colourfulness, (b) contrast and (c) lightness.

### 5.6.3 Warm – Cool

Figures 5.13 (a) to (b) show changes in colour heat plotted against the two image attributes of colourfulness and contrast. The 17 data points in the plots correspond to the original and 16 manipulated images. Different symbols represent each manipulation of chroma (crosses), contrast (solid squares) and lightness (empty circles).




(a) (b)

Figure 5.13 (a)-(b) Changes in colour weight plotted against changes in image (a) colourfulness and (b) lightness contrast with the model predictions for each relationship.(crosses for chroma manipulation; solid squares for contrast manipulation; empty circles for lightness manipulation).

Table 5.10 (a)-(b) (a) Coefficients used in Equation (5-1) as a function of colourfulness; (b) coefficients in Equation (5-2) as a function of image contrast for colour heat.

(a)

| | $k_0$ | $k_1$ | $k_2$ | $k_3$ | $\mu$ | $\sigma$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|---|---|
| $\Delta Heat\ (\Delta M)$ | -0.363 | 0.817 | -0.189 | -1390.957 | 7.237488 | 0.000380 | 0.99 | 0.00 |

(b)

| | $k_0$ | $k_1$ | $k_2$ | $\alpha$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|
| $\Delta Heat\ (\Delta CO)$ | 1.01 | -0.96 | 0.05 | 3.02 | 0.94 | 0.00 |

This relationship shown in Figure 5.13(a) between colour heat responses and colourfulness (and contrast) and were modelled using Equation (5-1) and the optimised coefficients are shown in Table 5.10 together with $R^2$ values and p-values. The $R^2$ and p-values for each model indicate that the goodness of fit for each model was significantly good at a significance level of 0.05.

As shown in Figure 5.13(a), colour heat becomes bigger in its value as image colourfulness increases and smaller when image colourfulness decreases. This indicates that more colourful colours make images warmer overall. This result disagrees with most of single colour-emotion theories by Ou, Sato and Xin, which claim that colour warmth is highly related to the hue angle of a colour, colours in the red-orange-yellow region are warm and colours in the green-blue-purple region are cool.

To investigate this result further, the effect of area proportion (Wang *et al.*: See Section 2.4.5.3) was also examined. Based on Ou *et al*'s *warm-cool* model for single colours, the scale value for each pixel for each was computed. Then, the percentage of warm pixels which have scale values greater than 0 was plotted against the mean chroma changes for all images manipulated in terms of colourfulness and is shown in Figure 5.14. It can be seen that the portion of warm pixels increases as the mean chroma of images increases regardless of the image subject. This indicates that the warm-cool response to images may be affected by the area proportion. This can be represented by the population of pixels of an image which have warm or cool colours according to the *warm-cool* single-colour emotion model.

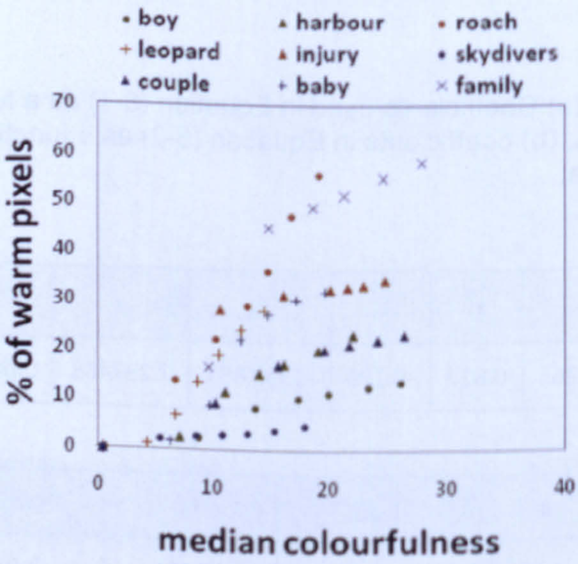



Figure 5.14 The percentage of warm pixels plotted against mean chroma changes for all colourfulness manipulated images.

On the other hand, according to many studies into the perception of image naturalness (see Section 2.5.4.5), colours of familiar objects such as human skin play a critical role in the assessment of image naturalness. For this reason, another approach for further investigation was attempted with a focus on skin colour.

To see how the colour of the skin part actually changes with an increase in colourfulness, six out of the 10 test images used in this experiment were selected and another version of each had a mask applied to the rest of the region excluding the skin. Figure 5.15 shows the original versions of these six images on top and the masked versions below. Then, the colour changes of the whole image and the changes in only the human skin parts were compared by plotting the mean $a_c$ and $b_c$ values for both regions against the mean colourfulness of the whole image.

Figures 5.16 (a)-(b) show the relationship between the changes in $a_c$ and $b_c$ for the whole of six image in Figure 5.15(a) (i.e. the versions before masks for the rest of the region were applied) against the mean colourfulness. Figures 5.17 (a)-(b) show the relationship between the changes in $a_c$ and $b_c$ only for the skin part as illustrated in Figure 5.15(b) (i.e. the versions after masks for the rest of the region were applied), against the mean colourfulness values. Looking at Figures 5.16(a)-(b), it can be found that there are no clear trends of changes in $a_c$ and $b_c$ values as image colourfulness increases. In contrast in Figure 5.17(a)-(b), clear trends of changes in $a_c$ and $b_c$ values were found. As image colourfulness increases, $a_c$ and $b_c$ also tended to increase, indicating that the skin regions have actually changed to more reddish and yellowish colours. Thus, it seems that the colour of the human skin part may be important for the *warm-cool* responses to images.

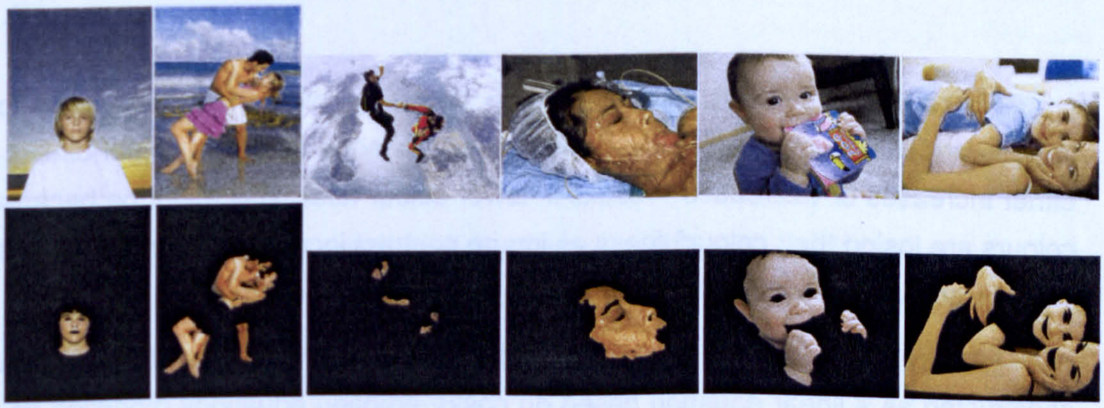
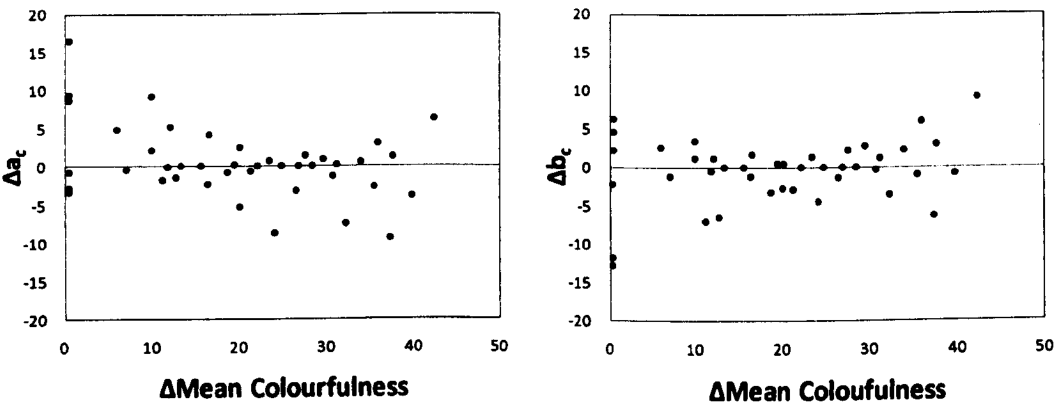
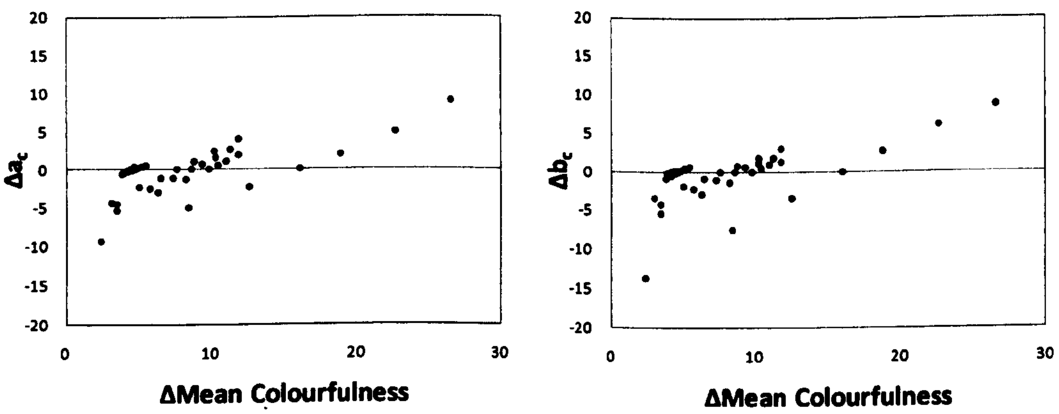


Figure 5.15 Images which include human skin taken from the test images used in Experiment 2 (upper row); masked images to cover the other regions of images except for skin (bottom row); original images from left: *boy, couple, skydivers, injury, baby* and *family*.




(a) (b)

Figure 5.16 (a)-(b) The relationship between the changes in (a) $a_c$ and (b) $b_c$ values and mean colourfulness values of the entire region of the images (i.e. without masks applied) shown in Figure 5.15.




(a) (b)

Figure 5.17 (a)-(b) The relationship between the changes in (a) $a_c$ and (b) $b_c$ values and mean colourfulness values only for skin part of images shown in Figure 5.15.

Figure 5.13(b) shows the relationship between colour heat responses for images and image contrast. It indicates that any change in image colourfulness - either increases or decreases - results in lower colour heat. This might be because colours are losing their colourfulness as image contrast increases when the number of black and white pixels increase or decreases as colour becomes greyish.

Finally, each factor of colour-emotion (activity, weight and heat) was constructed as a linear equation based on colour-emotion equations modelled as a function of three colour attributes including colourfulness (M), contrast (CO) and lightness (J) as shown in Table 5.11. The performance of each model was tested for the entire data set including all images manipulated in terms of colourfulness, contrast and lightness. These were found to determine 92%, 98% and 82% of the variance in visual results for the entire data set of colour activity, weight and heat. The goodness of fit for the three final models were statistically significant with p-values under 0.05. In the next section, the predicted colour-emotion factors for each image will be used to model the visual responses of image emotions (pleasantness and excitement) as a function of colour-emotion factors.

Note that the relationships between image emotions and two image colour attributes were investigated independently. Thus, cross terms of image colourfulness and contrast for inter-relationship between image emotions and two image colour attributes could be added to the equations shown in Table 5.11 for more robust performance of the models.

Table 5.11 Predictive models for three colour-emotion factors: activity, weight and heat developed as a linear equation based on the relationship with colour attributes colourfulness (*M*), contrast (*CO*) and lightness (*J*).

| Emotion Factor | Colour-emotion Models | $R^2$ | p-value |
|---|---|---|---|
| Activity | $\Delta Activity = 1.07 * A(\Delta M) + 1.00 * A(\Delta CO)$ | 0.92 | 0.00 |
| Weight | $\Delta Weight = 1.02 * W(\Delta M) + 0.86 * W(\Delta CO) + 0.79 * W(\Delta J)$ | 0.98 | 0.00 |
| Heat | $\Delta Heat = 1.07 * H(\Delta M) + 0.71 * H(\Delta CO)$ | 0.82 | 0.00 |

## 5.7 Modelling Image Emotion

One of aims in this chapter was to develop image emotion models for *pleasantness* and *excitement* as a function of the colour attributes of images such as lightness, colourfulness and lightness contrast. These models will be compared to the image emotion models that were constructed using three factors in Section 5.6.

The response of image emotion in terms of *pleasantness* and *excitement* was found to have a dependency on image subjects showing significantly different responses for positive and negative image subjects, as investigated in Section 5.4. Accordingly, the model of image emotion will be developed for those two groups of images separately in two ways: as a function of image colour attributes and using three colour-emotion factors.

Image colourfulness and lightness were determined from the median colourfulness and lightness in CAM02-UCS (Section 2.3.4.4) for the image in question. Image contrast was determined using the standard deviation of image lightness in CAM02-UCS.

### 5.7.1 Image Emotion based on Colour-Appearance Attributes

Figures 5.18 (a) to (f) show the changes in pleasantness responses plotted against image colourfulness, lightness contrast and lightness for two groups of image subjects: positive in (a) to (c) and negative in (d) to (f).

Figure 5.18 (a) shows that as image colourfulness increases or decreases, the pleasantness for positive images drops significantly. As shown in Figure 5.18 (b) and (c), increases in lightness contrast and lightness also result in lower pleasantness for positive images. This might imply that pleasant feelings tended to be affected more by image subjects than by colour reproduction scheme.

The change in pleasantness ( $\Delta Pleasantness$ ) for positive images was modelled as a function of the change in image colourfulness using the *Log Normal Distribution Function* in Equation (5-4) for best fit to the experimental data.

$$\Delta Pleasantness\,(\Delta M) = k_0 + \frac{k_1}{\sigma\sqrt{2\pi}(k_2\Delta M - k_3)}e^{\frac{-[\ln(k_2\Delta M - k_3)-\mu]^2}{2\sigma^2}} \tag{5-4}$$

This equation was also used to model the relationships between pleasantness and contrast based on the data for images manipulated in terms of contrast and between pleasantness and lightness using the data for lightness manipulated separately with a different set of coefficients. Table 5.12 (a) shows coefficients optimised for the three models in Equation (5-4) to predict pleasantness. These models determined the experimental data of image pleasantness to the extent of 91%, 98% and 96% respectively for colourfulness, contrast and lightness manipulated images. P-values shown in the table indicate that the agreement between model prediction and the data point are statistically significant at a significance level of 0.05.

For images with negative subjects, decreasing image colourfulness results in higher value in image pleasantness whereas the effect of increasing colourfulness is similar for positive images as shown in Figure 5.18 (d). In Figures 5.18 (e) and (f), the increase of lightness contrast and lightness also can be seen to result in lower pleasantness for negative images; however, the magnitude of changes according to the changes in contrast and lightness was smaller than for positive images. This implies that unpleasant feelings for negative images can hardly be affected by changing contrast and lightness, but can be significantly reduced by making images less colourful.

Additionally, a model of pleasantness for negative images as a function of each colour attribute was developed. For the relationship between pleasantness and colourfulness, Equation (5-4) was used and coefficients were optimised to find the best fit. For the models which were functions of contrast and lightness, Equation (5-4) was used and coefficients were found for the best fit.

$$\Delta Pleasantness(\Delta M) = k_0 + (k_1 - k_0) \times \left(1 + e^{\frac{(\Delta M - k_2)}{\alpha}}\right)^{-1} \qquad (5\text{-}5)$$

Table 5.12(b) shows the coefficients optimised for three models in Equation (5-4) to predict pleasantness for negative images. These models were found to determine the 88%, 79% and 75% of variance in experimental data of image pleasantness respectively for colourfulness, contrast and lightness manipulated images. P-values shown in the table indicate that the agreement between model prediction and the data point for two predictors: colourfulness and contrast are statistically significant at a significance level of 0.05.

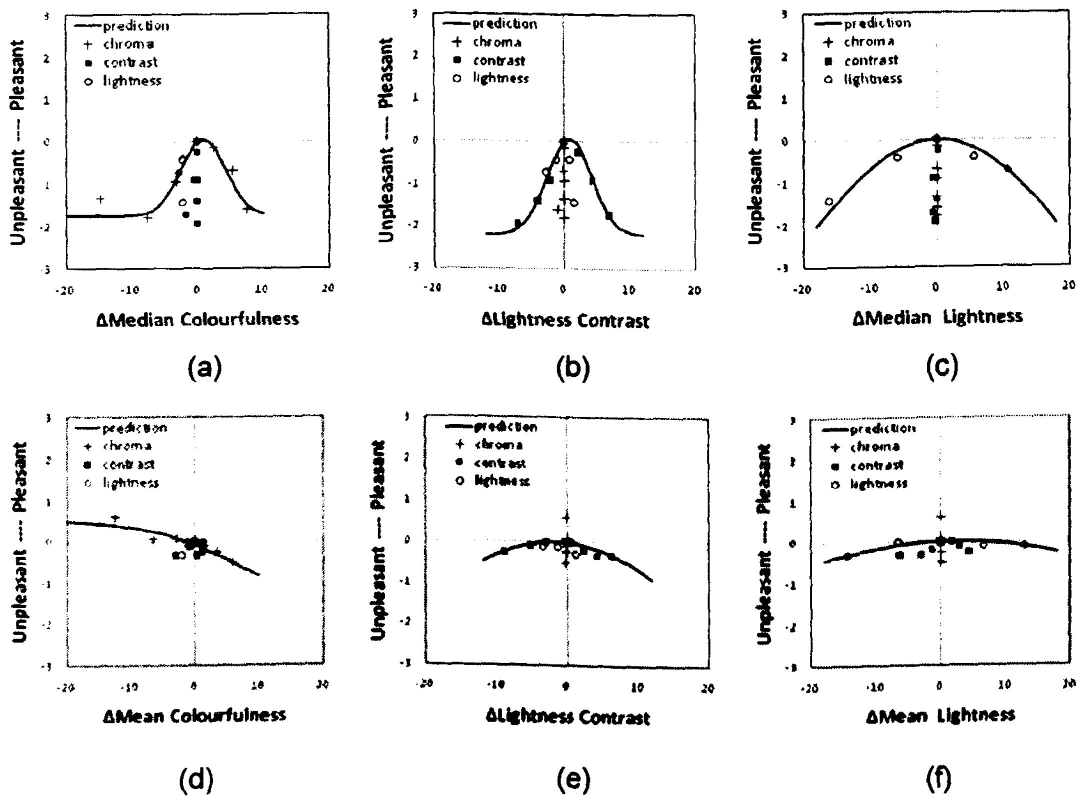



Figure 5.18 (a)-(f) Changes in image pleasantness plotted against changes in image colourfulness (a), lightness contrast (b) and lightness (c) together with the model predictions for each relationship for positive and negative imagae in (d) to (f). (Crosses represent chroma manipulation, solid squares for contrast manipulation and empty circles for lightness manipulation.)

Table 5.12(a)-(b) Coefficients of the image pleasantness model used in Equation (5-4) and (5-5) as a function of colourfulness, image contrast and lightness for (a) positive images and (b) negative images.

(a)

| **Positive Image** | $k_0$ | $k_1$ | $k_2$ | $k_3$ | $\mu$ | $\sigma$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|---|---|
| $\Delta P(\Delta M)$ | -1.743 | 2.188 | -0.144 | -1390.598 | 7.237399 | 0.000348 | 0.91 | 0.00 |
| $\Delta P(\Delta CO)$ | -2.198 | 2.102 | -0.109 | -1390.553 | 7.237396 | 0.000267 | 0.98 | 0.00 |
| $\Delta P(\Delta J)$ | -8.365 | 3.339 | -0.007 | -1390.485 | 7.237407 | 0.000115 | 0.96 | 0.00 |

(b)

| **Negative Image** | $k_0$ | $k_1$ | $k_2$ | $\alpha$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|
| $\Delta P(\Delta M)$ | -1.83 | 0.54 | 7.58 | 7.39 | 0.88 | 0.00 |

| | $k_0$ | $k_1$ | $k_2$ | $k_3$ | $\mu$ | $\sigma$ | $R^2$ | |
|---|---|---|---|---|---|---|---|---|
| $\Delta P(\Delta CO)$ | -12.884 | 121.406 | -0.103 | -54.208 | 4.001 | 0.06902 | 0.79 | 0.00 |
| $\Delta P(\Delta J)$ | -12.791 | 121.417 | -0.051 | -54.137 | 3.994 | 0.06991 | 0.75 | 0.06 |

For images containing positive subjects, decreasing image colourfulness results in significantly lower excitement whereas increasing colourfulness does not show any effect on emotional responses as shown in Figure 5.19 (a). As shown in Figures 5.19 (b) and (c), any changes in lightness contrast and lightness (either increase or decrease), result in lower excitement scores for positive images. This implies that the excitement of positive images can hardly be enhanced by changing any colour attribute because those images are already exciting enough. For positive images, the model of image excitement as separate functions of colourfulness, contrast and lightness was developed using Equation (5-4) and (5-5). Table 5.12 (a) shows the coefficients found for the three models. They were found to determine the data to the extent of 91%, 98% and 96% respectively for colourfulness, contrast and lightness manipulated images.

Figure 5.19 (d) shows that the excitement for negative images increases significantly as image colourfulness increases and decreases as colourfulness decreases. As shown in Figure 5.19 (e), an increase in lightness contrast also results in higher pleasantness and decrease lower values in pleasantness for negative images; however the extent of changes was relatively smaller than when colourfulness varied. For lightness changes, Figure 5.19(f) shows that an increase in lightness caused lower excitement and a decrease higher excitement. This implies that exciting feelings towards negative images can be easily enhanced by increasing colourfulness and contrast and decreasing lightness.

A model of image excitement ($\Delta Excitement$) for negative images as a function of each colour attribute of colourfulness, contrast and lightness was developed using Equation (5-5) and coefficients were optimised to find the best fit for the three data sets of manipulations. Table 5.12(b) shows the coefficients found for these models which determined the 88%, 79% and 75% of variance in experimental data for image pleasantness respectively for colourfulness, contrast and lightness manipulated images.

Note that p-values indicate that the agreement between model prediction and the data point for all predictors are statistically significant at a significance level of 0.05.

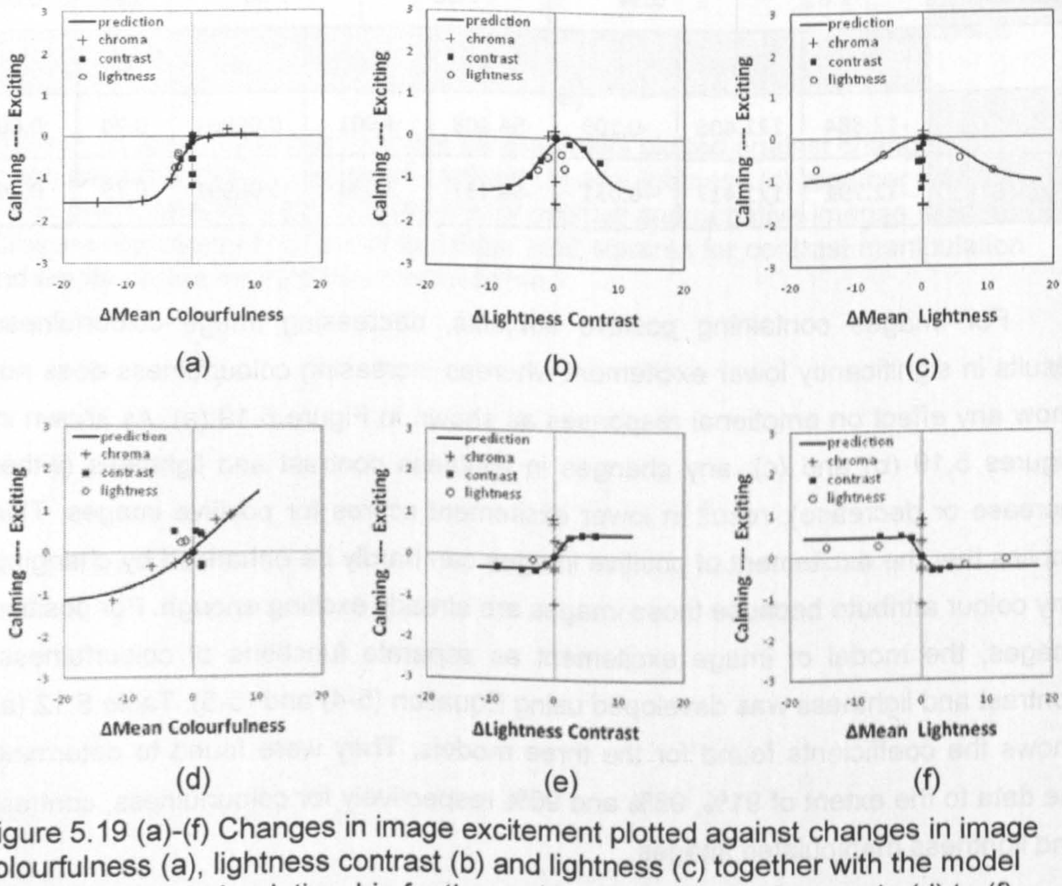



Figure 5.19 (a)-(f) Changes in image excitement plotted against changes in image colourfulness (a), lightness contrast (b) and lightness (c) together with the model predictions for each relationship for the positive and negative images in (d) to (f). (Crosses represent for chroma manipulation, solid squares for contrast manipulation and empty circles for lightness manipulation.)

Table 5.13(a)-(b) Coefficients of the image excitement model used in Equations (5-4) and (5-5) as a function of colourfulness, image contrast and lightness for (a) positive and (b) negative images.

(a)

| **Positive Image** | $k_0$ | $k_1$ | $k_2$ | $\alpha$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|
| $\Delta E(\Delta M)$ | 0.04 | -1.58 | -2.56 | 1.33 | 0.99 | 0.00 |

| | $k_0$ | $k_1$ | $k_2$ | $k_3$ | $\mu$ | $\sigma$ | $R^2$ | |
|---|---|---|---|---|---|---|---|---|
| $\Delta E\ (\Delta CO)$ | -1.249 | 1.158 | -0.098 | -1390.669 | 7.237429 | 0.000265 | 0.92 | 0.00 |
| $\Delta E\ (\Delta J)$ | -1.041 | 3.435 | -0.213 | -1390.596 | 7.237436 | 0.000955 | 0.86 | 0.02 |

(b)

| **Negative Image** | $k_0$ | $k_1$ | $k_2$ | $\alpha$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|
| $\Delta E(\Delta M)$ | 2.51 | -1.22 | 4.18 | 5.57 | 0.95 | 0.00 |
| $\Delta E(\Delta CO)$ | 1.30 | 0.51 | 0.45 | 0.79 | 0.99 | 0.00 |
| $\Delta E(\Delta J)$ | -1.00 | -0.27 | -0.17 | 0.32 | 0.96 | 0.00 |

Finally, the models of image pleasantness and excitement for positive and negative images were developed as a linear equation based on functions of the three colour attributes colourfulness (M), contrast (CO) and lightness (J) as shown in Table 5.14. The performance of each model was tested for the entire data set including all images manipulated in terms of colourfulness, contrast and lightness. Pleasantness models were found to determine 80% and 84% of variance in the data set for positive (Group 1) and negative (Group 2) images respectively. The excitement models determined 86% and 85% of variance in the data set for positive (Group 1) and negative (Group 2) images respectively. P-values shown with $R^2$ indicate that the agreement between model prediction and the data point are statistically significant at a significance level of 0.05.

Note that the relationships between image emotions and two image colour attributes were investigated independently as in Chapter 4. Thus, cross terms of image colourfulness and contrast for inter-relationship between image emotions and two image colour attributes could be added to the equations shown in Table 5.14 for more robust performance of the models and this could one of the future works.

Table 5.14 Predictive models for image pleasantness and excitement developed as a linear equation based on relationship with colourfulness (*M*), contrast (*CO*) and lightness (*J*).

| Image Emotion Models (colour attributes) | | | $R^2$ | p-value |
|---|---|---|---|---|
| Pleasantness | Positive | $\Delta P= 0.94*P(\Delta M) + 0.96*P(\Delta CO) + 0.36*P(\Delta J)$ | 0.80 | 0.00 |
| | Negative | $\Delta P = 0.96*P(\Delta M) + 1.38*P(\Delta CO) + 1.28*P(\Delta J)$ | 0.84 | 0.00 |
| Excitement | Positive | $\Delta E = 1.17*E(\Delta M) + 0.90*E(\Delta CO)$ | 0.86 | 0.00 |
| | Negative | $\Delta E = 1.07*E(\Delta M) + 1.23*E(\Delta CO) + 0.21*E(\Delta J)$ | 0.85 | 0.00 |

### 5.7.2 Image Emotion based on Colour-Emotion Components

As a second approach to image emotion modelling, the visual responses to image pleasantness and excitement were modelled as a function of the three colour-emotion factors developed in Section 5.6.

