Investigation of Colour Memory

Ph.D Dissertation

Tünde Tarczali

Supervisor:
Dr. Peter Bodrogi

Doctoral School of Information Sciences
University of Pannonia

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INVESTIGATION OF COLOUR MEMORY

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Írta:
Tarczali Tünde Tímea

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Abstract

Colour memory plays an important role in many practical tasks related to the choice, identification and assessment of colours. Customers of colour imaging products often prefer long-term memory colours or colour prototypes of familiar objects frequently seen in the past. Colour memory is also one of the factors responsible for the phenomenon of colour constancy. These facts motivated researchers in colour science to construct different psycho-physical methods to characterize human colour memory on a computer-controlled display.

In memory matching techniques, the remembered colour might differ from the original colour even if the viewing situation is the same. The aim of this thesis was to point out that these so-called memory shifts are significant in the every day - situations of viewing photo-realistic images depicting sky, skin, or plants, or viewing standalone uniform colour patches of sky, skin, or plants colours. In many cases, significant memory shifts have been found.

Several different psycho-physical methods were found in the literature for the investigation of human colour memory. New experimental methods were developed and realized to achieve more stable and reliable experimental results. In this thesis, experimental data resulting from different techniques were compared. For a given type of image context (e.g. human complexion), systematic colour shifts in human colour memory were observed, which could be explained by the existence of prototypical colours. In the experiments, the existence of these prototypical colour centres was confirmed. A cognitive theory of the memory shifts is presented.

A színmemória vizsgálata

A mindennapi gyakorlatban a színmemória kevésbé ismert, ám annál fontosabb szerepet játszik. A színmemória használata természetes, ha színt választunk ki, azonosítunk, vagy értékelünk. Képmegjelenítő eszközön megjelenő kép esetén a megfigyelők jobban kedvelik a képet, ha azon az ismert tárgyak hosszútávú memóriaszínei láthatók. Ezek a hosszútávú memóriaszínek vagy prototipikus színek nem mások, mint a látott tárgyhoz a múltban, az emlékezetben kapcsolt színek. A színmemória erősen kapcsolható a színkonstancia fogalmához is. Ezek a kérdések fordították a színekkel foglalkozó kutatók figyelmét a színmemória feltérképezését célzó speciális pszichofizikai kísérletek megalkotása felé. A pszichofizikai kísérletek elvégzésének egyik eszköze a számítógépes színes monitor.

A memóriaegyeztető technikák alkalmazásánál a szín, amelyre emlékezünk, különbözhet az eredetileg megjegyzett színtől még akkor is, ha a látási szituáció a megjegyzés és a visszaadás fázisában azonos. A szerző célja a színeltolódások szignifikáns voltának vizsgálata volt egy mindennapi élethelyzetben – számítógépes monitoron - leszűkítve ezt az irodalomban leggyakrabban vizsgált három színre, így az „ég kék", „kaukázusi bőr" és a „fű zöld" színekre. A színeltolódások vizsgálatánál fontos szerepet játszik a képi kulcs hatása a memóriára, amelynek megléte vagy hiánya a megfigyelés alatt különböző módon befolyásolhatja a memóriahatásokat.

Untersuchung vom Farbgedächtnis

Das Farbgedächtnis spielt in vielen praktischen Aufgaben, die mit der Wahl, Identifikation und Beschreibung der Farben verbunden sind, eine wichtige Rolle. Die Kunden bei Farbbildprodukten bevorzugen langfristige Gedächtnisfarben oder Farbprototype von Gegenständen, mit denen sie vertraut sind und in der Vergangenheit oft sahen. Das Farbgedächtnis ist auch eines der Faktoren, die für das Phänomen der Farbkonstanz verantwortlich sind. Diese Tatsachen haben die Forscher der Farbwissenschaft motiviert, um verschiedene psychophysischen Methoden an computergesteuerten Monitoren durchzuführen, damit das menschliche Farbgedächtnis beschrieben werden kann.

Obwohl die Sichtbedingungen dieselben sind, können die erinnerten Farben von den originalen Farben bei Farbvergleichungsexperimenten abweichen. Der Zweck des Autors war zu untersuchen, ob die so genannten Gedächtnisverschiebungen bei der Beobachtung von photorealistischen Bildern über Himmel, Haut und Pflanzen, oder bei Beobachtung von nur isolierten, homogenen Farbmustern, die Himmelblau, Hautfarbe und Pflanzengrün ähnlich sind, wichtig sind.

Mehrere psychophysische Methoden über die Untersuchung vom menschlichen Farbgedächtnis können in der Literatur gefunden werden. In dieser Dissertation wurden neue Versuchsmethoden entworfen und durchgeführt, um stabilere und zuverlässigere Versuchsergebnisse zu erreichen. Bei bestimmten Bildzusammenhängen (z. B. menschliche Gesichtsfarben) wurden systematische Farbverschiebungen in dem menschlichen Farbgedächtnis beobachtet, die mit den prototypischen Farben erklärt werden können. Bei weiteren Untersuchungen wurde die Existenz von diesen prototypischen Farbzentren bestätigt.

Chapter 1 Introduction

Colour stimuli can be defined in terms of three tristimulus values[1]. Perceived colour is an attribute of visual perception consisting of a combination of chromatic and achromatic content. In the psychological literature, the distinction between perception and cognition has been the subject of much debate. A common distinction is that while perception refers to an immediate mapping of objects or events of the real world into the brain, cognition refers to subsequent higher-order processes of semantic and verbal classification of the perceptions[2]. The term cognitive colour may be defined as follows: the result of the colour module of early visual processing is perceived colour with its three continuous perceptual attributes, hue, colourfulness, and brightness. After the early visual processing stage, colour perceptions are classified into conceptual categories if required by the visual task. Cognitive colour means one from the discrete set of these categories. This set may depend on the visual task, e.g. the set of the eleven basic colours, or the set of the colour prototypes or long-term memory colours of familiar objects[3].

Colour memory is often required to compare an original image with its reproduction both in the laboratory and in everyday life situations, for example a woman purchasing gloves to match a hat at home, an artist in his studio mixing a colour on his palette or a photographer looking at his photo in a viewing booth and then at the reproduction of his photo on a colour monitor, or a colour inspector comparing a colour sample with a colour standard at another location. In these situations, observers memorise an original colour in a 1st viewing situation. This becomes a so-called "instant memory colour". In traditional terminology[4], the term "memory colour" refers to colours that are recalled in association with familiar objects in long-term memory. The attribute "instant" indicates the difference between the terminology of the present work and traditional terminology. After a given time interval, observers compare their so-called "later memory colour" with an "actual colour". The actual colour is seen in a 2nd viewing situation usually different from the 1st one. In the 2nd viewing situation, observers may modify the actual colour until it matches the later memory colour. The result of the

[1] The traditional terminology and results of colour memory investigations will be discussed in Chapter 3 below.

modification of the actual colour is the "corresponding colour". In the present study the two viewing situations were identical. I expect that the difference between the original colours and the corresponding colours is completely due to memory effects.

I will show that there is a difference between the original colour and the later memory colour. Namely, the corresponding colour corresponds to the later memory colour and not to the original colour unless the original colour is very close to the corresponding colour in space and time. Later memory colours may differ from original colours or from instant memory colours due to "cognitive" effects like colour preference and other effects[5]. The difference between later memory colour and the instant memory colour is the memory shift.

The light entering the human eye evokes a colour perception, which depends both on the colour element considered and on the viewing condition. This colour perception is subject to changes in short-term colour memory from one view to the next. Thus in one view, observers tend to remember a different colour than seen in a previous view, even if the viewing condition is the same. In short-term colour memory, shifts in hue, chroma, and lightness occur. Several authors agree that these shifts cannot be explained by sensory mechanisms or adaptation differences[6,7,8,9]. In Bodrogi's[5] work, these shifts were explained by the cognitive effect hypothesis. According to this hypothesis the relevant cognitive factors are: exaggeration, focal colours, prototypical colours, colour regions, typicality of colours and the context of a colour. These quantities have different effect in colour perception and produce different amounts of colour memory shifts.

Several different psycho-physical methods have been found in the literature on the investigation of human colour memory. I shall discuss them in detail in Chapter 2 below.

Generally, every experimental technique in memory matching experiments consists of two main steps: 1. the observer whose colour memory is being examined is given a certain cognitive and/or perceptual cue, the so-called colour memory cue; and 2. the observer has to find their memory colours based on the colour memory cue. The experimental methods for the investigation of human colour memory are classified based on the type of the colour memory cue plus the type of the psycho-physical method[10] to find a colour stimulus equivalent to the memory colour. Four main types of colour memory cues have been defined:

1. The so-called “abstract cue without image context” is the name of a familiar object. In this case, the observers are given a word or an expression only (e. g. “green grass”) and then they have to find the memory colour corresponding to this word;
2. The so-called “abstract cue with image context” is the greyscale picture of a familiar object. In this case, the observers get a greyscale photo-realistic image (e. g. a landscape) in which an area is left blank. Then they have to find their memory colour that would best fit that blank area;
3. The so-called “memory matching cue without image context” is an alone standing uniform colour patch. In this case, the observers can see a so-called original colour (i.e. e. a colour that they have to memorise) as an alone standing uniform colour patch. "Alone standing" means that there is no visible image context (e. g. a photo depicting a familiar object) together with the original colour. After a time interval they have to find their memory colours;
4. The so-called “memory matching cue with image context” is a uniform colour patch (the original colour), which is part of a (coloured or greyscale) photo-realistic image. In this case, the observers have to memorise the original colour, and after a time interval they have to find their memory colours.

Three methods of finding the memory colour were categorised. The first method is a method of adjustment, the second and the third are constant methods[10]:

1. “Mixing-up” the memory colour on a colour output device (a visual colorimeter or a colour monitor) by adjusting the hue, the chroma, and the lightness of a so-called “actual” colour. Strengths of this method: all colour shades can be “mixed-up” within the output device's gamut and exactly the same viewing condition can be ensured by using greyscale images. Weakness of this method: it is sometimes difficult for the observer to use the tools to mix-up the memory colour. The description of this method can be found in the method section of this work in details.

2. Selecting the memory colour from several constant colour patches. Strength of this method is that it is simple for the observer. Weakness of this method is that there is a perceptual difference between the viewing situations of memorising and selecting. In

addition, the number of the constant patches and thus the colour gamut to select from is limited.

3. Deciding whether a just-presented colour patch is the memory colour or it is not. I used this method and it will be described in detail in the methods section of this dissertation. It is very easy for the observer. A weakness may be that the consecutive presentation of many colour patches may confuse the observer and has an influence on the short-term memory colour.

The so-called “preference task” must be well distinguished from the methods to investigate colour memory. In a “preference task” observers are taught to look for the preferred colour of a just-seen or imagined object instead of trying to reproduce an original colour or a mean long-term memory colour[7,11,12]. The advantage of the preference task is that it represents better the everyday situation in which the preferred or pleasing colour reproduction is sometimes more important than the accurate colour appearance reproduction[12].

Earlier the memory matching experiments were accomplished with some kind of coloured chips, in most cases Munsell colour chips. Nowadays people use computers more often for work and amusement therefore examining the colour matching on colour monitors is important. During a colour matching experiment it is very important to ensure an equal viewing situation and within this to ensure an identical adaptation condition for the matching colours. To achieve this objective I designed and used a novel experimental set-up on a colour CRT monitor.

Chapter 2 Overview of earlier investigations

Colour is a cognitive concept[2]. If we talk about colour we can talk about many properties of colour. A colour could be a category, a preference colour, a name; it could possess a naturalness degree, a semantic rating, and of course colours can be discriminated from each other. All of these attributes are in close connection with colour. In a deeper thought, they are in our mind; these attributes correspond to non-conscious mental processes involved in colour perception. In this section I summarize the literature in chronological order in connection with the concept of cognitive colour splitting into categories, starting with the most important in my study: the memory colours.

2.1 Memory matching experiments; memory colours

Many papers about colours in memory and memory effects on colours can be found in the literature. The first article in my collection dates from 1957, the last one is from 2004, so it covers almost 6 decades.

The first article I have to mention is Newhall and et al.'s work[9] in which the authors compared two colour matching methods: successive and simultaneous. Simultaneous or perceptual colour matching means modifying one of two simultaneously presented colour stimuli to make it visually match the other stimulus. Successive or delayed matching involves (short-term) colour memory thus it is sometimes memory matching, but "it is only half memory in the sense that only one of the two compared colours has to be remembered." They noted that successive matching (and thus the shifts of short-term colour memory) is very common in everyday life and cited some examples: a woman in the store purchasing gloves to match a hat at home, an artist in his studio mixing a colour on his palette to represent a tree he saw in the country, a photographer who is trying to decide whether a colour print is a faithful reproduction of the absent original, or any colour inspector who has to compare a colour sample in one location with a colour standard in another location.

[2] In this section I would like to distinguish sharply between colour perception and the colour stimulus. If I use the word colour alone it means always colour perception. The term colour will be used to describe colour stimulus only if it is quite clear from the text that it relates to the stimulus.

Newhall et al.[9] mentioned an important implication of their result on the judgment of acceptability of colour reproductions: it depends directly on short-term colour memory. This is because memory provides the standard for evaluating acceptability.

In one of my experimental methods I also compared successive and simultaneous matching using different experimental setups. In my opinion, Newhall's cited examples, concern long-term memory colours. In earlier research on the topic terminology was less well classified then it is today.

In talking about colour memory short- and long-term variants of colour memory have to be distinguished. The simplest example of using short-term colour memory is successive colour matching with 4-20 sec delay. In such an experiment the observer has to memorize a colour and then he/she has to reproduce it after the delay. Newhall's examples are the best ones to illustrate the functioning of long-term colour memory. These are cases where a longer time passes between the first and the second colour that has to be compared is seen. During longer delays certain effects occur that modify the original memory trace. The specification of these effects can be found in Bodrogi's work[5].

In 1960 Bartleson[4] carried out an experiment to determine the memory colours of ten familiar, naturally occurring objects. Bartleson summarized the experiment thus: "Everyday objects or scenes such as human complexions or landscapes with which people have frequent visual experience are likely to produce memory colours that are common to many people. The object of the investigation was to determine the nature and consistency of those memory colours associated with ten familiar objects".

In the procedure Munsell patches were used as colour samples. A total of 931 patches were arranged on seven cardboard mounts. Fifty observers participated in the experiment. Their task was to indicate their memory colours for each of ten familiar objects. The experimenter named an object or a substance and the observer examined the display of Munsell colour samples and then indicated the patch which seemed to him to best represent the colour of the object. Ten object colours were used: "red brick", "green grass", "dry grass", "blue sky", "skin", "tanned skin", "broad leaf summer foliage", "evergreen trees", "inland soil", and "beach sand".

He concluded that the mean memory colours for the familiar objects were not of the same chromaticities as the means of the original object-colour stimuli. This can be seen in Figure 2.1.1 and Table 2.1.1. There was an evidence of increased saturation in the memory colours. In most cases there were hue shifts with memory in the direction of what was probably the most impressive chromatic attribute of the object in question.

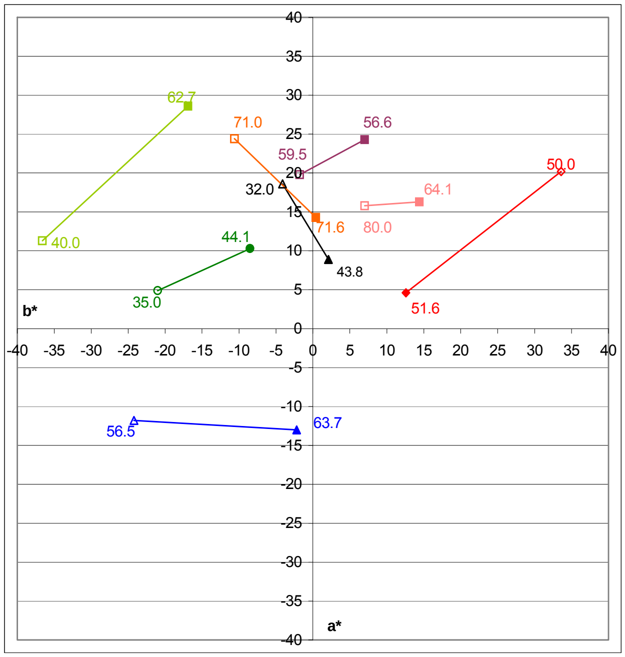

Figure 2.1.1 Shifts between the measured average natural colour (filled symbols) and the mean abstract memory colour (open symbols). Labels next to the symbols (with the same colour as the symbol) indicate corresponding CIELAB L^* values. Colours: light green: green grass; dark green: green foliage; orange: sand; pink: Caucasian skin; red: red brick; purple: tanned skin; black: soil; blue: sky; Figure originated from Bodrogi's dissertation[5].

Table 2.1.1 Comparison of the mean abstract memory colours (Bartleson[4], 1960), and the average measured colours of natural objects (Buck & Froehlich[14], 1948; Hendley & Hecht[15], 1949), transformed into CIELAB, under illuminant C.

Colour name	Mean abstract memory colour					Measured colour				
	L*	a*	b*	C_{ab}*	h	L*	a*	b*	C_{ab}*	h
Red brick	50	33.6	20.2	39.2	31.0	51.6	12.6	4.6	13.4	20.1
Green grass	40	-36.6	11.3	38.3	162.8	62.7	-16.9	28.6	33.2	120.6
Blue sky	56.5	-24.2	-11.8	26.9	206.0	63.7	-2.2	-13.0	13.2	260.4
Caucasian skin	80	7.0	15.8	17.3	66.1	64.1	14.4	16.3	21.7	48.5
Tan skin	59.5	-1.8	19.8	19.9	95.2	56.6	7.0	24.3	25.3	73.9
Green foliage	35	-21.0	4.9	21.6	166.9	44.1	-8.5	10.3	13.4	129.5
Inland soil	32	-4.1	18.6	19.0	102.4	43.8	2.1	8.9	9.1	76.7
Beach sand	71	-10.6	24.4	26.6	113.5	71.6	0.4	14.3	14.3	88.4

Abstract memory colours were compared with memory colours of colour patches in a 1961 paper of Bartleson[13]. The experimental setup was the following: four colour patches (originals) without any pictorial information, having average measured natural colours[14,15] of Caucasian skin, blue sky, beach sand, and green foliage, were used in a memory matching experiment. Each of the seven observers had to view each of the four colour patches with a neutral surround for 15 seconds. Then the colour patch was removed and the observer searched an array of 931 Munsell chips in order to find the one that they felt best matched the original colour patch.

Mean hues of the memory colours of patches were not significantly different from the originals but their chroma always increased. However, the hues as well as chroma and lightness for the abstract memory colours of Caucasian skin, blue sky, sand, and green foliage were found to be significantly different from those of the average measured natural colours found in the other experiments. These results can be seen on Figure 2.1.2.

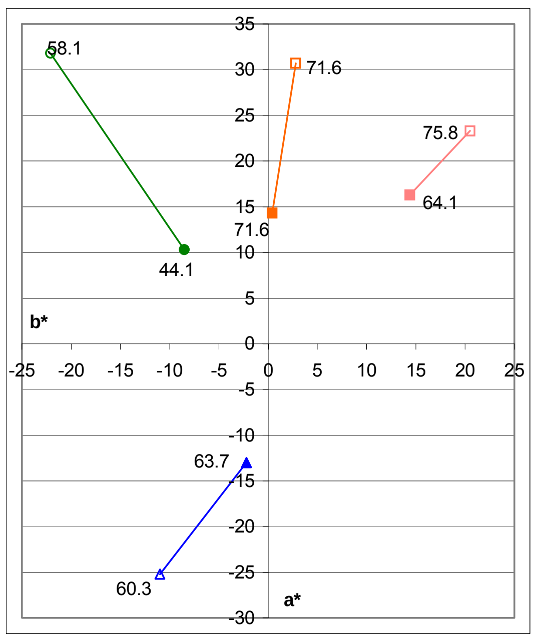

Figure 2.1.2 Shifts between the measured average natural colour (filled symbols) and the mean memory colour for uniform patches (open symbols). Labels next to the symbols (with the same colour as the symbol) indicate corresponding CIELAB L^* values. Colours: green: green grass; orange: sand; pink: Caucasian skin; blue: sky; Figure originated from Bodrogi's dissertation[5]

Table 2.1.2 Mean memory colours of uniform coloured patches found by Bartleson[13]

Colour name	Mean memory colours of uniform patches				
	L*	a*	b*	C_{ab}*	h
Blue sky	60.3	-11.0	-25.2	27.50	246.42
Caucasian skin	75.8	20.5	23.3	31.03	48.66
Green foliage	58.1	-22.1	31.8	38.73	124.80
Beach sand	71.6	2.8	30.7	30.83	84.79

Bartleson interpreted the shifts with the different frames of reference and adaptation level: "Only if these appearance differences are ignored may it be said that essentially the only difference in the two tasks is whether or not the observer's attitude is directed to a familiar object." My aim was to eliminate this disturbing effect in my experiments.

Nilsson and Nelson[8] measured short-term memory for 16 monochromatic stimuli from 425 to 640 nm, using six different delay period of ranging from 0.1 to 24.3 sec. They investigated the effect of the time on the hue shifts. The data were measured as the difference in wavelengths between the memorized stimulus and the stimulus that was adjusted by the observer to obtain a match. There was little difference in the hue matches of their observers, and no significant overall effect due to the length of delay interval. The sizes of the hue shifts were small. There was a consistent increase in the standard deviations when the delay was increased. The delayed matches indicated that in short-term colour memory, blues tended to become greener and reds became more yellow, whereas greens became more yellow for delays less than 1 sec but bluer at longer delays. The smallest shifts occurred for violets, for a 500-nm green-blue, and for yellow-oranges.

These smaller shifts may be due to the varying colour discriminability along the visible spectrum. Discriminability is known to be poor at both ends of the spectrum.

Siple and Springer[7] used 18 observers to investigate memory shifts of colours without context, with shape context, and with texture context. Stimuli were made from sets of photos of six fruits and vegetables (carrot, maize, lettuce, lime, orange, and peanut). Three experimental conditions were used: disk, silhouette, and texture. Colour selections were made by adjusting a colorimeter. First, observers were asked to select colours for the series of fruits and vegetables as they remembered the fruits and vegetables to be, typically, on the average. Observers could not preview the original colour. The task was somewhat similar to Bartleson's naming experiment[4]. In the second series, observers were asked to select the colours they would prefer for the fruits and vegetables to look like. Finally, each item was measured by a visual colorimeter. Original colours were subtracted from the memory or preference colours to get hue, lightness, and chroma shifts.

Change in context produced no change in the colour shifts. No significant hue shifts were found. Some items produced higher intra-subject variances (derived from three replications for each subject) than did others: memory hue for lettuce and preferred hue for peanut. The overall mean lightness shift did not differ from zero. Both memory chroma and preferred chroma were higher than the original. Items with midrange chroma values (carrot, maize, and lime) showed greater shifts than did those with high (orange) and low (lettuce and peanut) saturation. These data are in agreement with both Bartleson's and Newhall's findings[4,9].

In Uchikawa and Ikeda's experiment[16], successive and simultaneous brightness comparisons between test colours and comparison white were performed in order to study how accurately the brightness of coloured lights was maintained in memory. The result show, that the variability of successive brightness comparisons was 1.5-2 times greater than that of simultaneous brightness comparisons. This degree of deterioration of brightness discrimination is reasonably consistent with those of hue and saturation discrimination previously reported. The authors reported brightness shift into a darker region for most colours. The results were compared with Newhall's study[9].

Another study was done by Sachtler and Zaidi[17] to identify and analyse simple visual tasks in which chromatic information had a greater value to the observer than luminance information. The efficiency of chromatic and luminance signals was studied in a set of tasks requiring the discrimination of two colours. Two main issues were explored: 1. the effect of the addition of a memory requirement on discrimination tasks, in particular, differences in the capacities to remember chromatic and luminance components, and 2. the contribution of perceptual categories to discrimination when colours have to be compared by memory.

In experiment 1 they measured discrimination thresholds around a midwhite adapting light in a three-dimensional colour-space, employing tasks that permitted a side-by-side comparison of tests either in space or time. In experiment 2 discrimination was measured around a number of other points in the colour space, using the same tasks as in experiment 1, and thresholds were compared with those around the midwhite adapting colour. Discrimination was measured in experiment 3 around the same points with a task in which tests could not be compared on a side-by-side basis in space, or in time, so that memory was required to perform the comparison. Discrimination performances were then compared for the task requiring memory and the task from experiment 2 that had the same temporal component but that did not have a memory load. In experiment 4 tests were separated by a time delay to determine whether the results of the previous experiment could have been due to visual persistence. In experiment 5 observers were adapted to the judgement point around which discrimination was measured to control for the influence of adaptation processes. In experiment 6 they examined the effects of the categorization of test colours with respect to the surround colour.

When stimuli were separated in both space and time, so that memory was required for the comparison, the importance of luminance signals was attenuated further, while chromatic signals retained their importance. Further experiments showed that the addition of memory requirement did not impair the accuracy of luminance discrimination when the two test colours could be placed in distinct perceptual categories with respect to the surround colour. The results indicated that chromatic signals were particularly efficient in simple colour discrimination tasks requiring even the barest amount of memory especially when the perceptual categorization scheme was not available for the comparison of stimuli.

In a study of Heil et al.[18], Paivio's[19] dual code theory was tested in 5 experiments with a few paradigms for the FAN effect[3] that enforced genuine memory recall. Subjects

[3] The FAN effect is Anderson's explanation for the brain's ability to optimize memory retrieval by keeping better access to memories that are more likely to be relevant. This effect was proposed with Anderson's ACT (Advance Computer Tutoring) methodology for concept classification as a model for the human

had to learn associations between concepts and mediators. The FAN of the concepts in relation to the mediators was varied systematically. Response times were measured while subjects had to decide whether two concepts were linked to each other or not by a common mediator. In Experiment 1 the concepts and mediators were words, whereas in the other experiments the concepts were line drawings. Colours served as mediators in Experiment 2 and spatial locations served as mediators in Experiment 3, 4, and 5. All of the experiments were equivalent with respect to the FAN, the learning procedure, and the retrieval test. In all of the experiments, response time proved to be a linear function of the FAN. The results suggested that the same dynamics hold for all types of information stored in long-term memory.

Jin and Shevell[6] discussed the relationship between colour memory and colour constancy. They argued that because colour constancy is defined in terms of a change in illumination, it implies that the phenomenon occurs over some period of time. Therefore understanding shifts and accuracy of colour memory are fundamental to understanding colour constancy. They tested two hypotheses of colour memory: 1. the photoreceptor hypothesis, which states that the colour recalled from memory "reproduces" the light absorbed by each type of cone, and 2. the surface-reflectance hypothesis, which states that the colour recalled from memory is based on an inferred spectral reflectance of a surface that does not depend on the spectral distribution of the illuminant. They were interested in whether the illuminant under which one learned a surface colour altered the colour produced from memory or not.

Their experiments consisted of a training phase and a test phase. In the training phase, a central patch that had to be memorized was surrounded by either: 1. a complex pattern composed of several coloured patches; or 2. a uniform grey field at the chromaticity of the illuminant, or 3. in a control condition, the test colour was presented on a dark background. In the test phase (10 minutes after the training phase), the task of

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brain, and was based on the assumption that the brain uses a spreading activation of concepts in order to do classification. His conclusion is that the associativity of the brain is based on the probabilistic nature of the environment it is exposed to, and that the ability to classify is an extension of this; the FAN of the network is not the critical factor in classification. This is one of his arguments for the notion that to understand the workings of a cognitive architecture (namely, the human brain), one must look not within the architecture, but at the environment the architecture acts in. This is known as rational analysis.

the subject was to adjust the colour of the central patch so that it looked the same as the colour he/she saw during the training phase.

The results with the complex surround were consistent with the surface-reflectance hypothesis but not with the photoreceptor hypothesis. Colour memory with the grey surround on the other hand, showed a much stronger effect of the illuminant used during learning. The results were consistent with computational models of colour constancy.

Doing experiments with young children and older adults is an interesting task. As we know, young children's colour perception differs from that of adults' and there is a similar difference between younger and older adults.