First of all, the relationships between the visual results for *pleasantness* and *excitement* and the predicted values of colour activity, weight and heat by the colour-emotion models derived in the previous section were investigated for images in the two groups. Figures 5.20 (a) to (c) show the changes in the pleasantness responses for positive images plotted against predicted values for each colour-emotion factor. As shown in plots, any changes in colour-emotion do not result in enhancement of pleasantness. These relationships were modelled as a function of each colour-emotion factor ($\Delta Activity$, $\Delta Weight$ and $\Delta Heat$) using the *Log Normal Distribution Function* in Equation (5-6).

$$\Delta Pleasantness\ (\Delta Activity) = k_0 + \frac{k_1}{\sigma\sqrt{2\pi}(k_2\Delta A - k_3)} e^{\frac{-[ln(k_2\Delta A - k_3) - \mu]^2}{2\sigma^2}} \qquad (5\text{-}6)$$

The optimised coefficients in equations are listed in Table 5.16(a). These models determined 51%, 43% and 54% of visual results for the entire data set of colour activity, weight and heat respectively.

For negative images as shown in Figures 5.21 (d) to (f), it was found that a decrease in colour activity and heat can enhance their pleasantness whereas any changes in colour weight reduce pleasantness. According to the relationship between each colour attiribute and the colour-emotion factors investigated in Section 5.5, a decrease in colour activity and heat can be achieved by reducing colourfulness or by applying significant changes in image contrast and lightness (either increase or decrease). This might be because reducing colour activity and heat makes images looks unrealistic and this elicits less unpleasant feelings. These relationships were modelled as a function of each colour-emotion factor using Equations (5-6) and (5-7).

$$\Delta Pleasantness(\Delta Activity) = k_0 + (k_1 - k_0) \times \left(1 + e^{\frac{(\Delta A - k_2)}{\alpha}}\right)^{-1} \qquad (5\text{-}7)$$

The optimised coefficients in equations are listed in Table 5.15(b). These models were found to determine the 51%, 39% and 61% of the visual results for the entire data set of colour activity, weight and heat respectively.

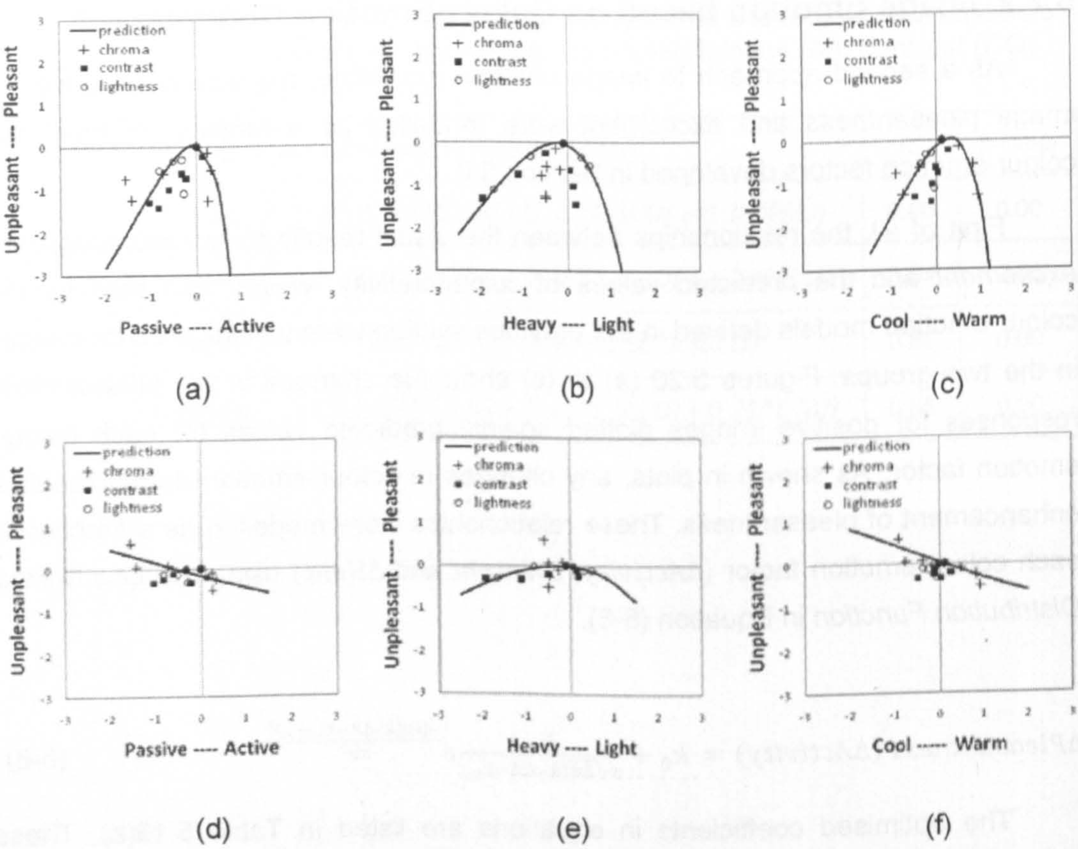



Figure 5.20 (a)-(f) Changes in image pleasantness plotted against changes in colour activity (a), weight (b) and heat (c) together with the model predictions for each relationship for positive and negative image in (d) to (f). (Crosses represent chroma manipulation, solid squares for contrast manipulation and empty circles for lightness manipulation.)

Table 5.15(a)-(b) Coefficients of the pleasantness model defined in Equation (5-6) and (5-7) as a function of colour activity, weight and heat for (a) positive and (b) negative images.

(a)

| Positive Image | $k_0$ | $k_1$ | $k_2$ | $k_3$ | $\mu$ | $\sigma$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|---|---|
| $\Delta Pleasantness(\Delta A)$ | -11.10 | 61.93 | -0.75 | -1.04 | 1.31 | 1.11 | 0.51 | 0.03 |
| $\Delta Pleasantness(\Delta W$ | -11.70 | 57.89 | -0.50 | -1.37 | 1.19 | 0.89 | 0.43 | 0.07 |
| $\Delta Pleasantness(\Delta H)$ | -11.20 | 61.92 | -0.78 | -1.48 | 1.29 | 1.03 | 0.54 | 0.01 |

(b)

| Negative Image | $k_0$ | $k_1$ | $k_2$ | $\alpha$ | | | $R^2$ | p-value |
|---|---|---|---|---|---|---|---|---|
| $\Delta Pleasantness(\Delta A)$ | 1.4984 | -1.2819 | -0.8404 | 2.1856 | | | 0.51 | 0.02 |
| $\Delta Pleasantness(\Delta H)$ | 1.8528 | -1.2481 | -0.6376 | 1.9206 | | | 0.61 | 0.08 |
| | $k_0$ | $k_1$ | $k_2$ | $k_3$ | $\mu$ | $\sigma$ | $R^2$ | |
| $\Delta Pleasantness\ (\Delta W$ | -11.69 | 57.88 | -0.24 | -1.36 | 1.19 | 0.91 | 0.39 | 0.00 |

For positive images, it was found that an increase in colour activity and heat can enhance excitement significantly whereas an increase in colour weight reduces it. This indicates that more active and warmer feelings make images more exciting. According to the colour-emotion models derived in Section 5.5, an increase in colour activity and heat can be achieved by increasing image colourfulness. These were also modelled as a function of each colour-emotion factor ($\Delta Activity$, $\Delta Weight$ and $\Delta Heat$) using Equations (5-6) and (5-7). The coefficients used in these equations are given in Table 5.16(a). The models were found to account for 98%, 82% and 76% of variance in the entire data set of colour activity, weight and heat, respectively.

Note that p-values for the *ΔPleasantness(ΔW)* for positive images and *ΔPleasantness(ΔH)* for negative images are greater than 0.05 indicating that the significance of model predictions are statistically small at a significance level of 0.05

For negative images, the results show that a decrease of colour weight with an increase of colour avtivity and heat can enhance the excitement significantly. This indicates that heavier feelings as well as more active and warmer feelings make images more exciting. According to the colour weight models derived in Section 5.6, heavier feelings can be mainly achieved by increasing contrast or decreasing lightness. The coefficients used in models as a function of each colour-emotion factor are given in Table 5.16(b). These models were found to account for 81%, 76% and 53% of variance in the entire data set of colour activity, weight and heat respectively.

Note that p-values for the *ΔExcitement(ΔW)* for both image groups are greater than 0.05 indicating that the significance of model predictions are statistically small at a significance level of 0.05

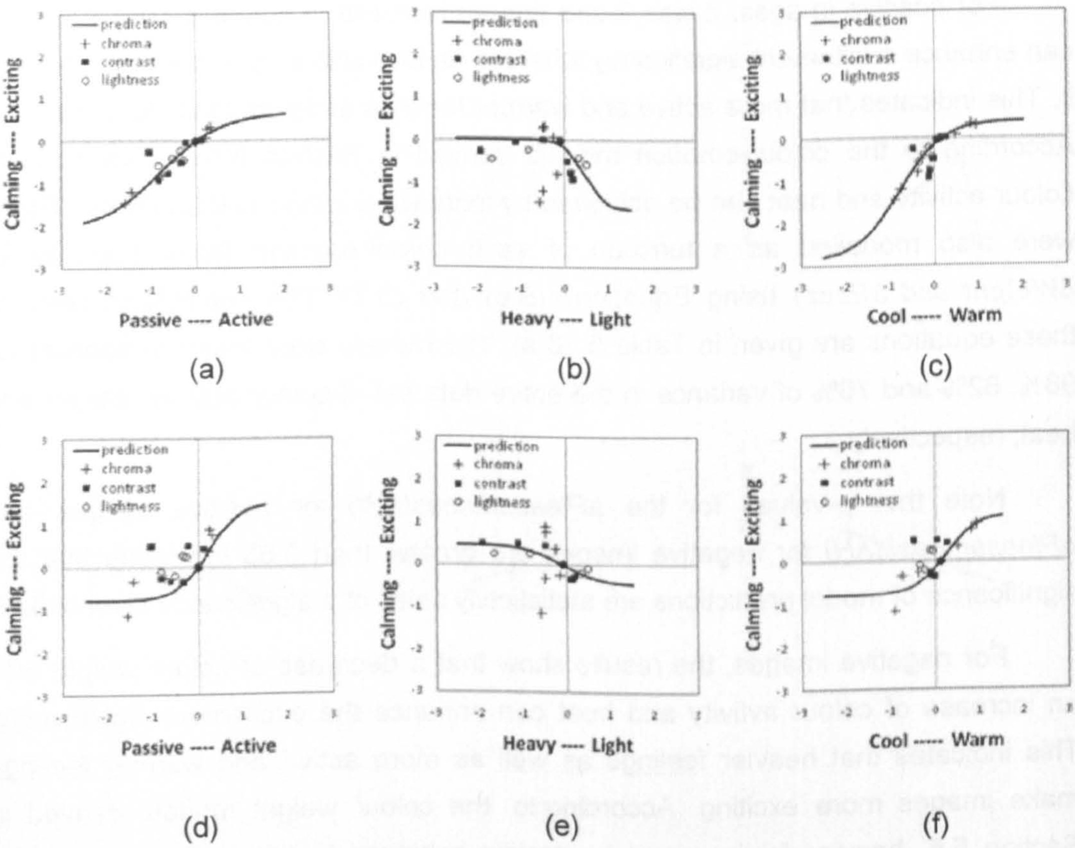



Figure 5.21 (a)-(f) Changes in image excitement plotted against changes in colour activity (a), weight (b) and heat (c) together with the model predictions for each relationship for positive and negative images in (d) to (f). (Crosses represent chroma manipulation, solid squares for contrast manipulation and empty circles for lightness manipulation.)

Table 5.16(a)-(b) Coefficients of the excitement model defined in Equation (5-6) and (5-7) as a function of colour activity, weight and heat for (a) positive and (b) negative images.

(a)

| **Positive Image** | $k_0$ | $k_1$ | $k_2$ | $\alpha$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|
| $\Delta Excitement(\Delta A)$ | -2.1099 | 0.6641 | -0.7833 | 0.6749 | 0.98 | 0.00 |
| $\Delta Excitement(\Delta W)$ | 0.0250 | -1.6452 | 0.4657 | 0.2301 | 0.82 | 0.43 |
| $\Delta Excitement(\Delta H)$ | -2.8957 | 0.3905 | -0.7901 | 0.4839 | 0.76 | 0.00 |

(b)

| **Negative Image** | $k_0$ | $k_1$ | $k_2$ | $\alpha$ | $R^2$ | p-value |
|---|---|---|---|---|---|---|
| $\Delta Excitement(\Delta A)$ | -0.7896 | 1.5217 | 0.2281 | 0.3481 | 0.81 | 0.00 |
| $\Delta Excitement(\Delta W)$ | 0.4829 | -0.4824 | -0.0974 | 0.4382 | 0.76 | 0.06 |
| $\Delta Excitement(\Delta H)$ | -0.7896 | 1.1217 | 0.2281 | 0.3481 | 0.53 | 0.00 |

The final models of image pleasantness and excitement for positive and negative images were developed as a linear equations based on colour-emotion equations modelled as a function of colourfulness (M), contrast (CO) and lightness (J) as shown in Table 5.17. The performance of each model was tested for the entire data set including all images manipulated in terms of colourfulness, contrast and lightness. Pleasantness models were found to account for 47% and 70% of variance of the visual results for positive (Group 1) and negative (Group 2) images respectively. The excitement models accounted for 82% and 76% of variance in visual results for positive (Group 1) and negative (Group 2) images respectively. These models performed less well than those based on changes in the colour attributes of images. However, these models might be useful for planning some sort of overall strategy to enhance the overall emotional impact of images. The models based on changes in colour attributes provide an actual means to implement the strategy. Although these models performed less well than those based on changes in the colour attributes of images, p-values shown in the table indicate that the agreement between model prediction and the data point are statistically significant at a significance level of 0.05.

Table 5.17 Predictive models for image pleasantness and excitement developed as a linear equations based on the relationship with colour-emotion models.

| Image Emotion Models (colour-emotion factors) | | | $R^2$ | p-value |
|---|---|---|---|---|
| Pleasantness | Positive | $\Delta P = -0.33*Activity + 1.06*Weight + 1.32*Heat$ | 0.47 | 0.00 |
| | Negative | $\Delta P = -0.47*Activity + 1.43*Weight + 2.27*Heat - 0.02$ | 0.70 | 0.00 |
| Excitement | Positive | $\Delta E = 1.54*Activity + 0.06*Weight + 0.08*Heat - 0.02$ | 0.82 | 0.00 |
| | Negative | $\Delta E = -0.58*Activity + 0.70*Weight + 1.41*Heat - 0.10$ | 0.76 | 0.00 |

## 5.8 Summary

The aim of this chapter was to develop quantitative models for three factors of colour-emotion (i.e. activity, weight and heat) for complex images and for the overall emotion of pleasantness and excitement as functions of colorimetric quantities for image stimuli. Moreover, the aim of this chapter also included to develop models of image pleasantness and excitement in terms of colour-emotion scales of images and to compare these models.

The inter- and intra-observer variabilities were compared between genders and between cultures. It was found that all observer groups had similar levels of observer accuracy and repeatability. As a result of comparing emotional responses between genders and cultures, it was found that all observer groups share a similar underlying emotional response for images, however some cultural differences were found for *active-passive* and *warm-cool* between Korean and Chinese and also between male and female groups. Principal component analysis was used to investigate the underlying structure between colour-emotion and image emotion. It was found that *like-dislike, pleasant-unpleasant* and *light-heavy* are highly related to the *evaluative* factor proposed by Osgood. In addition, *exciting–calming* and *warm-cool* are primarily related to the *activity* factor proposed by Osgood. However, it was also found that the *active-passive* scale has both evaluative and activity properties and this may present different responses for observer groups.

The influence of image subject on emotional responses was investigated by applying the method of principal component analysis to each emotion scale to find any similarity between images used in the experiment. As a result, the image emotion responses were significantly different for positive (including positive, neutral and personal) images and negative images, w hereas the responses of colour-emotion were subject independent. Thus, colour-emotion models were developed based on data averaged over all images used in the experiment, and image emotion models were developed separately based on data for positive and negative images.

The relationships between colour-emotion factors for all images used in the experiment and colour-appearance attributes were explored and developed as quantitative models as a function of colour attributes of images such as lightness, colourfulness and lightness contrast. From the results, it was found that colour activity for images can be enhanced by increasing image colourfulness, colour weight by increasing contrast or decreasing lightness, and colour heat by increasing colourfulness.

The relationships between image emotion and colour-appearance attributes were also investigated and developed as quantitative models in terms of colour attributes such as lightness, colourfulness and lightness contrast for positive and negative image groups. Image emotion models for the two groups of images were developed also as functions of the three factors of colour-emotion models developed in this chapter. Among the models developed those which were functions of colour-appearance attributes performed better than those which were functions of colour-emotion factors. Using the second model, images which are already pleasant enough, can only be enhanced in terms of excitement by making colours more active and warmer. For negative images, image pleasantness can be enhanced by more passive and cooler colours. Image excitement can be enhanced by more active, heavier and warmer colours.

# Chapter 6 Comparison of Image Emotion Model Developed for Different Media Based on Psychophysical Results

As shown in Chapter 4, the emotional responses for pleasantness and excitement to printed images were investigated with regard to image subjects showing significant differences between[ positive and negative images. Models of image emotion were developed for two image groups as a function of colourfulness and contrast. In Chapter 5, the emotional responses for pleasantness and excitement were studied for displayed images with regards to subjects showing significant differences between positive and negative images. The responses for colour-emotion factors to displayed images were also investigated. The emotional responses for pleasantness, excitement and also colour-emotion factors for displayed images were modelled as functions of image colourfulness and contrast. And the emotional responses for pleasantness and excitement were also modelled as a function of three factors of colour-emotion and the performance was compared to one of the former models.

In this chapter, the aim is focussed on a comparison of the image emotion model of pleasantness and excitement developed for printed and displayed images in Chapters 4 and 5. A combined universal model will be developed as a function of image colour attributes based on both data sets. Also, the colour-emotion models for images developed in Chapter 5 will be used again to model the image emotions of pleasantness and excitement.

In Section 6.1, the visual results for two different media will be compared. The performances of two sets of image emotion models obtained from printed and displayed images will be tested for the other data set.

In Section 6.2, a universal model of image emotion comprising displayed and printed versions will be proposed as a function of colour attributes.

## 6.1 Testing Model Performance for Different Media

In this section, the visual results for two different media will be compared and the performances of two emotion models obtained from printed images and displayed images will be tested for the other data set.

### 6.1.1 Comparison between visual results for printed and displayed images

Table 6.1 summarises the environmental conditions used in Experiments 1 and 2 including media, surround lightings, image size, distance and size of the viewing fields. Note that there was little size difference as the visual angles corresponding to images size with regards to the distance between the observers and images were almost the same for both conditions. Thus the size effect could be ignored and the media difference and the lighting conditions could cause any difference between visual results.

Table 6.1 Comparison of experimental condition used in Experiments 1 and 2.

| Media | Prints | Display |
|---|---|---|
| Surround Condition | Average | Dark |
| Surround Luminance (cd/m$^2$) | 279.9 | $\approx$0 |
| Size (cm) | 15.2(H) x 10.2(V) | 66.2(H) x 43.2(V) |
| Distance (cm) | 30 | 130 |
| Visual Angle (°) | 28.5(H) x 19.2(V) | 28.6(H) x 18.9(V) |

To compare the visual results from the two experiments, the visual results for image pleasantness and excitement for three images that were both printed and displayed in Experiments 1 and 2 (i.e. boy, harbour and family : See Section 3.4.1.1 and 3.4.2.1) were examined.

The mean of the visual pleasantness results for each of the three images are plotted against the corresponding changes in median colourfulness and image contrast together with the predictive models developed for positive images in printed (see Table 4.7(a) in Section 4.5.1) and displayed (Table 5.12(a) in Section 5.7.1) versions in Figures 6.1(a)-(b). In Figure 6.1(a), the trend of data points for the display (crosses) tends to be sharper than one for the photo data (empty circle). This indicates that the display model (solid line) tends to predict a change in visual response over a narrower range than does the photo model (dashed line). Also in Figure 6.1(b), it is found that the trends of the two data sets and two models seem to be very similar, as are the changes in contrast. It also shows that the trend of visual results for the displayed images is a little sharper than for printed images. This indicates that observers were more sensitive to changes in colourfulness and contrast for displayed images. This may be because visual changes in colour attributes in displayed images tended to be perceptually larger than in printed images. Leckner *et al.* (2002) showed that soft copies displayed on an LCD tended to give higher sharpness, higher chroma and brightness than the hard copy images under the same viewing conditions because of the large luminance (maximum 230cd/m$^2$) and contrast ratio of LCD. Reducing the luminance of the LCD (to about 100cd/m$^2$) tended to make displayed images appear closer to the hard copies.

Reducing the luminance levels of ambient lighting tended to make the perceived contrast of images larger (Choi, 2008). Thus the difference in visual results may be due to visual changes in the colour attributes of displayed images tending to be larger than for printed images.

The average results for excitement plotted against the corresponding changes in median colourfulness and image contrast together with the predictive models for positive images in their printed and displayed versions in Figures 6.1 (c)-(d) show a larger difference between the two media than in that for the pleasantness results. The responses of excitement for printed images increase significantly as image colourfulness increases and decrease with colourfulness, whereas the responses for displayed images increase just slightly as image colourfulness increases and decreases significantly as colourfulness decreases. For contrast changes, the excitement for printed images is just slightly enhanced as image contrast increases and slightly reduced as image contrast decreases. In contrast for displayed images, any changes in lightness contrast (either increase or decrease), result in reduced excitement. This may due to these images already being exciting enough; any changes other than increasing colourfulness just makes them less exciting as mentioned in Section 5.7.1. Also, as Leckner *et al.* (2002) pointed out, visually larger changes in colour attributes for displayed images rather than for printed images may contribute to the bigger changes in visual results for displayed images. Also, the lower level of surround lighting for displayed images may contribute to the visually larger changes in emotional responses.

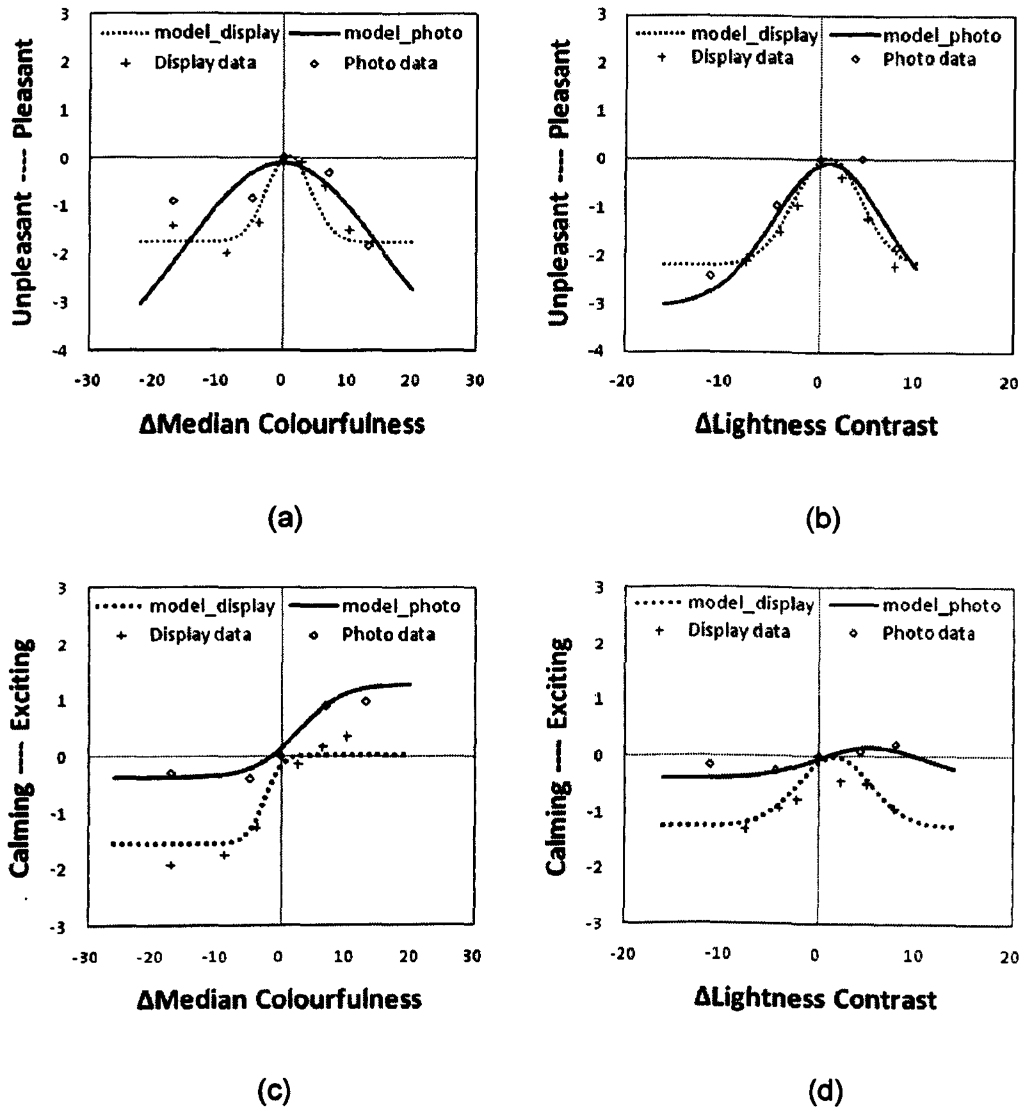



Figure 6.1 (a)-(d) The average visual results for image pleasantness plotted against the corresponding changes in (a) median colourfulness and (b) image contrast. The average visual results for image excitement plotted against the corresponding changes in (c) median colourfulness and (d) image contrast for the three images used as both printed and displayed stimuli in Experiments 1 and 2 (boy, harbour and family in Sections 3.4.1.1 and 3.4.2.1).

### 6.1.2 Testing Model Performance for Different Media

The predictive models of image pleasantness for positive images derived for printed images in Chapter 4 (see Table 4.7(a) in Section 4.5.1) and displayed images (display model) in Chapter 5 (Table 5.12(a) in Section 5.7.1) were tested agaiinst the visual results from both media. The results were compared in Figures 6.2(a)-(d). It was found that the visual data obtained from printed images could be better predicted by the model derived for printed images than by the model derived for displayed images, since all the data points shown in Figure 6.2(a) are located more closely to the 45° line than the results predicted by the display model as shown in Figure 6.2(b). The agreement between visual results and predictive values for Figure 6.2(a) had a higher correlation coefficient of 0.76 than 0.60 for Figure 6.2(b).

It was found that the visual data obtained from displayed images could be better predicted by the model derived for displayed images than by the model derived for printed images, since all the data points shown in Figure 6.2 (c) are located more closely to the 45° line than the results predicted by the photo model as shown in Figure 6.2 (d). The agreement between visual results and predictive values for Figure 6.2(c) had a higher correlation coefficient of 0.78 than 0.67 for Figure 6.2(d).

The predictive models of pleasantness for negative images derived for printed stimuli in Chapter 4 (see Table 4.7(b) in Section 4.5.1) and displayed stimuli in Chapter 5 (Table 5.12(b) in Section 5.7.1) were tested with the visual results from both media.

The visual data obtained from printed images can be better predicted by the model derived for printed images than by the model derived for displayed images, since all the data points shown in Figure 6.3 (a) are located more closely to the 45° line than those results predicted by the display model as shown in Figure 6.3(b). The agreement between visual results and predictive values for Figure 6.3(a) had a higher correlation coefficient of 0.66 than 0.64 for Figure 6.3(b).

The visual data obtained from printed images can be better predicted by the model derived for printed images than by the model derived for displayed images, since all the data points shown in Figure 6.3(c) are located more closely to the 45° line than those results predicted by display model shown in Figure 6.3(d). And the agreement between visual results and predictive values for Figure 6.3(c) showed higher correlation coefficient value of 0.60 than 0.56 for Figure 6.3(d).

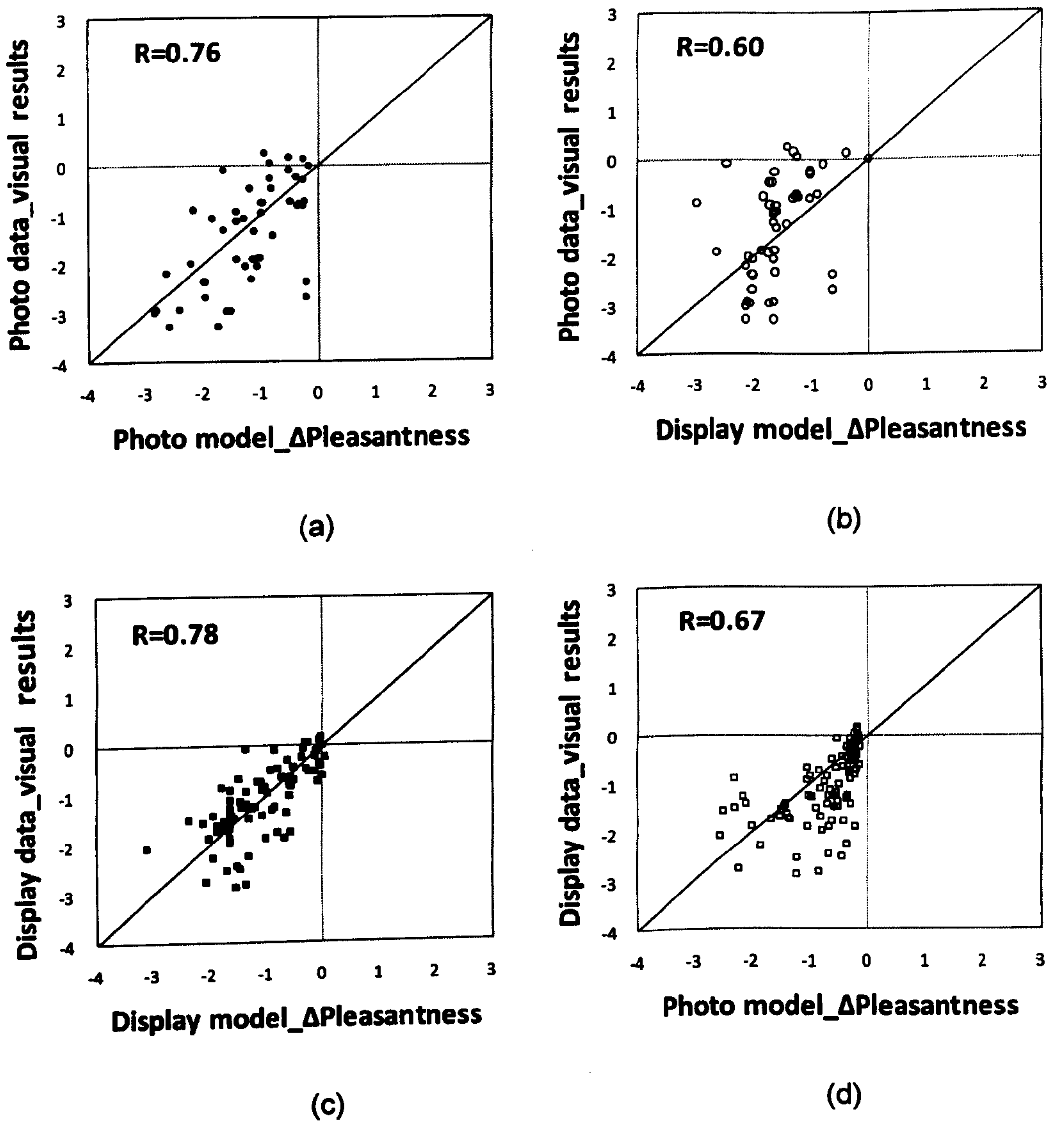



Figure 6.2 (a)-(d) The visual results of image pleasantness obtained for printed images plotted against the results predicted by (a) the photo model and by (b) the display model. The visual results of image pleasantness obtained for displayed images plotted against the results predicted by (c) the display model and by (d) the photo model (for positive images).

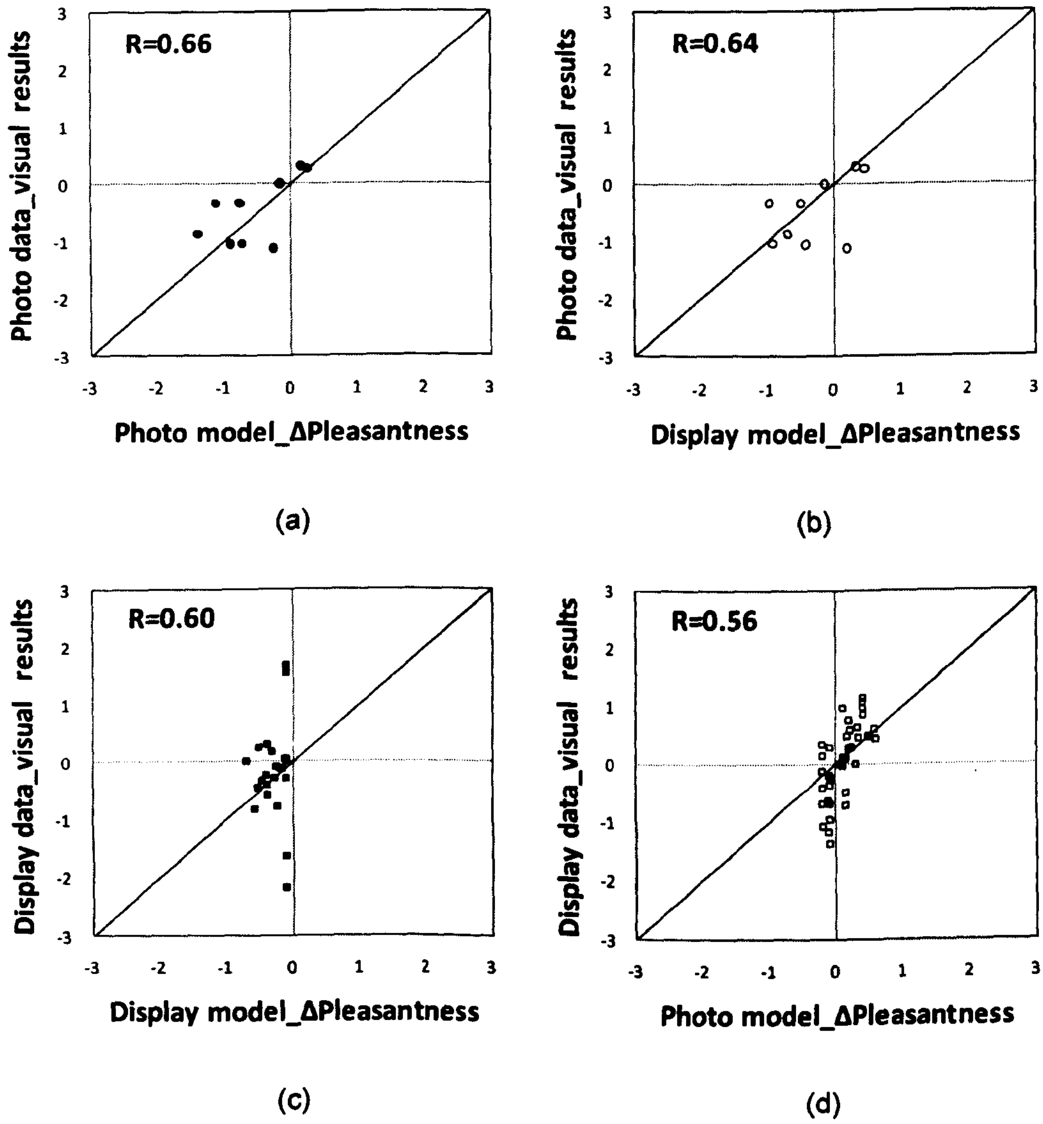



Figure 6.3 (a)-(d) The visual results of image pleasantness obtained for printed images plotted against the results predicted by (a) the photo model and by (b) the display model. The visual results of image pleasantness obtained for displayed images plotted against the results predicted by (c) the display model and by (d) the photo model (for negative images).

The predictive models of image excitement for positive images derived for printed images in Chapter 4 (see Table 4.8(a) in Section 4.5.1) and displayed images (display model) in Chapter 5 (Table 5.13(a) in Section 5.7.1) were tested using the visual results from both media. The results were compared in Figures 6.4 (a)-(d). It was found that the visual data obtained from printed images could be better predicted by the model derived for printed images than by the model derived for displayed images, since all the data points shown in Figure 6.4 (a) are located more closely to the 45° line than the results predicted by display model as shown in

Figure 6.4(b). The agreement between visual results and predictive values for Figure 6.4(a) had a higher correlation coefficient of 0.68 than 0.52 for Figure 6.4(b).

It was found that the visual data obtained from displayed images could be better predicted by the model derived for displayed images than by the model derived for printed images, since all the data points shown in Figures 6.4(c) are located more closely to the 45° line than the results predicted by the photo model as shown in Figure 6.4(d). The agreement between visual results and predictive values for Figure 6.4(c) had a higher correlation coefficient of 0.80 than 0.68 for Figure 6.4(d).

The predictive models of image pleasantness for negative images derived for printed images in Chapter 4 (see Table 4.8(b) in Section 4.5.1) and displayed images (display model) in Chapter 5 (Table 5.13(b) in Section 5.7.1) were tested using the visual results from both media. The results are compared in Figures 6.5 (a)-(d).

The visual data obtained from printed images can be better predicted by the model derived for printed images than by the model derived for displayed images, since all the data points shown in Figure 6.5(a) are located more closely to the 45° line than the predicted results by the display model as shown in Figure 6.5(b). The agreement between visual results and predictive values for Figure 6.5(a) had a higher correlation coefficient of 0.88 than 0.84 for Figure 6.5(b).

The visual data obtained from printed images can be better predicted by the model derived for printed images than by the model derived for displayed images, since all the data points shown in Figure 6.5(c) are located more closely to the 45° line than the predicted results by the display model as shown in Figure 6.5(d). The agreement between visual results and predictive values for Figure 6.5(c) had a higher correlation coefficient of 0.78 than 0.69 for Figure 6.5(d).

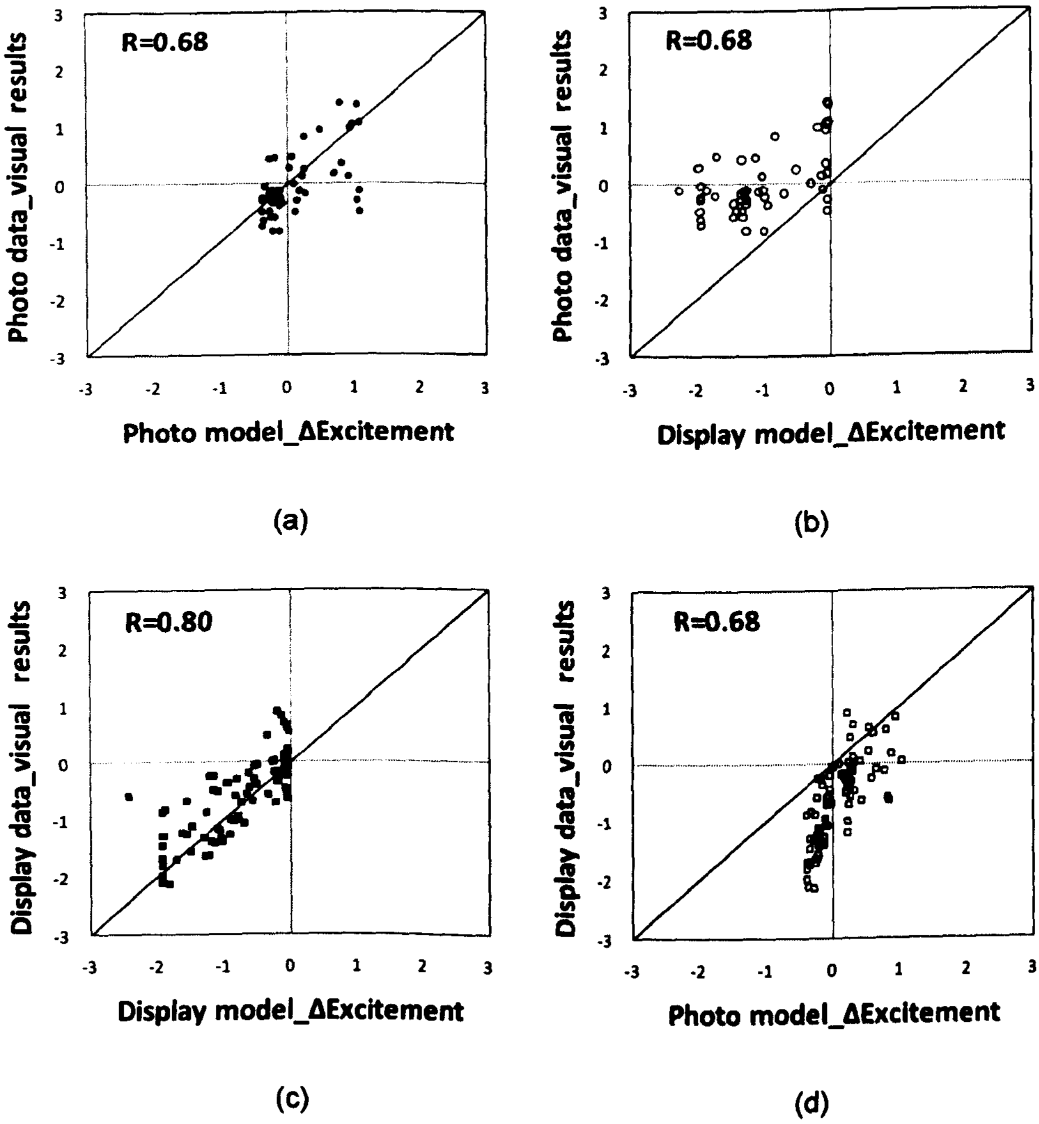



Figure 6.4(a)-(d) The visual results of image excitement obtained for printed stimuli plotted against the results predicted by (a) the photo model and by (b) the display model. The visual results of image excitement obtained for displayed stimuli plotted against the results predicted by (c) the display model and by (d) the photo model (for positive images).

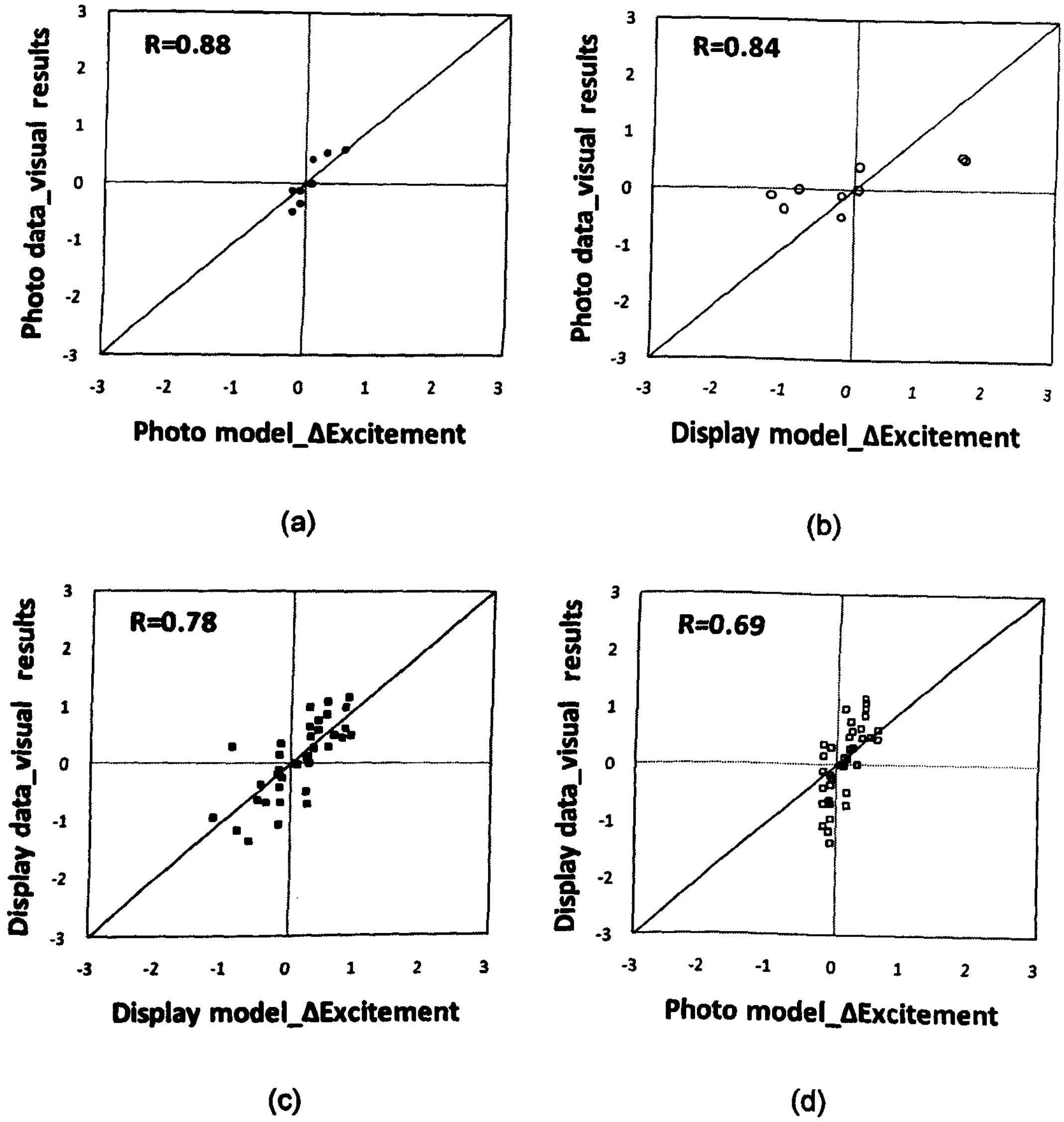



Figure 6.5(a)-(d) The visual results of image excitement obtained for printed stimuli plotted against the results predicted by (a) the photo model and by (b) the display model; The visual results of image excitement obtained for displayed stimuli plotted against the results predicted by (c) the display model and by (d) the photo model (for negative images).

## 6.2 Universal Models of Image Emotion

In this section, combined models of image pleasantness and excitement comprising the visual results both from printed images and displayed images will be proposed and their performance will be tested.

Figures 6.6 (a)-(b) show the visual results of image pleasantness for positive image group plotted against the corresponding changes in median colourfulness (left) and image contrast (right) for all images used in both versions of printed and displayed images in Experiment 1. Figure 6.6(a) shows that as image colourfulness increases or decreases, the pleasantness for positive images drops dramatically. As shown in Figure 6.6(b), the increase in lightness contrast also results in reduced value in pleasantness for positive images.

The change in image pleasantness ($\Delta Pleasantness$) for positive images was modelled as a function of the change in image colourfulness and contrast again using the *Log Normal Distribution Function* (Limpert, 2001) in Equation (6-1) to best fit the experimental data.

$$\Delta Pleasantness\,(\Delta M) = k_0 + \frac{k_1}{\sigma\sqrt{2\pi}(k_2\Delta M - k_3)} e^{\frac{-[ln(k_2\Delta M - k_3) - \mu]^2}{2\sigma^2}} \quad (6\text{-}1)$$

For negative images, decreasing image colourfulness results in greater pleasantness, whereas the effect of increasing colourfulness is similar for positive images as shown in Figure 6.7(a). Figure 6.6(b) shows that an increase in lightness contrast also results in reduced pleasantness for negative images. For the relationship between pleasantness and colourfulness, the *Boltzmann Distribution Function* shown in Equation (6-2) was again used and coefficients were optimised to find the best fit. For models as a function of contrast, Equation (6-1) was used again and the coefficients were found for the best fit.

$$\Delta Pleasantness(\Delta M) = k_0 + (k_1 - k_0) \times \left(1 + e^{\frac{(\Delta M - k_2)}{\alpha}}\right)^{-1} \quad (6\text{-}2)$$

The optimised coefficients for models as a function of each attribute are given in Table 6.2(a) for positive images and in Table 6.2(b) for negative images. The models for the positive image group were found to have correlation coefficients of 0.70 and 0.77 between the visual results and the model predictions respectively for colourfulness and contrast manipulations of all positive images. The models for the negative image group were found to have correlation coefficients of 0.84 and 0.72 between the visual results and the model predictions respectively for colourfulness and contrast manipulations of all negative images.

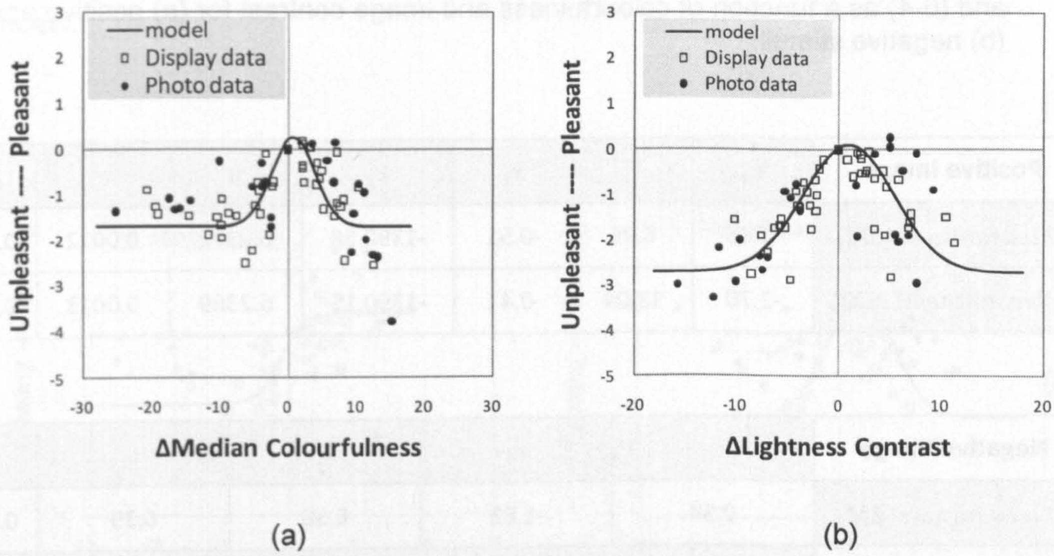



Figure 6.6(a)-(b) Visual results of image pleasantness for the positive image group plotted against the corresponding changes in (a) median colourfulness and (b) image contrast together with curves of the model derived using two attributes for all images used as both versions of printed and displayed stimuli in Experiments 1 and 2.

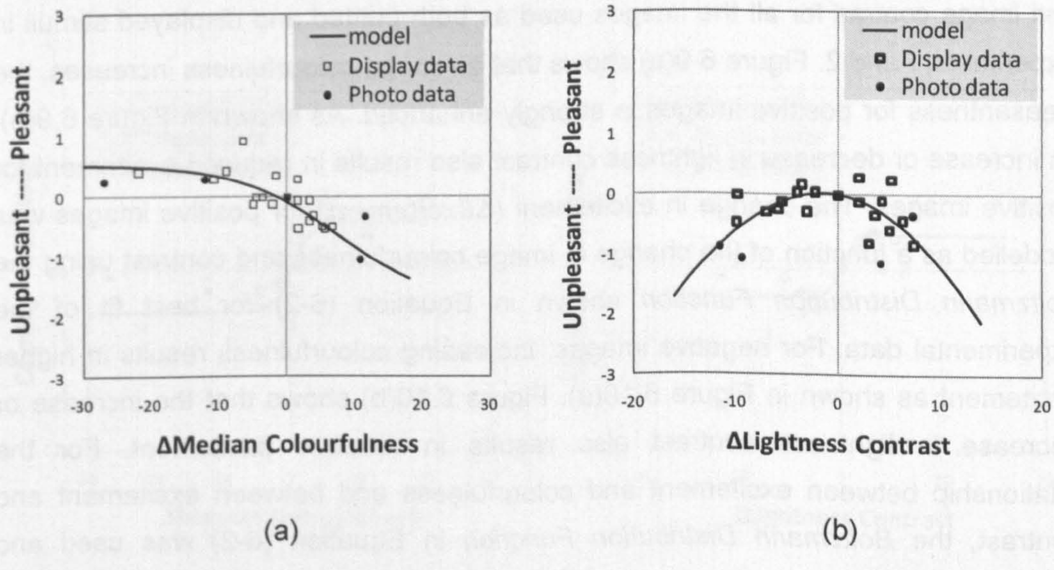



Figure 6.7(a)-(b) Visual results of image pleasantness for the negative image group plotted against the corresponding changes in (a) median colourfulness and (b) image contrast together with curves of the model derived using two attributes for all images used as both versions of printed and displayed stimuli in Experiments 1 and 2.

Table 6.2 Coefficients of the image pleasantness model used in Equations (6-3) and (6-4) as a function of colourfulness and image contrast for (a) positive and (b) negative stimuli.

(a)

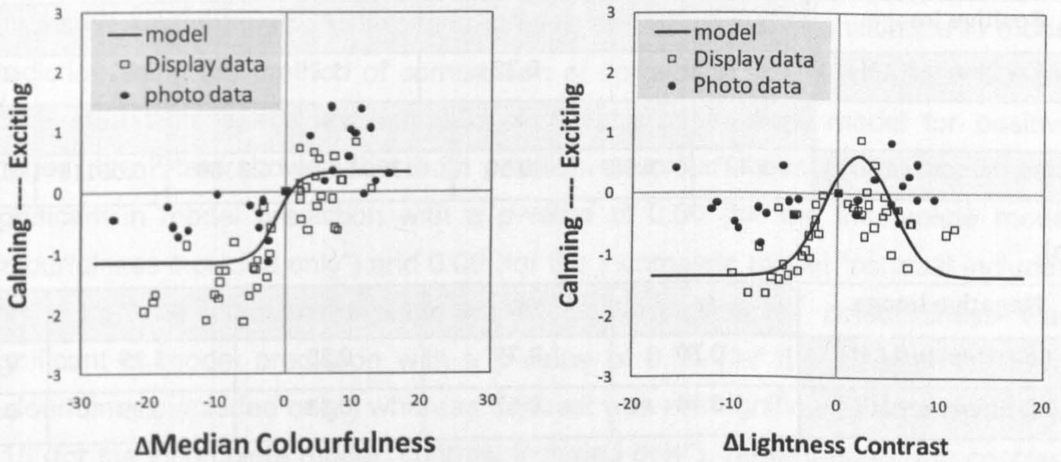
| **Positive Image** | $k_0$ | $k_1$ | $k_2$ | $k_3$ | μ | σ | R |
|---|---|---|---|---|---|---|---|
| $\Delta Pleasantness(\Delta M)$ | -1.68 | 6.96 | -0.51 | -1390.58 | 6.2372 | 0.0012 | 0.70 |
| $\Delta Pleasantness(\Delta CO)$ | -2.70 | 13.04 | -0.41 | -1390.15 | 6.2369 | 0.0013 | 0.77 |

(b)

| **Negative Image** | $k_0$ | $k_1$ | $k_2$ | α | R | | |
|---|---|---|---|---|---|---|---|
| $\Delta Pleasantness(\Delta M)$ | 0.54 | -1.83 | 6.58 | 6.39 | 0.84 | | |
| | $k_0$ | $k_1$ | $k_2$ | $k_3$ | μ | σ | R |
| $\Delta Pleasantness\ (\Delta CO)$ | -12.88 | 121.41 | -0.14 | -54.21 | 4.00 | 0.06878 | 0.72 |

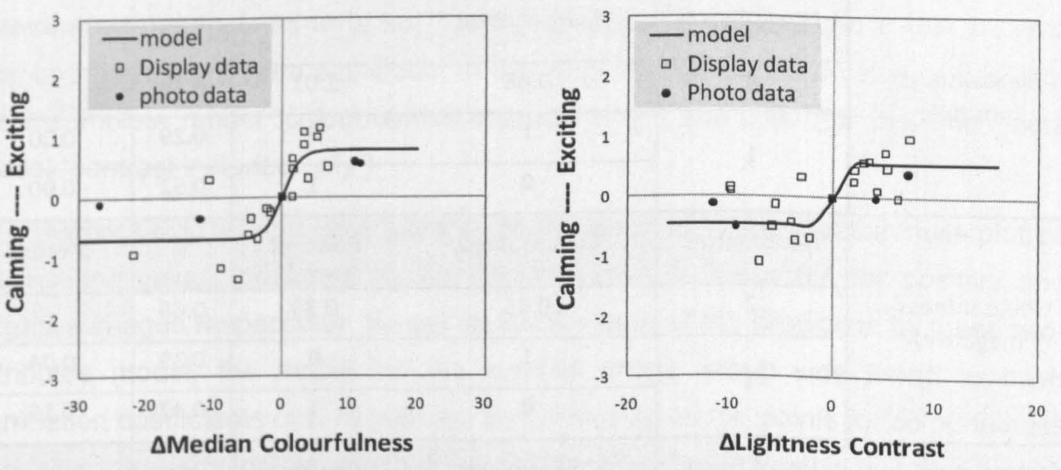
Figures 6.9(a)-(b) show the visual results of image excitement for positive and negative images plotted vs. the corresponding changes in median colourfulness and image contras for all the images used as both printed and displayed stimuli in Experiment 1 and 2. Figure 6.9(a) shows that as image colourfulness increases, the pleasantness for positive images is strongly enhanced. As shown in Figure 6.9(b), an increase or decrease in lightness contrast also results in reduced excitement for positive images. The change in excitement ($\Delta Excitement$) for positive images was modelled as a function of the change in image colourfulness and contrast using the *Boltzmann Distribution Function* shown in Equation (6-2) for best fit of the experimental data. For negative images, increasing colourfulness results in higher excitement as shown in Figure 6.10(a). Figure 6.10(b) shows that the increase or decrease in lightness contrast also results in reduced excitement. For the relationship between excitement and colourfulness and between excitement and contrast, the *Boltzmann Distribution Function* in Equation (6-2) was used and coefficients were optimised to find the best fit.