Petzold and Sharpe[20] carried out an experiment to investigate hue discrimination and hue memory in young children and compared their results with those of older children and adults. As Darwin reported in 1877, children have a difficulty in colour naming. The authors designed an experiment where they eliminated the influence of verbal factors as far as possible, so that only visual processing was tested. They found that hue discrimination of young children (3-6 years old) did not significantly differ from that of preadolescents (9-11 years old) or young adults (22-30 years old). However their short-term hue memory showed significant differences.

Bodrogi in 1998, in his Ph.D thesis[5] reports two types of experiments, which were carried out on colour monitor. In the first experiment, observers had to memorize a uniform colour element (called original) in a photo-realistic image inside a black frame. The uniform area was part of an identifiable object of well-known typical colour. After a short period of re-adaptation observers had to identify the colour they memorized. They had to select from fifteen colours (including the original) the one corresponding to their short-term memory. In a second experiment the image context was removed by replacing the entire photo by a medium grey but the uniform area. The colour shifts of short-term colour memory with and without image context were analysed. They were explained by the cognitive effect hypothesis. The cognitive effect hypothesis is a more detailed and refined formulation of the so-called retention hypothesis and it explains the colour shifts and their inter-observer variability in each perceptual colour dimension separately and accounts for the effect of the image context. The retention hypothesis stated that colour memory was a selective resultant of the relative impressiveness of the various aspects of stimulation. Selection occurs during perception. More dominant, characteristic, and attractive aspects tend to be more impressive and more prone to survival in short-term memory. Newhall et al. explained their experimental results by the retention hypothesis. The cognitive effect hypothesis states that memory shifts between the instant memory colour and the later memory colour result from one or more of three types of so-called cognitive effects: exaggeration, focality, and typicality.

Results suggested that both colour shifts and colour memory accuracy was systematically influenced by the presence or absence of the visible image context. Colour memory accuracy was found to be inversely related to the mean colour shift. The hue, lightness, and chroma ranges of the original colours of Caucasian skin, without hue, lightness, and chroma shifts in short-term colour memory were determined. These ranges were called prototypical hue, lightness, and chroma ranges.

Pérez-Carpinell et al.[21] made a comparison of the methods of simultaneous, successive or memory colour matching for 10 colour reference samples distributed in two groups, each performed by 50 observers. A total of 200 Munsell colour chips were arrayed on ten grey cardboard panels. Examination were carried out in the following categories: differences between simultaneous and memory colour matching, worst remembered colours, best remembered colours, the influence of the delay time (15 s, 15 min, 24 h), differences of the remembered mean colour between men and women. The mean colour differences obtained by memory are generally higher than by simultaneous matching. The worst remembered colours are yellow, light green, blue, pink, and the best remembered colour is orange. The influence of the delay time is significant for the remembered mean colour. Significant differences were found between men and women for the remembered mean colour. They found these differences when the mean of the ten examined colours and the three delay times were taken into account for both groups, men and women observers. Considering the remembered colours individually, there were no significant effects in the colour test – observers' sex interaction, so there were no significant differences in the remembered colours between men and women either with the delay time or with the mean over different time, but the trend was that women remembered better than men. Women were more accurate at 15 s and 15 min delays than men and, generally, more accurate for chroma and hue. Variability of the mean values was always smaller in the women's group.

In a study of Pérez-Carpinell et al.[22] in 1998, memory colours for a set of eight different familiar objects had been investigated. The eight familiar objects were: purple aubergine, green watermelon, green lettuce, yellow lemon, orange, pink rose, brown chestnut, and red tomato. 100 students were participated in the experiment. The experiments were carried out under two different illuminants, D65 and A, and using eighty colour samples of NCS. Their main results were: 1. the shifts that were produced in the dominant wavelength with memory depended on the familiarity of the object considered; 2. colorimetric purity, as a measure of saturation, of the remembered objects was not the same as that of the familiar objects; 3. in the SVF[4] representation space with illuminant D65 and regardless of experience in colour matching of the observer, the colour best remembered was purple aubergine and the worst remembered was brown chestnut. With the illuminant A, red tomato was the best remembered colour and yellow lemon the worst.

Bodrogi et al.[23] carried out a colour memory experiment with choice figures on a colour CRT monitor. The experiment was divided into two series: one with photo-realistic images and one with geometric images. 20 colour normal observers took part in the experiments. At the series with the photo-realistic images, the observers' task was to memorize the colour of an element of the image, indicated by a black rectangular frame. After a short delay, the observers saw a "choice figure" with 15 colour patches, and had to choose from these colours the one corresponding best to their memory.

[4] Seim and Valberg (1986)[90] proposed a uniform color space based on physiological mechanisms and showed that color chips in Munsell and OSA color order systems are uniformly distributed in this space.

Table 2.1.3 Original colours used in the photo-realistic images and geometric images experiment by Bodrogi et al[23]

Colour name	Original colours				
	L*	a*	b*	C_{ab}*	h
Face	70.21	14.41	2.51	14.63	9.88
Landscape	52.16	-19.17	37.91	42.48	116.82
Sand	62.00	0.22	28.30	28.30	89.55
Skin	73.52	21.10	11.93	24.24	29.48
Wood	67.85	13.96	55.29	57.03	75.83
Face	82.95	4.59	19.48	20.01	76.74
Snow	54.05	2.60	-10.63	10.94	283.74
Sky	24.01	61.13	-66.46	90.30	312.61
Face	75.38	13.22	32.10	34.72	67.62
Grass	30.44	-16.89	16.82	23.84	135.12

They examined the effect of long-term memory colours. Memory colour effect and preference were mentioned. The process of the other series with the geometric images was the same, with the same memorizable colours, except that there was only one colour patch in the picture, without photo-realistic image. The authors found that long-term memory colour tend to shift the memorized original colour towards itself in memory.

The article by Yendrikhovskij et al.[3], presents a general framework for modelling memory colours, supporting this model for one particular object, a banana. They carried out three experiments building on each other. The aim of the first experiment was to analyse the memory representation of banana colour in the CIELUV colour space. Next, they prepared images, imitating different colours of banana, and asked subjects to scale the similarity of a banana, shown on a CRT display, and the typical ripe banana as they remembered from their past experience. They found that the relationship between the similarity judgments and chromaticity coordinates representing the manipulated banana samples could be well described by a bivariate normal distribution.

The methods of simultaneous and successive colour matching were studied by Pérez-Carpinell et al.[24] for a set of 7 colour reference samples by 15 protanomalous and 21 deuteranomalous trichromat subjects. They compared their results with a similar experiment, used previously by J. Pérez-Carpinell et al.[21] with a group of normal trichromat observers.

They found significant differences between simultaneous and successive colour matching for anomalous and normal ones. In general, mean values plus standard deviations on the three components of colour difference were always higher for successive colour matching than simultaneous colour matching, the contribution of CIELAB chroma difference to the mean total colour difference were the highest for all populations and reference tests. In some reference tests correlations were found between the behaviour in some colour components by memory and the type of anomaly of the observer. For all populations, mean colour differences obtained by simultaneous matching were always lower than those obtained by memory. At simultaneous matching they found that for considering the mean of all the colours, normal subjects discriminate colour better than protanomalous ones. They did not found differences between protanomalous and deuteranomalous observers. With successive colour matching, the mean difference colour for the three populations depended significantly on the remembered colour if the mean of all the delayed times were taken into account. Normal trichromat observers didn't remember yellow as well as dark orange, dark blue, and violet, in the anomalous population this happened only between yellow and dark orange.

De Fez et al.[26] compared corresponding pairs obtained by simultaneous matching and by memory matching using 34 reference tests selected from the Munsell Atlas. They compared the colour samples under illuminants D65 and A. The four main hues of the samples were: 5Y, 5G, 5PB and 5RP. They found that for both kinds of matching a tendency to select more colourful colours than the original ones existed, with significant differences between matching and test colours, whereas hue did not seem to follow a definite pattern. The best matching colours lied on the red-green axis and the worst matching colours along the blue-yellow axis.

In 2002, Selinger[27] examined monochromatic wavelength of light as the only visual variable in short term delayed matching and in long-term recall protocols to quantify three types of colour memory in individuals with normal colour vision. The three types of colour memory matching protocols were the following: 1. delayed matching, in which individuals adjusted the wavelength setting of a monochromator to match their recent memories of a colour sensation produced by the same monochromator previously. Delayed matching measurements were made for different viewing times of test wavelength and for different delay times between viewing and matching; 2. alternately viewed delayed matching, in which the conditions of bipartite wavelength matching were approximated by two side-by-side test and viewing geometries; 3. long term recall, in which individuals adjusted monochromator wavelengths to match their long-term memories of colours of familiar objects. The colour memories of individuals were compared in terms of means and standard deviations. The variance of long term recall of colours of familiar objects was shown to be separable into two portions. The wavelength dependence of delayed matching exhibited minima of standard deviations at the same wavelength as those reported for colour discrimination measured by bipartite wavelength matching, and these wavelengths were shown to occur at the wavelength of the intersections of cone spectral sensitivities.

Amano et al.'s aim[28] was to examine the nature of the colour memory for complex coloured images. A memory-identification task was performed with differing colour contrast. Three of the contrasts were defined by chromatic and luminance components of the image and the others were defined with respect to the categorical colours. After observing a series pictures successively, subjects identified the pictures using a confidence rating. Detection of increased contrast tended to be harder than detection of decreased contrast, suggesting that chromaticness of the pictures was enhanced in memory. Detecting changes within each colour category was more difficult than across categories. A multiple mechanism that processes colour differences and categorical colours was briefly considered. "Visual memory for coloured scenes involves multiple mechanisms based on categorical colour perception and colour differencing."

A paper by Pérez-Carpinell et al.[30] is a follow up of an earlier publication[24] in which they examined the same observers using the same method except that the more recent article focuses on the matching time of the observers in successive and simultaneous colour matching. 21 deuteranomalous and 15 protanomalous and 25 normal trichromat observers participated in the experiment. At the memory matching experiment they used a 15 s, a 24 hours and a 1 week delay time. They found significant differences in matching times among observer types. The matching time was found to depend significantly on the test colours both for simultaneous and memory matching. In simultaneous matching normal trichromats were faster and deuteranomals were slower. In memory colour matching deuteranomals were slower and normal protanomals were equally fast. The ratio of matching time for both modes of presentation was significant between deuteranomals and normals for dark orange, light green, and pink.

Colour memory has been described as successive colour matching, a category of matching in which time elapses between presentation of a colour stimulus and the attempt to select a matching colour by Epps and Kaya[31]. In their study 40 university students, all having normal colour vision participated in a colour memory experiment. The participants were divided into two groups: 20 with prior coursework on colour, and 20 with no colour-related training. Short-term colour memory of the participants was evaluated in four hue categories: yellow, yellow-red, green, and purple. Munsell dimensions of hue, value, and chroma were used to select the four target colours and nine distractor colours for each of the targets. For each target colour, four of the distractor colours differed from the target in hue only, four were of the same hue as the target, but differed in both value and chroma, and one was identical to the target in both hue and value, but differed in chroma.

In each test, the subject was presented the target colour chip for 5 seconds, with the intent of remembering it. After an additional period of 5 seconds, the subject was given a stack of ten randomly arranged colour chips, including the target and the nine distractors, and asked to choose the target colour. On completion of the four colour tests, subjects were asked to explain what cues, if any, they used in recalling the targets. Of the four target colours, yellow was the most accurately remembered, and green was the least accurately remembered colour.

These results appear to contradict some earlier data[21]. In that experiment yellow was found to be one of the worst remembered colours, light green was also one of the worst remembered colours.

Let me close this section with an interesting article[32] about cognitive colour, and some important themes in connection with it and if someone is interested in this theme, this article is worthy of reading. Derefeld and her colleagues' report surveys the cognitive aspects of colour in terms of behavioural, neuropsychological, and neurophysiological data. Colour is usually defined as a colour stimulus or as a perceived colour. In the article, a definition of the concept of cognitive colour is formulated. To elucidate this concept, those visual tasks are described where it is relevant: in colour categorization, colour coding, colour naming, the Stroop effect, spatial organization of coloured visual objects, visual search and colour memory.

The report describes and illustrates some phenomena that the CIE definitions of psychophysical and perceived colour do not cover, although it gives notes on some of them. These phenomena could be referred to as "cognitive colour".

2.2 Colour discrimination

The basis of colour matching is colour discrimination. The first level of matching is the discrimination. The colour matching ellipses created by MacAdam[33] are the footstone of many studies written in the theme of colour discrimination. Some ellipses for the memory colours modelled after the MacAdam ellipses were formed in this thesis. In this subsection I will discuss some colour discrimination articles in chronological order.

Rich and Billmeyer[34] in 1975 developed a method for determining the parameters of colour-difference-perceptibility ellipses for surface colours and evaluated it by using new visual data. Four sets of samples that exhibit chromaticity differences from four reference samples, at essentially equal luminance, were prepared from hand coatings of gloss lacquers. The samples were viewed by fifteen observers, whose task was to sort the samples into two piles, those that matched the reference colour and those that did not.

This new method permitted the determination of colour-difference perceptibility ellipses obtained from visual data collected using surface-colour-difference experiments. A new theory was devised, based on the assumption of a normal distribution of colour differences in local areas of CIE 1931 chromaticity space.

An algorithm to define discrimination ellipsoids for surface colours in (x, y, l) space was described in a study by Indow et al.[35], where l was a function of Y. The data were a set of P_i, the proportion that a comparison stimulus s_i was judged discriminable from a standard (original) stimulus s_o (the method of constant stimuli). An ellipsoid was defined around s_o such that, if the distance between s_o and s_i was evaluated by the radius of the ellipsoid in that direction, then that distance was related to P_i in the form of a sigmoid curve (the cumulative normal distribution). The third axis of the ellipsoid was defined to be parallel with the Y axis and hence there were four free parameters – the three radii of the main axes of the ellipsoid, and the angle between axis x and the third main axis of the ellipsoid. These parameters were estimated by using the principles of either chi-square minimum or maximum likelihood estimation. The algorithm was applied to the data obtained from R. M. Rich[36], D. C. Rich[37], and Witt and Döring[38].

Results by the present method were compared with their results, which were obtained using different procedures. The method was also applied to the data of Bartleson[39] to test the possibility that the domain of colours called “brown” was ellipsoidal in form; the result was negative. A theoretical discussion on the nature of the sigmoid curve was included.

The article by Romero et al.[40] is about a colour discrimination experiment which was compared with previous experiments. The authors obtained the colour-differential thresholds for twenty stimuli and three observers within two colour-representation spaces: in the CIE-1931 colour space and compared them with the results by MacAdam[41], Brown and MacAdam[42], Brown[43] and Wyszecki and Fiedler[44] and in the cone-excitation space. The representation of the data in the cone-excitation space showed that all the discrimination ellipses were nearly oriented along the S-cone-variation axis. The characteristics of luminance discrimination were independent of the chromaticity of the stimuli.

In the study by Melgosa et al.[45] departures from exact ellipticity, when colour-discrimination ellipsoids or ellipses were translated to CIELAB had been numerically analysed. The distortions for ellipsoids were of the same order as those of the ellipses at the five CIE centres. These small distortions were well covered by the inter-observer variability and could be ignored in most cases, but an appropriate method had to be used for the translation of colour-threshold results to CIELAB. Experimental results published by Lou and Rigg[46] for 132 chromaticity discrimination ellipses were expressed in CIELAB.

2.3 Colour categorization

Common experience suggests that when colour must be remembered, categorization is required. One may remember the name of a colour category rather than retaining an image of the perceived colour itself. So colour categorization is very closely related to colour memory.

Most studies of colour categorization refer to the work of Berlin and Kay[47] in 1969 as one of the first attempts to deal with the subject. Regarding colour categorization as such, I would like to refer to the work of Uchikawa and Shinoda[55] who, in my opinion, characterize colour categorization well:"…colour memory is characterized by the colour categories, suggesting a colour category mechanism in a higher level of colour vision."

A description of Berlin and Kay[47]'s study can be found in an article of Hardin[48]. Berlin and Kay were struck by how easily common colour terms could be translated between languages from places as diverse as Tahiti and Mesoamerica. But if cultural relativists suggest that languages divide colour space arbitrarily, and moreover, shape the way that their speakers perceive coloured objects, how is this possible? To investigate the question, Berlin and Kay proposed criteria to separate the basic from the non-basic colour terms of a language. Basic terms are those that are general and salient. A term is general if it applies to diverse classes of objects and its meaning is not subsumable under the meaning of another term. A term is salient if it is readily elicitable, occurs in the idiolects of most informants, and is used consistently by individuals and with a high degree of consensus among individuals. To determine the references of the basic colour terms of a language, Berlin and Kay used a rectangular array of Munsell colour chips of maximum available chroma, vertically ordered in ten equal lightness steps, and horizontally ordered by hue, each column differing from its neighbours by nominal 2.5 Hue steps. Each informant was asked, for each basic colour term, to mark (a) the best example, or the focus of the colour, and (b) the reason of chips that could be called by the colour term. Native speaking informants were used in the San Francisco Bay Area for 20 languages, supplementing this limited field study with a literature search on 78 additional languages. Berlin and Kay found that languages vary in numbers of basic colour terms, from the minimum of two terms (Papuan Dani) to a (probable) maximum of eleven (black, white, grey, red, green, yellow, blue, purple, orange, pink, brown), Russian and Hungarian being possible exceptions. The foci of basic colour terms tend to cluster reliably in relatively narrow regions of the array, whereas boundaries are drawn unreliably, with low consistency and consensus for any language.

The diachronic conclusion was that if languages were ordered according to numbers of basic colour terms, the sequences of encodings of basic colour terms were tightly constrained (the conception of successive steps as encodings was subsequently changed by Berlin and Kay). For example, if a language has two basic colour terms (a "Stage I" language) those terms will encode black and white. If it has three ("Stage II"), those terms will encode black, white, and red. If it has four ("Stage III"), the terms will be for black, white, red, and either yellow or green. The entire sequence comprises seven stages and eleven basic colour terms. Berlin and Kay interpreted these as stages in an evolutionary sequence, and it is this interpretation that has occasioned the greatest controversy. The nature of the stages and the rules that govern their development are the points of the Berlin-Kay theses that have been most revised by their authors.

In a paper by Ostergaard and Davidoff[49] two experiments are described that extend the findings on the role of colour in object positioning. Two types of categorical judgments were investigated from pictorial stimuli: size judgment and living/non-living classification. It was found that colour did not affect either of the categorical judgment, but the facilitation occurring in object naming tasks was confirmed. It was argued that semantic judgments could precede name retrieval that physical colour input did not enter the semantic system, and that representation of object colour information in the semantic system could be largely verbal. The categorization responses were significantly faster than naming responses. That leaves open the possibility that there is a direct link between the representation of colour and the visual representation of shape information, but that this link is relatively slow thus colour only affects the slow naming responses and not the more rapid characterization decisions. The range of both naming and categorization latencies for the different items was relatively large, and there was considerable overlap between naming and categorization latencies. The findings of Ostergaard and Davidoff were that the colour of an object had no affect when the observers had to decide whether or not the presented item was a previously specified target. There was no attention on deeper examination of colours.

In a study by Boynton et al.[50] the so called “categorical colour preference index” (CCDI) that can be computed for any pair of colours in the OSA set of 424 samples was generated from data of earlier experiments[51,52,53,54,] where categorical colour perception was tested by using a naming method. A new experiment was performed in which categorical colour perception was encouraged without the explicit use of names by allowing 10 seconds to elapse between the presentation of two stimuli before they were judged to be the same or different. All of the colours being compared were either identical or nearest neighbours in the orange region of the OSA space. Nearest neighbours which were separated by two OSA units, clearly differed when presented simultaneously. However in delayed presentation errors (“same” responses) sometimes occurred. These errors decreased as CCDI increases, suggesting that categorization occurred when colours must have been remembered. Response time was independent of CCDI and therefore may have reflected colour differences upon discrimination, rather than identification.

Two colour memory experiments were performed by Uchikawa and Shinoda[55] to investigate whether observers tended to confuse colours with a smaller colour difference in memory or colours in a same colour category region. Their aim was to examine if colours are confused in memory on the basis of colour difference or on the basis of categorical difference. The authors presented colour stimuli on a colour CRT monitor. Colour difference was determined by a simultaneous colour discrimination experiment. Colour category regions were obtained by a categorical colour naming experiment using the 11 basic colour names: white, black, red, green, yellow, blue, brown, orange, purple, pink and grey. The results showed that colours with a certain colour difference could be confused more easily when they were in the same colour category then in different colour categories, and that colours identified with memory tended to distribute within their own colour category regions or their neighbour colour category regions, depending on their positions in colour space. These findings indicated that colour memory is characterized by the colour categories, suggesting a colour category mechanism in a higher level of colour vision.

The study by Sturges and Whitfield[56] provided a replication of Boynton and Olson's[57] work but used a more extensive model of colour space – Munsell as distinct from OSA-UCS. The paper focused upon the relative salience of the so-called "landmark colours" and "other basic colours" for the Munsell space, and the relevance of non-basic descriptors of colours and their identities. 20 subjects' observations of 446 colours were involved, in which monolexemic naming and response times were recorded. The observers' task was to name each Munsell colour sample using any monolexemic colour term. The 11 basic terms were used more quickly, with greater consistency within subjects and with greater consensus between subjects. The results clearly differentiated between basic and non-basic colour categories using measures of consistency, consensus and response time. In conclusion, the results of this study support the primacy of eleven basic colour categories and, in so doing, support the model proposed by Berlin and Kay[47].

Guest and Laar[58] described an experiment that replicated recent name mapping work, and delved further into the detailed structure of colour naming space. Observers freely named 1044 CRT-displayed colour-background combinations, sampled regularly along the *u*' *v*' axes of the 1976 UCS, and along the luminance axis. Three response measures – response times, confidence ratings and consistencies – were obtained. The structure of colour naming space and the use of different colour name types were investigated. Data confirmed the uniqueness of basic colour terms as compared with the non-basic terms, agreeing with previous constrained naming studies. Colour naming space was found to exhibit regular structure, which appears to be linked to fundamental response categories, and to previous observations[59,60] that colour naming space may be divided into five major regions. In addition to the "traditional" four (red, green, blue, yellow) the fifth region was violet.

Colour naming by panels of British and Taiwanese subjects (speaking English and Mandarin, respectively) was used to study colour categorization by Lin et al.[61], and the results applied to investigate differences of usage between the two languages. 50 British and 40 Chinese subjects took part in the experiment using an unconstrained method with 200 ISCC-NBS colour samples. Data analysis was performed to calculate the frequency and codability of a colour name in each group and subgroup. These names were then grouped using 7-category and 4-category methods to find the culture and gender differences. It was confirmed that the 11 basic names found by Berlin and Kay[47] were the most widely used for both languages. The results showed a close agreement between the two languages in terms of colour categories, but a large discrepancy in the use of secondary names due to cultural differences. The cross-cultural comparison revealed a clear pattern of the linkage between language and concepts of colour.

In the second article[62] of the study consisting of three parts, Lin et al. investigated the differences of colour naming between English (British) and Mandarin (Taiwanese) languages. A constrained method was employed, with 20 British and 20 Chinese adults. All the experiments were conducted under artificial daylight, using 1526 colours from the Natural Color System (NCS). Each subject was asked to find the colour(s) corresponding to basic names, modifiers, and secondary names in terms of one colour (focal colour) or a colour region (colour volume). Little difference in chromaticness and hue was found between the two languages, but a systematic discrepancy was found in blackness. Because it could have been caused by different surrounds, i.e., grey and white walls used for the British and Chinese experiments, respectively, a verification experiment was carried out using a panel of ten Taiwanese subjects against a grey surround. The results proved that the lightness difference found earlier was indeed caused by the surround.

A colour- naming model was developed to categorize volumes for each of the 11 basic names in CIELAB colour space in the third series of studies of Lin et al.[63]. This was tested with three different sets of data for two languages (English and Mandarin), derived from extensive colour categorization experiments. The performance of the model in predicting colour names was satisfactory, with an average prediction error of 8.3%.

Part I[61] of this study gathered a large number of colour names from subjects speaking the English and Mandarin languages, and analysed them to determine the culture and gender differences. It was confirmed that the 11 basic colour names found by Berlin and Kay were the most widely used ones for both languages. Codability analysis was applied to determine their relative consistency of usage. In Part II[62] of the study, colours were mapped to coordinates in the NCS colour space, and the centroid and spread of the volume occupied by each colour were determined from the analysis of observed data.

In Part III, a colour-naming model was developed based on the data gathered in Experiments I and II. Its validity was demonstrated with a third independent dataset, but it must be emphasized that it was based on data derived from British and Chinese observers viewing surface colours under specified viewing environments and that observers had different cultural or linguistic backgrounds. They should, therefore, be treated with caution. Many languages name colour categories - including primary basic colour categories, such as red – more broadly than does Mandarin.

The objective of the colour-naming model described above is to name a colour unambiguously whenever a colour specification is given in CIELAB values. The categorization of basic colours in CIELAB colour space was carried out using an optimising method. Boundaries for each of the 11 basic names were determined to minimize prediction errors from the experimental data. Finally, all 11 colour volumes were further refined to leave no gap in CIELAB space.

A colour-naming model was derived to categorize all colour coordinates in CIELAB colour space into 11 basic colour names. The model gave good predictions of results for the group of British subjects, and reasonable predictions of results for the Chinese subjects. The model was derived from colour names collected in two sets of experiments, which were conducted under a wide range of viewing conditions. Although observers and experimental techniques in Experiments I and II were largely different the results from the two sets of data were highly consistent.

The accepted model of colour naming postulates that 11 "basic" colour terms representing 11 common perceptual experiences show increased processing salience due to a theorized linkage between perception, visual neurophysiology and cognition. Jameson and Alvaro[64] tested this theory, originally proposed by Berlin and Kay[47] in

1969. Experiment 1 tested salience by comparing unconstrained colour naming across two languages, English and Vietnamese. Results were compared with previous research by Berlin and Kay[47], Boynton and Olson[50,56], and colleagues. Experiment 2 validated their stimuli comparing OSA, Munsell and newly rendered "basic" exemplars using colorimetry and behavioural measures. The results showed that the relationship between the visual and verbal domains was more complex than current theory acknowledges. An inter-point distance model of colour naming behaviour was proposed as an alternative perspective on colour naming universality and colour category structure.

Monroney and Tastl in their study[65] wrote about a web-based colour naming experiment that collected a small number of unconstrained colour names from a large number of observers. This resulted in a large database of colour names for a coarse sampling of RGB values. The paper built on a previous paper[66] that demonstrated the close agreement for the technique used in the paper to earlier results for the basic colours, and presented several applications of this database of colour names: first, the basic hue names could be further subdivided based on a number of modifiers. Pairs of modifiers were compared based on actual language usage patterns, rather than on a fixed hierarchical scheme; second, given a sufficient sampling of colour names using memory colour modifiers, such as sky or grass, comparisons could be made to other studies on memory colours and preference for colour reproduction. Finally, a dissimilarity coefficient could be computed for a set of 27 colour names. Multidimensional scaling could be applied to the matrix leading to a spatial configuration, which was solely based on patterns of colour naming.

2.4 Preferred colours

Colour preference is a subjective concept. Everyone has a preferred colour. It may be red, blue, green, white etc. But, for example, take the colour of the skin. There are some pictures about one person with different skin tones, for example pinkish skin, yellowish skin, or a tanned skin. Everyone can say which one is preferable for him or her. This kind of preference relies on the remembrance. It relies on the colour or colours in one's mind about the skin colour and it leads to the long term memory colour of the skin itself. In this section I collected some studies on the theme of colour preference without the demand of completeness. The most interesting one in my point of view is the one by Bartleson and Bray[12], in which the preferred colours for Caucasian skin, blue sky, and green grass were investigated.

Bartleson in 1959 remarked at the beginning of his paper[11] on the reproduction of skin colours: "In theoretical discussions of the quality of photographic colour reproduction, it is frequently assumed that the objective of the photographic process is to reproduce exactly the chromaticities of the original objects ... It has often been recognized that chromatic fidelity may not be necessary or even desirable..." Thus his aim was to study what skin colours observers prefer in pictorial reproductions.