The optimised coefficients for models as a function of each attributes are shown in Table 6.3(a) for positive images and in Table 6.3(b) for negative images. The models for the positive image group were found to have correlation coefficients of 0.78 and 0.46 with the data points respectively for colourfulness and contrast manipulated positive images. The models for the negative image group were found to have correlation coefficients of 0.78 and 0.46 with the data points respectively for colourfulness and contrast manipulated negative images. It seems to find the universal model of image emotion performs little less well than two individual models.




(a) (b)

Figure 6.8(a)-(b) Visual results of image excitement for the positive image group plotted against the corresponding changes in (a) median colourfulness and (b) image contrast together with curves from the model derived using two attributes for all printed and displayed images in Experiments 1 and 2.




(a) (b)

Figure 6.9(a)-(b) Visual results of image excitement for the negative image group plotted against the corresponding changes in (a) median colourfulness and (b) image contrast together with curves from the model derived using two attributes for all printed and displayed images in Experiments 1 and 2.

Table 6.3(a)-(b) Coefficients of the image excitement model used in Equation (6-3) and (6-4) as a function of colourfulness and image contrast for (a) positive and (b) negative images.

(a)

<table>
<tr><th>Positive Image</th><th colspan="2">$k_0$</th><th colspan="2">$k_1$</th><th colspan="2">$k_2$</th><th>α</th><th>R</th></tr>
<tr><td>$\Delta Excitement(\Delta M)$</td><td colspan="2">-1.16</td><td colspan="2">0.32</td><td colspan="2">-1.39</td><td>1.62</td><td>0.78</td></tr>
<tr><td></td><td>$k_0$</td><td>$k_1$</td><td>$k_2$</td><td colspan="2">$k_3$</td><td>μ</td><td>σ</td><td>R</td></tr>
<tr><td>$\Delta Excitement\ (\Delta CO)$</td><td>-1.37</td><td>6.98</td><td>-0.50</td><td colspan="2">-1390.58</td><td>6.2368</td><td>0.00116</td><td>0.46</td></tr>
</table>

(b)

| Negative Image | $k_0$ | $k_1$ | $k_2$ | α | R |
|---|---|---|---|---|---|
| $\Delta Excitement(\Delta M)$ | -0.70 | 0.79 | 0.20 | 1.29 | 0.79 |
| $\Delta Excitement(\Delta CO)$ | -0.44 | 0.57 | 0.13 | 0.39 | 0.57 |

Table 6.4 P-values for the significance test of two predictors, colourfulness and contrast, in predictions of emotion models for pleasantness and excitement for image groups using the comparison of correlation coefficients at a significance level of 0.05.

<table>
<tr><th>Emotion (Image groups)</th><th colspan="5">Coefficients</th></tr>
<tr><td rowspan="4">Pleasantness (positive)</td><td>No. of terms</td><td>Colourfulness</td><td>Contrast</td><td>R</td><td>p-value</td></tr>
<tr><td>2</td><td>0.88</td><td>1.01</td><td>0.74</td><td></td></tr>
<tr><td rowspan="2">1</td><td>1</td><td>0</td><td>0.29</td><td>0.00</td></tr>
<tr><td>0</td><td>1</td><td>0.52</td><td>0.00</td></tr>
<tr><td rowspan="4">Pleasantness (negative)</td><td>No. of terms</td><td>Colourfulness</td><td>Contrast</td><td>R</td><td>p-value</td></tr>
<tr><td>2</td><td>0.55</td><td>0.89</td><td>0.66</td><td></td></tr>
<tr><td rowspan="2">1</td><td>1</td><td>0</td><td>0.35</td><td>0.04</td></tr>
<tr><td>0</td><td>1</td><td>0.47</td><td>0.15</td></tr>
<tr><td rowspan="4">Excitement (positive)</td><td>No. of terms</td><td>Colourfulness</td><td>Contrast</td><td>R</td><td>p-value</td></tr>
<tr><td>2</td><td>1.21</td><td>0.37</td><td>0.62</td><td></td></tr>
<tr><td rowspan="2">1</td><td>1</td><td>0</td><td>0.60</td><td>0.00</td></tr>
<tr><td>0</td><td>1</td><td>0.20</td><td>0.21</td></tr>
<tr><td rowspan="4">Excitement (negative)</td><td>No. of terms</td><td>Colourfulness</td><td>Contrast</td><td>R</td><td>p-value</td></tr>
<tr><td>2</td><td>0.74</td><td>0.92</td><td>0.75</td><td></td></tr>
<tr><td rowspan="2">1</td><td>1</td><td>0</td><td>0.54</td><td>0.03</td></tr>
<tr><td>0</td><td>1</td><td>0.41</td><td>0.00</td></tr>
</table>

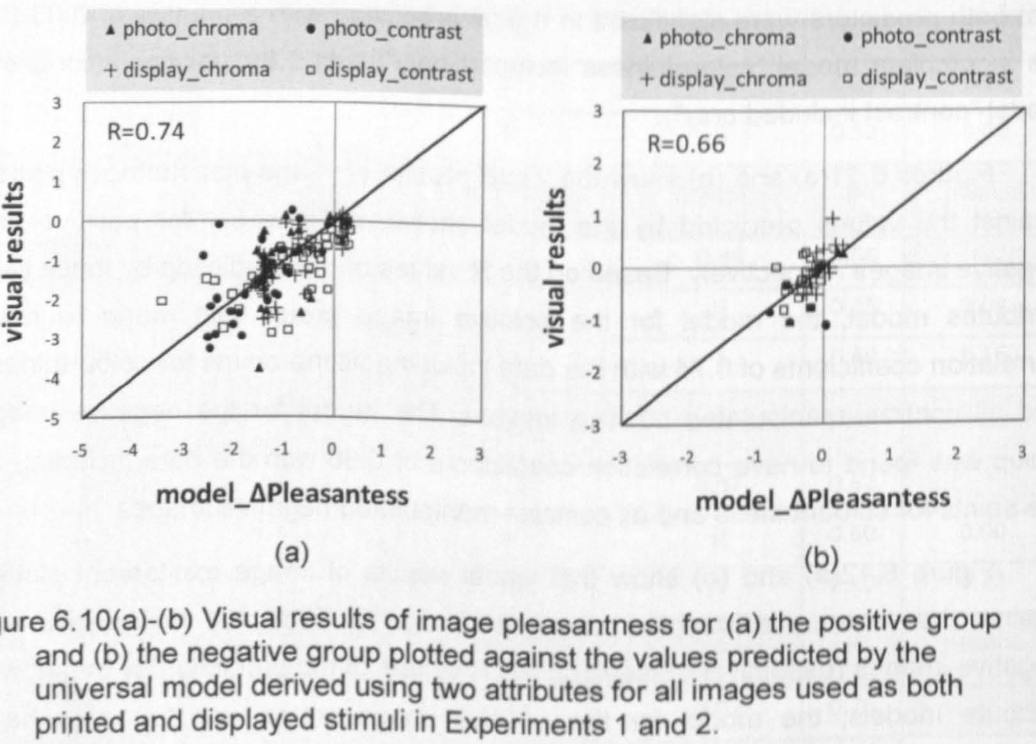
The models of image pleasantness and excitement for positive and negative images were developed as a linear equation based on models developed as a function of two colour attributes including colourfulness (M) and contrast (CO), as shown in Table 6.4. The two predictors: colourfulness and contrast in emotion models of pleasantness and excitement were tested for their significance in model prediction using the method of comparison of correlation coefficients (see Section 3.5.2) at a significance level of 0.05. For the pleasantness model for positive images, the F-test showed that both predictors, colourfulness and contrast, were significant in model prediction with a p-value of 0.00 (for the incomplete model "colourfulness included only") and 0.00 (for the incomplete model "contrast included only"). For the pleasantness model for negative images, colourfulness was significant in model prediction with a p-value of 0.04 (for the incomplete model "colourfulness included only") whereas contrast was not significant with a p-value of 0.15 (for the incomplete model "contrast included only"). Nevertheless, the contrast term was retained in the pleasantness model for negative images because it enables the contrast manipulated data set to be covered.

For the excitement model for positive images, colourfulness was significant in model prediction with a p-value of 0.00 (for the incomplete model "colourfulness included only") whereas contrast was not with a p-value of 0.21 (for the incomplete model "contrast included only"). However, the contrast term was retained to cover the contrast-manipulated data set again. For negative images, the F-test showed that both predictors were significant in model prediction with a p-value of 0.03 (for the incomplete model "colourfulness included only") and 0.00 (for the incomplete model "contrast included only").

Figures 6.11(a) and (b) show the visual results of image pleasantness plotted against the values predicted by the model shown in Table 6.4 for positive and negative images respectively. Based on the R values of the prediction by these two-attributes model, the model for the positive image group was found to have correlation coefficients of 0.74 with the data including all the points for colourfulness and all contrast-manipulated positive images. The model for the negative image group was found to have correlation coefficients of 0.66 with the data including all the points for colourfulness and all contrast-manipulated negative images.

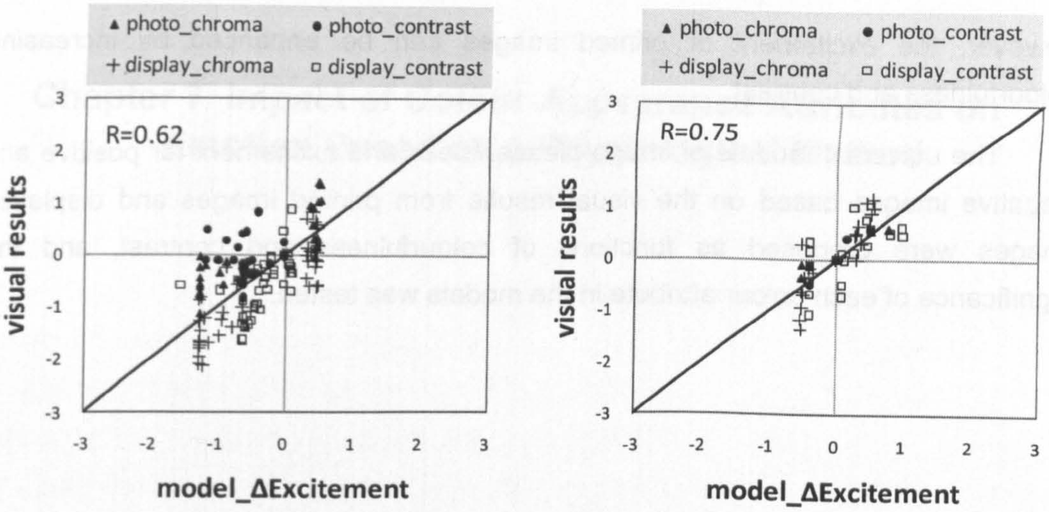
Figure 6.12(a) and (b) show that visual results of image excitement plotted against the values predicted by the model shown in Table 6.4 for positive and negative images respectively. Based on the R values of the prediction by these two-attribute models, the model for the positive image group was found to have correlation coefficients of 0.62 with the data including all the points for colourfulness and all contrast-manipulated positive images. The model for the negative image group was found to have correlation coefficients of 0.75 with the data including all the points for colour fulness and all contrast-manipulated negative images. T he performances of the universal models of image pleasantness for positive and negative images seem to be a little worse than those of the photo or display models tested for corresponding media: R = 0.78 for the photo model tested for photo data; R = 0.76 for the display model tested for display data (see Figures 6.2(a) and (c)).

The performances of the universal models of image pleasantness for positive and negative images seem to be a little worse than those of photo or display models tested for corresponding media (R = 0.78 for the photo model tested for photo data; R = 0.76 for the display model tested for display data for positive images (see Figures 6.2(a) and (c); R = 0.66 for the photo model tested for photo data; R = 0.66 for the display model tested for display data for negative images (see Figures 6.3(a) and (c)). Also for the performances of the universal models of image excitement for positive and negative images, seem again to be little worse than those of photo or display models tested for corresponding media.(R = 0.68 for the photo model tested for photo data; R = 0.80 for the display model tested for display data for positive images (see Figures 6.4(a) and (c); R = 0.88 for the photo model tested for photo data; R = 0.78 for the display model tested for display data for negative images (see Figures 6.5(a) and (c)).




(a) (b)

Figure 6.10(a)-(b) Visual results of image pleasantness for (a) the positive group and (b) the negative group plotted against the values predicted by the universal model derived using two attributes for all images used as both printed and displayed stimuli in Experiments 1 and 2.




(a) (b)

Figure 6.11(a)-(b) Visual results of image excitement for (a) the positive group and (b) the negative group plotted against the values predicted by the universal model derived using two attributes for all images used as both printed and displayed stimuli in Experiments 1 and 2.

## 6.3 Summary

The aim of this chapter was to compare the image emotion model for pleasantness and excitement developed for printed and displayed images as described in Chapter 4 and 5 and finally to develop a combined universal model as a function of the colour attributes of images comprising both data sets.

The visual results of image pleasantness and excitement for two different media were compared for three common images used as both printed and displayed stimuli in Experiments 1 and 2. As a result, it was found that image pleasantness for the displayed and printed images along with the changes in both colour attributes were a little different, showing that the changes in pleasantness in displayed images tended be larger than in printed images. The difference in the results may be due to the perceptually larger changes in colour attributes in displayed images rather than in printed images, which may emphasise the emotional impact of colour attributes on pleasantness for displayed images than for the printed images. The responses of excitement for printed images can be enhanced as image colourfulness and contrast increases, whereas the responses for displayed images can be enhanced just slightly when image colourfulness increases, otherwise it was just decreasing. This implies that displayed images are already exciting enough, so there was less chance to enhance their excitement;

however, the excitement of printed images can be enhanced by increasing colourfulness and contrast.

The universal models of image pleasantness and excitement for positive and negative images based on the visual results from printed images and displayed images were proposed as functions of colourfulness and contrast, and the significance of each colour attribute in the models was tested.

# Chapter 7 Impact of Colour-Appearance Attributes on Emotion Based on a Physiological Method

The aim of this experiment was to reveal the effect of image colour attributes on emotional responses in terms of physiological readings, and also to find differences in the effect of colour on the responses according to image content. To achieve these objectives, two sets of physiological experiments were designed and carried out as described in Chapter 3 (see Section 3.4.1 and 3.4.3).

In the physiological part of Experiment 1, 29 observers (9 British and 20 Chinese) viewed 178 original and manipulated images, which were divided into four *a-priori* categories: positive, neutral, negative and personal. In Experiment 3, 18 observers (1 European, 4 Chinese and 13 Korean) viewed 76 original and manipulated images comprised of four *a-priori* contents: positive, neutral, negative and personal. In this chapter, the results obtained from the two physiological experiments will be discussed and compared to the psychophysical results.

All data obtained from the physiological instruments (see Section 3.3) in the two experiments were collected at 0.5 sec intervals from which the baseline value (defined as the activity for each measure at the image onset) was subtracted. Each score for three measurements was computed per observer and each image and averaged for all observers. For facial EMG activity, the average change over 10-second image presentation period was used to estimate its reactivity. For skin conductance and heart rate, the maximum change occurring during the 10 seconds after image onset was recorded. The readings of each measure were normalised into *z-scores* for each observer. This was followed by the removal of outliers and then the average of scores for the remaining data was taken.

This chapter describes results of the two experiments for the following topics: comparison of physiological responses with the psychophysical responses (in terms of semantic scale value, i.e. the psychophysical scaling results according to two scales: *pleasant-unpleasant* and *exciting-calming*) in Sections 7.1.1 and 7.2.1; the effect of image content on physiological responses in Sections 7.1.2 and 7.2.2; the effect of colour attributes on physiological responses in Sections 7.1.3 and 7.2.3.

## 7.1 Experiment 1: Impacts of Colour-Appearance Attributes on Emotional Responses to Printed Images

In this section, the experimental results from the physiological part of Experiment 1 are described. Physiological responses and the psychophysical scaling results obtained are compared. In addition, the effect of *a-priori* im age content and the effect of colour attributes are analysed.

### 7.1.1 Effect of *A-priori* Categories of Images

To see whether there is any difference in psychophysical responses between different image contents, the mean z-score for physiological data from three measures were computed for each group of four *a-priori* contents: positive, neutral, negative and personal.

Figure 7.1 shows the comparisons of physiological results between the four types of images: positive, neutral, negative and personal as defined in the *a-priori* categories described in Section 3.4.2.1. All the physiological values shown in the graphs are z-scores, as defined in the previous section. Error bars indicate the 95% confidence interval.

In the graphs, "common" image represents the mean z-score values for physiological responses averaged for three types of common images: positive, neutral and negative. The graphs show that the skin conductance and heart rate responses were significantly different for personal images and common images. As shown in the graphs, the activities in skin conductance and heart rate are significantly higher for personal images than for the other common images, at a significance level of 0.05. For EMG activity, significant differences were found between personal and negative images and between personal and neutral images. However, no significant difference between personal and positive images was found.

Table 7.1 shows t-test results at a significance level 0.05 for the four types of images (neutral, negative, positive and personal). It is clear that for both skin conductance (SC) and heart rate (HR), there are significant differences between personal images and all of the other three types of images, with p-values lower than 0.01. For facial EMG, however, the test result does not seem to suggest a significant difference between personal images and positive images with a p-value of 0.92. There are, however, significant differences between personal images and the other two types, with p-values under 0.05. Regarding the correlation between physiological measures and subjective feelings as reviewed in Section 2.4.3.2, the test results seem to suggest that images involving personal experiences are much more pleasant and more arousing than common images.

This result seems to show good agreement with Miler *et al.*'s study (Miler 2002), as described in Section 2.4.3.2. In their study, *imagery* was used as emotional stimuli instead of presenting pictures. As personal stimuli, imagery of personal experiences was used as stimuli in comparison to standard ones. Their results showed that skin conductance and heart rate responses were found to evoke greater activities for personal than standard stimuli. However, no difference was found in corrugator EMG between personal and standard stimuli. They also found some differences in the responses of subjective feelings which showed that imagery of personal experiences were more arousing, vivid and interesting than standard imagery.

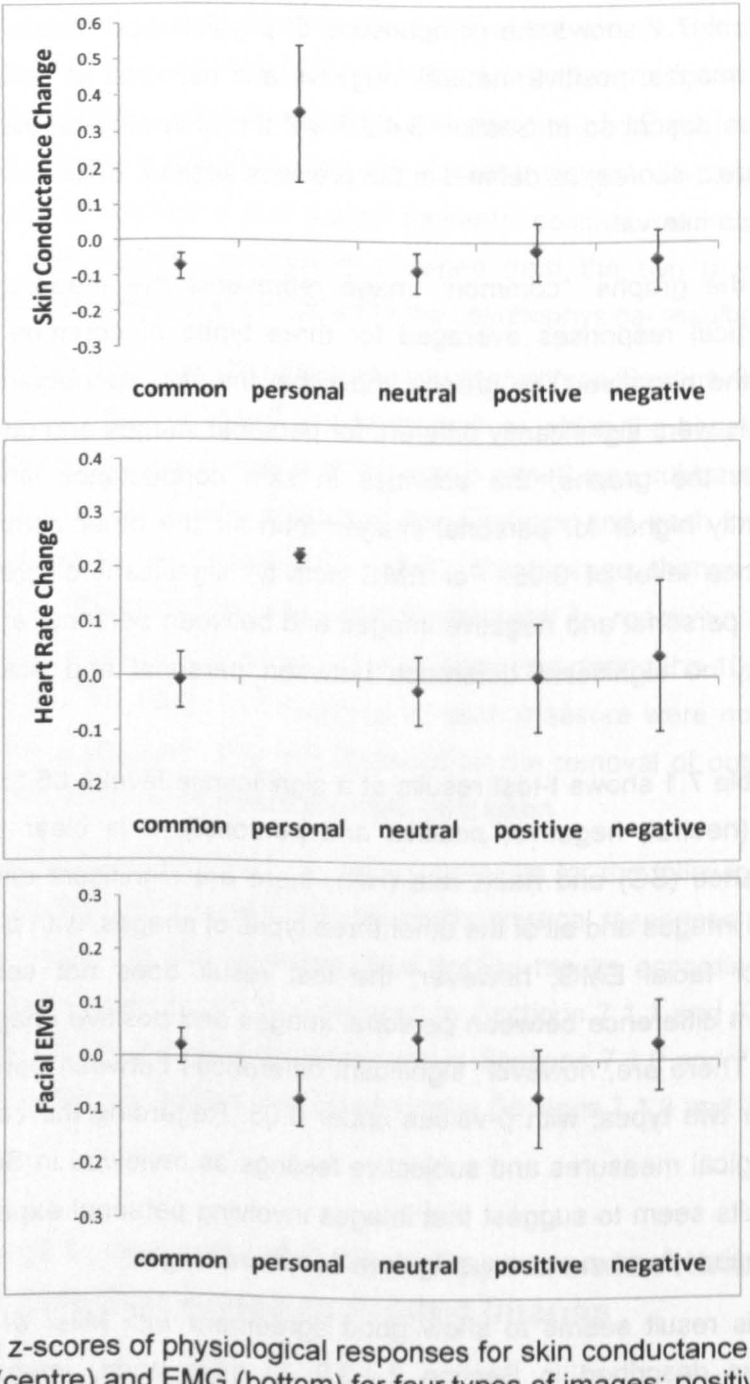



Figure 7.1 Mean z-scores of physiological responses for skin conductance (top), heart rate (centre) and EMG (bottom) for four types of images: positive, neutral, negative and personal. Common image corresponds to the average of positive, neutral and negative images. Error bars show 95% confidence intervals.

Table 7.1(a)-(c) The p values from the t-test comparing mean z-scores of physiological responses for (a) skin conductance (SC), (b) heart rate (HR) and (c) facial EMG (EMG) between the four different types of images.

(a) SC

| T-test | Neutral | Negative | Positive |
|---|---|---|---|
| **Neutral** | | | |
| **Negative** | 0.30 | | |
| **Positive** | 0.22 | 0.89 | |
| **Personal** | 0.00 | 0.00 | 0.00 |

(b) HR

| T-test | Neutral | Negative | Positive |
|---|---|---|---|
| **Neutral** | | | |
| **Negative** | 0.53 | | |
| **Positive** | 0.19 | 0.61 | |
| **Personal** | 0.00 | 0.00 | 0.00 |

(c) EMG

| T-test | Neutral | Negative | Positive |
|---|---|---|---|
| **Neutral** | | | |
| **Negative** | 0.80 | | |
| **Positive** | 0.01 | 0.12 | |
| **Personal** | 0.00 | 0.03 | 0.92 |

Although significant differences were found in the responses in skin conductance and heart rate between responses to personal images and common images, however, there was no significant difference found between three types of common images: neutral, positive and negative in Figure 7.1 and Table 7.1.

One of the possible reasons that no significant differences in physiological responses were found for three common image subjects in Experiment 1 could be the selection of images, especially for positive and negative images. For the pleasant and unpleasant stimuli, both arousing subjects were excluded such as erotica as the most pleasant subject and human/animal attack as the most unpleasant subject.

It could also be the number of presentation of the same image was repeated more than 15 times with different colour rendering but the same images. To examine whether the number of presentation affects the result, only the responses for the first presentation of each image subject with different colour rendering were averaged over the four image subjects and analysed. Note that the colour rendering applied to the first image in each subject are all different.

Figure 7.2 shows the comparisons of physiological results between the four types of images: positive, neutral, negative and personal. All the physiological values shown in the graphs are z-scores and Error bars indicate the 95% confidence interval. As shown in the graphs, most of them are overlapping and no significant difference was observed. Thus, t-test was again applied and summaries in Table 7.2. Table 7.2 shows t-test results at a significance level 0.05 for the four types of images (neutral, negative, positive and personal). It is clear that significant differences were found in EMG responses between neutral and negative and between personal and negative. However, it is difficult to conclude the reason that no differentiation did not appear from this analysis because there exist the effect of different colour rendering and also the effect of image subject and content. It is also possible that all of them might influence the result.

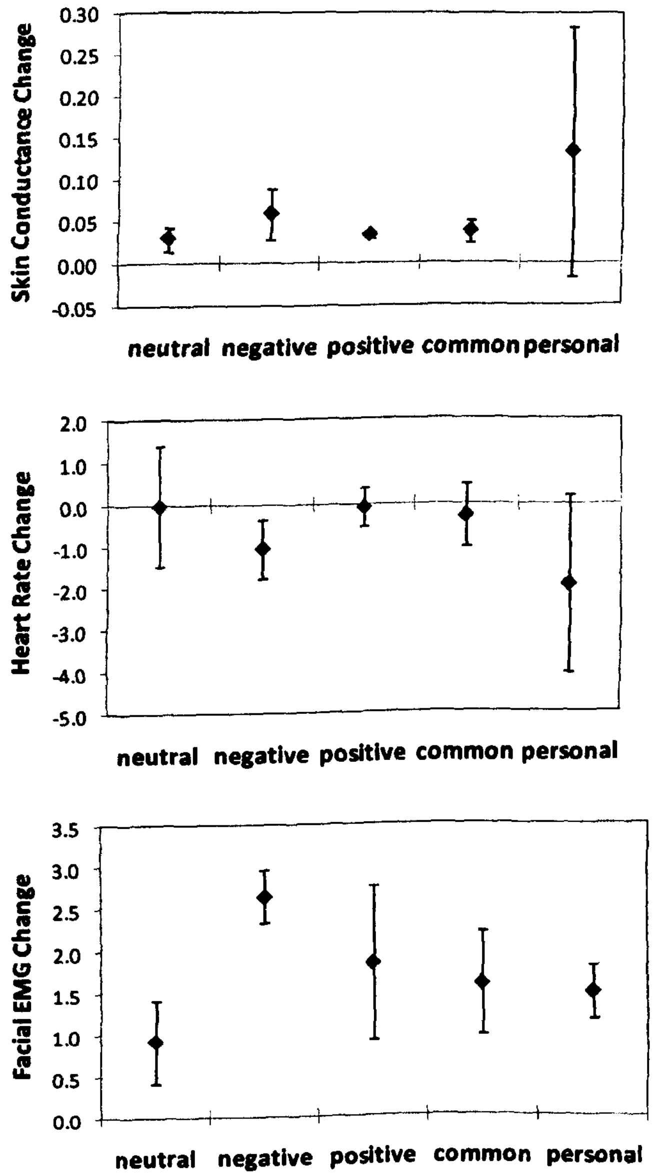



Figure 7.2 Mean z-scores physiological responses for skin conductance (top), heart rate (centre) and EMG (bottom) for the first presentation of four types of images: positive, neutral, negative and personal. Common image corresponds to the average of positive, neutral and negative images.

Table 7.2(a)-(c) The p values from the t-test comparing mean z-scores of physiological responses the first presentation of four types of images for (a) skin conductance (SC), (b) heart rate (HR) and (c) facial EMG (EMG) between the four different types of images.

(a) SC

| T-test | Neutral | Negative | Positive |
|---|---|---|---|
| **Neutral** | | | |
| **Negative** | 0.12 | | |
| **Positive** | 0.76 | 0.25 | |
| **Personal** | 0.10 | 0.44 | 0.32 |

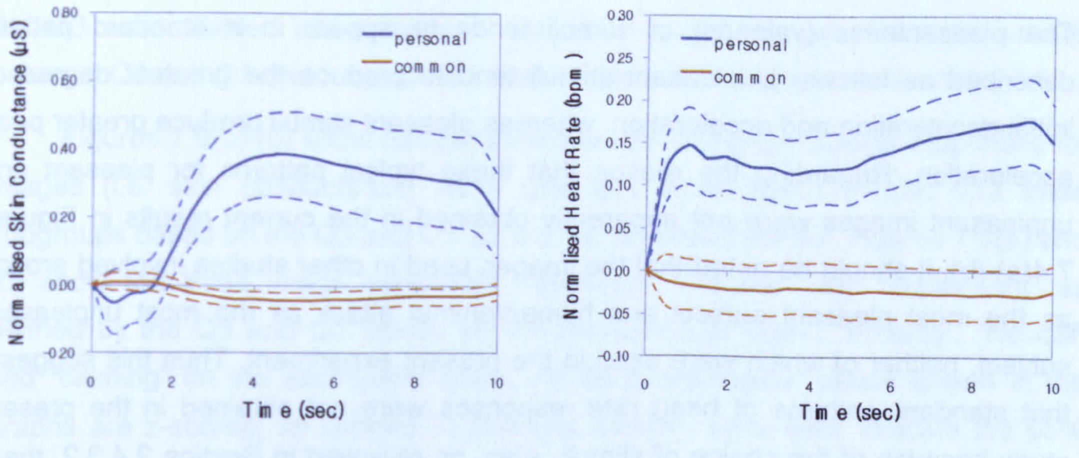
(b) HR

| T-test | Neutral | Negative | Positive |
|---|---|---|---|
| **Neutral** | | | |
| **Negative** | 0.41 | | |
| **Positive** | 0.97 | 0.16 | |
| **Personal** | 0.21 | 0.52 | 0.24 |

(c) EMG

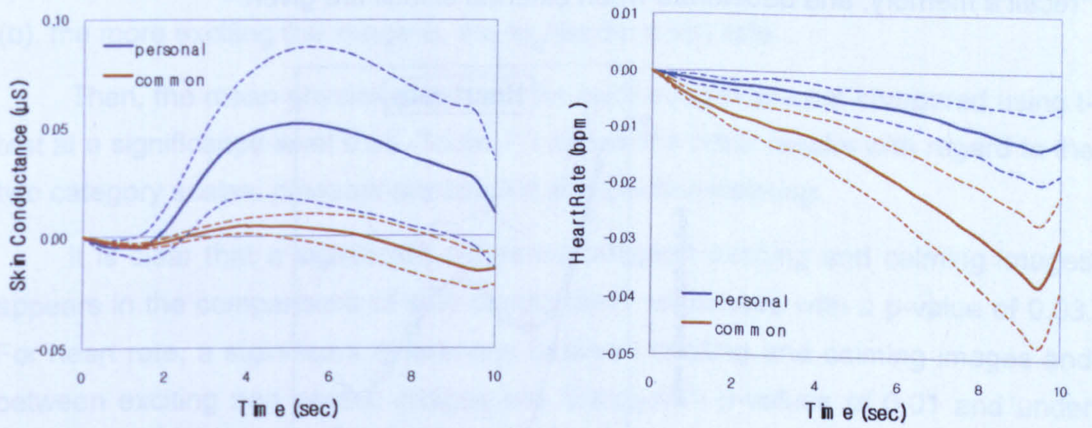
| T-test | Neutral | Negative | Positive |
|---|---|---|---|
| **Neutral** | | | |
| **Negative** | 0.01 | | |
| **Positive** | 0.13 | 0.25 | |
| **Personal** | 0.22 | 0.04 | 0.56 |

Figures 7.3 and 7.4 also show greater responses in heart rate and skin conductance for personal images than for common images. Figure 7.3 shows skin conductance responses recorded during 10 sec of picture presentation for personal (blue line) and common (red line) images with a 95% confidence interval (dashed lines). Figure 7.3 shows such differences in skin conductance using raw physiological data for graph (a) and normalised data for graph (b). Figure 7.4 also shows significant differences in heart rate using raw physiological data for the graph (a) and normalised data for graph (b). These graphs indicate that both skin conductance and heart rate tend to show higher activities for personal images than for common images. Based on the relationship between these two measures and the emotional structure of pleasure and excitation (Section 2.4.3.2), this also seems to support the assertion that personal images are more pleasant and exciting than common images.




(a) (b)

Figure 7.3(a)-(b) Comparisons between mean skin conductance for personal images (blue lines) and for common images (red lines) using (a) raw skin conductance and (b) normalised skin conductance (z-score; see Section 7.1). The dashed lines indicate 95% confidence intervals.




(a) (b)

Figure 7.4(a)-(b) Comparisons between mean heart rate for personal images (blue lines) and for common images (red lines) using (a) raw heart rate and (b) normalised heart rate (z-score; see Section 7.1). The dashed lines indicate 95% confidence intervals.

However, there exists another point of view concerning heart rate responses that heart rate activity is more reliable for predicting emotional arousal than for pleasantness in specific stimuli such as human-computer interaction (Mahlke, 2008). There was a difficulty to correlate the heart rate responses obtained in the present study and the pleasantness of image. This is because the heart rate responses shown in Figure 7.4 are not like the typical patterns which have been reported by many studies (Lang 1993; Cuthbert 1998; Bradley 2001) as shown in Figure 7.5. According to these studies, heart rate tends to decelerate when an affective picture is first presented. Then it tends to accelerate, followed by a secondary deceleration.

The pleasantness (valence) of stimuli tends to appear in a standard pattern described as follows. Unpleasant stimuli tend to produce the greatest degree of initial deceleration and acceleration, whereas pleasant stimuli produce greater peak acceleration. Regarding the reason that these typical patterns for pleasant and unpleasant images were not apparently obtained in the current results in Figures 7.4(a)-(b), it should be noted that the images used in other studies involved erotica as the most pleasant subject and human/animal attack as the most unpleasant subject, neither of which were used in the present experiment. Thus this suggests that standard patterns of heart rate responses were not obtained in the present study because of the choice of stimuli. Also, as reviewed in Section 2.4.3.2, there are a number of difficulties in using heart rate as a measure of emotional state. Several physical factors such as posture, height, weight and an individual's fitness level are known to have a significant influence on heart rate as well as its intrinsic variability. It is also known that heart rate tends to accelerate when attempting to recall a memory, and decelerate when external stimuli are given.

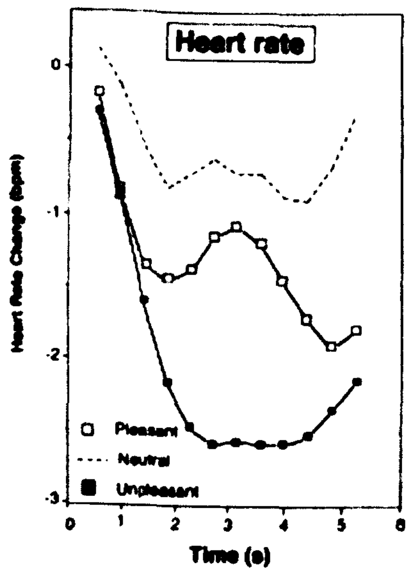



Figure 7.5 Pattern of heart rate responses as a function of the prior valence of IAPS pictures (Lang *et al.*, 2001).

### 7.1.2 Physiological Responses vs. Psychophysical Results

To see whether the physiological data agree with psychophysical responses in terms of scaling results such as *pleasant-unpleasant*, the physiological data for three measures were averaged for three subgroups of images as divided by the third quartile (Q3) and the first quartile (Q1) of the semantic scale values. Taking the *pleasant-unpleasant* scale as an example, all images scale values greater than the Q3 were divided into "pleasant images", "neutral images" for scale values between Q3 and Q1 and "unpleasant images" for scale values lower than the Q1.

Figures 7.6(a)-(b) show comparisons between the physiological responses for images (i.e. skin conductance, heart rate and facial EMG) divided into three subgroups based on the Q3 and Q1 values, as described earlier. Figures 7.5(a) and (b) show the three image subgroups: "pleasant", "neutral" and "unpleasant" as defined by the Q3 and Q1 values on the *pleasantness* scale; "exciting", "neutral" and "calming" on the *excitement* scale. All the physiological values shown in the graphs are z-scores, as defined in previous section. Error bars indicate the 95% confidence interval.

The graphs show that there is no significant difference in physiological responses between the three subgroups of images at a significance level of 0.05. The only exception is that the mean heart rates have significantly different values for the three subgroups: "exiting", "neutral" and "calming". As shown in Figure 7.5 (b), the more exciting the image is, the higher the heart rate.

Then, the mean physiological data for each subgroup were compared using t-test at a significance level 0.05. Table 7.3 shows the t-test results with regard to the two category scales: *pleasant-unpleasant* and *exciting-calming*.

It is clear that a siginificant difference between exciting and calming images appears in the comparisons of skin conductance responses with a p-value of 0.03. For heart rate, a siginificant differences between exciting and calming images and between exciting and neutral images are found, with p-values of 0.01 and under 0.01 respectively. For facial EMG activity, the p-value for the comparison between pleasant and unpleasant images is 0.09. This indicates that facial EMG activity of corrugator muscles shows some extent of difference between pleasant and unpleasant images. However, no significant difference is found between exciting and calming images for EMG activity.

Although it has been mentioned in Section 2.4.3.2 that heart rate could measure image pleasantness, several issues relating to the reliability of the correlation between heart rate responses and the level of pleasure were pointed out in the previous section. Regarding these points, the results from the present study (that reveal no significant differences between pleasant and unpleasant images for these two measures), may suggest both that skin conductance responses seem to be a good measure of image excitement whereas heart rate responses don't seem to be so reliable for both of image pleasantness and excitement.

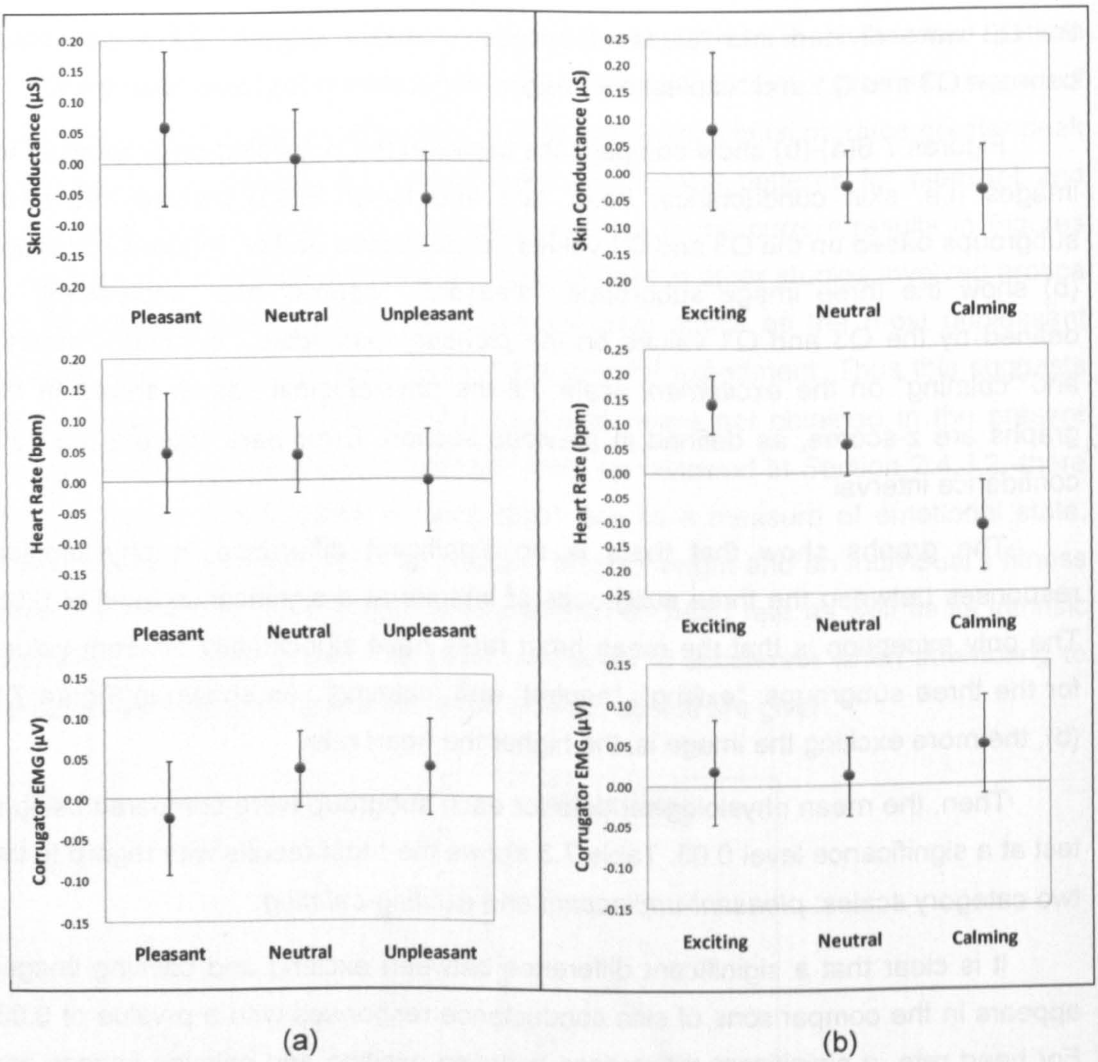



Figure 7.6 Mean z-scores of physiological responses for skin conductance (top), heart rate (centre) and EMG(bottom) for (a) images rated as pleasant, neutral and unpleasant and for (b) images rated as exciting, neutral and calming. Error bars show 95% confidence intervals.

Table 7.3 The p values from the t-test comparing mean z-scores of physiological responses between common images of different subgroups according to psychophysical scale values: (a) pleasantness and (b) excitement. The physiological responses are in terms of skin conductance (SC), heart rate (HR) and facial muscle movement (EMG) at corrugator.

(a)

| SC | | |
|---|---|---|
| T-test | Neutral | Unpleasant |
| Neutral | | |
| Unpleasant | 0.48 | |
| Pleasant | 0.63 | 0.18 |

| HR | | |
|---|---|---|
| T-test | Neutral | Unpleasant |
| Neutral | | |
| Unpleasant | 0.47 | |
| Pleasant | 0.74 | 0.72 |

| EMG | | |
|---|---|---|
| T-test | Neutral | Unpleasant |
| Neutral | | |
| Unpleasant | 0.32 | |
| Pleasant | 0.56 | 0.09 |

(b)

| SC | | |
|---|---|---|
| T-test | Neutral | Calming |
| Neutral | | |
| Calming | 0.66 | |
| Exciting | 0.16 | 0.03 |

| HR | | |
|---|---|---|
| T-test | Neutral | Calming |
| Neutral | | |
| Calming | 0.01 | |
| Exciting | 0.66 | 0.00 |

| EMG | | |
|---|---|---|
| T-test | Neutral | Calming |
| Neutral | | |
| Calming | 0.76 | |
| Exciting | 0.77 | 0.97 |

### 7.1.3 Physiological Responses vs. Colour Attributes

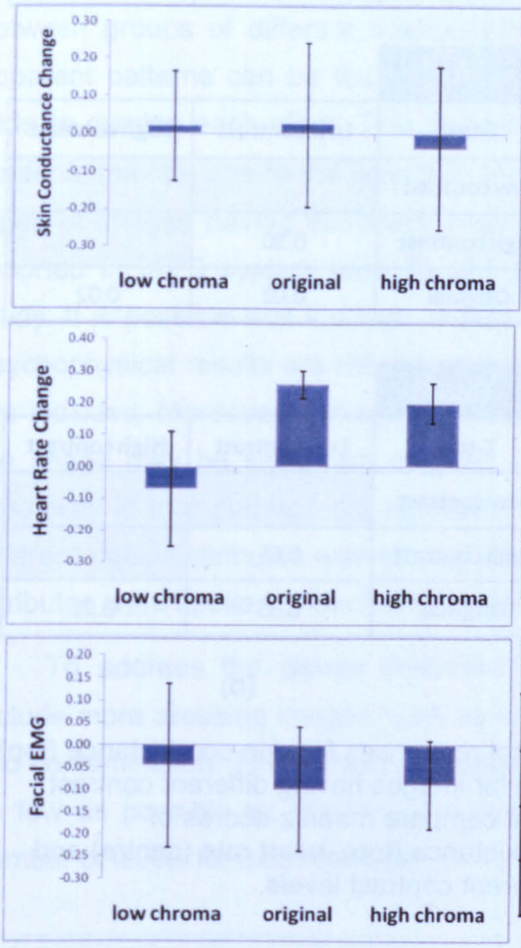
To see whether there is any colour effect on physiological responses of emotion elicited by images, the z scores of responses for three measures were averaged separately for three groups of images: original images, rendered images with decreased chroma and contrast, and rendered images with increased chroma and contrast.

Figure 7.7(a) shows comparisons of the mean values of physiological results with images rendered in terms of chroma. The error bars in each diagram represent 95% confidence intervals. It illustrates that the responses in skin conductance show no significant differences between images having any levels of chroma. Similarly, facial EMG showed no difference between different chroma levels. Only heart rate response was found to show significant difference between chroma levels. From the graph, higher activity is found for more chromatic images and no significant difference is found between original images and images with increased chroma. Considering that heart rate activity tends to be a good measure of pleasantness of stimuli (see Section 2.4.3.2), this result might imply that more chromatic images tend to be more pleasant than less chromatic images. However, another good measure of pleasantness of stimuli, activity of corrugator muscles, does not show any differences between different groups of chroma levels. Thus, it cannot be concluded that more chromatic images colours resulted in more pleasant feelings than less chromatic ones.

Figure 7.7(b), summarises the t-test results at a significance level 0.05 comparing the mean values of each group shown in the graphs on the left, also supports this trend. It is clear that for heart rate, the differences between the "low chroma" and "original" groups and between the "low chroma" and "high chroma" groups are significant with p-values of 0.01 for both.

Figure 7.8(a) compares the mean physiological results between images rendered in terms of contrast with error bars indicating the 95% confidence intervals. It shows that the responses in skin conductance present no significant differences between images having any levels of contrast values. Facial EMG also showed no difference between different contrast levels. Only heart rate response was found to show significant differences between different levels of contrast. The graph shows that the higher activity is found for original images than for images with rendered values of contrast and there is no significant difference between images with either decreased or increased contrast. Similarly for chroma rendering, activity of corrugator muscles did not show any differences between different groups of contrast levels. Thus, it cannot be concluded that higher contrast caused more pleasant feelings.

Figure 7.8(b), summarising the t-test results at a significance level 0.05 comparing the mean values of each group shown in the graphs on the left, also supports this trend. It is clear that for heart rate, the differences between the "original" and "low contrast" groups and between the "original" and "high contrast" groups are found to be significant with p-values of 0.02 for both pairs.




(a)

**SC**

| T-test | Low chroma | High chroma |
|---|---|---|
| Low chroma | | |
| High chroma | 0.67 | |
| Original | 0.97 | 0.70 |

**HR**

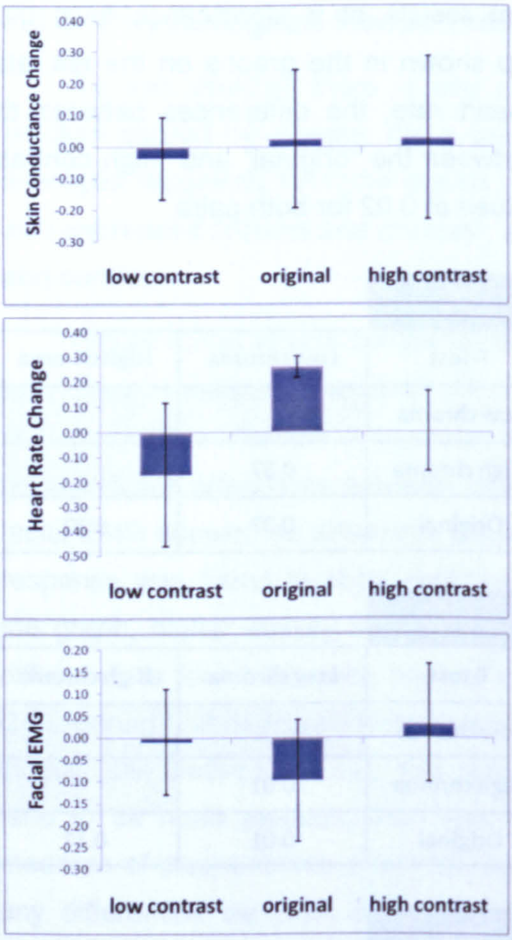
| T-test | Low chroma | High chroma |
|---|---|---|
| Low chroma | | |
| High chroma | 0.01 | |
| Original | 0.01 | 0.17 |

**EMG**

| T-test | Low chroma | High chroma |
|---|---|---|
| Low chroma | | |
| High chroma | 0.68 | |
| Original | 0.68 | 0.91 |

(b)

Figure 7.7 (a) Mean z-scores of physiological responses for skin conductance (top), heart rate (centre) and EMG (bottom) for images having different chroma levels; (b) The p-values from the t-test compare mean z-scores of physiological responses for skin conductance (top), heart rate (centre) and EMG (bottom) for images having different chroma levels.




| SC T-test | Low contrast | High contrast |
|---|---|---|
| Low contrast | | |
| High contrast | 0.67 | |
| Original | 0.62 | 0.99 |

| HR T-test | Low contrast | High contrast |
|---|---|---|
| Low contrast | | |
| High contrast | 0.30 | |
| Original | 0.02 | 0.02 |

| EMG T-test | Low contrast | High contrast |
|---|---|---|
| Low contrast | | |
| High contrast | 0.65 | |
| Original | 0.35 | 0.21 |

(a) (b)

Figure 7.8 (a) Mean z-scores of physiological responses for skin conductance (top), heart rate (centre) and EMG (bottom) for images having different contrast levels; (b) The p-values from the t-test compare mean z-scores of physiological responses for skin conductance (top), heart rate (centre) and EMG (bottom) for images having different contrast levels.

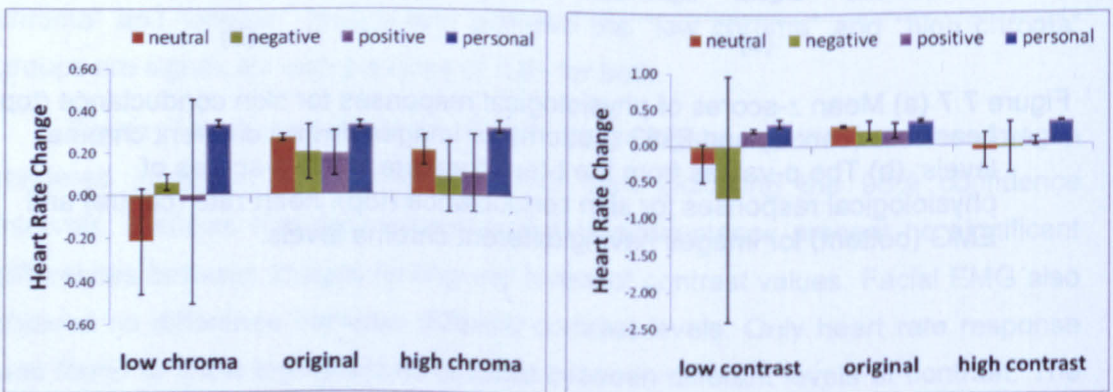



Figure 7.9 (a) Mean z-scores of physiological heart rate responses for images having different chroma levels for four image contents; (b) mean z-scores of physiological heart rate responses for images having different contrast levels for four image contents.

To see whether this disagreement is caused by any specific content of images, the mean z-scores of heart rate responses for image groups having different chroma and contrast levels were plotted separately for four image contents in Figures 7.9(a) and (b). The differences between image groups with different level of colour attributes seen in Figures 7.7(a) and 7.8(a) can be found only in neutral images for both manipulations. For personal images, no differences were found between groups of different manipulation. For negative and positive images, no apparent patterns can be found for both manipulations as the error bars are too wide to overlap each other. This disagreement of results between different image contents may be due to the selection of images in the experiment for which certain types of images having extremely high or extremely low pleasantness values as reported in IAPS system (see Section 2.5.4.1) were excluded from the present study. It is possible that the high correlation between physiological responses and psychophysical results are reliable and consistent only when such types of images are included. Moreover, there is a possibility that the effects of colour attributes in the image may be significant only for certain types of image contents. Another possibility is that perhaps the repetition rate of the same image reproduced with different colour attributes was too high, as many levels of manipulation for several attributes were applied to each original image.

To address the issues described above, Experiment 3 was designed to include more arousing images such as romantic scenes, adventures, human injury and contamination. The number of presentations of the same images was limited to as few as possible by reducing the number of colour attributes studied and the number of levels for each attribute.

## 7.2 Experiment 3: Impact of Colour-Appearance Attributes on Colour-emotion and Image Emotion for Displayed Images

In this section, the experimental results from Experiment 3 are described. Measured physiological responses and the psychophysical scaling results are compared. The effect of *a-priori* image content and the effect of colour attributes on the emotional responses are also discussed.

### 7.2.1 Effect of *A-priori* Categories of Images

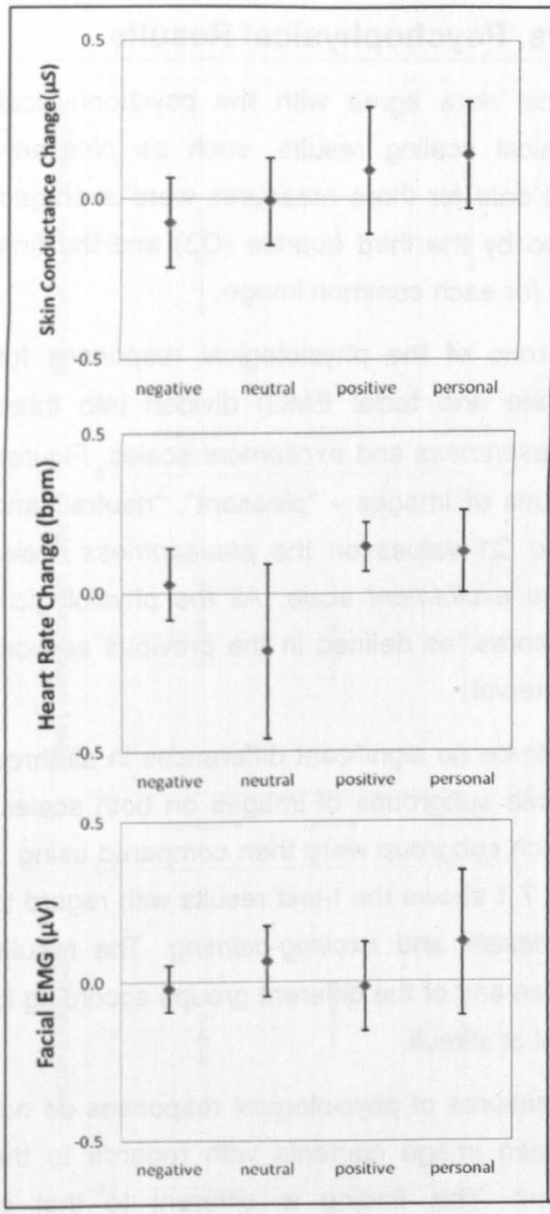
Figure 7.10(a) shows the comparisons of physiological responses between four types of images - "positive", "neutral", "negative" and "personal" - as defined in *a-priori* categories in Section 3.4.3.1. All the values shown in the graphs are z-scores, as defined in Section 7.1. The error bars indicate the 95% confidence interval.

The graphs show that differences in skin conductance and facial EMG are not found to be significant between all groups of images. Only heart rate responses are found to have some extent of difference between positive and neutral images. The activity in heart rate tends to be higher for positive images than for neutral images. Personal images are found not to have such a big difference in physiological responses as was obtained in Experiment 1.

The t-test result shown in Figure 7.10(b) clarifies these trends. It shows t-test results for the four types of images: neutral, negative, positive and personal. For skin conductance, all image groups seem to have very little differences between them. For heart rate, there is a significant difference between positive and negative images, with a p-value of 0.03. For facial EMG, however, no significant difference is found between any groups of images.

Comparing the result obtained from the one from Experiment 1, one of the diagreements in the result is no significant difference was found between common and personal images in Experiment 3. This may be due to the difference in contents for personal images used in both experiments. In Experiment 1, personal images were provided by the observers themselves. They depicted scenes involved with observers' experiences and memories and contained special meanings to them. In contrast in Experiment 3, the personal images were observers' self portraits taken by the author of this thesis using the same background to control the range of colour attributes. This means that observers may not have special meanings or personal attachments to those images. From Figure 7.10(a), the activities in the three measures for personal images were at very similar levels as for common images.

Instead, a significant difference was found in heart rate between negative and positive images. Regarding the correlation between heart rate responses and the level of pleasantness as reviewed in Chapter 2, this may reflect the difference in pleasantness levels for positive and negative images used in Experiment 3. However, conclusions should be drawn also considering the relationship between physiological responses and psychophysical results as will be described in the next section.