Twelve prints of the same subject (a photo of a woman's face) were produced in which the chromaticities of the complexion areas were systematically varied. Ten observers performed paired comparisons: they were asked to indicate which print of each pair they preferred. Preferred skin colours were compared with abstract (named) memory colours of Newhall et al.[9], with the abstract memory colours of Bartleson[4] (published one year later), and with Buck & Froelich's[14] measurements of average natural skin. Some evidence was found: preferred skin colours were of the same hue and saturation as the abstract (named) memory colour for skin, and, that preference contained more yellow than average measured skin colour.

In another paper by Bartleson and Bray[12], the preferred colours for Caucasian skin, blue sky, and green grass were investigated. The first experiment dealt with

Caucasian skin; the aim was to verify the results of Bartleson[11]. 11 observers saw 19 pictures with changes of the colours of only their skin areas, 20 observers saw two series of 14 and 9 prints with varied chromaticities of the blue sky areas, and 20 observers saw all together 30 prints with varied green grass areas. These coloured prints were ranked by preference.

The chromaticity of the mean abstract memory colour for skin turned out to be located near the most preferred skin colour but at some distance from average measured natural skin colour. However, this tendency was not true for the pictures containing blue sky or green grass colours in the second and third experiments. For these kinds of objects, the most preferred colour agreed rather with natural measured colours but not with the abstract memory colours. The following conclusion was drawn: "...it appears that one cannot assume simply that (abstract) memory colours represent a desirable reproduction aim for all object colours. It seems clear that the aim is not simply to attempt to reproduce the original chromaticities nor, except for skin at least, to attempt to match the memory colours."

160 American, Lebanese, Iranian, and Kuwaiti university students with equal number of males and females in each group, expressed their preferences for 8 Ostwald hues (Red, Orange, Yellow, Yellow-green, Green, Blue-green, Blue, Purple) in a study by Choungourian[67]. Each of these eight colours was paired with the other seven colours, so that there were 28 pairs for comparison. Results: only green had a consistently high preference over the rest of the colours in the four countries, while yellow and purple had low preference values for almost all the countries. Definite cultural and some sex differences were also found.

The results of three surveys were presented by Saito[68]. The first survey was carried out in four large cities in Japan, and the findings were analysed by factor analysis and cluster analysis. The second survey was carried out in Seoul, Korea and Tokyo, Japan to determine colour preference for the two countries, focusing on the preference for white. The last survey compared colour preference in Taipei and Tokyo, also with emphasis on the preference for white. In the successive studies on the colour preference in Japan and other Asian cities, the subjects were mainly asked to choose from a colour chart the three colours they liked most, and the three they liked least, and to state the reasons for their choices. The results of Survey 1 showed that colour preference could be influenced by differences in age, sex and geographical region. Also factor analysis and cluster analysis indicated some relation between colour preference and the subject’s life styles. Dual scaling analysis of the results of Survey 2 and 3 indicated that each Asian area has unique colour preference tendencies and that there are statistically significant differences in the frequency of selection of colours of certain hues and tones. However, high preference for white was common to all areas, along with preferences for some other colours. These results thus demonstrated a common strong preference for white in three neighbouring Asian areas.

2.5 Naturalness

Naturalness is an important aspect if we look at a colour picture. If we do not think that the colour of an object on the picture is natural, or the colour does not befit to the object, we will not like the picture. Although this is very important in everyday life and as an example commercials can be mentioned. A colour of an object is natural to us if the colour resembles to the colour we keep in our remembrances from the object. So, the naturalness is a cognitive concept and it is in deep connection with prototypical colour or long term memory colour. This statement can also be found in the article by Yendrikhovskij and Blommaert[70] in a form of a diagram.

In the study by Ridder et al.[69], the relation between perceptual image quality and naturalness was investigated by varying the colourfulness and hue of colour images of natural scenes. The main conclusions were: the perceptual quality of appreciation-oriented images was strongly related to naturalness; quality and naturalness deteriorated as soon as hues started to deviate from the ones in the original image; chroma variation affected image quality and naturalness to a lesser extent then did hue variation; subjects tended to prefer more colourful images although they realized that the images look somewhat unnatural; Only image manipulations producing natural transformations of the sensorial image should be considered as a means for improving image quality.

Yendrikhovskij and Blommaert[70] published an article about the naturalness constraint. The following diagram about the process of naturalness judgement shows the important role of prototypical colour in the process.

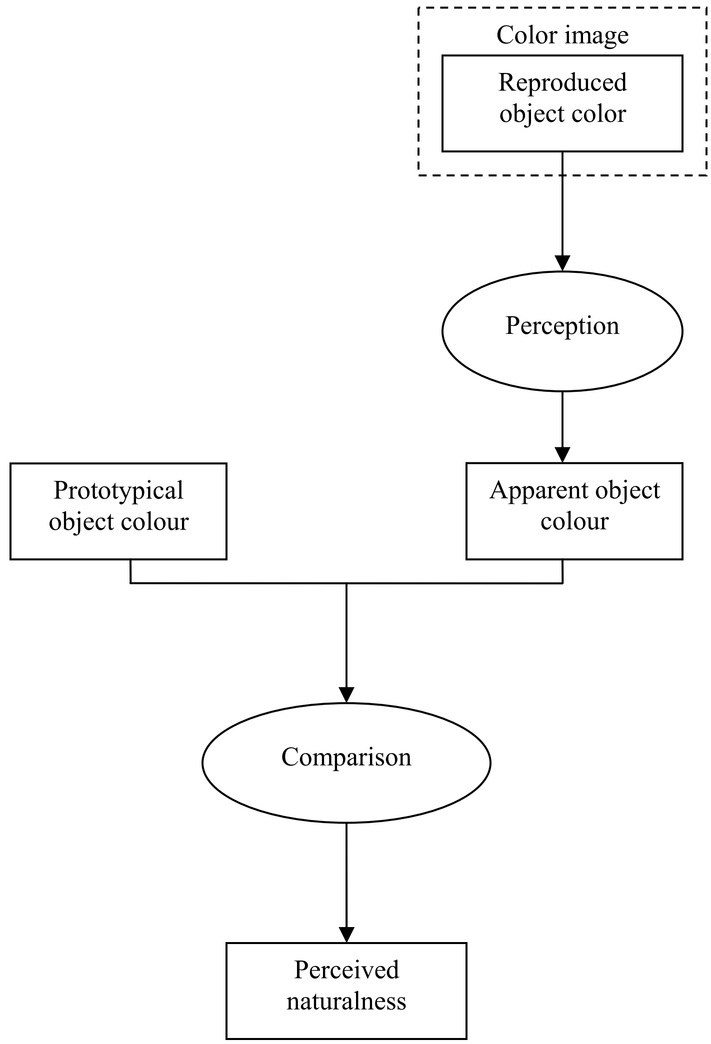


Figure 2.5.1 Process of naturalness judgement

In the first experimental set-up the authors made some changes on digital pictures containing skin. The subjects had to judge the naturalness of the skin colour. In the second experiment, the first group of observers (others than in the first one) had to estimate the similarity in skin colour samples displayed on a monitor screen and typical Caucasian skin colours stored in their memory. The second group of observers estimated the naturalness of the same images. Result of the second experiment: the naturalness judgments of the skin colour strongly correlated with the similarity judgments of the apparent and prototypical skin colours. In the third experiment they manipulated the whole image not just the skin colour of the image. The result of the third experiment was the following: the subjects were more tolerant of the global image processing, probably due to the colour constancy effect. In the fourth experiment the authors examined the naturalness of grass, sky and shirt reproductions with the same image changing method. The subjects found that the naturalness judgment of the shirt colour was a very difficult task. The naturalness judgments of sky and grass were consistent among observers. The hue angles, found for the prototypical skin, grass and sky colours were similar to the ones found by Hunt et al (1974)[71]. In the fifth experiment Yendrikhovskij and Blommaert examined to what degree the naturalness of reproduced object colours determined the naturalness of a whole picture. They manipulated shirt and skin types of colours on a picture. The subjects judged the whole reproduction. The naturalness judgment of the skin and the naturalness judgment of the whole picture were highly correlated. The naturalness of the whole reproduction might have been primarily determined by the naturalness of the most critical object in the reproduction. The main conclusion was the following: the perceived naturalness of colour reproduction was mainly determined by the similarity of apparent and prototypical object colours.

2.6 Semantic ratings

People can connect senses to colours. They can decide whether a colour is warm or cold, feminine or masculine; and whether they like it or not. These feelings are in connection with their former experiences about the colour itself, or about occurrence or the object, that attaches to it in their mind. So the semantic ratings of a colour also rely on the cognitive concept, the prototypical colour.

In a study on semantic ratings of colours by Taft[72], subjects evaluated with 7-step ratings on five semantic scales a set of 13 colour chips and 5 sets of objects, each appearing in the same 13 colours. The five semantic scales were: 1. beautiful-ugly, 2. elegant-vulgar, 3. loud-discreet, 4. masculine-feminine, 5. warm-cold. Taft's analysis indicated that generally few significant differences existed between chip and object ratings for the same colour; when such differences existed, the chip was always rated more beautiful, elegant, discreet, feminine, and warm than the object; and differences between chip and object ratings (i.e. the context effect) were confined to a limited number of colours. Ratings of yellow, red, and purple were most dependent on context, whereas ratings of grey, brown, and beige were least affected by context. In these experiments, a colour chip or an object represented the absence or the presence of the context, which is also an important detail in my study.

The key idea of Hard and Sivik's[73] study was the Color Combination Theory. The number of colours is very large and they rarely appear alone; the number of colour combinations is almost infinite. It is difficult to investigate how people perceive and evaluate colour constellations in various contexts. To bring order into the large number of possible colour combinations, Hard and Sivik made a structure for it. It is based on the Natural Color System for the ordering of singular colours, which is in turn the practical extension of Hering's phenomenologically based Opponent Color Theory. The model is descriptive; the variables carry immediate meaning regarding the actual colour appearance. Since the model is purely descriptive, it contains no information per se of whether colours are beautiful together or not. However, the model can be used as a reference structure to investigate the attributes and connotations of the experience of a given colour combination. The model did not deal with the influence of various lighting and viewing conditions on the perception of different objects with specific inherent colours. The Color Combination Theory should have been seen as a mental model for the formal description of the perceptual colour attributes that characterize a Colour Gestalt. The study was based on the NCS system for the ordering of singular colours. The most relevant attributes or dimensions of colour combinations were categorized in three main groups, each with subfactors: The Color Interval, with the subvariables Distinctness of Border, Interval Kind, and Interval Size, was the perceptual phenomenon that occurred with the transition from one colour percept to another. The Color Chord with subvariables Complexity, Chord Category, Chord Type, expressed the character of the combination, how the colour "sounds" together, i.e., the totality of the Color Gestalt. The Color Tuning, with subvariables Surface Relations, Color Relations, and Order Rhythm, referred to some of the different ways colour combinations could be varied. The presented colour model could be seen as a theoretical, albeit empirically based, starting point for further studies of people's perception of colour constellations, a scientific area that still, probably because of its complexity, seems to be uncharted territory.

The next three articles were written by Ou et al. They are in close connection with each other and besides that not all of them are written in the theme of semantic ratings I found that they have to be discussed after each other.

In the studies of Ou et al.[74,75,76], the overall goal was to clarify the relationship between colour emotion and colour preference. To determine this, a number of colour emotions were classified by the method of factor analysis. The results were used to derive preference models on the basis of colour-appearance attributes, such as hue, lightness, and chroma. The first part of this series of studies focused on colour emotions for single colours, as noted in their article. Studies on colour-combination emotions and colour-preference were presented in Part II[75] and III[76], respectively.

The first article[74] classified colour emotions for single colours and developed colour-science-based colour emotion models. In a psychophysical experiment, 31 observers, including 14 British and 17 Chinese subjects assessed 20 colours on 10 colour-emotion scales: warm-cool, heavy-light, modern-classical, clean-dirty, active-passive, hard-soft, tense-relaxed, fresh-stale, masculine-feminine, and like-dislike. Experimental results showed no significant difference between male and female data, whereas different results were found between British and Chinese observers for the tense-relaxed and like-dislike scales. The factor analysis identified three colour-emotion factors: colour activity, colour weight, and colour heat. The three factors agreed well with those found by Kobayashi[77] and Sato et al.[78]. Four colour emotion models were developed, including warm-cool, heavy-light, active-passive, and hard-soft. These models were compared with those developed by Sato et al.[78] and Xin and Cheng[79]. The results showed that for each colour emotion the models of the three studies agreed with each other, suggesting that the four colour emotions were culture independent across countries.

In the second part[75] of the previous study[74], it was aimed to find a simple method of modelling colour emotions for colour combinations. A psychophysical experiment was carried out to collect colour emotion data. Comparisons of colour emotions were made between genders and between cultures. Interrelationships between colour-combination emotions were clarified. Colour emotion models for colour combinations were developed on the basis of an additivity relationship in colour-emotions between single colours and colour combinations.

Eleven colour-emotion scales, warm-cool, heavy-light, modern-classical, clean-dirty, active-passive, hard-soft, harmonious-disharmonious, tense-relaxed, fresh-stale, masculine-feminine, and like-dislike, were investigated on 190 colour pairs with British and Chinese observers. Results showed that gender difference existed in genders, whereas no cultural difference was found between British and Chinese observers. Three colour-emotion factors were identified by the method of factor analysis and were labelled "colour activity", "colour weight", and "colour heat". These factors were similar to those extracted form the single colour emotions developed in Part I[74]. This indicated a coherent framework of colour emotion factors for single colours and two-colour combinations. An additivity relationship was found between single-colour and colour-combination emotions. This relationship predicted colour emotions for a colour pair by averaging the colour emotions of individual colours that generated the pair. However, it could not be applied to colour preference prediction. By combining the additivity relationship with a single-colour emotion model such as those developed in Part I[74], a colour-appearance based model was established for colour combination emotions. With this model one can predict colour emotions for a colour pair if colour-appearance attributes of the component colours in that pair are known.

In the third study by Ou et al.[76], three colour preference models for single colours were developed. The first model was developed on the basis of the colour emotions, clean-dirty, tense-relaxed, and heavy-light. In this model colour preference was found affected most by the emotional feeling “clean”. The second model was developed on the basis of the three colour emotion factors identified in Part I[74], colour activity, colour weight, and colour heat. By combining this model with the colour-science based formulae of these three factors, which have been developed in Part I[74], one can predict colour preference of a test colour from its colour-appearance attributes. The third colour preference model was directly developed from colour-appearance attributes. In this model colour preference was determined by the colour difference between a test colour and a reference colour. The above approaches to modelling single-colour preference were also adopted in modelling colour preference for colour combinations. The results show that it was difficult to predict colour-combination preference by colour emotions only. This study also clarified the relationship between colour preference and colour harmony. The results show that although colour preference was strongly correlated with colour harmony, there were still colours of which the two scales disagreed with each other.

2.7 Unique hues

Wyszecki and Stiles[80] defined unique hues as “unique hues cannot be further described by the use of the hue name other than its own. There are four unique hues…they are: red, green, yellow and blue. A colour stimulus perceived to be unique red is neither yellow nor blue. Similarly, unique yellow is neither red nor green…The hueness of a colour stimulus can be described as a combination of two unique hues; for example orange is a yellowish red or reddish yellow.”

“The focal colours are those that for the observer are ideal representatives of a given basic colour name.”[83]

Volbrecht et al.[81] obtained unique green measurements from 50 females and 50 males under 8 different experimental conditions. Combinations of two different test sizes (0.25 and 1.0 deg) and four different background fields comprised the experimental conditions under which unique green measurements were made. Group and gender frequency distributions of the unique green loci were examined for the 8 experimental conditions. They found that unique green distributions for the females deviated more from normal distribution than those of the males. Compared to the background condition, 49-63% of the observers at both test sizes and across three background conditions showed a shift greater than 5 nm. 39-48% of the unique green loci were effected by a change in test size form 1.0 to 0.25 deg across all four background conditions. The observers shifted more than 5 nm to longer wavelength. Differences in the shape of the frequency distributions were noted for the different test sizes and backgrounds as well as for gender, but none of the experimental parameters appeared to elicit a statistical bimodal distribution.

40 observers determined their unique hues from arrays of Munsell chips in a standard surround under artificial daylight in the study by Kuehni[82]. There was some discrepancy in the results of males and females. Essentially no variability due to age of observer was found. The standard deviation around total mean was less than 1 Munsell 40 hue step (Munsell Book of Color with 40 pages). Simple linear opponent-colour a and

b values were calculated. The ranges were found to straddle in all but the red colour the system axes for the CIE 2º observer, but not for the 10º observer. NCS unique hues determined at similar chroma and lightness values fell in all cases within the ranges. The shifts in cross-over wavelength of colour matching functions necessary to match the extreme range values were determined to be between 6-11 nm. The results provide support for an opponent colour system based on subtractions of colour-matching functions. They also point to significant variation of colour normal observers.

Unique hues determined by 40 observers using Munsell colour chips in another study[82], have been compared to published information on focal hues by Kuehni[83]. While there was good agreement in case of three hues, there was a significant disagreement (nearly 4 Munsell hue steps) in case of green. An experiment was performed using mostly the same observers, identical colour chips, and identical viewing conditions to have 40 observers to determine their focal green hue. While their average unique green hue was located at Munsell Hue 2.75 BG, their average focal green was located at 2.5 BG, thus being in agreement with the average World Color Survey[5] focal green. The results pointed to different concepts of the observers for unique green and focal green.

Webster and Webster[84] asked whether a difference existed between the determination of the unique colours and the focal colours at very different populations and environments. They found large between-group differences, and these results led the authors to try to define quantitative differences across different populations. The examined groups of the observers differed along many dimensions, including ethnic, language, culture and visual environment. The following groups participated: Elite School of Optometry (ESO), Chennai, India, 70 students; Silk merchants, Chennai, India, 70 employees; Rural Tamil Nadu, India, 26 subjects; Rural Maharashtra, India, 73 observers; University of Nevada (UNR), Reno, Nevada, 110 students.

The stimuli were Munsell chips, printed unique hue palettes, coloured patches presented on a colour monitor. The Munsell chip palette consisted of 320 glossy chips of the maximum available saturation. The observer was asked to select one chip from the

[5] http://www.icsi.berkeley.edu/wcs/

array that the best represent a particular colour. Chips were selected in order for the colours red, yellow, green, blue, purple and orange. The printed unique hue palettes were displayed as 24 uniformly coloured circles. Subjects were asked to select the one circle that appeared to be untinged by either of the secondary colours. At the computer test, stimuli were presented on a colour monitor in a uniform 2-deg square. A button box was used to indicate how the presented colour deviated from the unique point. ESO and UNR students were tested under natural outdoor lighting and a common incandescence source (Philips 60 W). The other groups were only tested under natural outdoor lighting.

In case of the Munsell chips, there were consistent differences in the mean focal colours across the groups. Relative to the UNR observers, blue was shifted toward greener values and red and yellow were both shifted to a lesser extent toward orange for the ESO observers. The distributions of focal stimuli were qualitatively similar, small but significant differences were apparent in the mean foci across the groups. In case of all colours the results showed differences across the different groups. At the experience with the hue palettes, difference across groups followed a pattern that was similar to those found with the Munsell chips. The UNR and the ESO students made the computer tests. The results were not the same as the authors found with the other tests.

Consistent with many previous reports, the range of unique hues within individual groups was large, implying that the hue loci were very variable. The differences between groups were by comparison small. The differences and the effect were traced back to different factors: 1. psychological factor: effects of the visual system (preretinal filtering, photopigment spectra, number of the cones). 2. environmental factors: differences in natural environment (illumination, the set of surfaces within a scene). 3. cultural factors: Several authors have noted that even the basic colour terms adopted by a language often have different specific referents. The unique hues involve very subjective judgments and that is possible to adopt different perceptual criteria for selecting them.

2.8 Reflections to the earlier investigations

In this section I started the overview of the articles with one of the first experiments on memory colours, with Newhall's experiment in 1957. The last article I mentioned is from nowadays. Many types of experimental methods were enumerated in this annotation. Every experimental method has its advantages and disadvantages. As this description covers about six decades; the aims and the practicability of the researchers was not the same at the beginning and nowadays. In the early years most of the experiments dealt with colour patches, like Munsell colour chips. In these cases the task of the observers was to choose their short- or long-term memory colours from many Munsell patches. As in the observation phase of the experiment – if we talk about short-term memory experiment – they saw only one alone standing colour patch, or the colour of an object which they had to memorize, the adaptation condition was not the same in the two phases.

Let's see, what kinds of colour memory matching experiments were carried out till today. The mentioned work of Newhall[9] deals with successive and simultaneous memory matching. In one of my experimental series I also compared successive and simultaneous matching which could be a comparison base. Bartleson[4,13] made also experiments with Munsell colour patches. Usually the colours which are under examination are natural colours. For example, Bartleson examined the memory colours of several natural objects. He said: "Everyday objects or scenes such as human complexions or landscapes with which people have frequent visual experience are likely to produce memory colours that are common to many people". My aim also was to determine a common memory colour for three colours: blue sky, Caucasian skin and green grass, and the comparison of the some authors and my findings can be found in the results section of this work. In most of memory matching experiments some chroma increase can be observed in the memory colours. Such chroma increase also appears in the results of my experiments.

Not just in the experiments with colour chips but also in other types of experiments it is important to ensure the equal adaptation condition during the experiment. At the beginnings the experiments were conducted in lighting booths.

Nowadays the computers and colour monitors are also available to use for colour experiments. It is more important to create experiments in a daily life space, where people live their everyday life and use their devices. From these devices the most frequent is the computers. Therefore I used computer and a CRT monitor to carry out colour memory experiments in such a condition which is near to the observer's everyday activities. I found a few experiments which were also carried out on colour monitors. Bodrogi and his college[5] made an experiment in which the role of the context on the picture had great importance. They showed that not the same colours would be chosen as memory colours if the context appears on the screen with the colour the observer had to memorize, or if no context was present. In my experimental series I also made experiments with and without contexts. It can be seen in the results section that the context had some influence on the memory colours. Yendrikhovskij[3] and his colleges also carried out their experiments on a CRT monitor. They made long-term memory experiment focused on banana.

Amano[28] mentioned an interesting thought about the connection of colour memory and colour categorization: "Visual memory for coloured scenes involves multiple mechanisms based on categorical colour perception and colour differencing." This notion can be the base of the different memorization of the colours with and without image context. Another considerable question in connection with the memorization of colours is the time between the memorization and when the observers have to determine the colour they remember[8]. There are many prospects that may be discussed in connection of memorization of colours. In my work I focused on the accomplishment of experiments on colour monitors and to ensure the equal adaptation condition during the experiment.

In this section I collected the relevant issues that are in close connection with colour memory, memory processes. Naturally the topics are not complete; it can be carried on for long. The topic of colour memory is the one were my theme can be set in. I found some problems that I wanted to eliminate in my experiments to create a better method to get more accurate information about colour processing of brain. In the colour memory part of the articles above most of the experiments were implemented with Munsell or other colour patches. My aim was to implement the colour memory experiments in an everyday viewing situation. Nowadays the application of the computers is prevalent, so it is important to evaluate these experiments on colour monitors. The other problem I found in the articles was that it is difficult to ensure the equal adaptation condition during the experiment and it is more conspicuous in case where some kind of context is presented together with the examined colour. It is not easy to create an experimental condition where the context is shown, but it does not represent a hint to the observer. The next section is about the methods that I created to sort out these problems. The investigated experimental methods are presented in the order as the experiments were completed. After the application of one of the experimental methods, the results were processed and presented; some problems came into light which had to be eliminated. From this series of eliminations and the refinement of experimental methods a developmental sequence was built up that will be introduced in the next section.

Chapter 3 Experimental methods

The examination of colour memory is usually done with a kind of colour matching experiment, by memory matching. Most of the experiments in the memory matching field use colour patches, but in my opinion with the spread of the computers in everyday life, it is important to involve the colour monitors in the exploration of colour memory. All of my methods that are described below used stimuli displayed on monitors.

At the end of the previous section I wrote about the problems I found in the implementation of memory matching experimental methods. In this section I will introduce a so-called developmental serial that I created to eliminate the mentioned difficulties.

The essence of the memory matching experiment is that the observers have to memorize a colour, the so called “original colour”, and then after some seconds, or hours, they are asked to recall this memorized colour from their memory. The method of re-calling is diverse[29]. The most often used ones are the following:

1. "Mixing-up" the memory colour on a colour output device (a visual colorimeter or a colour monitor) by adjusting the hue, the chroma, and the lightness of a so-called “actual” colour.

2. Selecting the memory colour from several constant colour patches.

3. Deciding whether a just presented colour patch is the memory colour or it is not.

The basis of my study was Bodrogi’s work[5] in the same field. He carried out memory matching experiments with the method of selecting. At the experiments the observers’ task was to memorize an original colour, and then to select the memory colour from several constant colour patches. The strength of this method is that it is simple for the observer; its weakness is that there is a perceptual difference between the viewing situations of memorising and selecting. In addition, the number of constant patches and thus the colour gamut to select from is limited.

The problems of the adaptation state and the viewing situation become more central if some context is represented on screen. It is difficult to ensure the equal conditions, so that the coloured context itself is not a hint to the observer.

I complemented the so-called “photo” experiments (a photo-realistic image on the screen appears as a context) with “colour patch” experiments. These kinds of experiments are in close connection with the adherent photo experiments. For example in Table 3.1 the first and second rows comprise the first experimental series. The experimental conditions, like the illumination, the set-up of the monitor, or the original colours are always the same in the photo and the colour patch experiment, in one series. In most cases these two experimental types together compose an experimental series. In some of the following series it sometimes occurs that other types of experiments were connected to the specific series. The role of these other experiments is written in the appropriate subsection, in the introduction of the series in details.

In this section of my thesis I will introduce my work that I did to create a better experimental method to characterize the memory colours. My aim was to eliminate the differences in the adaptation state and viewing situation in the memorization part and in the re-calling part of the experiment, in the 1st and 2nd viewing conditions. To fulfil these requirements some experimental methods were created in an evaluation procedure. Table 3.1 contains the short description of the established methods. The introduction of the methods can be found in the next subsections in detail (Sections 3.1-3.3).

Table 3.1 Experimental methods; the stages of the evolution.

	No. of exp. series	Name of the experiment	Type of re-call	Background at the memorizing phase	Background at the re-call phase	Existence of context	No. of original colours	Original colours	No. of repetitions	No. of subjects	References
1.	1	Mixing photo	mixing	Coloured photo-realistic images	Blurred photo-realistic image	Yes	3*20	The colours on the original pictures	-	11	25, 29, 85, 86
2.		Mixing colour patch	mixing	Grey background	Grey background	No	3*20	Same as at the mixing photo experiment	-	10	25, 29, 86
3.	2	Mixing greyscale photo-realistic images (Bartleson)	mixing	Greyscale photo-realistic images	Greyscale photo-realistic image	Yes	8, 8, 7	*	6	7	87, 88
4.		Mixing colour patch (Bartleson)	mixing	Grey background	Grey background	No	8, 8, 7	*	6	6	88
5.		Abstract photo	mixing	Greyscale photo-realistic images	Greyscale photo-realistic images	Yes	-	-	At least 6	4	92
6.		Abstract name	mixing	Grey background	Grey background	No	-	-	At least 4	4	87, 92
7.	3	Deciding photo	deciding	Greyscale photo-realistic images	Greyscale photo-realistic images	Yes	3*1	Prototypical colours from earlier experiments	50	10	89, 91
8.		Deciding colour patch	deciding	Grey background	Grey background	No	3*1	Prototypical colours from earlier experiments	50	10	89, 91
9.		Simultaneous	deciding	Grey background	Grey background	No	3*1	Prototypical colours from earlier experiments	50	10	89, 91

10		Long term colour memory Choice colours**	choose	-	Grey background	No	6*1 (No. of colour centres)	Colour centres from literature	30	8	92
		Long term colour memory Choice colours***	choose	-	Grey background	No	6*1 (No. of colour centres)	Colour centres: mean results of the 1st series	30	6	92
		Long term colour memory Reproducing a colour name	mixing	-	Grey background	No	6 (No. of colour names)	-	10	8+6	92
	4	Long term colour memory Reproducing the most appropriate	mixing	-	Greyscale photo-realistic images	Yes	6 (No. of colour names)	-	10	8+6	92
11		Long term colour memory Choice colours Korean	choose	-	Grey background	No	6*1 (No. of colour centres)	Colour centres from literature	10	9	92
		Long term colour memory Reproducing a colour name Korean	mixing	-	Grey background	No	6 (No. of colour names)	-	10	9	92
		Long term colour memory Reproducing the most appropriate Korean	mixing	-	Greyscale photo-realistic images	Yes	6 (No. of colour names)	-	10	9	92

*Bartleson's long term memory colours for sky and skin, median colour from previous studies for grass +6, 7, 7 colours around

**Hungarian 1st series

***Hungarian 2nd series

3.1 Mixing the later memory colour

The first stage (the first series on Table 3.1) of the evolution of experimental methods in my study are the so called “mixing photo” and “mixing colour patch” experiments (see the first and second row in Table 3.1). These together form the fist series of the experiments. All images were displayed in a dark room, on a well characterised and calibrated EIZO F784 21" colour monitor. The reference white (x=0.299; y=0.267; Y= 37 cd/m^2) was always displayed on the left side and on the right side of the screen as two vertical stripes. Subjects were adapting to this viewing situation for at least 2 minutes. In this phase of adaptation they had to practice their task by using two images different from those used in the mixing photo experiment, described in the following section.