(a)

**SC**

| | Negative | Neutral | Positive |
|---|---|---|---|
| Negative | | | |
| Neutral | 0.81 | | |
| Positive | 0.66 | 0.87 | |
| Personal | 0.62 | 0.81 | 0.87 |

**HR**

| | Negative | Neutral | Positive |
|---|---|---|---|
| Negative | | | |
| Neutral | 0.20 | | |
| Positive | 0.03 | 0.09 | |
| Personal | 0.36 | 0.43 | 0.98 |

**EMG**

| | Negative | Neutral | Positive |
|---|---|---|---|
| Negative | | | |
| Neutral | 0.10 | | |
| Positive | 0.32 | 0.66 | |
| Personal | 0.63 | 0.12 | 0.34 |

(b)

Figure 7.10 (a) Mean z-scores of physiological responses for skin conductance (top), heart rate (centre) and EMG (bottom) for four types of images: positive, neutral, negative and personal. Common image corresponds to the average of positive, neutral and negative images. Error bars show 95% confidence intervals. (b) The p-values from the t-test comparing the mean z-scores of physiological responses between common images of different subgroups (according to semantic scale values).

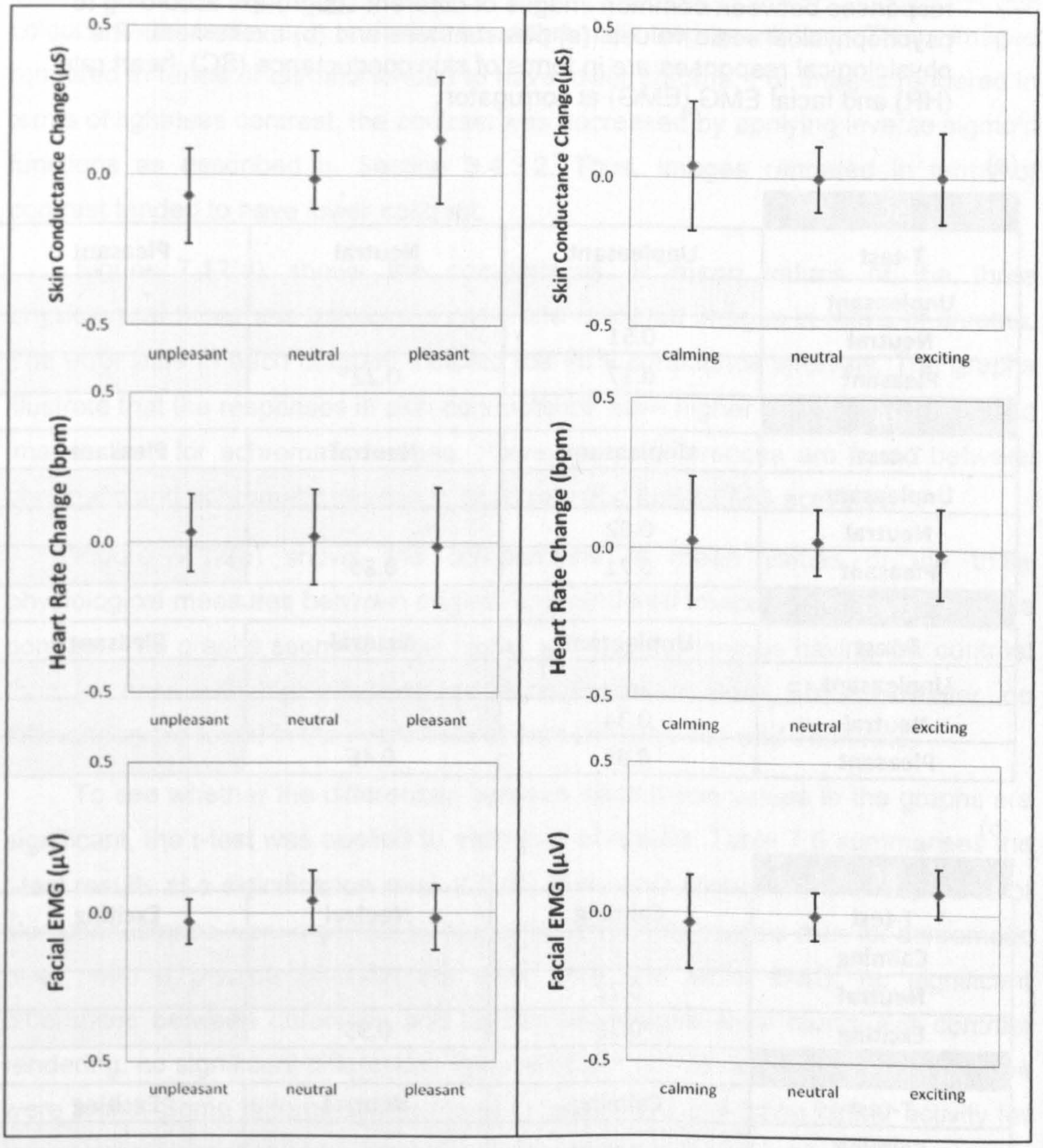
### 7.2.2 Physiological Responses vs. Psychophysical Results

To see whether these physiological data agree with the psychophysical responses in terms of the psychophysical scaling results, such as *pleasant-unpleasant*, the z-scores of physiological data for three measures were averaged for three subgroups of images as divided by the third quartile (Q3) and the first quartile (Q1) of the semantic scale values for each common image.

Figures 7.11(a)-(b) show comparisons of the physiological responses for images (i.e. skin conductance, heart rate and facial EMG) divided into three subgroups based on the Q3 and Q1 *pleasantness* and *excitement* scales. Figures 7.11(a) and (b) show the three subgroups of images - "pleasant", "neutral" and "unpleasant"- as defined by the Q3 and Q1 values on the *pleasantness* scale; "exciting", "neutral" and "calming" on the *excitement* scale. All the physiological values shown in the graphs are the z-scores, as defined in the previous section. Error bars indicate the 95% confidence interval.

The graphs show that there seem to be no significant differences in all three physiological responses between the three subgroups of images on both scales. Thus, the mean physiological data for each subgroup were then compared using t-test at a significance level of 0.05. Table 7.1 shows the t-test results with regard to the two category scales *pleasant-unpleasant* and *exciting-calming*. The results verify that there was no difference between any of the different groups according to the levels of pleasantness and excitement of stimuli.

The results show that the three measures of physiological responses do not reveal any significant differences between image contents with regards to the degree of pleasantness and excitement. This finding is different to that of Experiment 1 where significant differences were found in skin conductance and heart rate responses between different levels of excitement of images. This may be due to the difference of personal images for the two experiments, as mentioned in previous section. It may also reflect that the selection of images still did not include sufficient varieties in the levels of pleasantness and arousal so as to generate reliable responses in the physiological measures. Highly-arousing contents such as strongly erotic scenes, serious injury and mutilation were avoided for the selection of stimuli although the author tried to include relatively more arousing contents than for Experiment 1.




(a) (b)

Figure 7.11 Mean z-scores of physiological responses for skin conductance (top), heart rate (centre) and EMG (bottom) for (a) images rated as pleasant, neutral and unpleasant and for (b) images rated as exciting, neutral and calming. Error bars show 95% confidence intervals.

Table 7.4 The p values from the t-test comparing mean z-scores of physiological responses between common images of different subgroups according to psychophysical scale values: (a) pleasantness and (b) excitement. The physiological responses are in terms of skin conductance (SC), heart rate (HR) and facial EMG (EMG) at corrugator.

(a)

| SC | | | |
|---|---|---|---|
| T-test | Unpleasant | Neutral | Pleasant |
| Unpleasant | | | |
| Neutral | 0.51 | | |
| Pleasant | 0.17 | 0.22 | |
| **HR** | | | |
| T-test | Unpleasant | Neutral | Pleasant |
| Unpleasant | | | |
| Neutral | 0.92 | | |
| Pleasant | 0.71 | 0.80 | |
| **EMG** | | | |
| T-test | Unpleasant | Neutral | Pleasant |
| Unpleasant | | | |
| Neutral | 0.34 | | |
| Pleasant | 0.86 | 0.46 | |

(b)

| SC | | | |
|---|---|---|---|
| T-test | Calming | Neutral | Exciting |
| Calming | | | |
| Neutral | 0.72 | | |
| Exciting | 0.78 | 0.95 | |
| **HR** | | | |
| T-test | Calming | Neutral | Exciting |
| Calming | | | |
| Neutral | 0.92 | | |
| Exciting | 0.71 | 0.80 | |
| **EMG** | | | |
| T-test | Calming | Neutral | Exciting |
| Calming | | | |
| Neutral | 0.94 | | |
| Exciting | 0.30 | 0.19 | |

### 7.2.3 Physiological Responses vs. Colour Attributes

To see whether there is a colour effect on the physiological responses of emotion elicited by images, the z scores of physiological responses for three measures were averaged separately for original images and for images rendered in terms of chroma and lightness contrast. For images rendered in chroma, the colours were taken out to leave an achromatic representation. Thus, images rendered in terms of chroma tended to have lower chroma. For images rendered in terms of lightness contrast, the contrast was decreased by applying inverse sigmoid functions as described in Section 3.4.3.2. Thus, images rendered in terms of contrast tended to have lower contrast.

Figure 7.12(a) shows the comparisons of mean values of the three physiological measures between original and rendered images in terms of chroma. The error bars in each diagram indicate the 95% confidence intervals. The graphs illustrate that the responses in skin conductance have higher activities for chromatic images than for achromatic images. However, no differences are found between chromatic and achromatic images in heart rate and facial EMG activities.

Figure 7.12(b) shows the comparisons of mean values of the three physiological measures between original and rendered images in terms of lightness contrast. The graphs seem to show higher activities for images having low contrast than for ones with high contrast in the responses of facial EMG. However, no differences are found in the responses of skin conductance and heart rate.

To see whether the differences between each mean values in the graphs are significant, the t-test was applied to each pair of results. Table 7.5 summarises the t-test results at a siginificance level of 0.05. The result shows that the responses of skin conductance were significantly higher for chromatic images than for achromatic ones, with a p-value of 0.02. For heart rate and facial EMG, no significant differences between chromatic and achromatic images were found. For contrast rendering, no significant differences between high contrast and low contrast images were found. Some difference was found in facial EMG indicating higher activity for low contrast images than for original images with a p-value of 0.08.

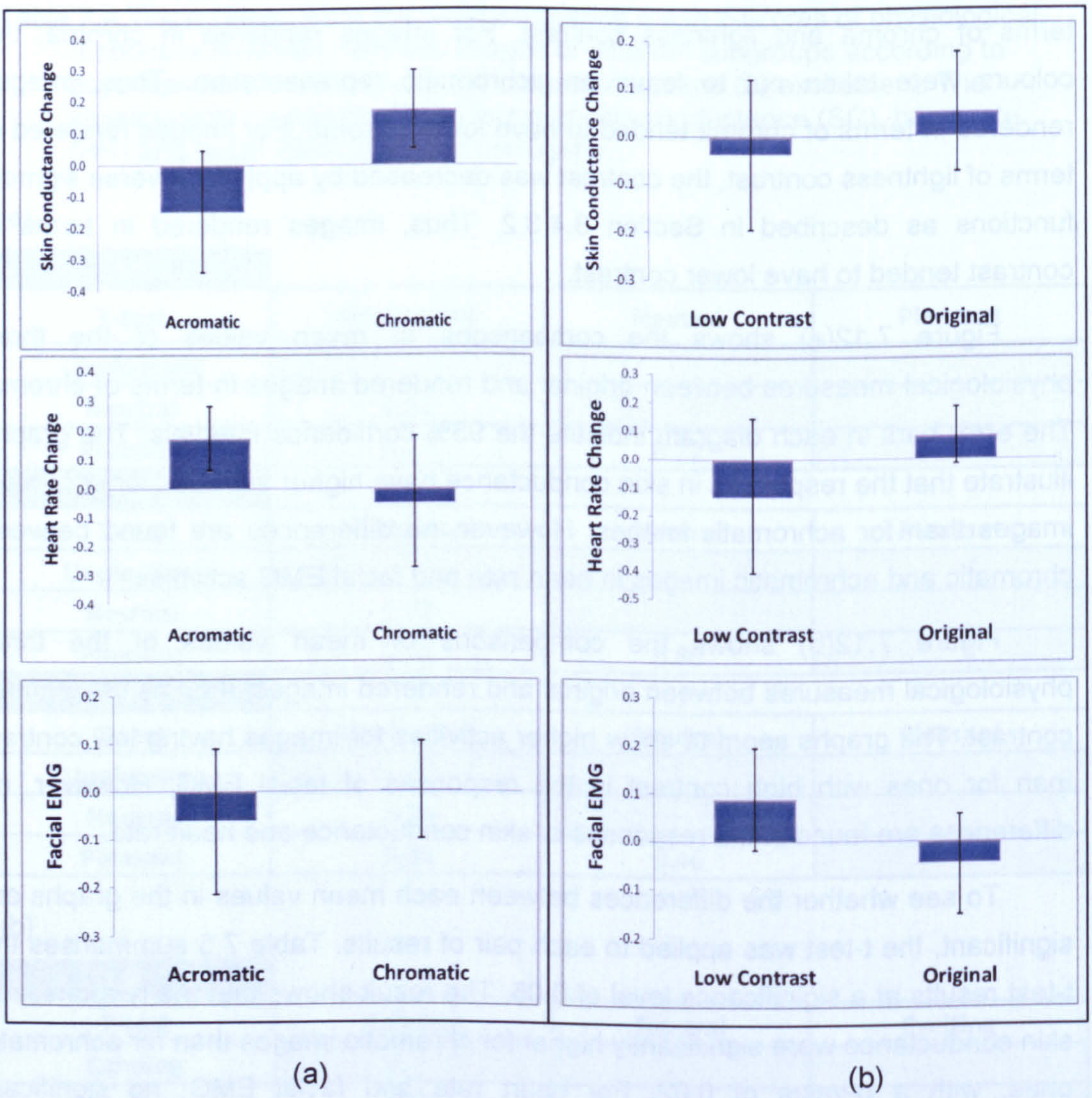



Figure 7.12(a)-(b) Mean z-scores of physiological responses for skin conductance (top), heart rate (centre) and EMG (bottom) for (a) chromatic and achromatic images and for (b) low contrast and original images.

Table 7.5 The T-test result for mean z-scores of physiological responses for skin conductance (top), heart rate (centre) and corrugators EMG (bottom) for chromatic and achromatic images and for low contrast and original images.

| SC | | |
|---|---|---|
| T-test | Chromatic (Original) | High Contrast (Original) |
| Achromatic (Rendered) | 0.02 | |
| Low Contrast (Rendered) | | 0.39 |

| HR | | |
|---|---|---|
| T-test | Chromatic (Original) | High Contrast (Original) |
| Achromatic (Rendered) | 0.17 | |
| Low Contrast (Rendered) | | 0.16 |

| Facial EMG | | |
|---|---|---|
| T-test | Chromatic (Original) | High Contrast (Original) |
| Achromatic (Rendered) | 0.82 | |
| Low Contrast (Rendered) | | 0.08 |

Comparing the results with those obtained from Experiment 1, one is that a significant difference was found in the skin conductance result between achromatic and chromatic images. In this experiment, each original image was rendered as only one achromatic version, whereas each original image was rendered at four different levels of chroma in Experiment 1. Thus the complete washed out effect in chroma level could lead to significantly smaller responses in skin conductance activity.

Another difference between the two results is that a significant difference was found in the corrugators EMG response between low contrast and original images. Also for contrast rendering, each original image was rendered in only one other version with lower contrast whereas each original image was rendered at four different levels of contrast in Experiment 1. This apparent reduction of contrast level may affect to some extent the greater response revealed in EMG activity.

One other dissimilarity is that no difference was found in heart rate responses between any groups of different colour attributes as observed in Experiment 1. For heart rate responses, it seems to be quite difficult to conclude that a meaningful difference was found between groups of images having any different features such as colour attributes and image content. This is because results obtained in the present study did not seem as reliable and consistent as to do so.

This is not only because of the difficulties in using heart rate activity as a measure of emotional state but also because the proper interpretation of heart rate activity in terms of its correlation with psychophysical results is still debatable. This also seems to be related to the selection of stimuli regarding a wide range of the contents in terms of pleasantness and arousal levels, for which reliable and consistent physiological responses could be generated. It is possible that this selection of image content also affects the possibility to observe reliable effects of colour attributes in the image as physiological responses may be significant only for certain types of images. It is also possible that the effect of image colour is not strong enough to evoke reliable, consistent physiological responses, as many other studies concluded as reviewed in Section 2.5.4.4. Thus, further study is needed regarding the effect of image colour on the physiological responses of emotion.

## 7.3 Summary

The aim of this chapter was to investigate the effect of image colour attributes on emotional responses in terms of physiological responses, and also to find any differences in the effect of colour according to image content. To achieve these objectives, two sets of physiological experiments (Experiments 1 and 3) were conducted.

First of all, the effect of *a-priori* categories of images was investigated based on the results from Experiments 1 and 3. From the result of Experiment 1, significantly greater responses in heart rate and skin conductance activities were found for personal images than for common images. However, the personal images used in Experiment 3 did not result in any greater activities in the physiological measures. This may be because the image contents depicted in Experiment 1 were highly related to observer experiences and memories, which seemed to be the main cause of the greater activation in physiological measures. Due to the debatable correlation between heart rate and the level of pleasantness, it can only be concluded for certain that personal images are more exciting than common images. Regarding other image contents, no consistent differences were found between positive, negative and neutral in both experimental results. Even for the results only from the first presentation of each image subject, no consistent differences were found between positive, negative and neutral. This could be because of the selection of the stimuli used for both experiments, which excluded highly arousing contents including both highly pleasant and unpleasant images.

The relationship between physiological responses and psychophysical data were compared for both experimental results. Although significantly greater activities were found in heart rate and skin conductance responses according to different excitement levels in the result of Experiment 1, the results from Experiment 3 did not show any agreement. This may be because the less personally related contents of the personal images used in Experiment 3 limited the activation of physiological responses. Also, the entire set of stimuli was not sufficiently varied in terms of levels of pleasantness and arousal to generate reliable and consistent activities in the physiological measures.

Finally, the effect of image colour attributes was investigated based on both experimental results. No significant difference was found according to different levels of chroma and contrast in Experiment 1. A significant difference was found in skin conductance data between achromatic and chromatic images from the result of Experiment 3. This may be due to chroma being limited to only two levels with smaller repeats of the same image. The apparent difference between the two levels of chroma may result in the significantly smaller response in skin conductance activity. For the contrast effect, some levels of difference were found in the corrugators EMG response between low contrast and original images. This may also be due to the smaller number of levels of contrast and number of presentations. Comparing the results from the two experiments, the number of presentations of the same image may be one of the critical factors to finding any differences in physiological activity.

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# Chapter 8 Conclusions

The goals of the present study have been to investigate the impact of colour-appearance attributes on the affective quality of images and to develop an affective quality model of images as a function of colorimetric parameters. The specific aims are summarised below:

(1) To investigate the relationship between colour-appearance attributes and the overall affective responses to images.

(2) To investigate the affective responses to images for different types of image contents including images having personal values.

(3) To investigate the relationships between colour-appearance attributes and colour-emotion responses for images, and between overall emotional responses and colour-emotion responses for complex images.

(4) To develop models predicting overall affective responses to different types of images based on colour-appearance attributes and also based on colour-emotion factors.

(5) To measure psycho-physiological responses to images, and compare them with the psychophysical responses to the same images.

To achieve these aims, three psychophysical physiological experiments were conducted.

Experiment 1 aimed to investigate the relationship between the colour-appearance attributes of images and image emotion, and the difference in these relationships for different image contents. In this experiment, the classification of image content was considered according to two criteria: the level of pleasantness and the level of personal attachment. Observers were asked to report their emotional responses to 178 printed images that had been manipulated by lightness contrast and colourfulness. Six scales were used: *pleasant-unpleasant, exciting-calming, like-dislike, natural-unnatural* and *appealing-unappealing.* The physiological responses to images were also taken by measuring skin conductance, heart rate and facial muscle movement.

Experiment 2 aimed to explore the relationship between the colour attributes and colour-emotion for complex images, and the relationship between colour-emotion and image emotion. Observers were asked to report their emotional responses to 208 displayed images manipulated by lightness contrast and colourfulness. Six scales were used, including *pleasant-unpleasant, exciting-calming, like-dislike, active-passive, heavy-light and warm-cool.*

Experiment 3 focused on measuring the effect of colour attributes of images on emotional responses, using physiological methods. Changes in skin conductance, heart rate and facial muscle movement were measured while observers viewed 76 images manipulated in terms of lightness contrast and colourfulness presented on a screen.

This chapter summarises the major findings obtained from these experiments.

## 8.1 Summary of Major Findings and Contributions

The principal findings from the present study are summarised below:

(1) The overall affective reactions to images in terms of psychophysical responses are found to be represented by two groups of emotion, pleasantness and excitement, in line with a two-dimensional model of emotion (see Section 2.5.4).

(2) Colourfulness and contrast are found to have a consistent and significant impact on affective responses to images in terms of pleasantness and excitement.

(3) The affective responses of pleasantness and excitement to images are found to depend on the type of image content. In terms of psychophysical reactions, the level of image pleasantness affects the relationship between colour attributes, in terms of colourfulness and contrast, and the affective responses pleasantness and excitement. However, the affective responses of image colour-emotion factors are not found to depend on the type of image content.

(4) The affective responses of pleasantness and excitement were found to be affected by changing the three factors of colour-emotion to those images differently for positive and negative images.

(5) In terms of physiological responses, much greater responses in skin conductance and heart rate were found to appear for images having personal attachment to observers.

(6) In terms of physiological responses, more chromatic image colours were found to generate greater activity in skin conductance responses. In addition, lower contrast image colours were found to increase activity in the corrugators EMG response.

The contributions of the present work to colour and imaging science are as follows:

(1) The study established an effective approach to assessing the affective quality of images considering the influence of context and personal aspects.

(2) The study revealed the relationship between colour attributes and the affective responses to images.

(3) The concept of colour-emotion was extended to complex images as means of defining and utilising their affective quality.

(4) By introducing physiological measurement methods, a different approach was used in this study to investigate the affective quality of images and to quantify the impact of colour attributes.

### 8.1.1 The Effect of Colour Attributes on Image Emotion

The models of image emotion for pleasantness and excitement developed in Chapters 4 and 5 were compared and tested across two media: print and display. Regarding image pleasantness, it was found that for the displayed images, this was slightly more sensitive changes than for printed images along with the changes in both colour attributes. This indicates that observers were more sensitive to changes in colourfulness and contrast in displayed images than to those in printed images. This may be because visual changes in the colour attributes of displayed images tended to be perceptually larger than for printed images.

Regarding image excitement, it was found that the responses for printed images can be enhanced dramatically by increasing image colourfulness, whereas the responses for displayed images can be enhanced only slightly by increasing image colourfulness. This may be because the emotional responses to displayed images are bigger than to the printed images and this may already be exciting enough, meaning that the excitement for displayed image cannot be further enhanced. However, further study is need to understand why there is no further enhancement in excitement for displays while there was an enhancement in excitement for print, despite the same amount of colourfulness increase.

### 8.1.2 The Effect of Image Content on the Affective Responses

The influence of image content on emotional responses was investigated using PCA (see Section 3.5.3) to find any similarity between images used in Experiments 1 and 2. As a result of psychophysical measurement in Experiments 1 and 2, the responses of image pleasantness and excitement for all test images were found to be slightly different in the positive group (including positive, neutral and personal images) and the negative group. The effect of the personal values of images on image pleasantness and excitement seemed to produce more sensitive changes along with the changes in colour attributes; however the effect of image content on psychophysical responses did not seem to be significant. Thus, quantitative models of image emotion for pleasantness and excitement were developed separately for the data sets corr esponding to positive and negative images.

The influence of image content on the responses for the colour-emotion scales *active-passive, heavy-light* and *warm-cool* was also investigated in Experiment 2. As a result, it was found that the responses of colour-emotion were not significantly different for positive and negative images. Thus, colour-emotion models were developed based on data averaged for all images used in Experiment 2.

As a result of physiological measurement in Experiment 1, it was found that the responses in skin conductance and heart rate showed significantly greater activities for personal images than for common images. However in Experiment 3, no significant differences between personal and common images were found for any physiological measures. The reason for these different results may be the images used in the two experiments. In Experiment 1, the personal images were provided by observers and thus had personal meaning and value to the observers. In Experiment 3, the personal images were photos of the observers themselves taken by the author of this thesis, and thus these personal images had no personal attachment. Regarding other image contents, no consistent differences in physiological responses were found between positive, negative and neutral groups in both experimental results. This may be because the selection of stimuli used for both experiments excluded highly arousing contents and highly pleasant or unpleasant images.

### 8.1.3 Colour-emotion for Images

The relationships between colour-appearance attributes and responses on colour-emotion scales (*active-passive, heavy-light* and *warm-cool*) were also studied for four different types of image contents. Quantitative models of the three colour-emotion scales were developed as a function of the colour attributes of images (i.e. lightness, colourfulness and lightness contrast). According to the model developed, *active-passive* responses for images can be enhanced by increasing image colourfulness, *heavy-light* responses by increasing contrast or decreasing lightness, and *warm-cool* by increasing colourfulness.

As an application of using the colour-emotion model developed for images, the relationships between colour-emotion scales and image emotion were also explored. The relationship was built as quantitative models for two separate groups of images: positive and negative. As the results using the model developed showed, we can enhance excitement for pleasant images by making the images feel more active and warmer. For negative images, image pleasantness can be enhanced by making the images feel more passive and cooler. Image excitement can be enhanced by making the image feel more active, heavier and warmer.

### 8.1.4 Physiological Responses to Colour Attributes of Images

The effect of image colour attributes was investigated based on the physiological results obtained in Experiments 1 and 3. From Experiment 1, no significant difference was found between different levels of chroma and between different levels of contrast. From Experiment 3, a significant difference was found in skin conductance result between achromatic and chromatic images. For the contrast effect, some levels of difference were found in the corrugators EMG response between low contrast and original images. The disagreement in the results obtained from the two experiments may be due to the repetition rate of the same image for the whole experimental sessions. Images were shown only four times at two levels for two attributes in Experiment 3, whereas they were shown more than 15 times in Experiment 1. Comparing the results from the two experiments, the number of presentations of the same image may be an important factor in studying physiological activity.

## 8.2 Future Work

Although a number of findings have been revealed in the present study about the impact of colour attributes on image emotion and colour-emotion for images, this study can be extended or further improved, as described below.

### 8.2.1 The Effect of Image Content

One limitation of this study is that the model for enhancing affective quality is defined by changes from the original images. Because the colour quality and overall image quality of the "original images" were very high or the colour attributes for original images were always symmetric, a very strong bias towards the original images was found from the results obtained in Chapters 4 and 5 for the relationship between image emotion and colour attributes. To remove this bias, a new approach to selecting the experimental stimuli will be needed.

One of the findings from this study is that changes in emotional responses to images due to changes in colour attributes are influenced by the level of pleasantness of the stimulus. In this study, image content was determined using Russell's two-dimensional emotion model (see Section 2.4.2) which was also used for image classification in the IAPS system (section 2.5.4.1). However in practice, there can be many other ways to classify the content of images, for example, based on the application or usage. In other applications, factors affecting image emotion need to be identified, and the relationship between colour attributes and emotion factors can be studied.

### 8.2.2 Media Effect

One of the findings in this study is that the impact of colour attributes was different for printed and displayed images. It was found that observer responses for image pleasantness for the displayed images tended to show larger changes than for printed images due to the changes in colour attributes. On the other hand, image excitement for printed images can be dramatically enhanced by increasing colourfulness, whereas no significant enhancement was found with displayed images for the same amount of change. In order to understand the media effect of colour attributes on emotional responses to images, further experimental studies need to be conducted.

### 8.2.3 Other Factors Influencing the Emotional Responses

As reviewed in Section 2.5.4, there are many factors which can influence the emotional responses to images such as image content, image size and previous experience. In this study, the gender and cultural differences in emotional responses to images could not be reliably concluded from the data obtained and only the influences of image content and colour attributes were investigated; however, there may be other factors which influence the emotional responses to images, such as cultural background, gender and personality. These social factors may have different effects on the emotional responses to various image contexts and extension of this study to investigate influences from these factors will be important for the usage of the results for the advertisement, marketing, etc.

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# Appendices

## Appendix A Observer Instructions in Experiment 1

## Instructions to observer

Thank you for participating in this visual assessment. While you are participating this experiment, you will be presented with a set of images on two different types of media: a printed version and one displayed on a TV screen. For both sessions of experiments, you will have three tasks to complete.

The first and second tasks verbally involve providing your impressions of the images. For first task, you need to provide a few words of description for each image based on your impression. For the second task, you will judge word pairs given to you.

Task 1. Provide a few words. It could be any word including nouns or adjectives containing your impressions from any features of the images.

Task 2. Judge five given word pairs based on a 1 to 9 scale. The five word pairs to be judged are shown below. Please score what you think based on this scale.
For example, in the case of Unpleasant-Pleasant pair:-

| Extremely **Unpleasant** | Very | Unpleasant | Slightly | Neutral | *Slightly* | Pleasant | Very | Extremely **Pleasant** |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |

1. **Unpleasant - Pleasant**
2. **Calming - Exciting**
3. **Unnatural - Natural**
4. **Dislike - Like**
5. **Unappealing - Appealing**

Task 3. The third task involves wearing physiological instruments on your body (face and one hand) and letting the experimenter to record your biofeedback including facial muscle activities, skin conductance and heart rate. To do this, you will wear three different sensors, one on your face and two on your one hand. A sensor will be attached on your face at the medial end of eyebrow for facial muscle activity recordings. If you have make-up on your forehead, you may need to clean your face with soap provided prior to taking part in the experiment. To re cord your skin conductance and heart rate, two different sensors will be put on your fingers. Please speak to the experimenter whenever you have questions or if you need something during the experiment.

# Appendix B Observer Instructions in Experiment 2

## Part 1: Semantic Scaling

You will be presented with a series of images. Your task is to judge which of the following words you would use to describe the image.

As an example, for the "**unpleasant-pleasant**" pair, your answer will be either "**pleasant**" or "**unpleasant**". Then judge how pleasant or unpleasant the image appears to you. Please base your judgement on the scale given below. Make your choice for other 5 scales as you did for unpleasant-pleasant scale.

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| **Unpleasant** | ◄ | — | — | — | — | — | ► | **Pleasant** |

| | |
|---|---|
| **9** | "**extremely**" pleasant |
| **8** | "**very much**" pleasant |
| **7** | "**moderately**" pleasant |
| **6** | "**slightly**" pleasant |
| **5** | not pleasant nor unpleasant (neutral) |
| **4** | "**slightly**" unpleasant |
| **3** | "**moderately**" unpleasant |
| **2** | "**very much**" unpleasant |
| **1** | "**extremely**" unpleasant |

The definitions of six word pairs in general are given below.

***Pleasant-Unpleasant***
Pleasant: enjoyable, attractive, friendly, or easy to like.
Unpleasant: not enjoyable or pleasant.

***Arousing (Exciting)-Calming***
Arousing: to cause someone to have a particular feeling (Excite: to cause a particular reaction).
Calming: to stop someone feeling excited.

***Warm-cool***
Warm: having or producing a comfortably high temperature, although not hot.
Cool: slightly cold; of a low temperature.

***Light-heavy***
Heavy: weighing a lot; needing effort to move or lift.
Light: weighing only a small amount; not heavy.

***Active-passive***
Active: busy in or ready to perform a particular activity.
Passive: not acting to influence or change a situation; allowing other people to be in control.

***Like-dislike***
Like: to enjoy or approve of something or someone.
Dislike: to not like someone or something.

## Appendix C: Observer Instructions in Experiment 3

***Task 1: Biofeedback Recordings***

The task for this session is to wear physiological instruments to record your biofeedback including facial muscle activities, skin conductance and heart rate while a series of images are presented on a screen. To do this, you will wear three different sensors, one on your face and two on one hand. A sensor will be attached on your face above the left eyebrow for facial muscle activity recordings. If you have make-up on your forehead, it may need to be cleansed with alcohol prior to placement of the sensor. To record your skin conductance and heart rate, two different sensors will be placed on your fingers. You need to stay still while recordings being taken because your movement will affect your biofeedback responses.

Once the experiment starts, you will need to sit in front of the screen and view the images. Then you will be presented with a series of images with a grey blank screen in between.

NOTE!! Please keep in mind that you have to try to stay still without moving any part of your body during this experiment. Eating or drinking is not allowed during the experiment. If you need any assistants during the experiment, please ask the experimenter for help.

**Task 2: Semantic Scaling**

After your biofeedback recordings, the final task is to judge which of the following words you would use to describe the image. For images you have seen while your biofeedback responses were recorded. Only two scales will be used for this task: "unpleasant-pleasant" and "calming-exciting (arousing)". Please make your judgement on the scale given below.

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| **Unpleasant**<br>**Calming** | ← | | | | | → | | **Pleasant**<br>**Arousing (Exciting)** |

| | |
|---|---|
| **9** | **"extremely"** pleasant |
| **8** | **"very much"** pleasant |
| **7** | **"moderately"** pleasant |
| **6** | ***"slightly"*** *pleasant* |
| **5** | not pleasant nor unpleasant *(neutral)* |
| **4** | **"slightly"** unpleasant |
| **3** | **"moderately"** unpleasant |
| **2** | **"very much"** unpleasant |
| **1** | **"extremely"** unpleasant |

# Appendix D: The source of images used in Experiment 3

## Images shown in Figure 3.28 (from top-left to bottom-right):

http://www.flickr.com/photos/Curtis Morton-Lowerlighter

http://www.flickr.com/photos/robferblue

http://www.flickr.com/photos/louisa_catlover

http://www.flickr.com/photos/kevindean

http://www.flickr.com/photos/ph0t0 (loves you too)

http://www.flickr.com/photos/Rusty Stewart

One selected from the privat e collection of collegues'

One selected from the privat e collection of collegues'

http://www.flickr.com/photos/Andrew*

http://www.flickr.com/photos/hotelgrandebretagne

http://www.flickr.com/photos/ohdearbarb

http://www.flickr.com/photos/vegaseddie

http://www.flickr.com/photos/Tom Carmony

http://www.flickr.com/photos/angiepics

http://www.flickr.com/photos/stardumb_21

http://www.flickr.com/photos/Steve Polyak

http://www.flickr.com/photos/johnchas

http://www.flickr.com/photos/yak_jake

## Images shown in Figure 3.29 (from top-left to bottom-right):

http://www.flickr.com/photos/Curtis Morton-Lowerlighter

http://www.flickr.com/photos/dracorubio

http://www.flickr.com/photos/louisa_catlover

IAPS

http://www.flickr.com/photos/python

http://www.flickr.com/photos/interplast

SHIPP (Standard High Precision Picture) collection

One selected from the private collection of collegues'

HP Labs

SHIPP (Standard High Precision Picture) collection

SHIPP (Standard High Precision Picture) collection

http://www.flickr.com/photos/vegaseddie

http://www.flickr.com/photos/Tom Carmony http://www.flickr.com/photos/angiepics

http://www.flickr.com/photos/Rev. Xanatos Satanicos Bombasticos (ClintJCL)

http://www.flickr.com/photos/rockabillyboy72

http://www.flickr.com/photos/johnchas

http://www.flickr.com/photos/yak_jake

# Appendix E: Experimental Data from Experiment 1 (psychophysical data)

Chroma manipulated

| Image | | pleasant | calming | natural | like | appealing | Contrast | median M |
|---|---|---|---|---|---|---|---|---|
| 1 (indoor) | 1 | 5.90 | 4.79 | 5.69 | 6.00 | 6.14 | 20.21 | 15.83 |
| 1 | 22 | 5.52 | 4.76 | 5.03 | 5.48 | 5.48 | 20.20 | 0.31 |
| 1 | 23 | 4.55 | 4.90 | 3.97 | 4.59 | 4.55 | 20.21 | 12.41 |
| 1 | 24 | 5.97 | 4.90 | 5.38 | 6.10 | 5.86 | 20.22 | 21.57 |
| 1 | 25 | 5.41 | 4.41 | 5.07 | 5.38 | 5.03 | 20.40 | 28.34 |
| 2 (boy) | 1 | 4.69 | 4.55 | 4.55 | 4.62 | 4.45 | 23.79 | 19.43 |
| 2 | 22 | 4.21 | 4.59 | 3.52 | 3.86 | 3.90 | 23.78 | 0.42 |
| 2 | 23 | 4.28 | 4.66 | 4.45 | 4.14 | 3.93 | 23.78 | 15.32 |
| 2 | 24 | 3.76 | 4.34 | 3.10 | 3.28 | 3.66 | 23.67 | 26.50 |
| 2 | 25 | 4.55 | 4.76 | 4.24 | 4.28 | 4.55 | 22.76 | 30.37 |
| 3 (fruits) | 1 | 5.83 | 4.55 | 4.79 | 5.62 | 5.45 | 25.65 | 19.18 |
| 3 | 22 | 4.10 | 4.79 | 2.38 | 3.97 | 4.10 | 25.65 | 0.36 |
| 3 | 23 | 4.59 | 4.48 | 4.17 | 4.62 | 4.69 | 25.66 | 15.11 |
| 3 | 24 | 4.83 | 4.17 | 4.59 | 5.17 | 4.66 | 25.67 | 22.88 |
| 3 | 25 | 5.55 | 4.66 | 4.45 | 5.34 | 5.55 | 25.53 | 29.21 |
| 4 (harbor) | 1 | 4.10 | 4.69 | 3.90 | 4.03 | 4.07 | 20.74 | 11.98 |
| 4 | 22 | 4.97 | 4.45 | 5.07 | 5.34 | 5.24 | 20.74 | 0.41 |
| 4 | 23 | 5.79 | 4.90 | 5.86 | 5.62 | 5.90 | 20.74 | 6.42 |
| 4 | 24 | 6.07 | 5.83 | 4.48 | 5.83 | 6.28 | 20.73 | 18.87 |
| 4 | 25 | 5.59 | 5.72 | 3.90 | 5.59 | 6.00 | 20.85 | 23.81 |
| 5 (baby) | 1 | 5.79 | 4.41 | 5.52 | 5.90 | 5.66 | 18.01 | 29.25 |
| 5 | 12 | 5.24 | 4.24 | 4.62 | 4.97 | 5.10 | 18.01 | 0.37 |
| 5 | 13 | 5.14 | 4.28 | 5.00 | 5.00 | 5.03 | 18.34 | 40.27 |
| 6 (rubbish) | 1 | 4.97 | 4.10 | 4.17 | 4.72 | 4.79 | 23.38 | 14.84 |
| 6 | 12 | 5.86 | 4.45 | 5.69 | 5.86 | 5.97 | 23.37 | 0.42 |
| 6 | 13 | 5.41 | 4.69 | 5.28 | 5.52 | 5.69 | 23.24 | 27.10 |
| 7 (horses) | 1 | 5.34 | 5.31 | 3.90 | 5.10 | 5.59 | 20.12 | 29.35 |
| 7 | 12 | 6.21 | 5.38 | 5.17 | 5.83 | 6.21 | 20.12 | 0.43 |
| 7 | 13 | 4.69 | 5.17 | 3.55 | 4.38 | 4.72 | 19.40 | 39.00 |
| 8 (family) | 1 | 5.10 | 4.31 | 5.00 | 4.86 | 5.03 | 20.00 | 21.07 |
| 8 | 12 | 6.24 | 5.24 | 5.24 | 5.90 | 6.41 | 20.01 | 0.37 |
| 8 | 13 | 5.55 | 5.86 | 3.72 | 5.17 | 5.69 | 19.43 | 37.70 |
| 11 (personal1) | 1 | 5.28 | 4.79 | 3.90 | 4.97 | 5.48 | 25.47 | 13.51 |
| 11 | 12 | 5.83 | 4.72 | 5.69 | 5.86 | 6.00 | 25.47 | 0.36 |
| 11 | 13 | 5.59 | 4.62 | 5.90 | 5.69 | 5.52 | 25.42 | 18.58 |
| 12 (personal2) | 1 | 4.90 | 3.97 | 4.41 | 4.90 | 4.69 | 25.05 | 12.65 |
| 12 | 12 | 3.86 | 4.31 | 2.93 | 3.59 | 3.34 | 25.04 | 0.37 |
| 12 | 13 | 4.83 | 5.31 | 3.76 | 4.31 | 4.69 | 25.01 | 16.80 |

Contrast manipulated

| image | | pleasant | calming | natural | like | appealing | Contrast | median M |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 5.90 | 4.79 | 5.69 | 6.00 | 6.14 | 20.21 | 15.83 |
| 1 | 26 | 4.93 | 4.97 | 4.00 | 4.86 | 5.14 | 13.30 | 15.84 |
| 1 | 27 | 3.31 | 5.66 | 2.24 | 3.21 | 3.72 | 16.36 | 15.86 |
| 1 | 28 | 5.90 | 4.21 | 5.31 | 5.93 | 5.66 | 22.06 | 3.80 |
| 1 | 29 | 5.14 | 4.38 | 4.10 | 4.90 | 4.83 | 21.96 | 11.59 |
| 2 | 1 | 4.69 | 4.55 | 4.55 | 4.62 | 4.45 | 23.79 | 19.43 |
| 2 | 26 | 3.69 | 4.55 | 3.24 | 3.62 | 3.83 | 14.21 | 19.40 |
| 2 | 27 | 4.48 | 4.90 | 3.55 | 4.31 | 4.66 | 19.61 | 19.45 |
| 2 | 28 | 4.14 | 5.31 | 2.69 | 3.45 | 3.97 | 33.10 | 15.87 |
| 2 | 29 | 4.38 | 4.97 | 3.10 | 4.07 | 4.07 | 28.88 | 18.96 |
| 3 | 1 | 5.83 | 4.55 | 4.79 | 5.62 | 5.45 | 25.65 | 19.18 |
| 3 | 26 | 6.03 | 4.97 | 4.90 | 5.83 | 6.00 | 9.97 | 19.21 |
| 3 | 27 | 4.14 | 5.86 | 2.48 | 3.66 | 4.21 | 20.37 | 19.18 |
| 3 | 28 | 3.83 | 4.45 | 3.28 | 3.66 | 3.52 | 33.33 | 16.74 |
| 3 | 29 | 4.86 | 4.69 | 4.17 | 4.59 | 4.76 | 30.76 | 18.44 |
| 4 | 1 | 4.10 | 4.69 | 3.90 | 4.03 | 4.07 | 20.74 | 11.98 |
| 4 | 26 | 4.83 | 4.17 | 4.45 | 4.69 | 4.83 | 9.06 | 11.98 |
| 4 | 27 | 4.21 | 4.31 | 3.72 | 4.48 | 4.28 | 15.98 | 11.99 |
| 4 | 28 | 5.52 | 4.93 | 5.34 | 5.21 | 5.45 | 27.61 | 8.35 |
| 4 | 29 | 5.38 | 4.90 | 4.48 | 4.93 | 5.45 | 24.24 | 11.37 |
| 5 | 1 | 5.79 | 4.41 | 5.52 | 5.90 | 5.66 | 18.01 | 29.25 |
| 5 | 14 | 4.72 | 4.38 | 4.00 | 4.48 | 4.72 | 8.61 | 29.24 |
| 5 | 15 | 6.00 | 4.62 | 5.41 | 5.83 | 5.86 | 22.18 | 5.80 |
| 6 | 1 | 4.97 | 4.10 | 4.17 | 4.72 | 4.79 | 23.38 | 14.84 |
| 6 | 14 | 5.14 | 4.86 | 4.97 | 5.00 | 5.31 | 11.80 | 14.84 |
| 6 | 15 | 5.31 | 4.31 | 4.79 | 5.17 | 5.28 | 30.69 | 11.64 |
| 7 | 1 | 5.34 | 5.31 | 3.90 | 5.10 | 5.59 | 20.12 | 29.35 |
| 7 | 14 | 6.24 | 5.10 | 5.52 | 6.03 | 6.38 | 10.15 | 29.34 |
| 7 | 15 | 4.76 | 4.66 | 4.66 | 4.72 | 4.72 | 26.40 | 28.44 |
| 8 | 1 | 5.10 | 4.31 | 5.00 | 4.86 | 5.03 | 20.00 | 21.07 |
| 8 | 14 | 4.28 | 4.31 | 3.17 | 3.86 | 3.90 | 7.81 | 21.07 |
| 8 | 15 | 5.31 | 4.52 | 4.76 | 5.07 | 5.03 | 27.69 | 19.90 |
| 11 | 1 | 5.28 | 4.79 | 3.90 | 4.97 | 5.48 | 25.47 | 13.51 |
| 11 | 14 | 6.17 | 5.62 | 5.62 | 6.10 | 6.21 | 17.78 | 13.52 |
| 11 | 15 | 5.76 | 5.76 | 4.69 | 5.52 | 5.79 | 31.36 | 11.05 |
| 12 | 1 | 4.90 | 3.97 | 4.41 | 4.90 | 4.69 | 25.05 | 12.65 |
| 12 | 14 | 4.86 | 5.24 | 3.66 | 4.28 | 4.59 | 17.62 | 12.65 |
| 12 | 15 | 5.93 | 5.14 | 5.90 | 5.76 | 5.76 | 30.66 | 10.56 |

# Appendix F: Experimental Data from Experiment 1 (physiological data)

Chroma manipulation

| Image | | SC | HR | EMG |
|---|---|---|---|---|
| 1 (indoor) | 1 | -0.214 | 0.290 | -0.342 |
| 1 | 22 | 0.289 | -0.617 | 0.266 |
| 1 | 23 | -0.211 | 0.189 | 0.610 |
| 1 | 24 | 0.138 | 0.346 | -0.010 |
| 1 | 25 | 0.045 | 0.298 | -0.080 |
| 2 (boy) | 1 | -0.274 | 0.282 | 0.377 |
| 2 | 22 | -0.158 | 0.239 | -0.087 |
| 2 | 23 | -0.217 | -0.214 | -0.129 |
| 2 | 24 | 0.083 | 0.260 | -0.090 |
| 2 | 25 | -0.410 | 0.227 | 0.002 |
| 3 (fruits) | 1 | 0.440 | 0.137 | -0.523 |
| 3 | 22 | -0.031 | 0.054 | 0.137 |
| 3 | 23 | -0.338 | -0.119 | -0.544 |
| 3 | 24 | 0.677 | 0.104 | 0.117 |
| 3 | 25 | -0.381 | 0.012 | 0.191 |
| 4 (harbor) | 1 | -0.401 | 0.109 | 0.070 |
| 4 | 22 | 0.125 | -0.070 | -0.019 |
| 4 | 23 | 0.181 | -0.627 | -0.023 |
| 4 | 24 | -0.056 | 0.148 | -0.210 |
| 4 | 25 | -0.205 | 0.103 | -0.041 |
| 5 (baby) | 1 | 0.170 | 0.081 | -0.228 |
| 5 | 12 | -0.017 | 0.107 | 0.028 |
| 5 | 13 | -0.182 | 0.029 | -0.247 |
| 6 (rubbish) | 1 | 0.288 | 0.263 | -0.245 |
| 6 | 12 | 0.476 | 0.132 | 0.111 |
| 6 | 13 | -0.307 | 0.171 | 0.021 |
| 7 (horses) | 1 | -0.252 | 0.264 | -0.131 |
| 7 | 12 | 0.018 | -0.287 | 0.106 |
| 7 | 13 | -0.138 | 0.195 | 0.066 |
| 8 (family) | 1 | 0.045 | 0.136 | -0.033 |
| 8 | 12 | -0.079 | 0.199 | -0.384 |
| 8 | 13 | -0.278 | 0.069 | -0.131 |
| 11 (personal1) | 1 | 0.441 | 0.309 | -0.012 |
| 11 | 12 | 0.309 | 0.323 | -0.059 |
| 11 | 13 | 0.740 | 0.278 | -0.123 |
| 12 (personal2) | 1 | 0.105 | -0.269 | -0.042 |
| 12 | 12 | -0.191 | 0.280 | -0.242 |
| 12 | 13 | 0.089 | 0.349 | -0.074 |

Contrast manipulated

| image | | SC | HR | EMG |
|---|---|---|---|---|
| 1 | 1 | -0.214 | 0.290 | -0.342 |
| 1 | 26 | -0.289 | 0.159 | 0.254 |
| 1 | 27 | -0.150 | -0.605 | -0.017 |
| 1 | 28 | -0.518 | 0.324 | -0.338 |
| 1 | 29 | 0.398 | 0.266 | -0.327 |
| 2 | 1 | -0.274 | 0.282 | 0.377 |
| 2 | 26 | -0.125 | -0.044 | 0.077 |
| 2 | 27 | -0.155 | -0.508 | -0.132 |
| 2 | 28 | -0.101 | -1.097 | 0.416 |
| 2 | 29 | -0.345 | -0.126 | 0.200 |
| 3 | 1 | 0.440 | 0.137 | -0.523 |
| 3 | 26 | 0.048 | -0.132 | -0.440 |
| 3 | 27 | 0.150 | 0.007 | 0.201 |
| 3 | 28 | -0.218 | -0.096 | 0.256 |
| 3 | 29 | -0.527 | -0.005 | 0.229 |
| 4 | 1 | -0.401 | 0.109 | 0.070 |
| 4 | 26 | -0.149 | -0.092 | 0.139 |
| 4 | 27 | 0.125 | -0.624 | 0.010 |
| 4 | 28 | -0.458 | -0.253 | 0.022 |
| 4 | 29 | -0.197 | 0.142 | 0.342 |
| 5 | 1 | 0.170 | 0.081 | -0.228 |
| 5 | 14 | -0.167 | 0.147 | 0.202 |
| 5 | 15 | -0.011 | 0.137 | -0.044 |
| 6 | 1 | 0.288 | 0.263 | -0.245 |
| 6 | 14 | -0.018 | -1.147 | -0.133 |
| 6 | 15 | -0.034 | -0.173 | 0.192 |
| 7 | 1 | -0.252 | 0.264 | -0.131 |
| 7 | 14 | -0.139 | 0.164 | -0.207 |
| 7 | 15 | 0.143 | 0.025 | -0.055 |
| 8 | 1 | 0.045 | 0.136 | -0.033 |
| 8 | 14 | 0.104 | 0.015 | -0.135 |
| 8 | 15 | -0.010 | 0.091 | -0.602 |
| 11 | 1 | 0.441 | 0.309 | -0.012 |
| 11 | 14 | 0.110 | 0.254 | -0.051 |
| 11 | 15 | 0.690 | 0.179 | 0.101 |
| 12 | 1 | 0.105 | -0.269 | -0.042 |
| 12 | 14 | 0.436 | 0.030 | -0.057 |
| 12 | 15 | 1.069 | 0.320 | -0.026 |

# Appendix G: Experimental Data from Experiment 2

Chroma manipulated

| | image | active | heavy | warm | like | pleasant | exciting | Median J' | contrast (std J') | Median M' |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 (boy) | 101 | 4.59 | 5.88 | 5.59 | 6.06 | 6.24 | 5.06 | 57.29 | 23.79 | 17.36 |
| 1 | 112 | 3.25 | 5.19 | 4.25 | 5.00 | 4.81 | 3.38 | 57.29 | 23.78 | 0.47 |
| 1 | 113 | 3.53 | 5.12 | 4.41 | 4.29 | 4.29 | 3.59 | 57.28 | 23.79 | 8.83 |
| 1 | 114 | 3.50 | 5.88 | 4.63 | 5.13 | 4.81 | 3.94 | 57.30 | 23.78 | 13.69 |
| 1 | 115 | 5.47 | 5.71 | 5.88 | 6.12 | 6.29 | 5.12 | 57.29 | 23.78 | 20.02 |
| 1 | 116 | 5.59 | 5.29 | 6.06 | 6.06 | 6.18 | 5.65 | 57.44 | 23.67 | 23.32 |
| 1 | 117 | 6.00 | 4.47 | 5.94 | 4.88 | 5.41 | 5.88 | 58.32 | 22.96 | 26.09 |
| 2 (harbor) | 201 | 6.31 | 5.44 | 5.13 | 6.50 | 6.88 | 5.88 | 46.24 | 20.74 | 13.99 |
| 2 | 212 | 3.59 | 4.18 | 4.00 | 4.71 | 5.00 | 3.76 | 46.24 | 20.74 | 0.44 |
| 2 | 213 | 3.69 | 3.94 | 3.81 | 4.56 | 4.38 | 3.75 | 46.25 | 20.74 | 7.10 |
| 2 | 214 | 4.82 | 4.29 | 4.47 | 5.47 | 5.00 | 4.47 | 46.24 | 20.74 | 11.04 |
| 2 | 215 | 6.88 | 5.12 | 6.29 | 6.71 | 6.47 | 6.00 | 46.25 | 20.74 | 16.16 |
| 2 | 216 | 6.71 | 5.00 | 6.35 | 6.12 | 6.41 | 6.41 | 46.30 | 20.73 | 19.01 |
| 2 | 217 | 6.94 | 5.06 | 6.53 | 5.06 | 5.76 | 6.06 | 46.63 | 20.76 | 21.99 |
| 3 (skydivers) | 301 | 7.47 | 6.53 | 4.65 | 7.35 | 7.41 | 7.41 | 74.43 | 19.25 | 10.85 |
| 3 | 312 | 5.63 | 5.44 | 4.00 | 6.25 | 6.31 | 6.13 | 74.43 | 19.24 | 0.47 |
| 3 | 313 | 5.76 | 5.76 | 3.71 | 5.29 | 5.18 | 5.71 | 74.43 | 19.24 | 5.43 |
| 3 | 314 | 6.67 | 6.27 | 4.20 | 6.73 | 6.60 | 6.40 | 74.43 | 19.25 | 8.51 |
| 3 | 315 | 7.35 | 6.24 | 4.53 | 6.82 | 7.06 | 7.41 | 74.44 | 19.22 | 13.00 |
| 3 | 316 | 7.24 | 5.53 | 5.24 | 6.59 | 6.76 | 7.18 | 74.46 | 19.19 | 15.36 |
| 3 | 317 | 6.88 | 5.47 | 5.59 | 5.71 | 6.24 | 6.82 | 74.47 | 19.13 | 17.85 |
| 5 (couple) | 501 | 6.69 | 6.25 | 4.75 | 7.00 | 7.38 | 6.69 | 60.18 | 17.57 | 19.65 |
| 5 | 512 | 5.06 | 5.47 | 4.47 | 5.71 | 6.12 | 4.88 | 60.18 | 17.57 | 0.46 |
| 5 | 513 | 5.00 | 5.65 | 4.35 | 5.53 | 5.71 | 4.94 | 60.18 | 17.57 | 10.27 |
| 5 | 514 | 5.76 | 6.35 | 5.06 | 6.41 | 6.47 | 5.12 | 60.18 | 17.57 | 15.69 |
| 5 | 515 | 6.59 | 5.53 | 5.71 | 6.29 | 6.65 | 6.24 | 60.20 | 17.55 | 21.76 |
| 5 | 516 | 6.53 | 4.87 | 6.00 | 5.53 | 6.07 | 6.60 | 60.35 | 17.50 | 24.18 |
| 5 | 517 | 6.31 | 4.06 | 6.38 | 5.06 | 4.94 | 6.88 | 60.70 | 17.43 | 26.43 |
| 6 (roach) | 601 | 4.38 | 4.19 | 6.06 | 3.13 | 2.69 | 5.88 | 71.60 | 29.20 | 12.96 |
| 6 | 612 | 2.94 | 4.47 | 4.35 | 3.12 | 3.12 | 4.71 | 71.57 | 29.17 | 0.61 |
| 6 | 613 | 3.31 | 4.50 | 4.56 | 2.63 | 2.56 | 5.25 | 71.57 | 29.18 | 6.79 |
| 6 | 614 | 3.69 | 5.25 | 4.81 | 2.44 | 2.56 | 5.69 | 71.59 | 29.20 | 10.34 |
| 6 | 615 | 4.63 | 4.25 | 6.13 | 2.63 | 2.63 | 5.88 | 71.60 | 29.14 | 14.76 |
| 6 | 616 | 4.63 | 3.56 | 6.88 | 2.56 | 2.38 | 6.19 | 71.71 | 28.92 | 16.87 |
| 6 | 617 | 4.69 | 3.50 | 7.06 | 2.44 | 2.19 | 6.38 | 71.91 | 28.55 | 19.10 |
| 7 (leopard) | 701 | 6.06 | 3.69 | 4.44 | 3.19 | 3.06 | 6.19 | 43.78 | 26.91 | 8.70 |
| 7 | 712 | 5.06 | 4.53 | 3.71 | 4.00 | 4.00 | 4.82 | 43.77 | 26.90 | 0.42 |
| 7 | 713 | 5.19 | 4.69 | 4.63 | 3.31 | 3.06 | 5.50 | 43.78 | 26.90 | 4.29 |
| 7 | 714 | 5.59 | 4.29 | 4.82 | 3.65 | 3.41 | 5.94 | 43.78 | 26.91 | 6.79 |
| 7 | 715 | 6.35 | 3.94 | 5.06 | 3.29 | 3.35 | 6.82 | 43.78 | 26.91 | 10.51 |
| 7 | 716 | 6.47 | 3.71 | 5.88 | 3.41 | 3.00 | 7.06 | 43.79 | 26.91 | 12.47 |
| 7 | 717 | 6.50 | 3.38 | 6.00 | 2.88 | 2.56 | 7.19 | 43.81 | 26.90 | 14.47 |
| 8 (injury) | 801 | 3.65 | 3.88 | 5.65 | 2.65 | 2.59 | 5.47 | 50.85 | 25.37 | 20.20 |
| 8 | 812 | 2.94 | 3.59 | 4.41 | 2.94 | 3.00 | 4.53 | 50.85 | 25.37 | 0.42 |
| 8 | 813 | 3.18 | 4.06 | 4.29 | 2.82 | 2.88 | 5.76 | 50.85 | 25.37 | 10.68 |
| 8 | 814 | 3.53 | 3.06 | 4.53 | 2.65 | 2.59 | 5.12 | 50.85 | 25.38 | 16.20 |
| 8 | 815 | 3.44 | 3.13 | 5.88 | 2.13 | 2.06 | 5.94 | 50.85 | 25.38 | 21.65 |
| 8 | 816 | 4.31 | 2.81 | 6.31 | 2.19 | 2.19 | 6.56 | 50.86 | 25.37 | 23.02 |
| 8 | 817 | 3.94 | 2.31 | 6.50 | 1.88 | 2.06 | 6.63 | 50.90 | 25.36 | 24.84 |
| 9 (baby) | 901 | 5.65 | 5.94 | 5.47 | 7.12 | 7.18 | 5.88 | 53.31 | 25.70 | 12.43 |
| 9 | 912 | 4.47 | 5.00 | 4.88 | 6.24 | 5.76 | 4.59 | 53.31 | 25.69 | 0.42 |
| 9 | 913 | 4.41 | 4.88 | 4.24 | 5.65 | 5.94 | 4.65 | 53.31 | 25.70 | 6.27 |
| 9 | 914 | 5.71 | 5.59 | 4.82 | 6.41 | 6.47 | 5.29 | 53.31 | 25.70 | 9.78 |
| 9 | 915 | 6.41 | 6.12 | 5.47 | 7.35 | 7.29 | 5.76 | 53.33 | 25.69 | 14.80 |
| 9 | 916 | 6.12 | 5.59 | 5.94 | 6.94 | 6.88 | 6.12 | 53.37 | 25.64 | 17.24 |
| 9 | 917 | 5.71 | 4.35 | 5.71 | 5.18 | 5.71 | 5.76 | 53.48 | 25.50 | 19.70 |
| 10 (family) | 1001 | 5.93 | 6.73 | 5.93 | 7.40 | 7.60 | 6.27 | 72.54 | 20.00 | 18.65 |
| 10 | 1012 | 4.29 | 6.35 | 5.29 | 6.71 | 6.71 | 4.29 | 72.54 | 20.01 | 0.39 |
| 10 | 1013 | 4.71 | 6.29 | 4.88 | 6.00 | 6.12 | 4.59 | 72.54 | 20.00 | 9.65 |
| 10 | 1014 | 5.00 | 6.59 | 5.41 | 7.06 | 6.88 | 5.00 | 72.54 | 20.00 | 14.84 |
| 10 | 1015 | 6.18 | 6.41 | 6.06 | 7.65 | 7.65 | 5.65 | 72.59 | 19.96 | 21.32 |
| 10 | 1016 | 5.94 | 5.41 | 6.35 | 6.06 | 6.35 | 5.65 | 72.78 | 19.85 | 24.70 |
| 10 | 1017 | 6.13 | 4.06 | 6.69 | 4.81 | 5.06 | 6.31 | 73.14 | 19.68 | 27.95 |

| | image | active | heavy | warm | like | pleasant | exciting | Median J' | contrast (std J') | Median M' |
|---|---|---|---|---|---|---|---|---|---|---|
| 11 (personal) | A01 | 5.41 | 5.94 | 5.59 | 6.29 | 6.47 | 5.06 | 69.52 | 23.91 | 16.82 |
| 11 | A12 | 3.88 | 4.81 | 4.44 | 5.50 | 5.00 | 4.19 | 69.52 | 23.90 | 0.40 |
| 11 | A13 | 4.18 | 5.35 | 4.29 | 5.24 | 5.00 | 4.24 | 69.52 | 23.91 | 8.71 |
| 11 | A14 | 5.00 | 5.81 | 5.25 | 6.13 | 6.38 | 4.81 | 69.52 | 23.91 | 13.38 |
| 11 | A15 | 5.82 | 5.41 | 6.29 | 6.29 | 6.65 | 5.76 | 69.51 | 23.89 | 18.86 |
| 11 | A16 | 5.76 | 4.88 | 6.41 | 5.00 | 5.71 | 5.71 | 69.53 | 23.84 | 20.85 |