3.1.1 Mixing photo experiment

In this experiment, photo-realistic images were used as contexts. Several pictures that were used as contexts can be seen on Figure 3.1.1. (All of the presented photorealistic images can be seen in Appendix 1.) The black rectangle on the pictures contained the original colours that the observer had to memorize. At the first viewing condition each of 11 colour normal subjects observed 20 different photo-realistic images containing "sky" (so-called "sky" photos, each depicting a different scene, two examples are shown in the first row of Figure 3.1.1) + 20 different "Caucasian skin" photos (each depicting a different scene, two examples are shown in the middle row of Figure 3.1.1) + 20 different "plant" photos (each depicting a different scene, two examples are shown in the last row of Figure 3.1.1). The presentation sequence of the photos was the following: sky, skin, plant, sky, skin ... etc. With this sequence, the disturbing effect of seeing lots of colours in one colour category was prevented. If one kind of original colours would have been observed one after the other, the later memory colour could have been shifted. But with applying the written presentation sequence, this disturbing effect was eliminated. The original photos were put into a middle grey field with two white bars in the left and right side. The choice of the background was conscious: the colour of the background had to be not eye-catching. The selected middle grey colour is equal to the mean brightness of the pictures. At this juncture, choosing white as a background colour would have not been a good alternative, because it would had deranged the luminance balance of the whole picture. The white colour as a border has not a so strong effect, but ensures the white reference point.

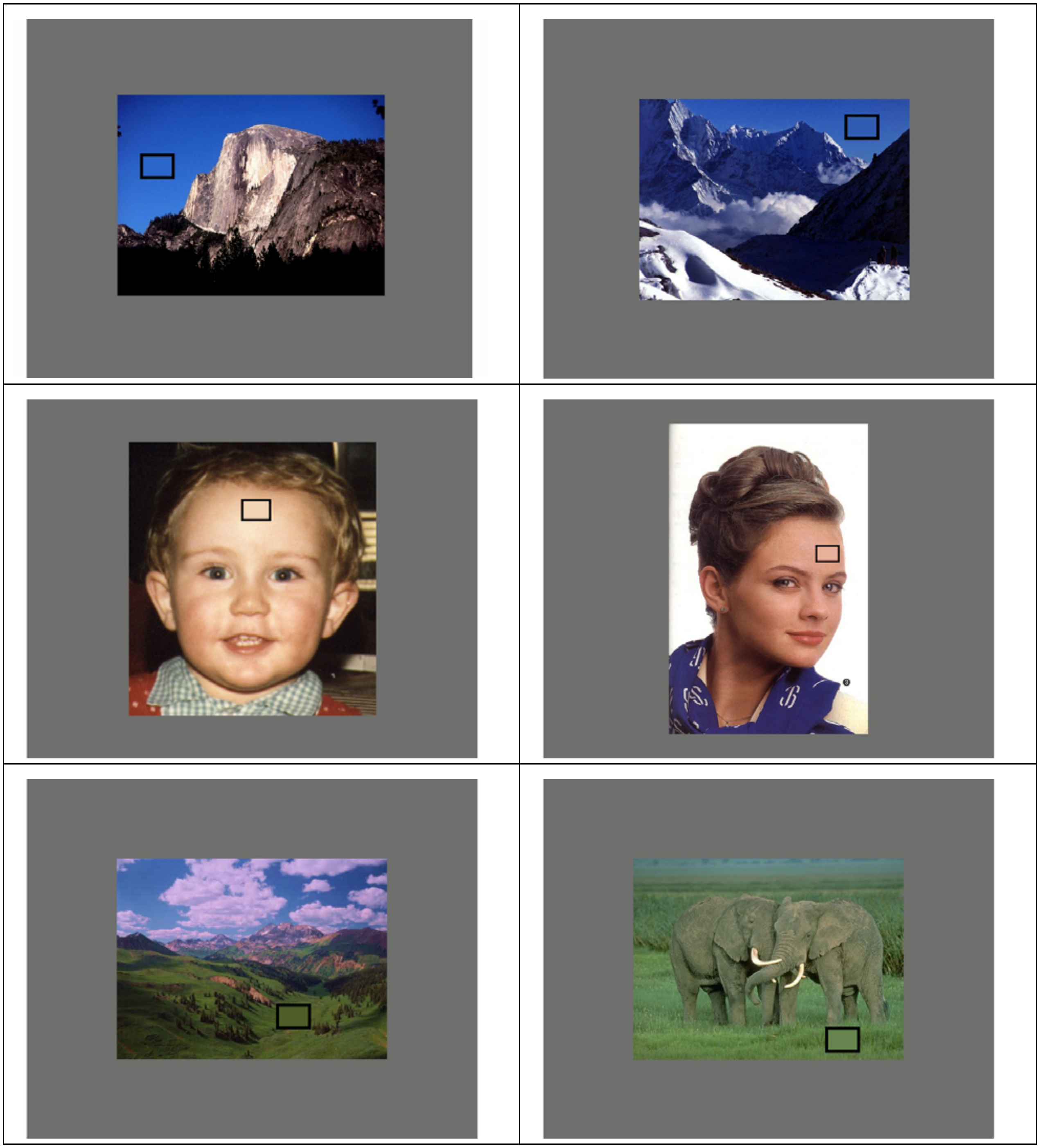


Figure 3.1.1 For the colour memory cue, the uniform colour patch of the original colour was displayed together with the image context, i.e. it was displayed as a part of a photo-realistic image. Original colour is in a black frame. Six examples: first row: sky, middle row: Caucasian skin and last row: plant.

At the beginning of the experiment subjects had to read a written instruction (see Appendix 2.). The observers' task was the following: first a photo containing the original colour was presented. The original colour was a uniform rectangular patch (subtending typically 2º times 2º) in a black frame, see Figure 3.1.1. There was no time limit to memorize it. After this, a full-screen uniform middle-grey image was displayed for 4 s. Then subjects were asked to adjust the hue, lightness, and saturation of the colour of the rectangular patch on the blurred version of the photo (see Figure 3.1.2). The adjustment was done by the aid of three "slides" (see Figure 3.1.3) - displayed at the top of the screen - until the best match to their later memory colour was achieved. The rectangle of the colour patch had the same dimensions as the rectangle of the original colour and it was displayed at the same screen position in the same black frame. The initial colour of the adjustable colour patch was middle grey, and the observers started from this chromaticity to select first the correct colour category, where the actual colour formed part of, and then in steps, with bringing up the trace of the original colour, mixed the exact colour. The adaptation background (the >10° of arc surrounding the task) stayed practically constant during this procedure. This matching experiment lasted for one to three minutes in time.

To ensure equal viewing condition and adaptation condition in the two experimental situations - the 2nd viewing situation (mixing the later memory colour) to be the same as the 1st viewing situation (containing the original colour stimulus) - the photo-realistic image surrounding the adjustable actual colour should be the same as it was for the original colour. So the colour of the proximal field of the actual colour would be similar to the original colour because the colours of small areas do not change rapidly in photo-realistic images. This would be a hint for the observer searching for the later memory colour. To avoid this hint of the proximal field of the actual colour when the observer had to mix the actual colour, the proximal field was re-coloured with colour shades differing from the original colour in hue, chroma, and lightness. In addition, the photo-realistic image was blurred outside the black rectangle. Thus the image surrounding (see Figure 3.1.2) became slightly different from the image surrounding of the original colour (compare with the corresponding photos shown in Figure 3.1.1) but it was assumed that this difference did not cause a perceptible difference in the adaptation condition. To avoid that the observers mix the colour of the proximal field as an actual colour – to consider their task as a simultaneous colour matching task – they were informed that the colour of the proximal field had been changed.

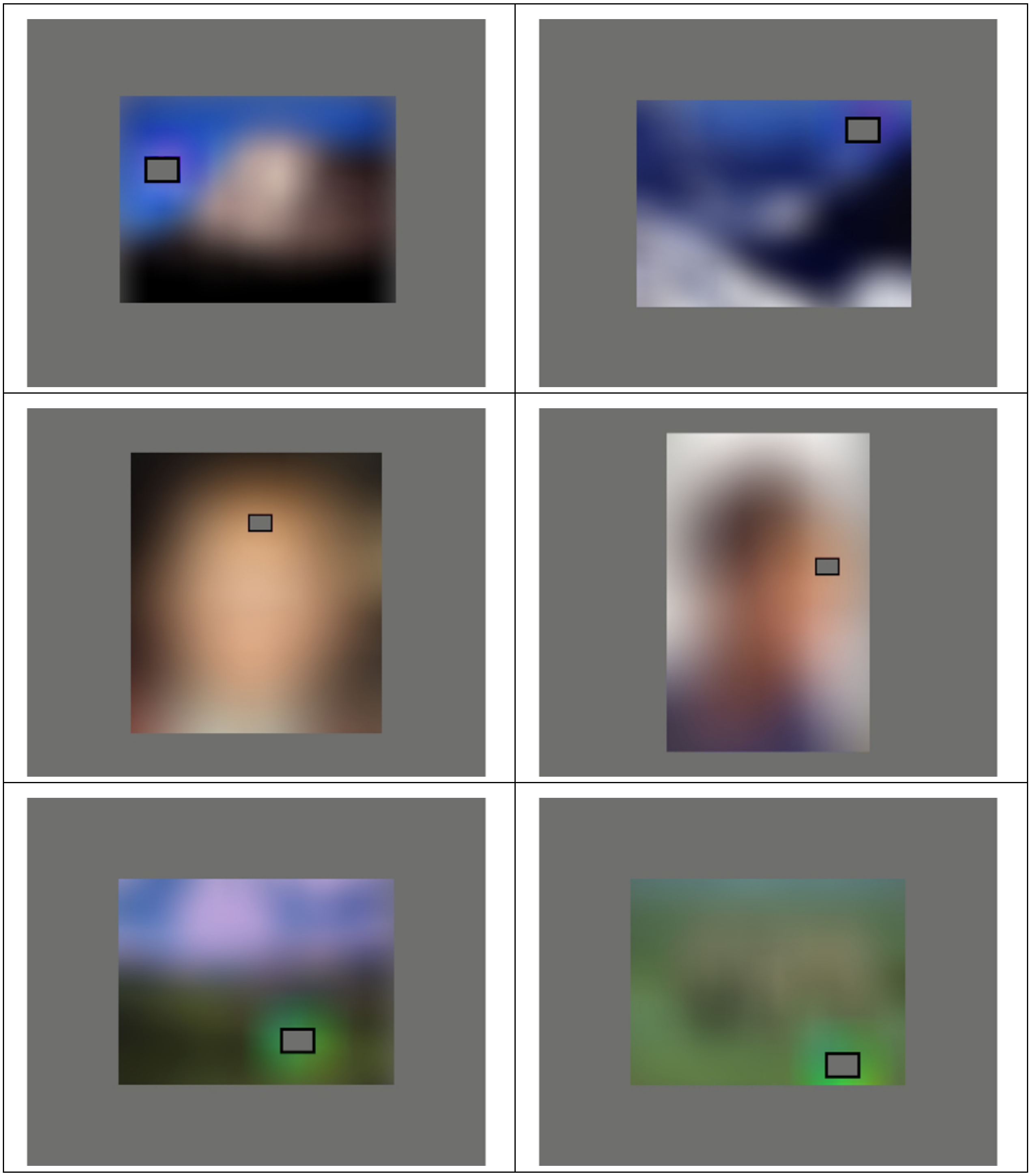


Figure 3.1.2 Blurred images corresponding to the photo-realistic images of Figure 3.1.1.

To ensure, that the difference did not cause a perceptible difference in the adaptation condition, measurements were made in Adobe Photoshop on the images. In Photoshop, for original and blurred images the histogram palette was applied. The Histogram palette offers many options for viewing tonal and colour information about an image. By default, the histogram displays the tonal range of the entire image, but to display histogram data for a portion of the image is also possible. Statistical information about the intensity values of the pixels appears below the histogram. The statistical information includes: mean (represents the average intensity value), standard deviation (represents how widely intensity values vary), median (shows the middle value in the range of intensity values), pixels (represents the total number of pixels used to calculate the histogram), etc. For a selected image in each type of memory cues the results in CIELAB values can be found in Table 3.1.1.

Table 3.1.1 Average CIELAB values for an original and a blurred sky, original and blurred skin and original and blurred grass image

	Sky		**Skin**		**Grass**	
	Original	**Blurred**	**Original**	**Blurred**	**Original**	**Blurred**
L*	33.13	34.52	62.60	62.70	48.9	49.10
a*	12.44	11.86	12.49	11.35	-16.68	-17.58
b*	-20.29	-18.77	16.44	15.90	16.07	16.35
C*	23.81	22.21	20.64	19.59	23.16	24.00
h*	301°	302°	53°	55°	136°	137°

As can be seen from Table 3.1.1 the average CIELAB values are not significantly different for the original and the blurred image. From this one can conclude that the adaptation condition in the two phases of the experiment was the same.

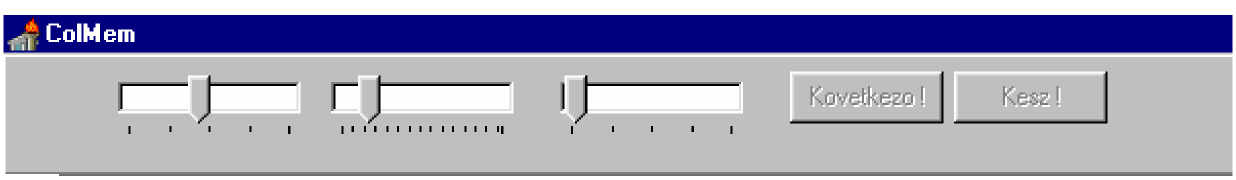


Figure 3.1.3 The three slides, to adjust the lightness, hue and saturation of actual colour; displayed at the top of the screen.

3.1.2 Memory matching without image context experiment

The description of this series can be seen in the second row of Table 3.1, called "mixing colour patch". Each of 10 colour normal subjects (all different from the previous 11 subjects of Section 3.1.1) observed 3 x 20 isolated patches taken from the 3 x 20 photos of the implementation of the memory matching with image context, as in Section 3.1.1. An example is shown in Figure 3.1.4. It corresponds to the first coloured photo in the middle row of Figure 3.1.1. The experiment was similar to the one described in Section 3.1.1 except that

1. the entire photo but the uniform rectangle of the original colour in the black frame was substituted by middle-grey, see Figure 3.1.4; and
2. during the adjustment of the actual colour the blurred version of the photo was substituted by the middle grey. Thus, in case of the invisible image context, the identity of the 1st and the 2nd viewing conditions was achieved.

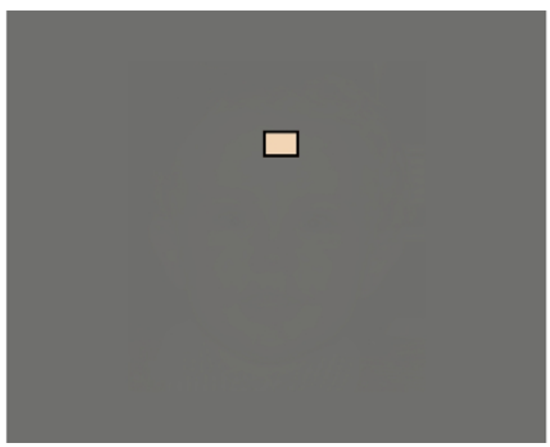


Figure 3.1.4 Memory matching without image context; subjects observed alone standing colour patches. This example corresponds to the first coloured photo in the middle row of Figure 3.1.1.

These two experiments - the mixing photo experiment and the memory matching without image context experiment - constitute the first stage of the advancement of an appropriate memory matching experimental method. This means that for coloured photo-realistic images the equal viewing situation was ensured in the 1st and 2nd viewing situation, namely in the memorization and the mixing part of the experiment.

3.2 Experiments with Bartleson's memory colours

The second stage (the second series on Table 3.1) of the evolution of experimental methods in my study are the so called "mixing greyscale photo-realistic images (Bartleson)", "mixing colour patch (Bartleson)", "abstract photo", and "abstract name" experiments (see 3rd-6th row in Table 3.1). These together form the second series of the experiments. All images were displayed in a dark room, on a well-characterized and calibrated HP P1100 21" colour monitor. The reference white (x=0.33; y=0.32; Y=56 cd/m^2) was always displayed on the left side and on the right side of the screen as two vertical stripes. Subjects were adapting to this viewing situation for at least 2 minutes. The observers got only a short oral instruction about their task, which was confined to the substance of the task. They were not given any other information about the purpose of the experiment.

3.2.1 Mixing greyscale photo-realistic images (Bartleson) experiment

In this experiment, greyscale photo-realistic images were used as contexts. The photo-realistic images can be seen on Figure 3.2.1. On the pictures the black rectangle contained the original colours that the observer had to memorize. At the first viewing condition each of 7 colour normal subjects observed 23 different original colours placed one at a time into greyscale photo-realistic images. From the 23 original colours 8 were so called "grass" type, 8 were so called "Caucasian skin" type, and 7 were so called "sky" type ones. These original colours were placed into the three corresponding greyscale images into the black rectangle. 6 repetitions were applied for each type of original colours. So, an observer made (8+8+7)*6=138 observations. The origin of the original colours was the following: for each type – grass, skin, sky – there was one primary original colour. For sky and skin Bartleson's[4] long term memory colours, and for grass a median colour from the previous study[25] have been picked. The aim of applying Bartleson's memory colours was that many experiments have been made in connection with memory colours after Bartleson's observation, and with making this experiment some comparisons could be made between the results. In addition, six (for sky) or seven (for grass and for skin) other original colours have been selected around the primary original at regular distances in a^*, b^* plane. The selected original colours can be seen on Figure 3.2.2. The presentation sequence of the photos was the following: grass, skin, sky, grass, skin ... etc.

Subjects got an oral instruction from the experimental process. First, a greyscale photo containing one of the original colours was presented. The original colour was a uniform rectangular patch (subtending typically 2º times 2º) in a black frame, see Figure 3.2.1. There was no time limit to memorize it. After this, a full-screen uniform middle-grey image was displayed for 4 s. Then subjects were asked to adjust the hue, lightness, and saturation of the colour patch on the same photo until they got the colour they remembered. The initial colour of the adjustable colour patch was middle grey. The adjustment was done by the aid of three "slides" (see Figure 3.1.3) displayed at the top of the screen until the best match to their later memory colour was achieved. The rectangle of the colour patch had the same dimensions as the rectangle of the original colour and it was displayed at the same screen position in the same black frame.

The observer had to mix the memorized colour - in this situation this is called “actual colour” – by changing the colour of the uniform grey colour patch, which was displayed together with the image context i.e. it was displayed as a part of a greyscale photo-realistic image on the place of the original colour. Equal viewing situation was ensured in the 1st and 2nd viewing situations, because the same greyscale photo-realistic image was shown in the two situations. The familiar objects included on the images denoted the context in the experiment. So, in this method I solved the problem of equal viewing conditions and adaptation situation for displaying image context.

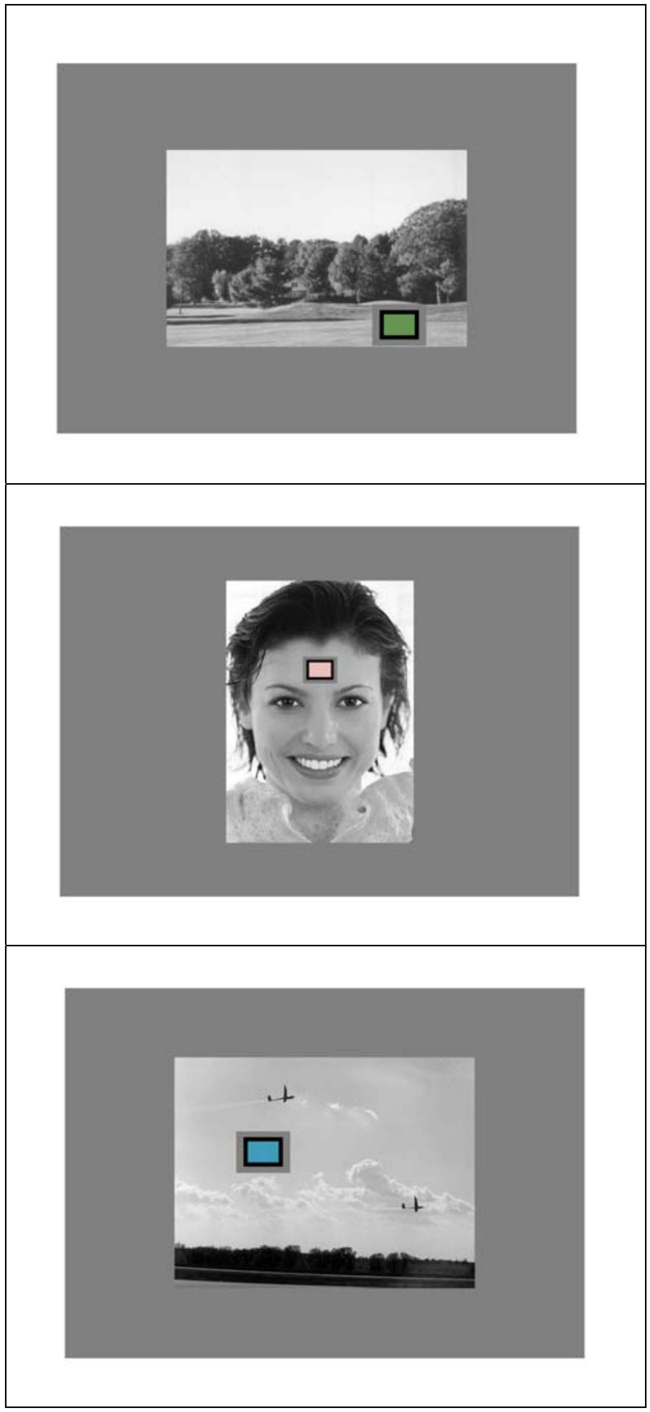


Figure 3.2.1 For the colour memory cue, the uniform colour patch of the original colour was displayed together with the image context i.e. it was displayed as a part of a photo-realistic image. Original colour is in a black frame. Three examples: first row – grass, middle row: Caucasian skin and last row: sky.

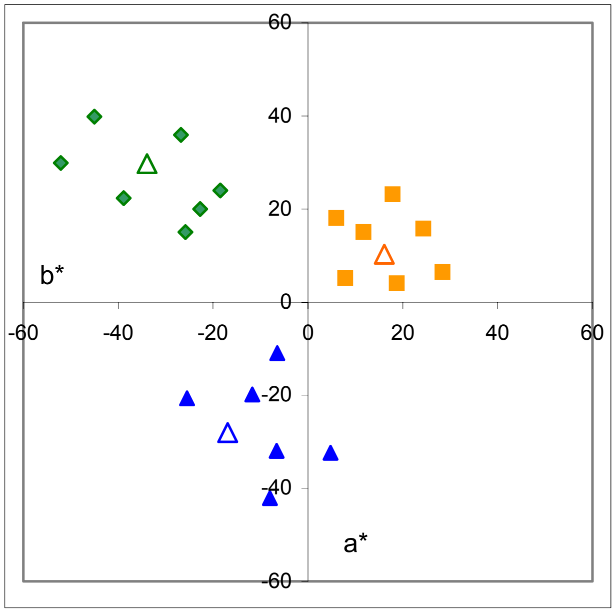


Figure 3.2.2 Original colours in *a**, *b** diagram. 8 green grass (diamonds, for each one, *L**=50), 8 Caucasian skin (squares, for each one, *L**=79.5), and 7 blue sky (triangles, for each one, *L**=54) shades. Open triangles depict "primary" original colours.

3.2.2 Mixing colour patch (Bartleson) experiment

The description of this series can be seen in the 4^{th} row of Table 3.1. Each of 6 colour normal subjects observed (8+8+7)x6 alone standing colour patches taken with the same original colours as in the previous Mixing greyscale photo-realistic images experiment. The experiment was similar to the one described in Section 3.2.1 except that the entire photo but the uniform rectangle of the original colour in the black frame was substituted by middle-grey, see Figure 3.2.3.

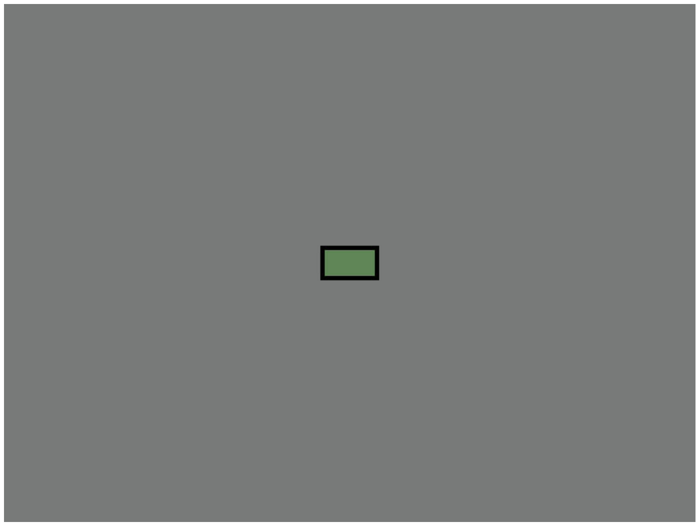


Figure 3.2.3 For the mixing colour patch cue subjects observed alone standing colour patches. An example.

3.2.3 Abstract photo experiment

In this series a so-called abstract photo experiment was realized. The description of the experiment is on the 5th row in Table 3.1. This kind of experiment is not a memory matching experiment, but a preference experiment. The aim of this experiment was to get the preference colours for grass, Caucasian skin and sky objects, and to compare them with the results of the memory matching experiments. Four observers took part in the experiment. All of them took part in the previous mixing experiments as well (Section 3.2.1-2). In the experimental process the observers saw a greyscale photo-realistic image on the screen. The same greyscale photo-realistic images were applied as in the mixing greyscale photo-realistic images (Bartleson) experiment, described in Section 3.2.1, (see Figure 3.2.1) except that there were no original colours in the viewing situations. The subjects were asked to adjust the hue, lightness, and saturation of the colour patch on the photo until they got the colour that in their opinion was best suited for the object that was shown on the image. The initial colour of the adjustable colour patch was middle grey. The adjustment was done by the aid of three "slides" (see Figure 3.1.3) displayed at the top of the screen until the best match to their later memory colour was achieved. The observers mixed the best suited colours at least 6-times for each type of greyscale photo-realistic images (Figure 3.2.1).

3.2.4 Abstract name

The “abstract name” experiment is the imageless type of the previous abstract photo experiment. The description of the experiment is in the 6th row in Table 3.1. 4 colour normal observers took part in the experiment. They saw only a grey patch with black contour, and they had to mix the colours that were written onto a paper. Next to the regular colours (grass, Caucasian skin, sky), there were some other colours enumerated. The reason for applying other colours was to make the experiment less monotonic. The other colours were foliage, banana and orange for two observers and some colours of familiar objects like red apple, plum, carrot, orange and lemon, for the other two observers, but the results of these will not be discussed here. The repetition was at least 4 in this case.

3.3 Adopting a new decision method for previous findings

The so-called "deciding photo", "deciding colour patch" and "simultaneous" experiments (see 7th-9th rows in Table 3.1) are the third stage of the evolution of experimental methods in my study. These together form the third series of the experiments. All images were displayed in a dark room, on a well-characterized and calibrated HP P1100 21" colour monitor. The reference white (x=0.33; y=0.33; Y=54 cd/m^2) was always displayed around the images. Subjects were adapting to this viewing situation for at least 2 minutes. The observers got only a short oral instruction about their task, which was confined to the substance of the task. They were not given any other information about the purpose of the experiment.

The substance of this method is that the observer's task is to decide whether the presented colour patch in the 2nd viewing condition (decision colour) is the colour seen before or it is not. This method is very easy to do for the observer.

3.3.1 Deciding photo experiment

The deciding photo experiment is the first experiment of the third series (7th row in Table 3.1). The most important advantage of the method of deciding is that very similar viewing conditions can be ensured for the "original" colour and the "decision" colour, in the 1st and 2nd viewing condition. All visual experiments were carried out on a well calibrated and characterised colour monitor in a dark room. 10 colour normal observers took part in the experiment. In this experiment, greyscale photo-realistic images were used as contexts. The pictures are shown in Figure 3.3.1. The black rectangle on the pictures contained the original colours (or colour centres) that the observer had to memorize. In the first viewing condition each of 10 colour normal subjects observed 3 different greyscale photo-realistic images containing "grass", "Caucasian skin" and "sky" photos (the presentation sequence of the photos was the following: grass, skin, sky, grass, skin ... etc. with 50 repetitions each). First, a greyscale photo containing the original colour was presented. The original colour was a uniform rectangle patch in a black frame on the images, see Figure 3.3.1. These colours were found as nearly prototypical colours in previous experiments; see 1st-6th rows in Table 3.1. The determination of the original colours can be found in the results section of this experimental series (Section 4.3). There was a 4 seconds time limit to memorize the colour. After this, a full-screen uniform middle-grey image was displayed for 4 s. Then the same greyscale photo-realistic image was seen with an actual colour at the place of the original colour. 50 actual (or decision) colours were used for each type of colour centres, so an observer had to make 3*50 decisions during the experiment. The actual colours were chosen as random colours so that the colour difference between the colour centres and the actual colours were less than 20 and $\Delta L*$ was equal to zero. The decision colour was allowed to be the same as the original colour. The observer had to decide whether the just-seen actual colour is equal to the original colour or not. The deciding colour was seen for 4 seconds and then a full-screen uniform middle-grey image was displayed. The observer had to make his/her decision with pushing the appropriate button.

Figure 3.3.1 For the deciding picture cue the uniform colour patch of the original colour and the deciding colour were displayed together with the image context: they were displayed as a part of a greyscale photo-realistic image. The original colour was displayed in a black frame. Three examples: first row: grass, middle row: Caucasian skin and last row: sky.

3.3.2 Deciding colour patch experiment

The description of this series can be seen in the 8th row of Table 3.1, called "deciding colour patch". 10 colour normal subjects (same subjects took part as in the deciding photo experiment, described in Section 3.3.1) observed the three colour centres or original colours as alone standing colour patches. The colour centres were the same as in the previous deciding photo experiment. All colour patches were placed at the centre of the screen. The experimental process was also the same. An example for the alone standing colour patch is shown in Figure 3.3.2.

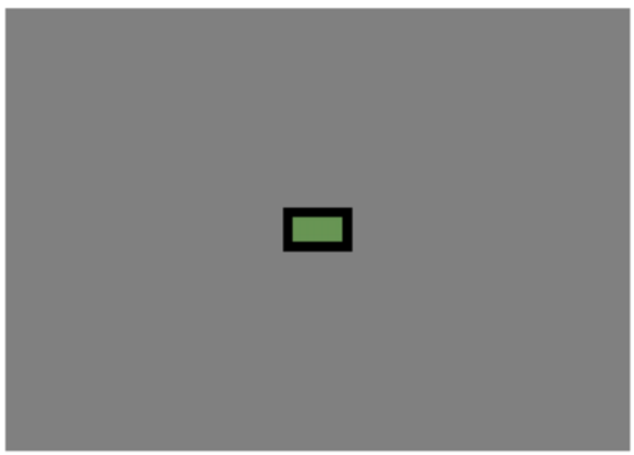


Figure 3.3.2 Example for the colour memory cue, subjects observed alone standing colour patches.

3.3.3 Simultaneous experiment

The reason of making the simultaneous experiment in this experimental series was to make a comparison between the results of the different types of experiments. This experimental type is a colour discrimination experiment. In the simultaneous series, the observer saw two colour patches with 2º viewing angle on a grey background. The description of this series can be found in the 9th row of Table 3.1. Figure 3.3.3 is an example for the picture the observer saw. The observer's answer was "yes" or "no" to the question whether the two patches were of the same colour. One of the two colour patches was called "colour centre" and the other was called "decision colour". The colour centre was one of the three colour centres used in the deciding picture or in the deciding colour patch experiment. Naturally all colour centres were applied in this series too. The observer had to decide about 3*50 colour pairs whether they were the same.

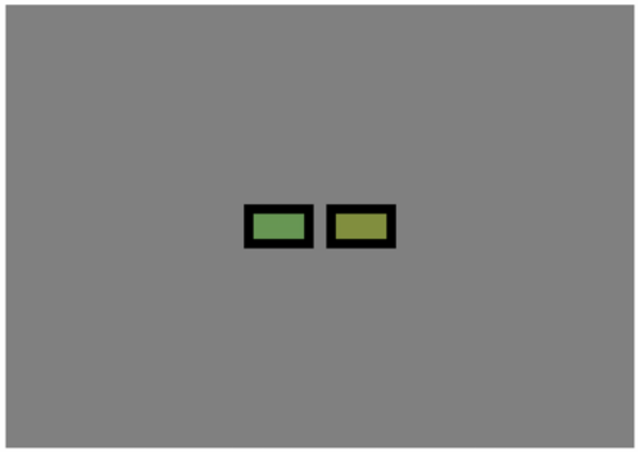


Figure 3.3.3 Example for the simultaneous cue, subjects observed two colour patches.

In this series these three experiments embody the third stage of the advancement of an appropriate memory matching experimental method. First each observer carried out the simultaneous series, then, after 1-2 days, the deciding colour patch series, and then, after 2-3 weeks, the deciding picture series. The aim of the time intervals inserted between the series was to minimise the learning effect. There was 4500 decisions altogether: 10 observers * 3 series * 3 colour centres * 50 decision colours.

The advantage of the decision experimental method was not only that it ensured the equal viewing situation in the 1st and 2nd conditions, but it is very easy for the observer. In the previous series at the mixing methods the equal conditions were also ensured, but the pursuit to mix the appropriate colour was really straining for the observers. With the application of the simple binary decision method, the procedure became more effective and less demanding.

3.4 Korean – Hungarian study for long-term memory colours

In this experiment, I wanted to investigate the important issue of long-term memory colours. In this experiment I used a three-phase psycho-physical method to quantify six of the long-term memory colours, in the viewing situation of self-luminous computer-controlled colour monitors. This is a very important application today. One further aim is to point out how these long-term memory colours vary between different cultures, namely among Korean and Hungarian observers who participated in the experiments.

3.4.1 Characterization of the colour monitor used in the visual experiment with Hungarian observers

Colour CRT monitors were used to display all stimuli, with 6500 K white point setting and of 116 cd/m^2 luminance at the Hungarian and 117cd/m^2 luminance at the Korean experiments. Verification measurements showed that the accuracy was within +/-2% for the tri-stimulus values by using this monitor characterization model, for both the Korean and the Hungarian experiment.

3.4.2 Psychometric method to find the long-term memory colours of Hungarian observers

All observations were carried out in a completely dark room where the colour monitor was the only light source. Two series of observations were carried out within one month with 8 observers in the first series, and 6 observers in the second series. There were 11 Hungarian observers altogether, thus the observer set of the second series was partially overlapping with the one of the first series. All Hungarian observers had normal colour vision. All Hungarian observers were young adults, college students familiar with computers and computer monitors. The subjects' viewing distance was 60 cm. The viewing area of the monitor was 32 cm (horizontal) times 24 cm (vertical).

3.4.2.1 The method of choice colours (selecting a memory colour from 16 constant colours)

Four lines of four constant colour patches (4x4=16 colour patches called choice colours) were displayed on a middle grey background. Its luminance was 42.8 cd/m^2, its CIELAB values were equal L^*=67.1, a^*=0.0, b^*=0.0. The middle grey background covered a rectangular area of 29 cm (horizontal) times 20 cm (vertical). The size of any rectangular colour patch was 2.5 cm (horizontal) times 1.5 cm (vertical). The colour patches were uniformly spaced. The separation between the patches was 4 cm (horizontal) and 2.5 cm (vertical). There was a white border at the screen boundary outside the middle grey background. At the top of the middle grey background, a colour name was displayed as a label. There was a checkbox under every colour patch. Observers had to check only one checkbox associated with that colour patch which was perceived to best correspond to the colour name shown at the top. Following memory colour names were displayed: non-tanned skin, blue-sky, green-grass, deciduous foliage, banana, and orange.

The 16 choice colours were shown to the observer on one screen for each of the six colour names. The observer indicated his/her choice for the colour name shown. 30 repetitions have been carried out with a random array of choice colours for each of the 6 memory colours. Therefore the output of each observer was a set of 30 choices per memory colour. The colour centres and the random choice colours can be seen in Figure 3.4.1.

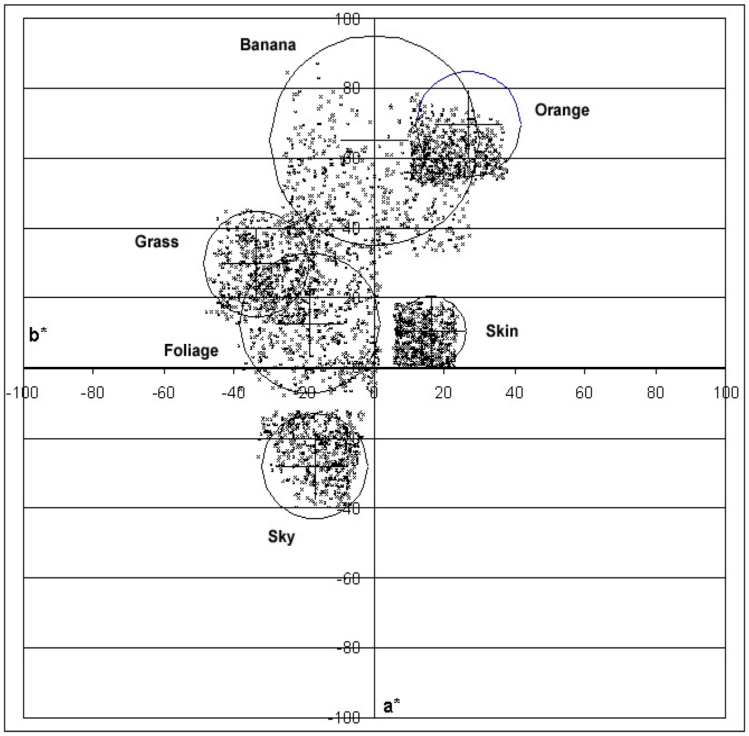


Figure 3.4.1 Colour centres and random choice colours in the 1st Hungarian series

In the second series of Hungarian observations, the colour centres were estimated from the overall mean results of seven observers of the first series, one observer was excluded due to irregular results. The new tolerance values were estimated as twice the mean standard deviations of those six observers. The colour centres and the random choice colours can be seen in Figure 3.4.2.

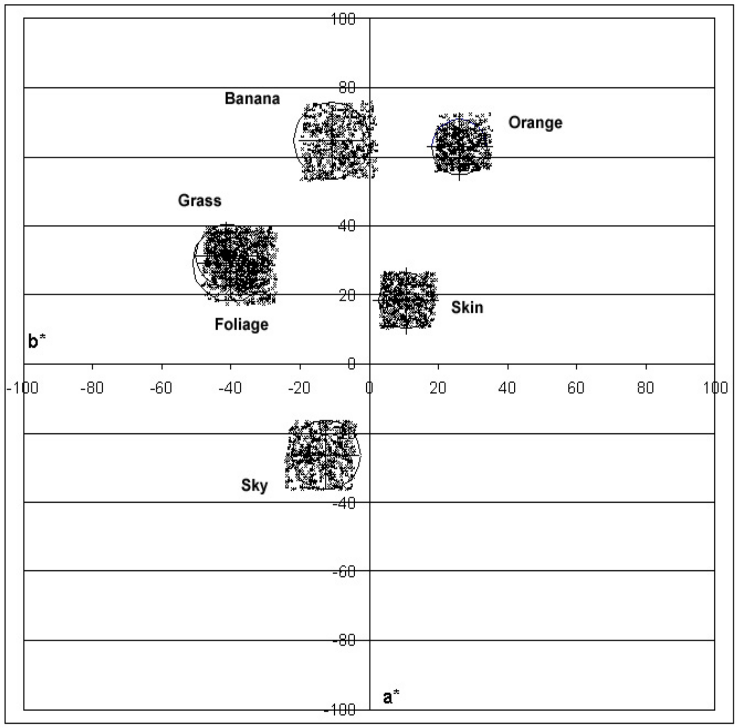


Figure 3.4.2 Colour centres and random choice colours in the 2nd Hungarian series

3.4.2.2 The method of "reproducing a colour name"

In both series of observations, immediately after the method of choice colours, the observer carried out the method of "reproducing a colour name". In this method, there was a changeable square-shaped colour patch (2.5 cm times 2.5 cm), in the middle of the screen, in a 2 mm dark grey frame. The colour of the uniform background was middle grey. The middle grey background covered a rectangular area of 29 cm (horizontal) times 20 cm (vertical). Its luminance was 24.4 cd/m^2, its CIELAB values were equal L^*=52.9, a^*=0.0, b^*=0.0. There was a white border at the boundary of the screen, same as for the method of choice colours. There was a colour name written by white characters above the changeable colour patch. In the middle of the right half of the screen there were three "sliders" to change the three perceptual dimensions of colour in the HSV colour space: hue, saturation, and lightness. The HSV colour space is very far from being perceptually uniform but it was appropriate for just finding the memory colour. Below the three sliders there was a "Ready" button. At the beginning, the colour bar was dark grey with the first colour name at the top. By the aid of the three sliders, the observer had to reproduce his/her memory colour corresponding to a colour name. Then the observer pushed the

"Ready" button. This memory colour was stored. The output of each observer was a set of 10 colours per memory colour, presented in random order for the six colour names, which were used in the method of choice colours.

3.4.2.3 The method of "reproducing the most appropriate colour in a greyscale photo"

Immediately after the method of "reproducing a colour name", the observer carried out an experiment according to the method of "reproducing the most appropriate colour in a greyscale photo". The test image and the experimental procedure were very similar to the method of "reproducing a colour name", with the following differences: 1. Colour patches of changeable colour were within greyscale photo-realistic images in such a part of the picture that could be described by a colour name of an object, e.g. in the "grass" part of a landscape image; 2. Colour names were substituted by these greyscale images instead of the middle grey background. By the aid of the three sliders, the observer had to reproduce his/her "most appropriate" or "most suitable" colours corresponding to that part of the greyscale image where the changeable colour patch was displayed. The output of each observer was a set of 10 colours per memory colour, reproduced for each of the six greyscale photos containing non-tanned skin, blue-sky, green-grass, deciduous foliage, banana, and orange.

3.4.3 The Korean experiment

Viewing conditions of the Korean and Hungarian visual experiments are compared in Table 3.4.1. As can be seen, the Korean viewing conditions were very similar to the Hungarian viewing conditions. Experiments were carried out in separate laboratories, in Korea and in Hungary, respectively. The way of monitor characterization and the psychometric method were the same as in the Hungarian observations. There was only *one* Korean series. For the Korean experiment, the luminance of the middle grey background in the method of "choice colours" was 48.2 cd/m^2, its CIELAB values were equal L^*=70.2, a^*=-0.21, b^*=0.59, and, in the method of "reproducing a colour name" 29.3 cd/m^2, and L^*=57.0, a^*=-0.18, b^*=0.50. The Korean choice colour centres were the same as in the Hungarian first series except that instead of Caucasian skin, Oriental skin was used. A plot of the actual random choice colours used in the Korean series is shown in Figure 3.4.3, with the Oriental skin colour centre.

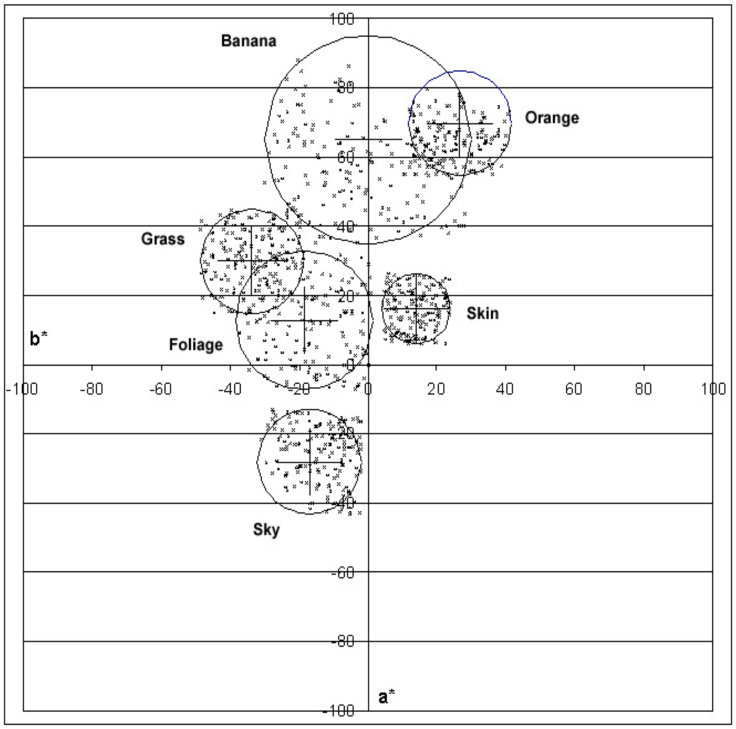


Figure 3.4.3 Colour centres and random choice colours in Korean series

In the Korean greyscale photo experiment, an image depicting an Oriental woman was used instead of the Hungarian image depicting a Caucasian woman. Nine observers were used in the Korean experiment. All Korean observers had normal colour vision tested by the same method as the Hungarian observers. All Korean observers were young adults, researchers involved in digital imaging research.

Table 3.4.1 Comparison of the Korean and Hungarian viewing conditions

Condition	**Hungarian experiment**	**Korean experiment**
Viewing environment	dark room	dark room
Monitor white point	about 6500K (x=0.310; y=0.331)	about 6500K (x=0.311; y=0.318)
Peak white luminance	116cd/m^2	117cd/m^2
Monitor channel independence[6], $Y_W/(Y_R+Y_G+Y_B)$[10]	excellent (0.98)	excellent (1.01)
Number of observers in all types of experiments (choice, name, photo)	8 (1st series) + 6 (2nd series), partially overlapping	9
Choice colours - number of repetitions / memory colour	30 (in both series)	10
Choice colours - colour centres and tolerance values	see Table 1 and 2	see Table 1 (and Table A1, in Appendix, for Oriental skin)
Choice colours – memory colour names	not-tanned skin, blue-sky, green-grass, deciduous foliage, banana, orange	skin, blue-sky, green-grass, deciduous-foliage, banana, orange
Colour name - number of repetitions / memory colour	10 (in both series)	10
Colour name – memory colour names	same as for the choice colours (in both series)	same as for the choice colours
Greyscale photo - number of repetitions / memory colour	10 (in both series)	10
Greyscale photo - greyscale pictures	see the choice colours	see the choice colours
Colour vision of observers	normal	normal

6 This quantity describes how well the monitor approximates additivity of its color primaries. In the formula, Y_W is the measured luminance of its peak white, and the other values are the measured luminance values of its RGB color primaries.

Chapter 4 Results and discussion

This section contains the results of the performed experiments listed in the previous section. First, the results of the methods are discussed in the orders can be found in the previous section, and then the comparison of the results of experiments based on the methods are described.

4.1 Results of the first experimental series

In this section I construe the results of this first experimental series. The description of the series can be found in the 1st and 2nd row of Table 3.1 and in Section 3.1. In this series the observers' task was to mix the actual colour they remember from the first viewing condition with the help of three slides. Original colours used in the first series can be found in Appendix 3 for sky, skin and grass types of colours in CIELAB. On Figure 4.1.1 these original colours are visualized in a^*, b^* diagram. The colours in the diagram have different L^* values, so the aim of the diagram is just to represent the position of the colours in an a^*, b^* plane. The comparisons of the different colours have to be made circumspectly. As I mentioned in Section 3.1 the same original colours were used in the two parts of the first series. The difference between the two parts of the experimental series was the presence or the absence of the image context. 11 observers took part in the mixing photo part of the series but just 10 observer's results were taken into consideration during the processing, because one observers results were not reliable. 10 observers made the mixing task in the mixing colour patch part of the experiment.

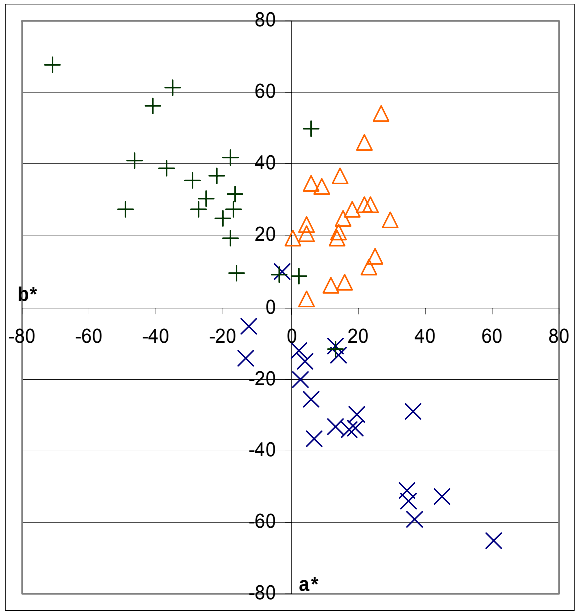


Figure 4.1.1 Original colours in the first experimental series; Section 3.1; “x” signs – sky colours; “Δ” signs – skin colours; “+” signs – grass colours

4.1.1 Results of the mixing photo experiment

In this experiment coloured photo-realistic images were visualized on the screen one after the other. The observers' task was to mix the colour that was present in their mind about the original colour showed previously. The visualized original colours and the photo-realistic images used as contexts can be seen in Figure 4.1.1 and Appendix 1, respectively. The mixed colours of the observers in CIELAB values can be found in Appendix 4 for each picture shown in Appendix 1. The position of the colours in an *a**, *b** colour diagram can be seen on Figure 4.1.2.

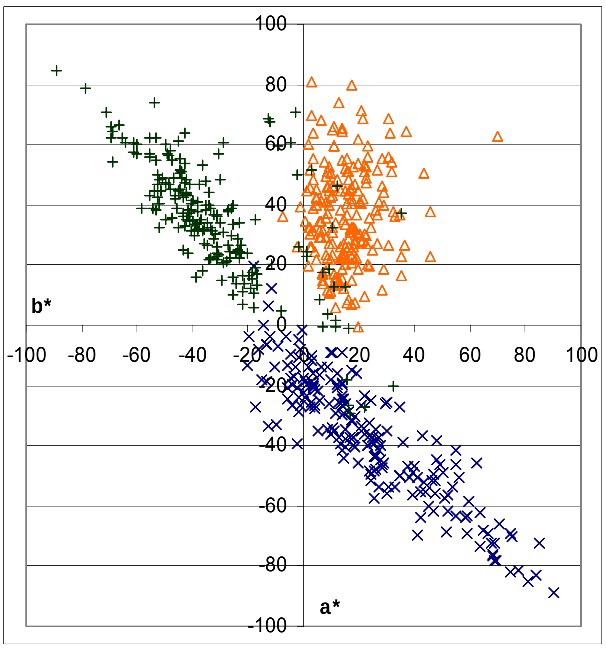


Figure 4.1.2 Results of mixing photo experiment. "x" signs – sky colours; "Δ" signs – skin colours; "+" signs – grass colours.

From Figure 4.1.1 and Figure 4.1.2 it can be seen that the spread of mixed or actual colours is bigger than the set of the original colours. The deviation is greater in case of the mixed colours, which can be clearly seen in the figures. In Table 4.1.1 the mean values of the actual colours and the standard deviations are listed for each original colour for sky colours. The same values can be seen in Table 4.1.2 and Table 4.1.3 for skin and for grass colours. In the last row of each table the mean values are presented.

Table 4.1.1 Mean actual colours and standard deviations for each sky type of original colour. Mean for all can be found in the last row.

	Original colours			**Mean actual colours**			**STD**		
	L*	***a****	***b****	***L****	***a****	***b****	***L****	***a****	***b****
1	45.70	37.03	-59.37	43.82	49.67	-62.26	5.93	20.56	16.33
2	82.57	4.24	-15.07	65.24	7.11	-25.95	10.44	11.43	11.36
3	85.09	-13.24	-14.33	69.64	-2.33	-23.12	7.55	11.79	12.44
4	75.77	2.48	-12.19	68.00	1.07	-18.61	7.78	8.49	9.01
5	41.46	2.98	-19.98	44.87	20.99	-39.30	8.13	20.52	17.11
6	62.90	34.47	-51.21	51.59	26.60	-43.23	7.37	23.00	15.89
7	96.33	-12.31	-5.34	76.62	-4.59	-19.32	10.69	11.82	10.35
8	20.33	19.34	-33.74	26.13	40.59	-51.02	9.52	17.91	14.91
9	65.56	19.68	-30.07	58.77	27.25	-35.78	10.71	15.69	13.70
10	39.76	17.39	-34.34	42.65	32.99	-44.67	12.01	26.05	20.02
11	43.51	14.40	-13.48	44.35	23.29	-28.07	7.89	17.70	16.92
12	39.98	35.17	-54.23	38.24	40.27	-56.53	8.45	20.01	15.59
13	21.68	60.67	-65.14	29.13	51.26	-60.37	11.59	24.45	16.82
14	91.79	13.50	-10.74	73.99	12.78	-15.41	11.80	18.57	17.43
15	63.25	6.82	-36.82	52.77	14.47	-39.50	10.66	17.31	15.46
16	23.66	36.42	-29.23	25.56	53.11	-45.12	8.68	13.55	11.72
17	69.14	5.97	-25.54	60.35	9.30	-29.77	9.05	11.38	11.79
18	41.31	44.97	-52.72	39.73	43.55	-49.43	9.45	22.06	12.50
19	54.61	13.56	-33.30	52.00	19.65	-36.04	7.05	19.57	18.55
20	79.36	-2.53	9.96	70.01	-1.85	-7.08	8.28	10.24	13.51
Mean	**57.19**	**17.05**	**-29.34**	**51.67**	**23.26**	**-36.53**	**9.15**	**17.10**	**14.57**

Table 4.1.2 Mean actual colours and standard deviations for each skin type of original colour. Mean for all can be found in the last row.