Contrast manipulated

| | image | active | heavy | warm | like | pleasant | exciting | Median J' | contrast (std J') | Median M' |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 101 | 4.59 | 5.88 | 5.59 | 6.06 | 6.24 | 5.06 | 57.29 | 23.79 | 17.36 |
| 1 | 118 | 4.24 | 6.24 | 5.00 | 4.53 | 4.35 | 4.18 | 61.95 | 16.26 | 17.36 |
| 1 | 119 | 4.75 | 6.06 | 5.19 | 5.38 | 5.31 | 4.69 | 60.25 | 19.61 | 17.35 |
| 1 | 120 | 5.06 | 6.50 | 4.88 | 5.50 | 5.56 | 4.50 | 58.91 | 21.48 | 17.36 |
| 1 | 121 | 3.59 | 3.00 | 4.24 | 4.29 | 4.18 | 4.47 | 49.30 | 35.20 | 13.50 |
| 1 | 122 | 4.38 | 4.69 | 4.50 | 5.13 | 4.81 | 4.56 | 51.29 | 30.92 | 16.30 |
| 1 | 123 | 5.12 | 5.59 | 5.35 | 5.94 | 5.71 | 4.35 | 55.35 | 26.38 | 17.37 |
| 2 | 201 | 6.31 | 5.44 | 5.13 | 6.50 | 6.88 | 5.88 | 46.24 | 20.74 | 13.99 |
| 2 | 218 | 3.94 | 5.12 | 4.65 | 3.53 | 4.12 | 4.24 | 53.89 | 12.23 | 13.99 |
| 2 | 219 | 4.18 | 4.65 | 4.47 | 4.12 | 4.00 | 4.53 | 50.73 | 15.98 | 14.01 |
| 2 | 220 | 5.06 | 5.06 | 4.88 | 5.31 | 5.13 | 4.81 | 48.67 | 18.11 | 13.99 |
| 2 | 221 | 5.06 | 2.65 | 4.41 | 4.24 | 4.06 | 4.88 | 39.30 | 25.93 | 13.02 |
| 2 | 222 | 5.31 | 3.38 | 4.88 | 5.25 | 5.13 | 5.31 | 42.07 | 24.24 | 13.84 |
| 2 | 223 | 6.06 | 4.53 | 5.35 | 6.18 | 6.35 | 5.53 | 43.87 | 23.04 | 14.06 |
| 3 | 301 | 7.47 | 6.53 | 4.65 | 7.35 | 7.41 | 7.41 | 74.43 | 19.25 | 10.85 |
| 3 | 318 | 6.24 | 6.06 | 4.41 | 5.76 | 5.71 | 6.24 | 72.41 | 14.03 | 10.86 |
| 3 | 319 | 6.65 | 6.29 | 4.12 | 6.35 | 6.18 | 6.71 | 73.65 | 16.47 | 10.85 |
| 3 | 320 | 7.31 | 6.94 | 4.88 | 7.13 | 7.19 | 7.38 | 73.99 | 17.77 | 10.85 |
| 3 | 321 | 7.31 | 5.63 | 5.06 | 7.00 | 6.94 | 7.44 | 77.12 | 21.99 | 10.70 |
| 3 | 322 | 6.81 | 6.00 | 4.69 | 6.56 | 6.81 | 7.19 | 75.57 | 20.75 | 10.80 |
| 3 | 323 | 7.25 | 6.38 | 5.00 | 7.31 | 7.19 | 7.25 | 75.05 | 20.12 | 10.82 |
| 5 | 501 | 6.69 | 6.25 | 4.75 | 7.00 | 7.38 | 6.69 | 60.18 | 17.57 | 19.65 |
| 5 | 518 | 5.59 | 5.53 | 4.82 | 4.71 | 5.12 | 5.06 | 62.15 | 10.65 | 19.65 |
| 5 | 519 | 5.82 | 6.12 | 5.29 | 5.71 | 6.12 | 5.41 | 61.51 | 13.72 | 19.65 |
| 5 | 520 | 6.38 | 5.81 | 5.00 | 6.25 | 6.38 | 6.25 | 60.86 | 15.45 | 19.65 |
| 5 | 521 | 5.94 | 4.18 | 4.82 | 5.82 | 5.88 | 6.00 | 57.10 | 28.12 | 18.28 |
| 5 | 522 | 6.47 | 5.29 | 5.59 | 6.35 | 6.71 | 6.41 | 57.21 | 23.48 | 19.20 |
| 5 | 523 | 6.59 | 5.82 | 5.47 | 6.94 | 7.18 | 6.35 | 59.38 | 19.81 | 19.62 |
| 6 | 601 | 4.38 | 4.19 | 6.06 | 3.13 | 2.69 | 5.88 | 71.60 | 29.20 | 12.96 |
| 6 | 618 | 4.47 | 4.53 | 5.13 | 2.87 | 2.40 | 4.80 | 73.93 | 22.17 | 12.96 |
| 6 | 619 | 4.33 | 4.73 | 5.47 | 2.40 | 2.73 | 5.47 | 73.19 | 25.19 | 12.96 |
| 6 | 620 | 4.33 | 4.40 | 5.80 | 2.73 | 2.73 | 5.20 | 72.48 | 26.99 | 12.96 |
| 6 | 621 | 3.60 | 2.47 | 5.13 | 2.27 | 2.27 | 5.87 | 70.02 | 35.53 | 10.07 |
| 6 | 622 | 4.33 | 2.87 | 6.07 | 2.47 | 2.60 | 6.00 | 69.74 | 33.48 | 11.49 |
| 6 | 623 | 4.29 | 3.14 | 6.50 | 2.57 | 2.57 | 6.14 | 70.76 | 31.24 | 12.65 |
| 7 | 701 | 6.06 | 3.69 | 4.44 | 3.19 | 3.06 | 6.19 | 43.78 | 26.91 | 8.70 |
| 7 | 718 | 5.35 | 4.47 | 4.71 | 2.94 | 3.06 | 6.29 | 53.41 | 17.08 | 11.72 |
| 7 | 719 | 5.59 | 4.12 | 4.59 | 3.18 | 2.82 | 5.71 | 49.38 | 21.05 | 11.72 |
| 7 | 720 | 5.88 | 4.41 | 5.06 | 3.41 | 3.24 | 5.47 | 46.78 | 23.33 | 11.71 |
| 7 | 721 | 6.13 | 2.81 | 5.00 | 3.31 | 3.31 | 6.69 | 36.04 | 32.16 | 10.09 |
| 7 | 722 | 6.60 | 3.67 | 5.47 | 3.13 | 2.73 | 6.80 | 38.20 | 30.48 | 11.44 |
| 7 | 723 | 6.29 | 3.71 | 5.82 | 3.76 | 3.35 | 6.65 | 40.29 | 28.97 | 11.56 |
| 8 | 801 | 3.65 | 3.88 | 5.65 | 2.65 | 2.59 | 5.47 | 50.85 | 25.37 | 20.20 |
| 8 | 818 | 3.44 | 4.06 | 5.63 | 2.25 | 2.13 | 5.63 | 57.14 | 15.45 | 20.20 |
| 8 | 819 | 3.18 | 3.76 | 5.47 | 2.29 | 2.47 | 5.35 | 54.68 | 19.87 | 20.20 |
| 8 | 820 | 3.44 | 3.88 | 5.13 | 2.44 | 2.31 | 5.81 | 52.95 | 22.34 | 20.20 |
| 8 | 821 | 3.59 | 2.00 | 6.06 | 1.82 | 1.76 | 6.47 | 45.91 | 32.81 | 18.73 |
| 8 | 822 | 3.65 | 2.47 | 5.94 | 2.29 | 2.00 | 6.24 | 47.10 | 30.42 | 19.81 |
| 8 | 823 | 3.33 | 2.80 | 5.47 | 2.20 | 1.80 | 6.07 | 48.71 | 28.35 | 20.09 |
| 9 | 901 | 5.65 | 5.94 | 5.47 | 7.12 | 7.18 | 5.88 | 53.31 | 25.70 | 12.43 |
| 9 | 918 | 4.63 | 5.94 | 4.81 | 5.31 | 5.63 | 4.56 | 58.45 | 15.56 | 12.44 |
| 9 | 919 | 4.82 | 5.76 | 4.76 | 5.88 | 5.65 | 4.47 | 56.46 | 20.07 | 12.43 |
| 9 | 920 | 5.41 | 5.82 | 4.82 | 6.29 | 6.24 | 4.94 | 55.02 | 22.59 | 12.44 |
| 9 | 921 | 5.06 | 3.81 | 4.56 | 5.63 | 5.56 | 5.38 | 50.37 | 32.75 | 11.55 |
| 9 | 922 | 5.24 | 4.59 | 5.35 | 6.18 | 6.35 | 5.59 | 50.71 | 30.39 | 12.25 |
| 9 | 923 | 6.12 | 5.24 | 5.24 | 7.00 | 7.12 | 5.71 | 51.66 | 28.64 | 12.40 |
| 10 | 1001 | 5.93 | 6.73 | 5.93 | 7.40 | 7.60 | 6.27 | 72.54 | 20.00 | 18.65 |
| 10 | 1018 | 4.94 | 6.12 | 5.29 | 6.00 | 5.88 | 4.88 | 71.04 | 13.71 | 18.65 |
| 10 | 1019 | 5.18 | 6.88 | 5.65 | 6.59 | 6.88 | 5.24 | 72.10 | 16.58 | 18.65 |
| 10 | 1020 | 5.41 | 6.71 | 5.71 | 7.06 | 7.18 | 5.59 | 72.30 | 18.14 | 18.66 |
| 10 | 1021 | 5.31 | 5.13 | 5.13 | 5.56 | 5.88 | 5.06 | 75.71 | 26.85 | 17.78 |
| 10 | 1022 | 5.94 | 5.88 | 6.00 | 7.06 | 7.12 | 5.88 | 72.99 | 24.38 | 18.30 |
| | image | active | heavy | warm | like | pleasant | exciting | Median J' | contrast (std J') | Median M' |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 1023 | 6.12 | 6.53 | 6.12 | 7.24 | 7.53 | 6.00 | 72.75 | 21.89 | 18.63 |
| 11 | A01 | 5.41 | 5.94 | 5.59 | 6.29 | 6.47 | 5.06 | 69.52 | 23.91 | 16.82 |
| 11 | A17 | 4.38 | 5.38 | 5.19 | 4.88 | 4.81 | 4.81 | 70.36 | 18.13 | 16.82 |
| 11 | A18 | 4.59 | 5.71 | 5.12 | 5.12 | 5.24 | 4.71 | 70.05 | 19.89 | 16.82 |
| 11 | A19 | 4.63 | 5.19 | 5.31 | 5.31 | 5.13 | 4.88 | 69.81 | 21.71 | 16.82 |
| 11 | A20 | 4.59 | 3.41 | 5.59 | 4.71 | 4.59 | 5.00 | 68.97 | 28.45 | 16.39 |
| 11 | A21 | 5.12 | 4.24 | 5.35 | 5.88 | 5.82 | 5.53 | 69.12 | 27.42 | 16.64 |
| 11 | A22 | 5.71 | 5.06 | 5.53 | 6.29 | 6.35 | 5.94 | 69.20 | 26.07 | 16.78 |

Lightness manipulated

| | image | active | heavy | warm | like | pleasant | exciting | Median J' | contrast (std J') | Median M' |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 101 | 4.59 | 5.88 | 5.59 | 6.06 | 6.24 | 5.06 | 57.29 | 23.79 | 17.36 |
| 1 | 124 | 4.80 | 6.47 | 5.27 | 5.40 | 5.47 | 4.27 | 63.69 | 20.68 | 13.86 |
| 1 | 125 | 4.41 | 6.59 | 5.06 | 5.82 | 5.47 | 4.71 | 69.90 | 17.31 | 12.71 |
| 1 | 126 | 4.88 | 5.44 | 5.94 | 5.38 | 5.69 | 4.69 | 51.41 | 26.18 | 14.28 |
| 1 | 127 | 4.12 | 3.82 | 5.65 | 4.76 | 4.76 | 4.41 | 43.21 | 27.96 | 13.41 |
| 2 | 201 | 6.31 | 5.44 | 5.13 | 6.50 | 6.88 | 5.88 | 46.24 | 20.74 | 13.99 |
| 2 | 224 | 5.47 | 5.47 | 5.12 | 6.12 | 6.00 | 4.76 | 52.42 | 21.21 | 11.64 |
| 2 | 225 | 5.35 | 5.94 | 5.47 | 6.00 | 5.76 | 4.94 | 58.68 | 21.13 | 11.39 |
| 2 | 226 | 5.41 | 4.29 | 5.18 | 5.88 | 5.88 | 5.29 | 40.55 | 19.98 | 11.89 |
| 2 | 227 | 5.06 | 3.31 | 5.19 | 5.13 | 4.69 | 4.94 | 31.40 | 17.91 | 11.26 |
| 3 | 301 | 7.47 | 6.53 | 4.65 | 7.35 | 7.41 | 7.41 | 74.43 | 19.25 | 10.85 |
| 3 | 324 | 7.00 | 7.06 | 4.44 | 7.06 | 7.31 | 7.31 | 78.04 | 18.36 | 8.16 |
| 3 | 325 | 6.81 | 6.50 | 4.75 | 6.75 | 6.88 | 7.00 | 81.27 | 17.58 | 7.76 |
| 3 | 326 | 7.13 | 6.06 | 4.44 | 6.94 | 7.06 | 6.81 | 70.71 | 20.23 | 9.04 |
| 3 | 327 | 6.50 | 4.63 | 5.00 | 5.75 | 6.25 | 6.69 | 63.39 | 22.32 | 9.92 |
| 5 | 501 | 6.69 | 6.25 | 4.75 | 7.00 | 7.38 | 6.69 | 60.18 | 17.57 | 19.65 |
| 5 | 524 | 6.44 | 6.56 | 4.88 | 6.69 | 6.69 | 6.25 | 66.19 | 16.12 | 17.05 |
| 5 | 525 | 5.59 | 6.59 | 5.00 | 5.59 | 6.06 | 5.47 | 71.79 | 14.36 | 15.98 |
| 5 | 526 | 6.71 | 5.71 | 4.94 | 6.53 | 6.82 | 6.18 | 54.47 | 18.81 | 18.81 |
| 5 | 527 | 5.59 | 3.94 | 4.47 | 5.00 | 5.24 | 5.18 | 44.60 | 19.61 | 18.70 |
| 6 | 601 | 4.38 | 4.19 | 6.06 | 3.13 | 2.69 | 5.88 | 71.60 | 29.20 | 12.96 |
| 6 | 624 | 4.12 | 4.18 | 5.65 | 2.29 | 2.47 | 5.65 | 74.65 | 27.20 | 13.05 |
| 6 | 625 | 3.94 | 5.50 | 5.50 | 3.13 | 2.44 | 6.00 | 77.88 | 24.80 | 13.02 |
| 6 | 626 | 4.63 | 4.13 | 6.00 | 2.63 | 2.94 | 5.63 | 68.52 | 30.98 | 12.68 |
| 6 | 627 | 4.00 | 2.87 | 5.53 | 2.33 | 2.33 | 5.80 | 63.48 | 33.44 | 11.75 |
| 7 | 701 | 6.06 | 3.69 | 4.44 | 3.19 | 3.06 | 6.19 | 43.78 | 26.91 | 8.70 |
| 7 | 724 | 4.94 | 5.24 | 5.06 | 3.18 | 3.06 | 5.65 | 49.14 | 26.12 | 8.99 |
| 7 | 725 | 5.18 | 4.65 | 4.76 | 3.35 | 3.24 | 5.88 | 55.50 | 24.36 | 9.31 |
| 7 | 726 | 6.47 | 3.88 | 5.00 | 3.53 | 3.12 | 6.65 | 39.31 | 27.14 | 7.87 |
| 7 | 727 | 6.12 | 3.65 | 4.53 | 3.18 | 3.00 | 6.53 | 34.14 | 26.99 | 7.06 |
| 8 | 801 | 3.65 | 3.88 | 5.65 | 2.65 | 2.59 | 5.47 | 50.85 | 25.37 | 20.20 |
| 8 | 824 | 3.19 | 4.25 | 5.31 | 2.56 | 2.44 | 5.63 | 56.48 | 24.38 | 19.35 |
| 8 | 825 | 3.06 | 4.06 | 5.50 | 2.38 | 2.31 | 5.38 | 62.71 | 22.23 | 18.84 |
| 8 | 826 | 3.47 | 2.88 | 5.88 | 2.47 | 2.24 | 6.06 | 46.39 | 25.50 | 19.12 |
| 8 | 827 | 3.76 | 2.29 | 6.41 | 2.06 | 2.06 | 5.94 | 40.63 | 24.96 | 18.43 |
| 9 | 901 | 5.65 | 5.94 | 5.47 | 7.12 | 7.18 | 5.88 | 53.31 | 25.70 | 12.43 |
| 9 | 924 | 5.71 | 6.12 | 5.59 | 6.71 | 6.94 | 5.12 | 58.35 | 25.29 | 11.32 |
| 9 | 925 | 5.88 | 6.47 | 5.47 | 6.76 | 6.65 | 4.76 | 63.79 | 23.93 | 11.06 |
| 9 | 926 | 5.81 | 5.38 | 5.88 | 6.50 | 6.63 | 5.44 | 48.69 | 25.59 | 11.09 |
| 9 | 927 | 5.50 | 4.44 | 5.06 | 6.00 | 5.94 | 5.38 | 41.06 | 24.31 | 10.78 |
| 10 | 1001 | 5.93 | 6.73 | 5.93 | 7.40 | 7.60 | 6.27 | 72.54 | 20.00 | 18.65 |
| 10 | 1024 | 5.63 | 6.94 | 5.63 | 7.19 | 7.19 | 5.69 | 76.46 | 18.37 | 17.23 |
| 10 | 1025 | 5.31 | 7.00 | 5.81 | 7.44 | 7.31 | 5.06 | 80.18 | 16.40 | 16.40 |
| 10 | 1026 | 6.12 | 6.41 | 6.35 | 7.71 | 7.82 | 5.65 | 68.65 | 21.26 | 18.54 |
| 10 | 1027 | 5.88 | 5.19 | 6.69 | 7.13 | 7.06 | 5.69 | 63.03 | 22.57 | 19.13 |
| 11 | A01 | 5.41 | 5.94 | 5.59 | 6.29 | 6.47 | 5.06 | 69.52 | 23.91 | 16.82 |
| 11 | A23 | 5.65 | 6.18 | 6.12 | 6.71 | 6.59 | 5.47 | 72.90 | 22.52 | 15.02 |
| 11 | A24 | 4.94 | 6.06 | 5.47 | 5.71 | 5.88 | 4.88 | 76.01 | 21.00 | 14.85 |
| 11 | A25 | 5.24 | 4.88 | 5.94 | 6.24 | 6.24 | 5.24 | 65.38 | 25.12 | 15.26 |
| 11 | A26 | 4.88 | 3.56 | 5.44 | 5.38 | 5.19 | 4.81 | 61.33 | 26.13 | 15.22 |

## Appendix H: Experimental Data of Experiment 3

Image number from 1 to 18: from top left to bottom right in Figure 3.28

Image number from 19 to 36: from top left to bottom right in Figure 3.29

| image | level | SC | HR | EMG | image | level | SC | HR | EMG |
|---|---|---|---|---|---|---|---|---|---|
| 1 | achromatic | -0.378 | -0.312 | -0.465 | 19 | low contrast | -0.234 | 0.060 | 0.147 |
| 2 | achromatic | -0.571 | 0.186 | -0.161 | 20 | low contrast | -0.492 | 0.327 | -0.079 |
| 3 | achromatic | -0.099 | 0.336 | -0.028 | 21 | low contrast | 0.475 | 0.096 | 0.142 |
| 4 | achromatic | -0.398 | -0.129 | -0.156 | 22 | low contrast | -0.161 | -0.133 | 0.058 |
| 5 | achromatic | 0.425 | 0.187 | 0.085 | 23 | low contrast | -0.298 | 0.026 | 0.052 |
| 6 | achromatic | -0.085 | -0.687 | 0.072 | 24 | low contrast | -0.441 | 0.271 | -0.074 |
| 7 | achromatic | -0.014 | 0.357 | 0.095 | 25 | low contrast | 1.045 | -1.502 | -0.177 |
| 8 | achromatic | 0.463 | 0.223 | 0.571 | 26 | low contrast | 0.118 | -0.691 | 0.023 |
| 9 | achromatic | -0.106 | 0.243 | 0.728 | 27 | low contrast | -0.105 | -1.379 | -0.021 |
| 10 | achromatic | -0.225 | 0.280 | -0.001 | 28 | low contrast | -0.509 | 0.212 | -0.089 |
| 11 | achromatic | -0.125 | 0.198 | 0.198 | 29 | low contrast | -0.170 | 0.205 | 0.257 |
| 12 | achromatic | -0.219 | 0.199 | 0.071 | 30 | low contrast | -0.018 | -1.536 | 0.129 |
| 13 | achromatic | -0.215 | 0.122 | -0.114 | 31 | low contrast | -0.013 | -0.264 | -0.059 |
| 14 | achromatic | -0.246 | 0.300 | -0.617 | 32 | low contrast | 0.069 | 0.177 | -0.213 |
| 15 | achromatic | -0.151 | 0.171 | 0.201 | 33 | low contrast | -0.278 | 0.250 | 0.216 |
| 16 | achromatic | -0.348 | 0.437 | 0.011 | 34 | low contrast | -0.052 | 0.286 | 0.077 |
| 17 | achromatic | 0.237 | 0.104 | -0.675 | 35 | low contrast | 0.115 | 0.255 | 0.803 |
| 18 | achromatic | -0.577 | 0.130 | -0.117 | 36 | low contrast | -0.215 | 0.287 | 0.484 |
| personal | achromatic | -0.007 | 0.202 | 0.464 | personal | low contrast | 0.214 | 0.077 | 0.011 |
| 1 | chromatic | 0.280 | 0.353 | -0.015 | 19 | high contrast | 0.144 | -0.053 | 0.186 |
| 2 | chromatic | -0.239 | -0.019 | -0.257 | 20 | high contrast | 0.442 | -0.333 | -0.291 |
| 3 | chromatic | 0.597 | 0.154 | -0.049 | 21 | high contrast | -0.112 | 0.287 | -0.162 |
| 4 | chromatic | -0.489 | 0.284 | 0.220 | 22 | high contrast | -0.085 | -0.625 | 0.239 |
| 5 | chromatic | -0.438 | 0.250 | 0.082 | 23 | high contrast | -0.211 | 0.195 | -0.126 |
| 6 | chromatic | 0.297 | 0.037 | 0.240 | 24 | high contrast | 0.264 | -0.090 | -0.174 |
| 7 | chromatic | -0.277 | 0.181 | -0.504 | 25 | high contrast | 0.544 | 0.108 | -0.022 |
| 8 | chromatic | 0.169 | -0.722 | 0.083 | 26 | high contrast | -0.346 | 0.270 | -0.106 |
| 9 | chromatic | -0.270 | 0.200 | 0.016 | 27 | high contrast | -0.340 | 0.230 | -0.061 |
| 10 | chromatic | -0.359 | -0.189 | -0.265 | 28 | high contrast | 0.117 | 0.239 | 0.222 |
| 11 | chromatic | 0.158 | 0.297 | 0.295 | 29 | high contrast | 0.077 | 0.144 | -0.368 |
| 12 | chromatic | 0.228 | -1.865 | 0.327 | 30 | high contrast | 0.014 | -0.061 | 0.109 |
| 13 | chromatic | 1.754 | 0.063 | -0.195 | 31 | high contrast | -0.344 | 0.141 | -0.264 |
| 14 | chromatic | 0.978 | 0.002 | 0.091 | 32 | high contrast | 0.258 | 0.195 | -0.609 |
| 15 | chromatic | 0.152 | 0.352 | -0.306 | 33 | high contrast | 0.120 | 0.193 | 0.135 |
| 16 | chromatic | 0.207 | -0.497 | -0.029 | 34 | high contrast | -0.218 | 0.115 | 0.190 |
| 17 | chromatic | 0.512 | 0.273 | 0.313 | 35 | high contrast | 0.656 | 0.330 | -0.009 |
| 18 | chromatic | -0.251 | 0.072 | 0.073 | 36 | high contrast | 0.059 | 0.061 | 0.202 |
| personal | chromatic | 0.347 | -0.029 | 0.006 | personal | high contrast | 0.008 | 0.273 | -0.009 |