	Original colours			**Mean actual colours**			**STD**		
	L*	***a****	***b****	***L****	***a****	***b****	***L****	***a****	***b****
1	64.47	26.88	54.05	59.17	26.52	54.99	7.35	10.46	16.58
2	48.68	29.51	24.29	49.65	32.00	38.05	5.95	18.46	14.37
3	65.53	12.02	6.05	62.52	13.66	25.49	6.55	5.75	22.42
4	85.91	4.69	23.12	67.49	14.06	37.91	6.74	9.10	20.12
5	70.59	21.96	28.47	63.52	17.87	37.05	6.06	9.22	13.99
6	70.75	16.22	6.82	66.86	17.75	28.38	6.44	9.28	15.37
7	77.42	4.91	20.63	67.06	11.29	33.62	9.50	8.17	12.05
8	91.64	4.95	2.19	77.81	7.55	18.07	10.48	8.30	7.36
9	71.05	15.55	24.89	67.42	14.18	29.40	8.40	7.24	12.33
10	61.37	14.12	21.12	63.79	13.15	35.85	8.93	5.90	16.95
11	72.44	18.34	27.33	66.01	18.25	37.90	4.85	8.11	7.58
12	78.63	13.89	19.21	67.09	15.42	32.36	4.90	4.13	11.07
13	75.08	9.30	33.94	63.55	10.62	45.27	6.84	8.08	13.34
14	74.02	25.27	14.42	66.05	16.29	37.58	6.59	6.63	17.85
15	89.08	0.51	19.27	75.23	6.27	35.40	5.92	3.95	14.07
16	44.10	23.29	11.38	54.15	18.97	30.96	8.12	5.26	19.25
17	83.39	6.02	34.50	72.55	5.84	45.98	5.62	6.49	17.65
18	63.45	21.97	45.96	53.05	19.21	43.70	12.06	7.27	12.94
19	69.40	23.76	28.67	62.94	17.77	35.78	5.36	7.64	10.54
20	75.93	14.68	36.76	64.68	14.37	44.11	6.96	7.88	13.91
Mean	**71.65**	**15.39**	**24.15**	**64.53**	**15.55**	**36.39**	**7.18**	**7.87**	**14.49**

Table 4.1.3 Mean actual colours and standard deviations for each grass type of original colour. Mean for all can be found in the last row.

	Original colours			**Mean actual colours**			**STD**		
	L*	***a****	***b****	***L****	***a****	***b****	***L****	***a****	***b****
1	67.81	-71.09	67.80	60.72	-65.27	61.21	8.73	14.53	15.57
2	52.03	-41.22	56.36	52.40	-52.66	53.54	7.41	8.64	13.32
3	17.91	-20.26	24.71	29.78	-35.04	33.35	13.54	14.41	15.04
4	36.61	-27.60	27.28	38.80	-35.34	32.53	11.01	13.02	11.99
5	72.25	6.26	50.00	61.51	-1.20	49.06	13.19	15.14	20.06
6	46.24	-18.05	41.90	46.10	-33.09	39.71	6.33	10.86	12.66
7	27.54	-3.61	9.20	32.47	-3.64	13.47	13.29	15.91	17.04
8	29.47	-16.91	27.42	36.55	-34.10	32.17	5.47	11.46	11.17
9	55.18	-16.00	9.47	53.09	-33.61	27.47	10.19	11.59	14.55
10	32.05	2.66	8.49	32.35	-3.59	20.17	10.93	14.94	13.93
11	47.69	-49.28	27.21	50.36	-46.14	39.20	7.16	9.45	14.29
12	50.98	-25.08	30.56	51.02	-38.82	40.71	6.63	9.00	13.60
13	58.12	-35.15	61.21	57.86	-49.75	50.40	7.13	6.77	11.81
14	42.42	-21.79	36.57	47.81	-38.08	38.80	5.81	9.45	10.25
15	48.71	-37.02	38.68	50.25	-41.44	37.91	2.93	9.08	10.54
16	39.52	-29.25	35.29	46.10	-39.81	34.51	5.46	6.24	7.81
17	33.39	-16.66	31.78	39.92	-35.08	35.26	7.25	7.65	12.60
18	20.51	-18.10	19.44	29.05	-27.29	27.23	8.39	6.02	7.80
19	18.91	13.48	-11.84	25.75	12.20	-9.26	9.35	14.80	19.23
20	33.25	-46.55	41.11	46.34	-46.49	47.57	4.02	6.97	9.68
Mean	**41.53**	**-23.56**	**31.63**	**44.41**	**-32.41**	**35.25**	**8.21**	**10.80**	**13.15**

For sky colours (Table 4.1.1) a smaller mean actual L^* value was found compared to the mean original L^* value. If we look inside the table the following can be observed: if the value of original L^* is found to be too small, i.e. the colour is dark, then the observers mixed a lighter sky colour, but if the original colour is light, they mixed a darker colour. From these observations an L^* range can be determined in which the prototypical L^* value can be found for sky colours. In Figure 4.1.3 the L^* values of original colours can be seen on the x axis, and the corresponding mean L^* values for actual colours on the y axis. The straight line denotes the case where the lightness of the original colour is equal to that of mean mixed colour. The best matches can be found between the L^* value 35 and 60 of the original colours, where the mean mixed colours and the original colours are nearly the same. The prototypical L^* value of sky colour can be found in this range.

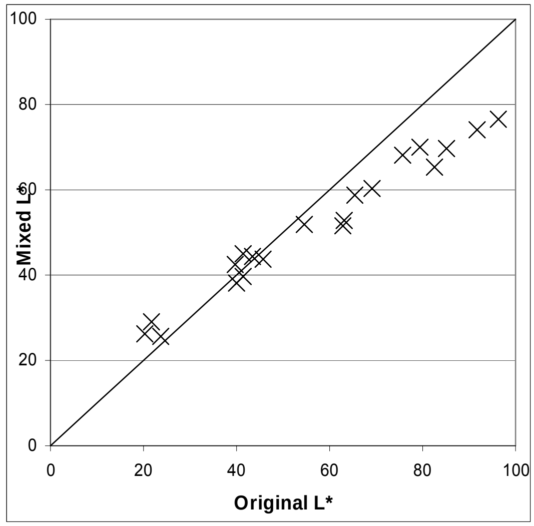


Figure 4.1.3 Mean L^* values of mixed colours in the function of the corresponding L^* values of the original colours for sky colours at the mixing picture experiment. The straight line denotes the perfect match.

For the a^* b^* values the following can be established: in case of the mean of all values a shift can be seen from the greener to the bluer colours. This shift is more conspicuous in Figure 4.1.4 where the original colours and the mean actual colour are presented in an a^*, b^* colour diagram. "x" depicts original colours, "♦" depicts mean actual (or mixed) colours. The arrows show the shift that occurs from the original to the mixed colour. It is clearly seen that the shifts tend to one domain, which contains the prototypical colour presumably. Not just the hue shift but the chroma shift is observable. The observers mixed more saturated colours but in case of some highly saturated colours a reduction occurs. Increasing of chroma can be observed. The hue and the chroma differences can be seen in Table 4.1.4, where $\Delta h=h_o-h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belonging to the original colour. $\Delta C=C_o-C_{mixed}$ where C_o is the chroma value of the original colour, C_{mixed} is the chroma value of the mean of all mixed colours belonging to the original colour. The mean of all can be found in the last row.

The mean actual colours and h_{ab} values for each sky colour for the L^* values that locates in the domain of the best matches can be found in Table 4.1.5. In the table $\Delta h=h_o-h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belonging to the original colour. $\Delta C=C_o-C_{mixed}$ where C_o is the chroma value of the original colour, C_{mixed} is the chroma value of the mean of all mixed colours belonging to the original colour. The interval of h_{ab} values are between -48 and -69, and this domain determines the location of the prototypical colour of sky and from this we might conclude that the prototypical sky colour has to fall into this range.

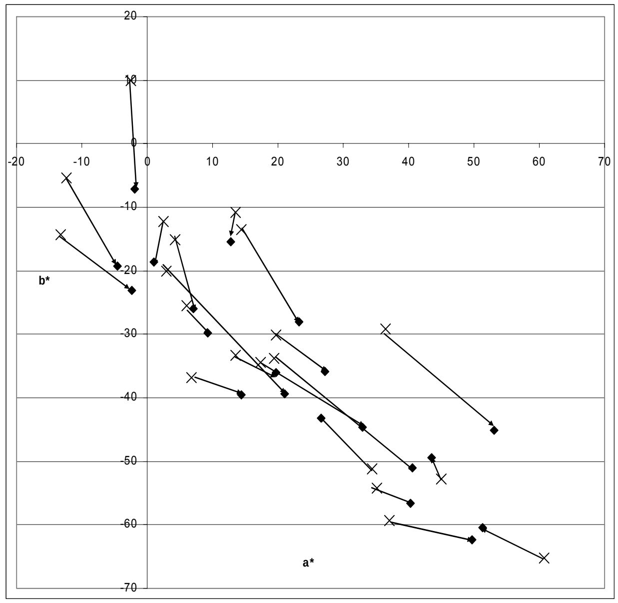


Figure 4.1.4 Chromaticity shifts found for sky colours in the mixing photo experiment. "x" – original colour, "♦" – mean of the colours mixed by the observers for an allotted original colour. Arrows show the colour shifts from the original colour to the mean actual colour found by the observers.

Table 4.1.4 Hue and chroma differences between the original and the mixed mean colours for each picture in the mixing picture experiment for sky colours.

No	Δh	ΔC
1	-5.39	-9.98
2	3.76	-12.72
3	-30.58	-6.01
4	10.87	-7.75
5	-15.37	-25.20
6	9.85	9.12
7	-44.63	-10.45
8	-6.92	-26.59
9	-2.04	-9.28
10	-3.52	-18.08
11	8.90	-17.02
12	-1.06	-5.11
13	7.17	8.67
14	47.81	-9.52
15	-0.76	-6.85
16	1.56	-23.06
17	3.44	-6.65
18	1.66	2.78
19	-2.16	-5.85
20	-139.30	-5.20
mean	**-7.84**	**-9.24**

Table 4.1.5 Mean actual colours and h_{ab} values for each sky colour for the L^* values that locates in the domain of the best matches.

Mean actual colours			
L^*	a^*	b^*	h_{ab}
43.82	49.67	-62.26	308.58
44.87	20.99	-39.30	298.11
51.59	26.60	-43.23	301.61
58.77	27.25	-35.78	307.29
42.65	32.99	-44.67	306.45
44.35	23.29	-28.07	309.68
38.24	40.27	-56.53	305.47
52.77	14.47	-39.50	290.12
39.73	43.55	-49.43	311.38
52.00	19.65	-36.04	298.60

For skin colours (Table 4.1.2) a similar effect can be observed as in case of sky colours: a smaller mean actual L^* value was found compared to the mean original L^* value. This effect is not as strong as in the sky colour case, but it is typical. If we look inside the table the following can be observed: if the value of L^* is found to be too small, i.e. the colour is dark, than the observers mixed a lighter skin colour, but if the original colour is light, they mixed a darker colour. From these observations an L^* range can be determined in which the prototypical L^* value can be found for skin colours. In Figure 4.1.5 the L^* values of original colours can be seen on the x axis, and the corresponding mean L^* values for mixed colours on the y axis. The straight line denotes the case where the lightness of the original colour is equal to that of mean mixed colour. The best matches can be found between the L^* value 45 and 70 of the original colours, where the mean mixed colours and the original colours are nearly the same. The prototypical L^* value of skin colour can be found in this range.

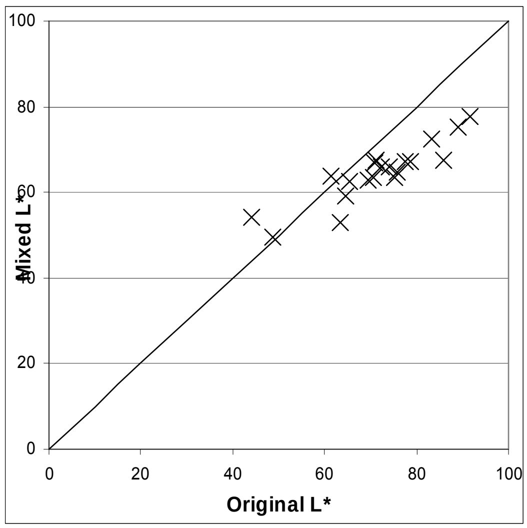


Figure 4.1.5 Mean L^* values of mixed colours in the function of the corresponding L^* values of the original colours for skin colours at the mixing picture experiment. The straight line denotes the perfect match.

For the a^* b^* values the following can be established: in case of the mean of all values a shift can be seen from a redder to a more yellowish hue. This shift is more conspicuous in Figure 4.1.6 where the original colours and the mean actual colours are presented in an a^*, b^* colour diagram. "x" depicts original colours, "♦" depicts mean actual or mixed colours. The arrows show the shift that occurs from the original to the mixed colour. It is clearly seen that the shifts tends to one domain, which contains the prototypical colour presumably. In case of skin colours the observers also mixed more saturated colours than the original colours but the intensity of the chroma shift is not as high as at sky colours. The hue and the chroma differences can be seen in Table 4.1.6, where $\Delta h=h_o-h_{mixed}$, and h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belonging to the original colour. $\Delta C=C_o-C_{mixed}$ where C_o

is the chroma value of the original colour, C_{mixed} is the chroma value of the mean of all mixed colours belonging to the original colour. The mean of all can be found in the last row.

The mean actual colours and h_{ab} values for each skin colour for the L^* values that locate in the domain of the best matches can be found in Table 4.1.7. The interval of h_{ab} values are between 48 and 77, and this domain can be regarded as the location of the prototypical colour of skin.

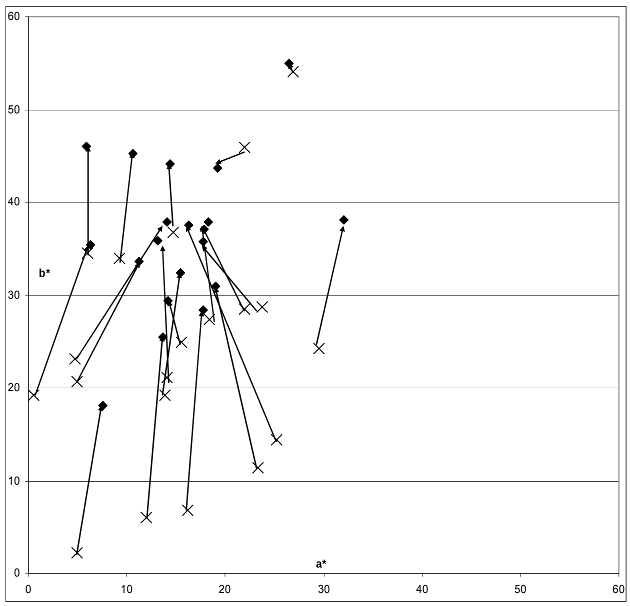


Figure 4.1.6 Chromaticity shifts found for skin colours in the mixing photo experiment. “x” – original colour, “♦” – mean of the colours mixed by the observers for an allotted original colour. Arrows show the colour shifts from the original colour to the mean actual colour found by the observers.

Table 4.1.6 Hue and chroma differences between the original and the mixed mean colours for each picture in the mixing picture experiment for skin colours. $\Delta h = h_o - h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belonging to the original colour. $\Delta C = C_o - C_{mixed}$ where C_o is the chroma value of the original colour, C_{mixed} is the chroma value of the mean of all mixed colours belonging to the original colour.

No	Δh	ΔC
1	1.05	-2.11
2	-11.01	-13.79
3	-25.58	-17.76
4	13.20	-18.50
5	-10.51	-6.24
6	-32.40	-17.71
7	6.78	-15.33
8	-42.05	-15.83
9	-4.51	-4.14
10	-10.45	-13.46
11	-8.59	-9.66
12	-8.90	-12.50
13	-0.75	-12.15
14	-34.02	-12.49
15	8.88	-16.83
16	-61.24	-12.22
17	-1.02	-12.01
18	-0.98	2.59
19	-12.28	-3.60
20	-2.51	-7.50
mean	**-11.85**	**-11.06**

Table 4.1.7 Mean actual colours and h_{ab} values for each skin colour for the L^* values that locates in the domain of the best matches.

Mean actual colours			
L*	***a****	***b****	h_{ab}
59.17	26.52	54.99	64.25
49.65	32.00	38.05	49.93
62.52	13.66	25.49	61.81
67.49	14.06	37.91	69.65
63.52	17.87	37.05	64.25
66.86	17.75	28.38	57.98
67.06	11.29	33.62	71.44
67.42	14.18	29.40	64.25
63.79	13.15	35.85	69.86
66.01	18.25	37.90	64.29
67.09	15.42	32.36	64.52
63.55	10.62	45.27	76.80
66.05	16.29	37.58	66.57
54.15	18.97	30.96	58.51
53.05	19.21	43.70	66.27
62.94	17.77	35.78	63.60
64.68	14.37	44.11	71.96

For grass colours (Table 4.1.3) a larger mean actual L^* value can be established compared to the mean original L^* value. If we look at the table the following can be observed: if the value of L^* is found to be too small, i.e. the colour is dark, then the observers mixed a lighter grass colour, but if the original colour is light, they mixed a darker colour. From these observations an L^* range can be determined in which the prototypical L^* value can be found for grass colours. In Figure 4.1.7 the L^* values of original colours can be seen on the x axis, and the corresponding mean L^* values for actual colours on the y axis. The straight line denotes the case where lightness of the original colour is equal to that of mean mixed colour. The domain of the best matches is wider and more difficult to determine than in case of the skin and sky colours. The best matches can be found between the L^* value 45 and 60 of the original colours, where the lightness of the mean mixed colours and of the original colours are nearly the same, but the scatter of the lightness values is large. The prototypical L^* value of grass colour can be found in this range.

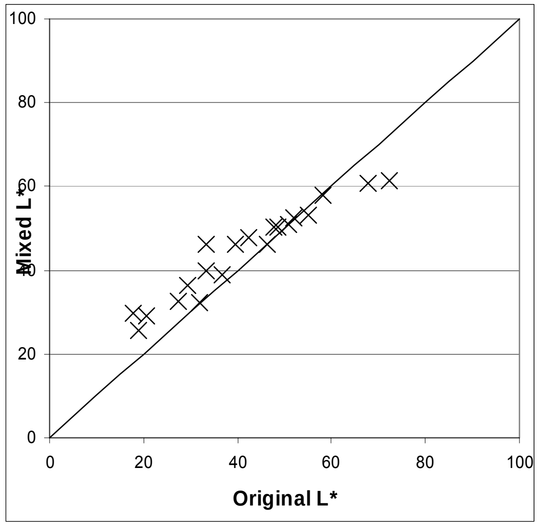


Figure 4.1.7 Mean L^* values of mixed colours in the function of the corresponding L^* values of the original colours for grass colours at the mixing picture experiment. The straight line denotes the perfect match.

For the a^*, b^* values the following can be established: in case of the mean of all values a shift can be seen from the yellower to the greener colours. This shift is more conspicuous in Figure 4.1.8 where the original colours and the mean actual colours are presented in an a^*, b^* colour diagram. "x" depicts original colours, "♦" depicts mean actual (or mixed) colours. The arrows show the shift that occurs from the original to the mixed colour. It is clearly seen that the shifts tends to one domain, which contains the prototypical colour presumably. A chroma increase is also observable, as seen also in case of sky colours, but the extremely high values are not acceptable. The hue and the chroma differences can be seen in Table 4.1.8, where $\Delta h=h_o-h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belonging to the original colour. $\Delta C=C_o-C_{mixed}$, where C_o is the chroma value of the original colour, C_{mixed} is the chroma value of the mean of all mixed colours belonging to the original colour. The mean of all can be found in the last row.

The mean actual colours and h_{ab} values for each grass colour for the L^* values that locates in the domain of the best matches can be found in Table 4.1.9. The interval of h_{ab} values are between 129 and 141, and this domain determines the location of the prototypical colour of grass and from this we might conclude that the prototypical grass colour has to fall into this range.

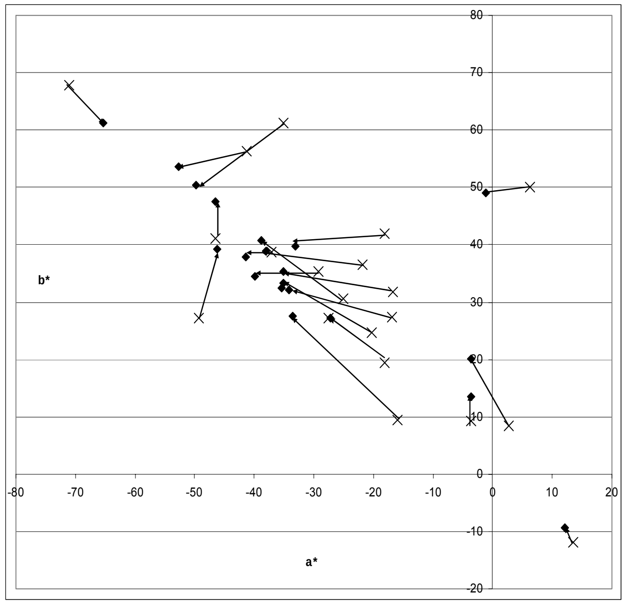


Figure 4.1.8 Chromaticity shifts found for grass colours in the mixing photo experiment. “x” – original colour, “♦” – mean of the colours mixed by the observers for an allotted original colour. Arrows show the colour shifts from the original colour to the mean actual colour found by the observers.

Table 4.1.8 Hue and chroma differences between the original and the mixed mean colours for each picture in the mixing picture experiment for grass colours. $\Delta h=h_o-h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belonging to the original colour. $\Delta C=C_o-C_{mixed}$ where C_o is the chroma value of the original colour, C_{mixed} is the chroma value of the mean of all mixed colours belonging to the original colour.

No	Δh	ΔC
1	-0.70	8.69
2	-8.92	-5.54
3	-7.75	-16.56
4	-1.92	-9.38
5	-5.09	-1.18
6	-17.36	-6.66
7	-46.01	-13.87
8	-15.32	-15.07
9	6.08	-25.30
10	-14.67	-16.77
11	10.43	-4.64
12	-5.24	-17.38
13	-15.31	-0.65
14	-13.90	-12.30
15	-4.23	-2.74
16	-9.70	-7.20
17	-18.48	-14.15
18	-2.50	-12.14
19	62.30	-7.90
20	3.84	-4.57
mean	**-5.22**	**-9.27**

Table 4.1.9 Mean actual colours and h_{ab} values for each grass colour for the L^* values that locates in the domain of the best matches.

Mean actual colours			
L^*	a^*	b^*	h_{ab}
60.72	-65.27	61.21	136.84
52.40	-52.66	53.54	134.53
46.10	-33.09	39.71	129.80
53.09	-33.61	27.47	140.74
50.36	-46.14	39.20	139.65
51.02	-38.82	40.71	133.64
57.86	-49.75	50.40	134.63
47.81	-38.08	38.80	134.46
50.25	-41.44	37.91	137.55
46.10	-39.81	34.51	139.08
46.34	-46.49	47.57	134.34

4.1.2 Results of the mixing colour patch experiment

In this experimental situation colour patches were visualized on the screen one after the other. The colours of the patches were equal to the original colours in the previous mixing photo experiment in Section 4.1.1. The observers' task was to mix the colour that was present in their mind about the original colour showed previously. The mixed colours of the observers in CIELAB values can be found in Appendix 5 for each colour patch. The position of the colours in an *a*, b** colour plane can be seen on Figure 4.1.9.

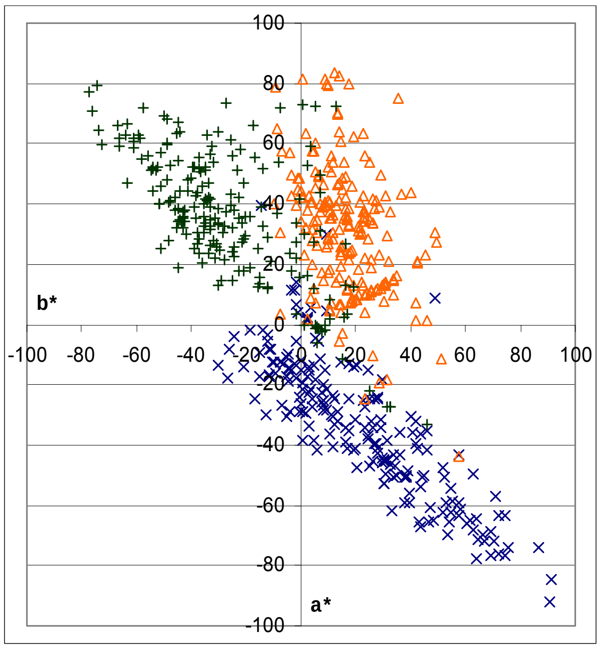


Figure 4.1.9 Results of mixing colour patch experiment. "x" signs – sky colours; "Δ" signs – skin colours; "+" signs – grass colours.

From Figure 4.1.1 and Figure 4.1.9, it can be seen that the spread of mixed or actual colours is bigger than the spread of the original colours. The scatter is greater in case of the mixed colours, which can be clearly seen in the figures. In Table 4.1.10 the mean values of the actual colours and the standard deviations are listed for each original colour for sky colours. The same values can be seen in Table 4.1.11 and Table 4.1.12 for skin and for grass colours. At the last row of each Table the mean values are presented.

Table 4.1.10 Mean actual colours and standard deviations for each sky type of original colour. Mean for all can be found in the last row.

	Original colours			**Mean actual colours**			**STD**		
	L*	***a****	***b****	***L****	***a****	***b****	***L****	***a****	***b****
1	45.70	37.03	-59.37	44.81	40.06	-57.36	5.36	20.00	14.89
2	82.57	4.24	-15.07	75.12	-1.49	-13.00	7.30	8.73	6.44
3	85.09	-13.24	-14.33	75.71	-6.71	-20.15	5.18	16.05	11.32
4	75.77	2.48	-12.19	75.35	1.55	-15.51	4.09	7.58	6.16
5	41.46	2.98	-19.98	45.97	22.89	-35.88	7.16	27.44	16.61
6	62.90	34.47	-51.21	59.11	18.51	-42.57	4.42	18.89	16.14
7	96.33	-12.31	-5.34	79.76	-6.33	-16.57	11.70	14.33	12.39
8	20.33	19.34	-33.74	22.73	44.72	-52.60	4.62	16.88	11.98
9	65.56	19.68	-30.07	63.10	23.14	-34.99	11.87	16.55	7.18
10	39.76	17.39	-34.34	42.83	32.24	-39.55	9.08	18.00	20.77
11	43.51	14.40	-13.48	43.94	25.54	-25.32	6.28	9.54	8.34
12	39.98	35.17	-54.23	36.47	45.29	-59.13	5.86	19.84	11.55
13	21.68	60.67	-65.14	29.12	67.61	-71.08	7.24	13.44	10.40
14	91.79	13.50	-10.74	80.57	16.11	-6.87	13.95	8.79	15.77
15	63.25	6.82	-36.82	60.48	10.32	-34.55	8.38	17.99	15.32
16	23.66	36.42	-29.23	33.97	47.96	-39.65	7.79	12.34	8.50
17	69.14	5.97	-25.54	67.50	3.99	-25.81	8.76	22.14	15.31
18	41.31	44.97	-52.72	45.34	48.65	-54.21	9.65	23.61	12.38
19	54.61	13.56	-33.30	57.01	12.59	-33.65	6.46	18.17	14.36
20	79.36	-2.53	9.96	78.40	-1.18	9.32	5.90	5.62	12.02
Mean	**57.19**	**17.05**	**-29.34**	**55.87**	**22.27**	**-33.46**	**7.55**	**15.80**	**12.39**

Table 4.1.11 Mean actual colours and standard deviations for each skin type of original colour. Mean for all can be found in the last row.

	Original colours			**Mean actual colours**			**STD**		
	L*	***a****	***b****	***L****	***a****	***b****	***L****	***a****	***b****
1	64.47	26.88	54.05	62.93	17.40	68.33	7.01	7.97	10.14
2	48.68	29.51	24.29	43.86	37.07	30.82	9.28	9.32	15.40
3	65.53	12.02	6.05	59.30	16.01	7.77	6.60	8.30	10.24
4	85.91	4.69	23.12	69.83	11.43	41.42	9.52	9.28	25.15
5	70.59	21.96	28.47	60.27	20.65	42.49	9.11	11.59	20.53
6	70.75	16.22	6.82	66.42	14.12	23.35	6.07	9.53	19.53
7	77.42	4.91	20.63	67.99	7.42	27.63	8.00	10.14	13.49
8	91.64	4.95	2.19	80.07	7.98	3.69	7.11	8.53	14.22
9	71.05	15.55	24.89	66.53	14.37	27.56	5.78	8.45	13.31
10	61.37	14.12	21.12	60.26	18.66	25.17	3.61	11.79	12.82
11	72.44	18.34	27.33	65.37	15.99	37.98	5.25	13.13	14.85
12	78.63	13.89	19.21	69.62	12.04	31.70	4.64	11.54	15.39
13	75.08	9.30	33.94	64.99	16.26	34.61	5.94	6.73	12.10
14	74.02	25.27	14.42	68.38	26.79	11.83	7.50	10.93	17.26
15	89.08	0.51	19.27	75.83	8.38	27.77	8.05	11.85	14.05
16	44.10	23.29	11.38	44.98	31.38	9.01	7.37	11.73	23.48
17	83.39	6.02	34.50	70.94	7.78	43.32	6.07	8.22	9.97
18	63.45	21.97	45.96	60.49	16.44	51.61	5.56	7.62	13.25
19	69.40	23.76	28.67	63.87	18.41	39.09	6.32	14.12	17.72
20	75.93	14.68	36.76	68.09	15.66	37.60	6.23	9.28	9.81
Mean	**71.65**	**15.39**	**24.15**	**64.50**	**16.71**	**31.14**	**6.75**	**10.00**	**15.13**

Table 4.1.12 Mean actual colours and standard deviations for each grass type of original colour. Mean for all can be found in the last row.

	Original colours			**Mean actual colours**			**STD**		
	L*	***a****	***b****	***L****	***a****	***b****	***L****	***a****	***b****
1	67.81	-71.09	67.80	66.28	-67.25	65.30	3.21	9.39	9.63
2	52.03	-41.22	56.36	52.63	-53.60	55.80	4.87	8.25	10.71
3	17.91	-20.26	24.71	21.05	-22.60	23.67	9.61	20.18	15.27
4	36.61	-27.60	27.28	40.27	-38.18	41.40	8.33	6.83	12.32
5	72.25	6.26	50.00	64.60	2.94	57.98	6.35	6.50	14.47
6	46.24	-18.05	41.90	48.94	-25.71	47.43	8.95	6.92	14.07
7	27.54	-3.61	9.20	26.25	-0.65	11.89	8.01	9.40	12.29
8	29.47	-16.91	27.42	32.37	-23.59	35.34	7.22	6.92	10.95
9	55.18	-16.00	9.47	57.72	-28.01	21.64	10.92	11.05	5.68
10	32.05	2.66	8.49	28.28	4.83	13.17	6.33	9.88	11.21
11	47.69	-49.28	27.21	48.14	-51.04	48.18	7.91	7.95	9.67
12	50.98	-25.08	30.56	51.99	-34.06	41.36	8.66	6.52	18.28
13	58.12	-35.15	61.21	59.59	-43.80	52.17	5.12	11.29	7.82
14	42.42	-21.79	36.57	46.01	-32.41	37.61	7.96	7.81	11.20
15	48.71	-37.02	38.68	54.41	-38.22	40.39	10.98	8.56	13.07
16	39.52	-29.25	35.29	45.48	-36.62	39.56	7.43	7.63	10.29
17	33.39	-16.66	31.78	37.75	-23.23	39.55	8.52	16.52	14.83
18	20.51	-18.10	19.44	25.68	-12.64	25.80	14.40	19.93	19.90
19	18.91	13.48	-11.84	16.23	22.05	-13.83	7.98	13.41	15.39
20	33.25	-46.55	41.11	40.57	-46.39	38.87	9.32	8.24	13.84
Mean	**41.53**	**-23.56**	**31.63**	**43.21**	**-27.41**	**36.16**	**8.10**	**10.16**	**12.54**

For sky colours (Table 4.1.10) smaller mean actual L^* value was found compared to the mean original L^* value but the difference is not significant. In Figure 4.1.10 the L^* values of original colours can be seen on the x axis, and the corresponding mean L^* values for mixed colours on the y axis. The straight line denotes the case where the original colour is equal to the mean mixed colour. Significant deviations can not be observed between the lightness values of the original and mixed colours.

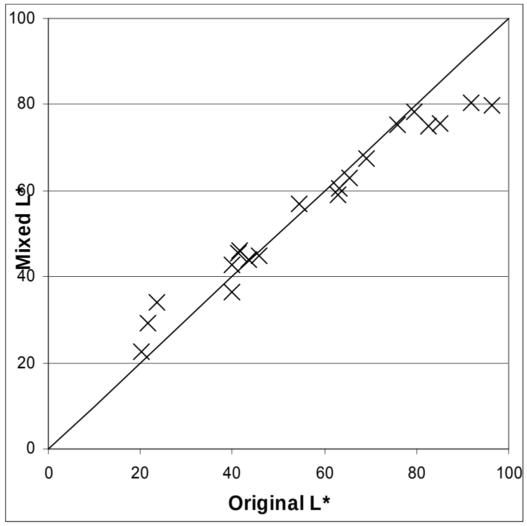


Figure 4.1.10 Mean L^* values of mixed colours in the function of the corresponding L^* values of the original colours for sky colours at the mixing colour patch experiment. The straight line denotes the perfect match.

For the a^* b^* values some tendencies can be observed, but it do not tend toward specific direction. This can be seen in Figure 4.1.11 where the original colours and the mean actual colour are presented in an a^*, b^* colour diagram. "x" depicts original colours, "♦" depicts mean actual (or mixed) colours. Some chroma shift can be seen to the more saturated regions, so the observers mixed more saturated colours. The hue and the chroma differences can be seen in Table 4.1.13, where $\Delta h = h_o - h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belonging to the original colour. $\Delta C = C_o - C_{mixed}$, where C_o is the chroma value of the original colour, C_{mixed} is the chroma value of the mean of all mixed colours belonging to the original colour. The mean of all can be found in the last row.

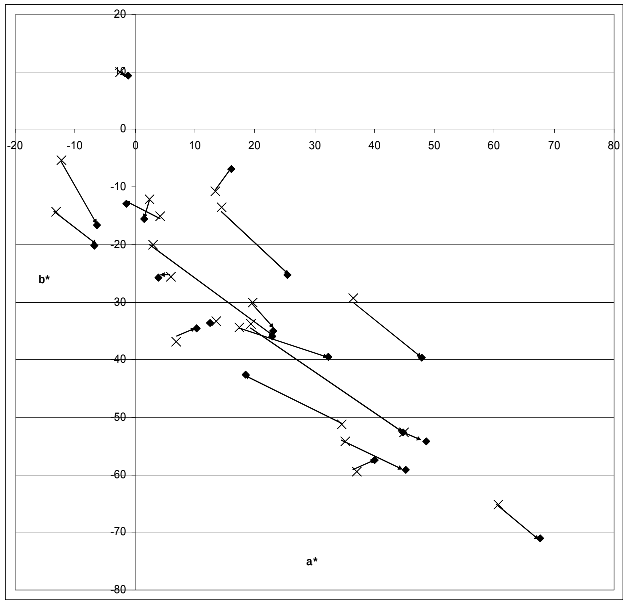


Figure 4.1.11 Chromaticity shifts found for sky colours in the mixing colour patch experiment. "x" – original colour, "♦" – mean of the colours mixed by the observers for an allotted original colour. Arrows show the colour shifts from the original colour to the mean actual colour found by the observers.

Table 4.1.13 Hue and chroma differences between the original and the mixed mean colours for each picture in the mixing colour patch experiment for sky colours. $\Delta h=h_o-h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belonging to the original colour. $\Delta C=C_o-C_{mixed}$ where C_o is the chroma value of the original colour, C_{mixed} is the chroma value of the mean of all mixed colours belonging to the original colour.

No	Δh	ΔC
1	0.24	-0.93
2	28.07	-0.15
3	-18.04	-6.07
4	13.50	-5.00
5	-15.48	-24.05
6	15.77	14.00
7	-35.33	-9.79
8	-9.44	-30.34
9	3.85	-8.19
10	24.95	-15.79
11	2.40	-16.35
12	-2.78	-10.33
13	-0.39	-9.15
14	82.79	-4.79
15	3.55	-1.48
16	1.14	-15.60
17	19.55	-6.54
18	2.40	-4.68
19	9.24	-1.73
20	-4.81	-0.90
mean	**6.06**	**-7.89**

For skin colours (Table 4.1.8) a smaller mean actual L^* value was found compared to the mean original L^* value. Except one value, all of the L^* values of the mean mixed colours are smaller than that of original colours. So, the observers mixed darker colours mostly. In Figure 4.1.12 the L^* values of original colours can be seen on the x axis, and the corresponding mean L^* values for mixed colours on the y axis. The straight line denotes the case where the original colour is equal to the mean mixed colour.

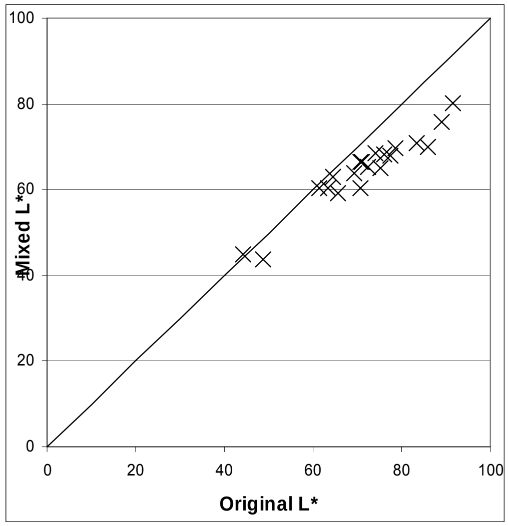


Figure 4.1.12 Mean L^* values of mixed colours in the function of the L^* values of the original colours for skin colours at the mixing colour patch experiment. The straight line denotes the perfect match.

For the a^* b^* values the following could be established: some kind of shift was found from the orange to yellower colours, but for the red colour this trend is not typical. In Figure 4.1.13 the original colours and the mean actual colour have been presented in an a^*, b^* colour diagram. “x” depicts original colours, “♦” depicts mean actual or mixed colours. The arrows show the shift that occurs from the original to the mixed colour. Some chroma increase can be noticed. The hue and chroma differences can be seen in Table 4.1.14, where $\Delta h=h_o-h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belonging to the original colour. $\Delta C=C_o-C_{mixed}$, where C_o is the chroma value of the original colour, C_{mixed} is the chroma value of the mean of all mixed colours belonging to the original colour. The mean of all can be found in the last row.

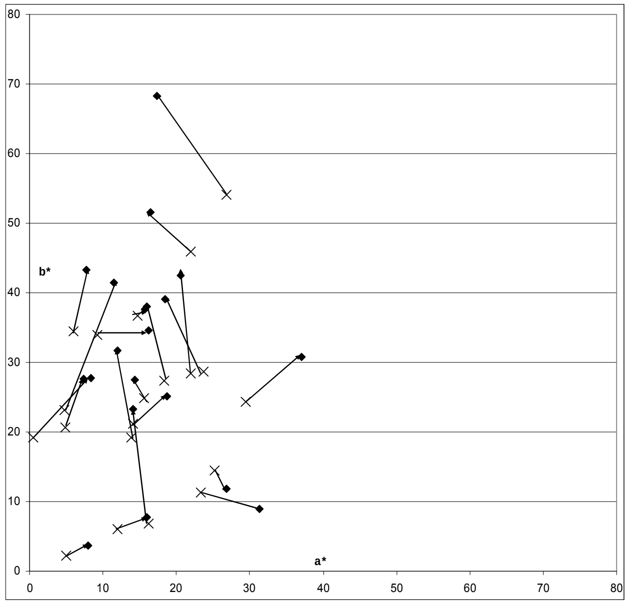


Figure 4.1.13 Chromaticity shifts found for skin colours in the mixing colour patch experiment. “x” – original colour, “♦” – mean of the colours mixed by the observers for an allotted original colour. Arrows show the colour shifts from the original colour to the mean actual colour found by the observers.

Table 4.1.14 Hue and chroma differences between the original and the mixed mean colours for each picture in the mixing colour patch experiment for skin colours. $\Delta h=h_o-h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belonging to the original colour. $\Delta C=C_o-C_{mixed}$, where C_o is the chroma value of the original colour, C_{mixed} is the chroma value of the mean of all mixed colours belonging to the original colour.

No	***Δh***	***ΔC***
1	-11.93	-10.57
2	0.89	-12.41
3	-40.32	-7.06
4	11.45	-21.85
5	-8.30	-14.12
6	-27.94	-13.57
7	9.04	-10.29
8	-123.53	-9.98
9	0.36	-4.14
10	3.45	-9.55
11	-8.39	-10.78
12	-9.72	-12.65
13	12.46	-4.51
14	-67.38	-5.22
15	19.22	-12.92
16	-63.92	-12.54
17	1.68	-9.91
18	-6.84	-4.00
19	-10.71	-9.34
20	1.90	-2.57
mean	**-15.93**	**-9.90**

For grass colours (Table 4.1.12) a larger mean actual L^* value was found compared to the mean original L^* value. If we look at the table the following can be observed: for most of the colours the L^* value of the mixed colour is larger than the L^* value of the original colour. In Figure 4.1.14 the L^* values of original colours can be seen on the x axis, and the corresponding mean L^* values for mixed colours on the y axis. The straight line denotes the case where the original colour is equal to the mean mixed colour.

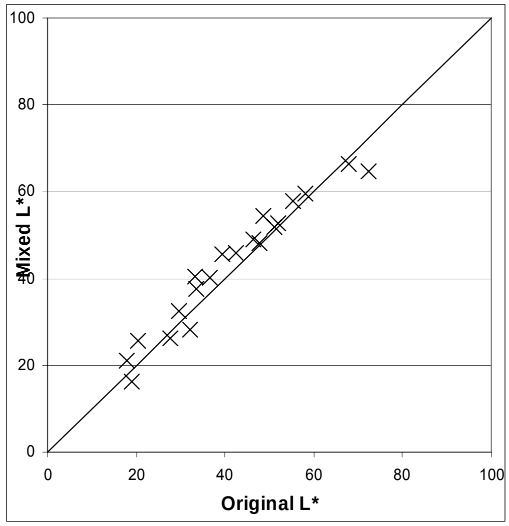


Figure 4.1.14 Mean L^* values of mixed colours in the function of the corresponding L^* values of the original colours for grass colours at the mixing colour patch experiment. The straight line denotes the perfect match.

For the a^* b^* values the following could be established: some kind of shift occurred, but the chroma increase is more significant. In Figure 4.1.15 the original colours and the mean actual colour are presented in an a^*, b^* colour diagram. "x" depicts original colours, "♦" depicts mean actual or mixed colours. The arrows show the shift that occurs from the original to the mixed colour. The hue and the chroma differences can be seen in Table 4.1.15, where $\Delta h=h_o-h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belonging to the original colour. $\Delta C=C_o-C_{mixed}$, where C_o is the chroma value of the original colour, C_{mixed} is the chroma value of the mean of all mixed colours belonging to the original colour. The mean of all can be found in the last row.

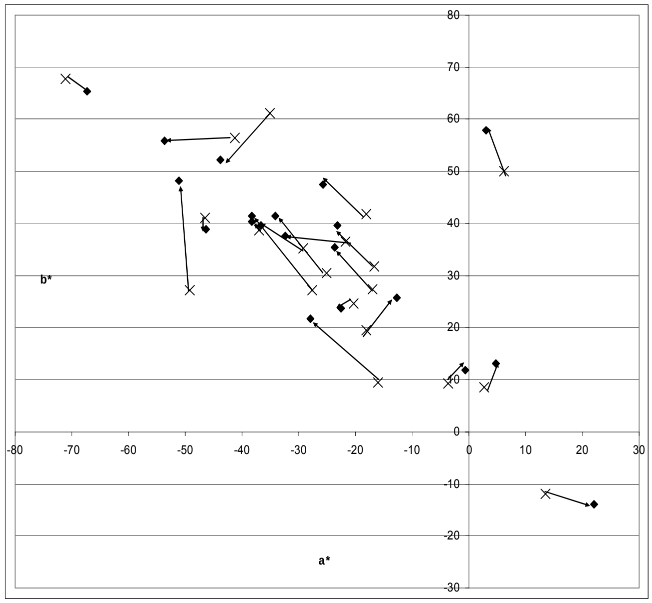


Figure 4.1.15 Chromaticity shifts found for grass colours in the mixing colour patch experiment. “x” – original colour, “♦” – mean of the colours mixed by the observers for an allotted original colour. Arrows show the colour shifts from the original colour to the mean actual colour.

Table 4.1.15 Hue and chroma differences between the original and the mixed mean colours for each original colour patch in the mixing picture experiment for grass colours. $\Delta h=h_o-h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belonging to the original colour. $\Delta C=C_o-C_{mixed}$ where C_o is the chroma value of the original colour, C_{mixed} is the chroma value of the mean of all mixed colours belonging to the original colour.

No	***Δh***	***ΔC***
1	0.50	4.36
2	-7.95	-7.82
3	-45.34	-4.62
4	1.97	-17.89
5	-3.59	-8.01
6	-6.04	-8.83
7	-56.17	-6.93
8	-3.26	-10.88
9	8.26	-17.15
10	-53.45	-9.21
11	14.27	-14.07
12	-2.56	-15.01
13	-9.89	1.56
14	-10.62	-7.64
15	-0.50	-3.20
16	-3.55	-8.51
17	-2.68	-11.89
18	-3.05	-5.83
19	50.58	-9.77
20	-2.55	1.21
mean	**-6.78**	**-8.01**

4.1.3 Comparison of the results in the first series of experiments

In the first experimental series the difference between the two experiments was only the absence or the presence of the photo-realistic images. In the literature, many observations can be found for the shift of the colours in a memory matching experiment. In this experiment my aim was to prove this memory shift with two kinds of experiments where different image contexts were used.

The presence of the memory shift has been confirmed. It can be seen well on Figure 4.1.4, 4.1.6 and 4.1.8. Comparing these Figures with Figure 4.1.11, 4.1.13 and 4.1.15 the following can be observed: on the results of the mixing photo experiment a strong orientation can be seen. This orientation is not so significant on the results of mixing colour patch experiment. This stronger hue shift can be caused by the presence of the photo-realistic images at the mixing photo experiment, because at the mixing colour patch experiment no pictures were shown. The lightness of the mixed colours in the mixing photo experiment tends to a lightness domain. This tending is weaker in case of the mixing colour patch experiment and this can be seen Table 4.1.16, where the STD values of the mixing colour patch experiment are bigger. Table 4.1.15 shows the result of a statistical analysis about the significance of the differences between mixing photo and mixing colour patch experiment. The results showed nearly normal distribution, so applying the statistical analysis was available. Significant differences can be seen in case of the lightness of the sky and in the hue angle at sky, skin and grass cases. In Table 4.1.16 mean and STD values of the results of the first series can be seen.

Table 4.1.15 Significance of the differences between the actual colours of mixing photo and mixing colour patch experiment. T-test. Bold numbers show significant differences, at the p=0.05 level

	Sky	**Skin**	**Grass**
<L*>	**0.025**	0.977	0.423
$\langle C_{ab} \rangle$	0.633	0.468	0.568
<h>	**0.006**	**0.000**	**0.013**

Table 4.1.16 Mean and STD values of the results in the first series of experiments

Colour		Experiment	Mean	STD
Sky	***L******	Photo	51.67	17.83
		Colour patch	55.87	19.43
	C_{ab}	Photo	43.31	27.85
		Colour patch	40.19	28.36
	h	Photo	302.49	33.39
		Colour patch	303.65	63.43
Skin	***L******	Photo	64.53	9.73
		Colour patch	64.50	10.67
	C_{ab}	Photo	41.03	15.79
		Colour patch	35.34	16.28
	h	Photo	64.57	16.72
		Colour patch	61.78	29.87
Grass	***L******	Photo	44.41	13.42
		Colour patch	43.21	16.34
	C_{ab}	Photo	52.03	21.10
		Colour patch	45.38	22.97
	h	Photo	122.57	41.26
		Colour patch	127.16	47.05

The basis of these observations is that in the mixing photo experiment, the presence of the photo-realistic image had an effect on the memorized original colour. This effect can be caused by the earlier experiences of the observers about the objects on the images. These experiences are stored in the memory with the colour of the object, and the observer unconsciously uses these experiences and not the original colour in mixing the actual colour and this shifts the colour toward to a long-term memory colour, or prototypical colour.

The experimental method I used here was not perfect. I got some feedback about that the smoothed colour at the mixing phase of the experiment may have had some effect on the results of the experiment. To make sure that this effect is not significant I had to set up a new experimental method, see Section 3.2. The results of the new experimental method can be read in the next section.

4.2 Results of the second experimental series

In the second experimental series (Section 3.2) I carried on the first experimental series. The result of the previous experiments showed that a memory shift exists if the observer knows about the object the colour of which has to be mixed. In the second experimental series I prove this assumption with the help of previously found long-term memory colours.

For sky and skin, Bartleson's[4] long-term memory colours, and for grass, a median colour from a previous experiment[25] have been picked out as a "primary" original colour. In the previous experiment constant hue, chroma and lightness intervals were defined. Having regard the median colours of the intervals and the general tendency of increasing of chroma and lightness values in the memory matching, for grass the primary original colour was selected that can be found in Table 4.2.1. Primary original colours were intended to represent a colour prototype for a given type (sky, skin, or grass). The aim of applying Bartleson's memory colours was that many experiments have been made in connection with memory colours after Bartleson's observation, and with making this experiment some comparisons could be made between the results. In addition, six (for sky) and seven (for grass and for skin) other original colours have been selected around the primary original at regular distances in the a^*, b^* plane (Figure 4.2.1). The original colours are enumerated in Table 4.2.1. The primary original colours are typed in bold letters. The same original colours were used in two parts of the experimental series: in the mixing greyscale photo-realistic images experiment and in the mixing colour patch experiment.

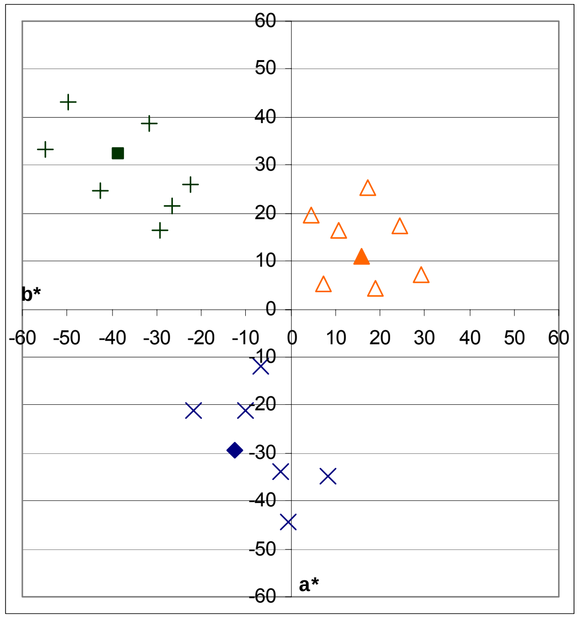


Figure 4.2.1 Original colours in the second experimental series. “x” signs – sky colours; “Δ” signs – skin colours; “+” signs – grass colours; The primary colours are accentuated in their groups.

Table 4.2.1 CIELAB values of original colours with the number of the colour in the second experimental series. Primary original colours are signed with bold letters.

	Sky				**Skin**				**Grass**		
	L*	***a****	***b****		***L****	***a****	***b****		***L****	***a****	***b****
3	49.49	-6.56	-11.98	**2**	**77.10**	**15.83**	**11.11**	**1**	45.02	-26.65	21.57
6	49.85	-9.95	-21.19	**5**	77.07	7.28	5.40	**4**	**45.39**	**-38.52**	**32.36**
9	**50.44**	**-12.48**	**-29.34**	**8**	77.08	24.49	17.33	**7**	45.65	-49.60	43.11
12	50.71	-0.39	-44.27	**11**	76.96	19.01	4.29	**10**	45.25	-29.27	16.38
15	50.37	-21.87	-21.18	**14**	77.02	10.86	16.27	**13**	45.46	-42.54	24.68
18	50.26	-2.31	-34.03	**17**	76.91	4.49	19.53	**16**	46.05	-54.82	33.19
21	49.98	8.45	-34.99	**20**	76.95	17.14	25.27	**19**	45.05	-22.54	25.83
				23	77.06	29.26	7.13	**22**	44.95	-31.64	38.81

4.2.1 Results of the mixing greyscale photo-realistic images (Bartleson) experiment

In this experiment, greyscale photo-realistic images were used as contexts. First, a greyscale photo containing one of the original colours was presented. The original colour was a uniform rectangular patch (subtending typically 2º times 2º) in a black frame, see Figure 3.2.1. There was no time limit to memorize it. From the 23 original colours 8 were of “grass” type, 8 of “Caucasian skin” type, and 7 were of “sky” type colours. These original colours were placed into the three corresponding greyscale images into the black rectangle. Six repetitions were applied for each type of original colours. In the mixing phase subjects’ task was to mix the colour they remembered with adjusting the hue, lightness, and saturation of the colour patch on the same photo until they got the colour they remembered. The initial colour of the adjustable colour patch was middle grey.

The visualized original colours and the photo-realistic images used as contexts can be seen in Figure 4.2.1 and Figure 3.2.1. The CIELAB values of the mixed colours of the observers can be found in Appendix 6 for each original colour shown in Table 4.2.1. The position of the colours in a *a*, b** colour plane can be seen on Figure 4.2.2.

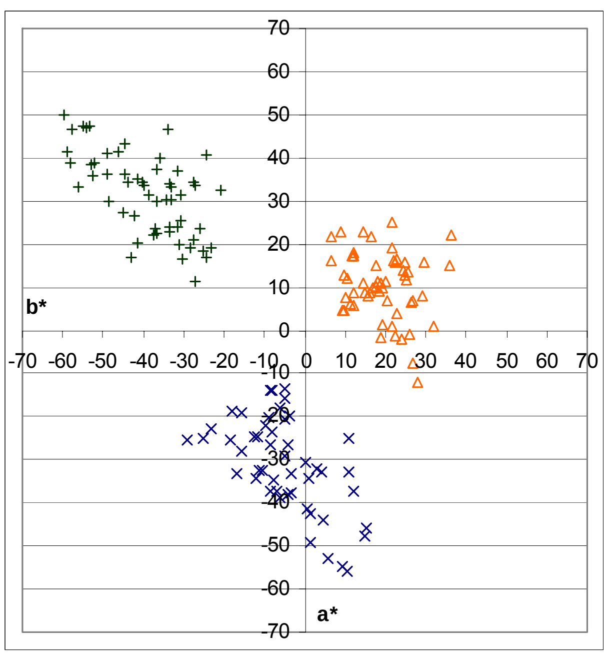


Figure 4.2.2 Results of mixing greyscale photo-realistic images experiment. “x” – sky colours; “Δ” – skin colours; “+” – grass colours.

The set of mixing colours is not spread in Figure 4.2.2. The numerical results confirm this observation in Table 4.2.2, where the mean actual colours and the standard deviations can be seen for each original sky colour. Corresponding values can be seen in Table 4.2.3 and Table 4.2.4 for skin and grass colours. In the last row of each table the mean values are presented.

Table 4.2.2 Mean actual colours and standard deviations for each sky type of original colour. Mean for all can be found in the last row.

	Original colours			**Mean actual colours**			**STD**		
	L*	***a****	***b****	***L****	***a****	***b****	***L****	***a****	***b****
3	49.49	-6.56	-11.98	48.71	-3.51	-18.46	5.12	6.71	4.28
6	49.85	-9.95	-21.19	48.97	-9.02	-21.95	4.76	4.80	5.29
9	**50.45**	**-12.48**	**-29.34**	55.08	-9.42	-33.97	4.54	5.85	5.52
12	50.71	-0.40	-44.27	51.50	0.97	-44.15	4.34	8.22	12.14
15	50.37	-21.87	-21.18	55.33	-18.59	-26.88	6.71	7.95	6.16
18	50.26	-2.31	-34.03	50.12	-3.17	-35.58	4.07	6.27	6.90
21	49.99	8.45	-34.99	51.08	8.35	-37.39	6.21	6.34	6.82
Mean	**50.16**	**-6.45**	**-28.14**	**51.54**	**-4.91**	**-31.20**	**5.11**	**6.59**	**6.73**

Table 4.2.3 Mean actual colours and standard deviations for each skin type of original colour. Mean for all can be found in the last row.

	Original colours			**Mean actual colours**			**STD**		
	L*	***a****	***b****	***L****	***a****	***b****	***L****	***a****	***b****
2	**77.10**	**15.83**	**11.11**	75.83	20.57	9.69	3.49	2.62	6.14
5	77.07	7.28	5.40	82.04	11.88	6.60	2.17	2.56	1.81
8	77.08	24.49	17.33	74.09	26.96	12.55	4.56	4.60	7.33
11	76.96	19.01	4.30	79.96	22.16	6.11	4.96	3.97	6.49
14	77.02	10.86	16.27	78.47	15.03	12.15	4.75	3.48	3.78
17	76.91	4.49	19.53	79.10	11.14	13.01	3.90	4.48	8.39
20	76.95	17.14	25.28	76.60	19.34	18.50	5.32	5.11	6.10
23	77.06	29.26	7.13	75.17	30.17	2.42	3.23	5.01	10.32
Mean	**77.02**	**16.05**	**13.29**	**77.66**	**19.66**	**10.13**	**4.05**	**3.98**	**6.29**

Table 4.2.4 Mean actual colours and standard deviations for each grass type of original colour. Mean for all can be found in the last row.

	Original colours			**Mean actual colours**			**STD**		
	L*	***a****	***b****	***L****	***a****	***b****	***L****	***a****	***b****
1	45.02	-26.65	21.57	48.48	-32.11	22.52	6.07	5.28	3.98
2	**45.39**	**-38.52**	**32.36**	47.95	-43.40	35.27	2.41	6.85	9.00
3	45.65	-49.60	43.11	48.95	-52.73	41.59	3.33	5.83	5.32
4	45.25	-29.27	16.38	45.68	-32.39	21.11	2.70	8.09	8.97
5	45.46	-42.54	24.68	46.67	-40.00	27.63	3.47	5.92	5.27
6	46.06	-54.82	33.19	48.68	-52.05	37.76	5.74	7.28	8.10
7	45.05	-22.54	25.82	45.36	-26.74	31.35	3.88	3.84	6.85
8	44.95	-31.64	38.81	46.18	-33.71	36.16	3.21	2.20	5.97
Mean	**45.35**	**-36.95**	**29.49**	**47.24**	**-39.14**	**31.67**	**3.85**	**5.66**	**6.68**

For sky colours some differences can be seen between the original and the mixed values. The L^* values of the mixed colours are larger than the L^* values of the original colours. Some chromaticity shift occurred, which can be seen on Figure 4.2.3. These shifts are in the blue-green region, and are oriented from the green to the blue axis. The hue and chroma differences between the original and the mixed mean colours can be seen in Table 4.2.5. In Table 4.2.5 $\Delta h = h_o - h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belongs to the original colour. $\Delta C = C_o - C_{mixed}$ where C_o is the chroma value of the original colour, C_{mixed} is the mean chroma value of all mixed colours belongs to the original colour. No significant chroma shift can be observed for the colours near the blue axis. Standard deviations of mixed hue and chroma values for each original colour are presented. The STD values of the hue are large. Results of a one sample t-test are shown in the last two columns. The results of the experiment showed nearly normal distribution, so applying the statistical analysis was available. A one sample t-test allows us to test whether a sample mean significantly differs from a hypothesized value. The hypothesized value here is the chroma and hue values of each original colour. Bold letters show significant differences, at the p=0.05 level. The significance of the hue shift can be seen in Table 4.2.6, where the results of a one sample t-test are shown. The hypothesized value here is the lightness, chroma and hue values of the primary original colour. Bold numbers show significant differences, at the p=0.05 level. The hue difference is significant in case of the primary original colour.

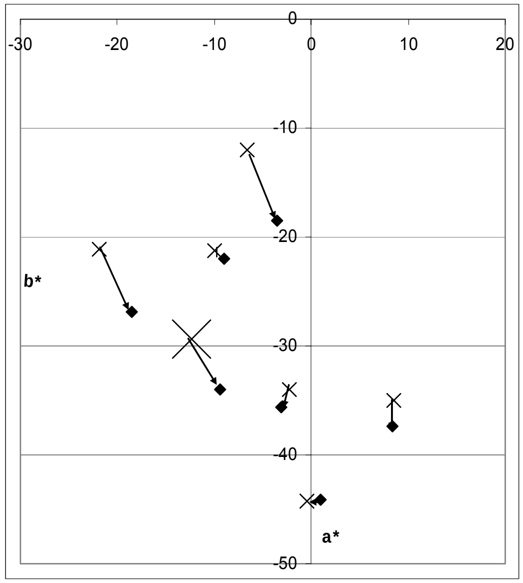


Figure 4.2.3 Chromaticity shift found for sky colours in the mixing greyscale photo-realistic image experiment. “x” – original colour, “♦” – mean of the colours mixed by the observers for an allotted original colour. Arrows show the colour shifts from the original colour to the mean actual colour found by the observers.

Table 4.2.5 Chroma and hue values of the original and the actual colours for each original colour and differences (ΔC, Δh) between them in the mixing greyscale photo-realistic image experiment for sky colours. Results of one sample t-test in the last two columns

	Original colours		**Mean actual colours**				**STD**		**p**	
	C*	***h***	***C****	***h***	***ΔC***	***Δh***	***C***	***h***	***C****	***h***
3	13.66	241.29	19.74	256.87	-6.08	-15.58	4.53	17.52	**0.012**	0.057
6	23.41	244.84	24.23	247.04	-0.82	-2.20	4.79	12.18	0.667	0.650
9	**31.88**	**246.96**	35.77	253.79	-3.88	-6.84	4.65	10.32	0.069	0.130
12	44.27	269.49	44.93	268.47	-0.65	1.01	11.65	12.97	0.886	0.843
15	30.44	224.08	33.68	235.10	-3.24	-11.02	4.83	14.58	0.126	0.092
18	34.11	266.12	36.25	263.91	-2.14	2.21	6.51	10.85	0.498	0.610
21	36.00	283.58	38.62	281.63	-2.62	1.95	7.70	8.09	0.403	0.547
mean	**30.54**	**253.77**	**33.32**	**258.12**	**-2.78**	**-4.35**	**6.38**	**12.36**		

Table 4.2.6 Significance of the difference between the primary original and all of the actual colours of sky. One sample t-test. Bold numbers show significant differences, at the p=0.05 level

	Sky
<L*>	0.169
<C_{ab}>	0.333
<h>	**0.000**

For skin colours some differences can be seen between the original and the mixed values. The mean $L*$ values are nearly the same. Some chromaticity shift occurred, which can be seen on Figure 4.2.4. These shifts are in the red-yellow region, and orient from the yellow to the red axis. Near the red axis few shifts occur to a more yellow region. The hue and chroma differences between the original and the mixed mean colours can be seen in Table 4.2.7. In Table 4.2.7 $\Delta h=h_o-h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belongs to the original colour. $\Delta C=C_o-C_{mixed}$ where C_o is the chroma value of the original colour, C_{mixed} is the mean chroma value of all mixed colours belongs to the original colour. Some chroma increase can be observed for the colours. The saturation of the mixed colours is larger than the saturation of the original colours. Standard deviations of mixed hue and chroma values for each original colour are presented. The STD values of the hue are large. Results of a one sample t-test are shown in the last two columns. The hypothesized values here are the chroma and hue values of each original colour. Bold letters show significant differences, at the p=0.05 level. In Table 4.2.8 the results of a one sample t-test is shown. The hypothesized values here are the lightness, chroma and hue values of the primary original colour. Bold numbers show significant differences, at the p=0.05 level. The chroma and hue difference is also significant in case of the primary original colour.

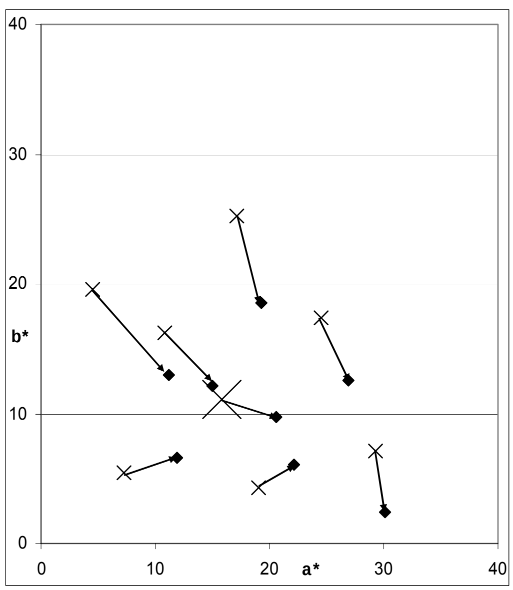


Figure 4.2.4 Chromaticity shifts found for skin colours in the mixing greyscale photo-realistic image experiment. “x” – original colour, “♦” – mean of the colours mixed by the observers for an allotted original colour. Arrows show the colour shifts from the original colour to the mean actual colour found by the observers.

Table 4.2.7 Chroma and hue values of the original and the actual colours for each original colour and differences (ΔC, Δh) between them in the mixing greyscale photo-realistic image experiment for skin colours. Results of one sample t-test in the last two columns

	Original colours		**Mean actual colours**				**STD**		**p**	
	C*	***h***	***C****	***h***	***ΔC***	***Δh***	***C***	***h***	***C****	***h***
2	**19.34**	**35.05**	23.38	24.21	-4.04	10.84	3.12	15.18	**0.014**	0.108
5	9.06	36.57	13.62	28.85	-4.55	7.73	3.00	3.96	**0.007**	**0.002**
8	30.01	35.29	30.37	24.18	-0.37	11.11	5.50	13.35	0.867	0.070
11	19.49	12.74	23.67	14.96	-4.17	-2.22	4.57	14.82	0.052	0.705
14	19.56	56.28	19.80	38.99	-0.24	17.29	2.18	13.46	0.780	**0.015**
17	20.04	77.07	18.99	46.83	1.05	30.24	3.43	27.61	0.451	**0.027**
20	30.54	55.86	27.59	43.82	2.95	12.04	3.34	15.48	0.058	0.085
23	30.12	13.70	31.78	4.12	-1.66	9.58	4.67	19.67	0.384	0.245
mean	**22.27**	**40.32**	**23.65**	**28.24**	**-1.38**	**12.07**	**3.73**	**15.44**		

Table 4.2.8 Significance of the difference between the primary original and actual colours of skin. One sample t-test. Bold numbers show significant differences, at the p=0.05 level

	Skin
<L*>	0.374
<C_{ab}>	**0.000**
<h>	**0.017**

For grass colours some differences can be seen between the original and the mixed values. The observers shifted the lightness of the mixed colour to a larger value. The chromaticity shifts can be seen in Figure 4.2.5. The mean hue shift is very small. The mean chroma shift is more significant; the observers shifted the saturation of the mixed colour to a larger value. The hue and chroma differences between the original and the mixed mean colours can be seen in Table 4.2.9. In Table 4.2.9 $\Delta h=h_o-h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belongs to the original colour. $\Delta C=C_o-C_{mixed}$ where C_o is the chroma value of the original colour, C_{mixed} is the mean chroma value of all mixed colours belongs to the original colour. Standard deviations of mixed hue and chroma values for each original colour are presented. The STD values of hue are smaller than at sky and skin colours. Results of a one sample t-test are shown in the last two columns. The hypothesized value here is the chroma and hue values of each original colour. Bold letters show significant differences, at the p=0.05 level. No significance of the hue and chroma values can be seen in Table 4.2.10, where the results of a one sample t-test are shown. The hypothesized value here is the lightness, chroma and hue values of the primary original colour. Bold numbers show significant differences, at the p=0.05 level. No significant hue and chroma difference can be observed, so this colour can be regarded as a good representative of the observers' prototypical colour.

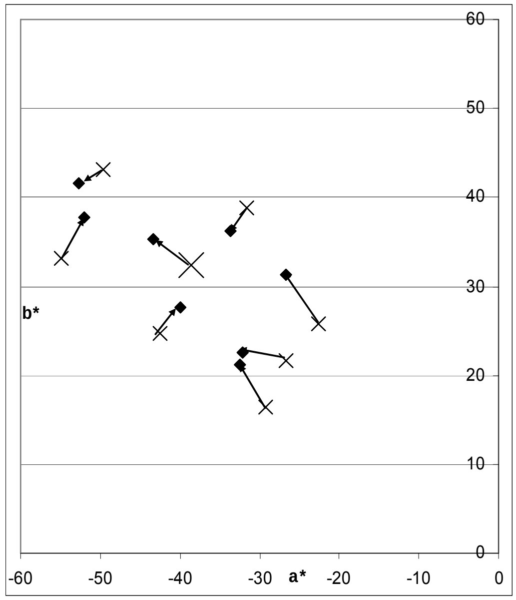


Figure 4.2.5 Chromaticity shifts found for grass colours in the mixing greyscale photo-realistic image experiment. "x" – original colour, "♦" – mean of the colours mixed by the observers for an allotted original colour. Arrows show the colour shifts from the original colour to the mean actual colour found by the observers.

Table 4.2.9 Hue and chroma differences between the original and the mixed mean colours for each original colour in the mixing greyscale photo-realistic image experiment for grass colours. Results of one sample t-test in the last two columns.

	Original colours		**Mean actual colours**				**STD**		**p**	
	C*	***h***	***C****	***h***	***ΔC***	***Δh***	**C**	***h***	***C****	***h***
1	**34.29**	**141.02**	39.30	144.87	-5.02	-3.85	6.00	4.00	0.069	**0.044**
4	50.31	139.96	56.04	141.37	-5.73	-1.40	10.63	4.10	0.204	0.399
7	65.72	139.01	67.23	141.75	-1.51	-2.74	7.16	2.84	0.598	**0.043**
10	33.55	150.76	39.07	147.55	-5.52	3.21	10.44	8.61	0.211	0.363
13	49.18	149.88	48.79	145.37	0.39	4.51	6.56	5.20	0.880	0.062
16	64.09	148.81	64.43	144.31	-0.34	4.50	10.00	3.80	0.932	**0.020**
19	34.28	131.11	41.53	130.98	-7.26	0.13	5.42	8.08	**0.012**	0.967
22	50.07	129.19	49.55	133.28	0.52	-4.09	5.14	4.26	0.799	**0.044**
mean	**47.68**	**141.22**	**50.74**	**141.19**	**-3.06**	**0.03**	**7.67**	**5.11**		

Table 4.2.10 Significance of the difference between the primary original and actual colours of grass. One sample t-test. Bold numbers show significant differences, at the *p*=0.05 level

	Grass
<L*>	**0.001**
<C_{ab}>	0.801
<h>	0.233

4.2.2 Results of the mixing colour patch (Bartleson) experiment

In this experimental situation alone standing colour patches were visualized on the screen one after the other. The six observers' task was to mix the colour that was presented in their mind about the original colour showed previously. The original colours and the task of the observers were the same as in the previous experiment (Section 4.2.2). The original colours can be seen in Figure 4.2.1. The mixed colours of the observers in CIELAB values can be found in Appendix 7 for each original colour shown in Table 4.2.1. The position of the colours in a *a*, b** colour diagram can be seen on Figure 4.2.6.

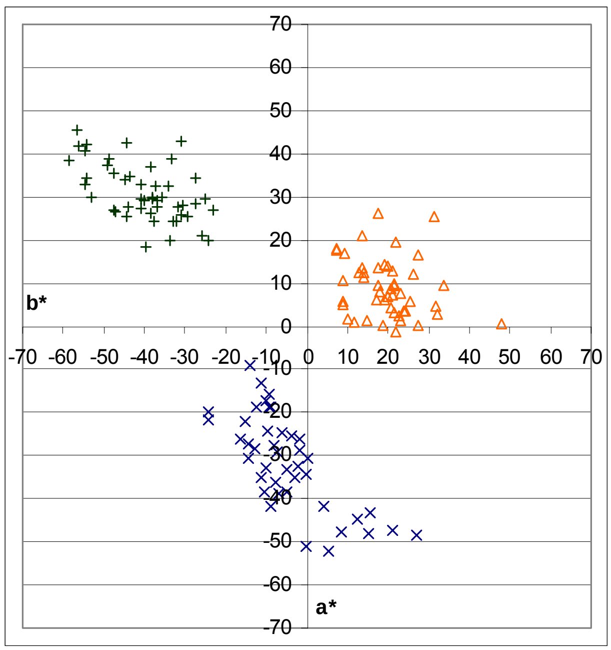


Figure 4.2.6 Results of mixing colour patch (Bartleson) experiment. "x" – sky colours; "Δ" – skin colours; "+" – grass colours.

The set of mixed colours is not spread in Figure 4.2.6. The mixed colours locate near around the original colours. The numerical results confirm this observation in Table 4.2.11, where the mean actual colours and the standard deviations can be seen for each original sky colour. Similar values can be seen in Table 4.2.12 and Table 4.2.13 for skin and grass colours. At the last row of each table the mean values are presented. The results showed nearly normal distribution, so applying statistical analysis was available.

Table 4.2.11 Mean actual colours and standard deviations for each sky type of original colour. Mean for all can be found in the last row.

	Original colours			Mean actual colours			STD		
	L*	***a****	***b****	***L****	***a****	***b****	***L****	***a****	***b****
3	49.49	-6.56	-11.98	50.64	-10.50	-15.48	7.07	1.99	3.78
6	49.85	-9.95	-21.19	50.53	-6.94	-24.92	5.21	3.83	3.53
9	**50.45**	**-12.48**	**-29.34**	52.31	-10.06	-31.88	4.48	7.62	5.21
12	50.71	-0.40	-44.27	51.95	-1.09	-43.88	4.67	7.23	7.27
15	50.37	-21.87	-21.18	53.84	-15.01	-27.45	4.47	6.13	6.67
18	50.26	-2.31	-34.03	53.53	-4.45	-32.92	4.98	6.40	6.97
21	49.99	8.45	-34.99	50.73	15.23	-44.41	6.32	9.09	5.38
Mean	**50.16**	**-6.45**	**-28.14**	**51.93**	**-4.69**	**-31.56**	**5.31**	**6.04**	**5.54**

Table 4.2.12 Mean actual colours and standard deviations for each skin type of original colour. Mean for all can be found in the last row.

	Original colours			Mean actual colours			STD		
	L*	***a****	***b****	***L****	***a****	***b****	***L****	***a****	***b****
2	**77.10**	**15.83**	**11.11**	80.63	19.61	7.80	2.88	4.62	5.46
5	77.07	7.28	5.40	83.49	12.14	2.46	1.82	3.99	2.35
8	77.08	24.49	17.33	80.20	23.75	12.21	2.38	2.62	5.53
11	76.96	19.01	4.30	81.46	22.68	3.66	1.78	1.88	3.47
14	77.02	10.86	16.27	81.13	17.85	10.62	2.28	3.72	2.84
17	76.91	4.49	19.53	82.63	11.53	12.54	2.33	5.31	5.65
20	76.95	17.14	25.28	79.59	19.55	18.07	2.17	6.43	7.09
23	77.06	29.26	7.13	79.84	28.09	4.54	2.80	4.96	3.47
Mean	**77.02**	**16.05**	**13.29**	**81.12**	**19.40**	**8.99**	**2.30**	**4.19**	**4.48**

Table 4.2.13 Mean actual colours and standard deviations for each grass type of original colour. Mean for all can be found in the last row.

	Original colours			Mean actual colours			STD		
	L*	***a****	***b****	***L****	***a****	***b****	***L****	***a****	***b****
1	45.02	-26.65	21.57	50.56	-31.14	23.98	4.62	7.00	2.99
2	**45.39**	**-38.52**	**32.36**	51.72	-42.05	31.75	4.74	4.87	4.92
3	45.65	-49.60	4.54	48.88	-48.82	35.24	3.50	4.59	5.74
4	45.25	-29.27	16.38	50.24	-35.74	26.85	5.71	3.52	4.44
5	45.46	-42.54	24.68	49.67	-41.17	26.84	3.89	4.54	6.27
6	46.06	-54.82	33.19	50.11	-55.41	38.61	3.02	2.00	5.75
7	45.05	-22.54	25.82	51.42	-29.12	30.09	4.61	6.24	3.01
8	44.95	-31.64	38.81	49.38	-35.70	34.42	4.81	4.36	5.70
Mean	**45.35**	**-36.95**	**24.67**	**50.25**	**-39.89**	**30.97**	**4.36**	**4.64**	**4.85**

For sky colours some differences can be seen between the original and the mixed values. The L^* values are somewhat larger in case of the mixed colours. Some chromaticity shift occurred, which can be seen on Figure 4.2.7. The hue shifts don't show determining orientation. The hue and chroma differences between the original and the mixed mean colours can be seen in Table 4.2.14. In the table, $\Delta h=h_o-h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belongs to the original colour. $\Delta C=C_o-C_{mixed}$ where C_o is the chroma value of the original colour, C_{mixed} is the chroma value of the mean of all mixed colours belongs to the original colour. Chroma increase can be observed for the mixed colours. Standard deviations of mixed hue and chroma values for each original colour are presented. The STD values of the hue are large. Results of a one sample t-test are shown in the last two columns. The hypothesized value here is the chroma and hue values of each original colour. Bold numbers show significant differences, at the p=0.05 level. In Table 4.2.15 the results of a one sample t-test is shown. The hypothesized value here is the lightness, chroma and hue values of the primary original colour. Significant hue difference can be observed.

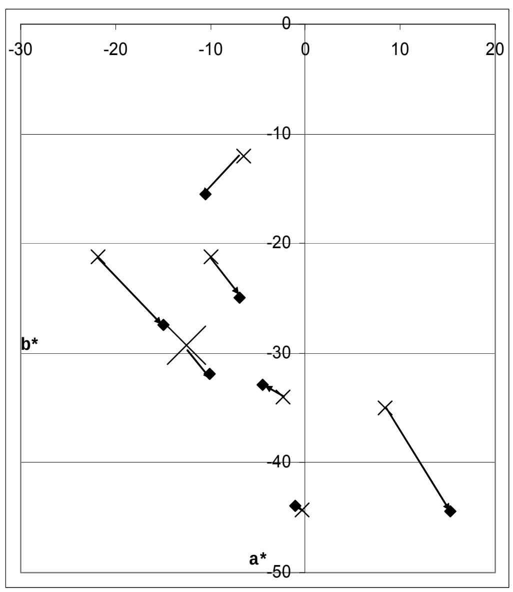


Figure 4.2.7 Chromaticity shifts found for sky colours in the mixing colour patch experiment. “x” – original colour, “♦” – mean of the colours mixed by the observers for an allotted original colour. Arrows show the colour shifts from the original colour to the mean actual colour.

Table 4.2.14 Chroma and hue values of the original and the actual colours for each original colour and differences (ΔC, Δh) between them in the mixing colour patch experiment for sky colours. Results of one sample t-test in the last two columns

	Original colours		Mean actual colours				STD		p	
	*C**	*h*	*C**	*h*	*ΔC*	*Δh*	*C*	*h*	*C**	*h*
3	13.66	241.29	19.03	234.94	-5.37	6.35	1.81	12.12	**0.001**	0.256
6	23.41	244.84	26.21	253.81	-2.80	-8.98	2.45	10.42	**0.038**	0.089
9	**31.88**	**246.96**	34.42	252.09	-2.54	-5.14	2.03	15.65	**0.028**	0.458
12	44.27	269.49	44.41	267.64	-0.14	1.85	7.11	9.60	0.963	0.657
15	30.44	224.08	32.15	240.29	-1.71	-16.21	4.03	14.07	0.345	**0.037**
18	34.11	266.12	33.74	261.89	0.37	4.24	6.87	10.96	0.901	0.388
21	36.00	283.58	47.46	287.66	-11.46	-4.08	7.36	9.93	**0.012**	0.360
mean	**30.54**	**253.77**	**33.92**	**256.90**	**-3.38**	**-3.14**	**4.52**	**11.82**		

Table 4.2.15 Significance of the difference between the primary original and actual colours of sky. One sample t-test. Bold numbers show significant differences, at the p=0.05 level

	Sky
<L*>	0.069
<C_{ab}>	0.208
<h>	**0.002**

For skin colours some differences can be seen between the original and the mixed values. The L^* values are larger for the mean actual colours and chromaticity shift occurred, which can be seen on Figure 4.2.8. These shifts are in the red-yellow region, and orient form the yellow to the red axis, so the observers mixed a redder colour than the original. The hue and chroma differences between the original and the mixed mean colours can be seen in Table 4.2.16. In the table, $\Delta h=h_o-h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belongs to the original colour. $\Delta C=C_o-C_{mixed}$ where C_o is the chroma value of the original colour, C_{mixed} is the chroma value of the mean of all mixed colours belongs to the original colour. Hue shift can be observed for the colours. Standard deviations of mixed hue and chroma values for each original colour are presented. The STD values of the hue are large. Results of a one sample t-test are shown in the last two columns. The hypothesized value here is the chroma and hue values of each original colour. Bold numbers show significant differences, at the p=0.05 level. Significant hue differences can be observed. In Table 4.2.17 the results of a one sample t-test is shown. The hypothesized value here is the lightness, chroma and hue values of the primary original colour. Significant lightness, hue and chroma difference can be observed.

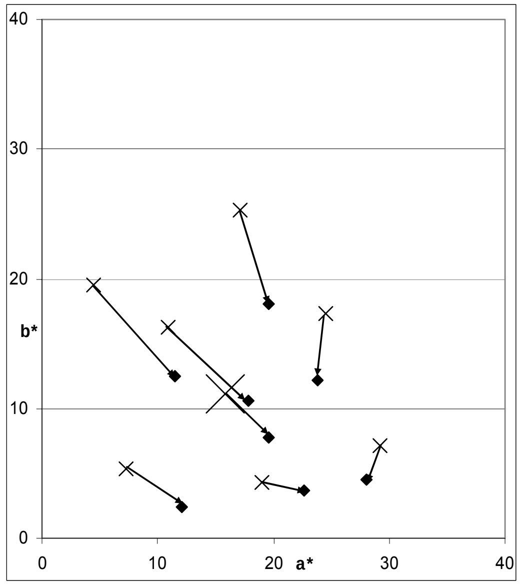


Figure 4.2.8 Chromaticity shifts found for skin colours in the mixing colour patch experiment. "x" – original colour, "♦" – mean of the colours mixed by the observers for an allotted original colour. Arrows show the colour shifts from the original colour to the mean actual colour.

Table 4.2.16 Chroma and hue values of the original and the actual colours for each original colour and differences (*ΔC, Δh*) between them in the mixing colour patch experiment for skin colours. Results of one sample t-test in the last two columns

	Original colours		**Mean actual colours**				**STD**		**p**	
	C*	***h***	***C****	***h***	***ΔC***	***Δh***	***C***	***h***	***C****	***h***
2	**19.34**	**35.05**	21.93	23.04	-2.59	12.01	2.85	17.09	0.076	0.146
5	9.06	36.57	12.69	13.67	-3.62	22.90	3.52	14.09	0.053	**0.011**
8	30.01	35.29	27.12	26.60	2.88	8.69	3.30	11.15	0.085	0.115
11	19.49	12.74	23.19	9.09	-3.70	3.64	1.78	8.88	**0.004**	0.361
14	19.56	56.28	21.06	31.35	-1.49	24.93	2.70	10.71	0.231	**0.002**
17	20.04	77.07	18.32	47.31	1.72	29.75	2.37	23.07	0.137	**0.025**
20	30.54	55.86	27.12	42.14	3.42	13.71	7.73	12.25	0.327	**0.041**
23	30.12	13.70	28.61	8.98	1.51	4.72	5.10	6.67	0.502	0.144
mean	**22.27**	**40.32**	**22.51**	**25.27**	**-0.23**	**15.04**	**3.67**	**12.99**		

Table 4.2.17 Significance of the difference between the primary original and actual colours of skin. One sample t-test. Bold numbers show significant differences, at the p=0.05 level

	Skin
<L*>	**0.000**
<C_{ab}>	**0.001**
<h>	**0.001**

For grass colours some differences can also be seen between the original and the mixed values. The $L*$ values are larger for the actual colours than the original colours. The chromaticity shifts can be seen in Figure 4.2.18. The hue shift is very small. The chroma shift is more significant; the observers shifted the saturation of the mixed colour to a larger value. The hue and chroma differences between the original and the mixed mean colours can be seen in Table 4.2.18. In the table, $\Delta h=h_o-h_{mixed}$, where h_o is the hue value of the original colour, h_{mixed} is the hue value of the mean of all mixed colours belongs to the original colour. $\Delta C=C_o-C_{mixed}$ where C_o is the chroma value of the original colour, C_{mixed} is the chroma value of the mean of all mixed colours belongs to the original colour. Chroma increase can be observed for the colours. Standard deviations of mixed hue and chroma values for each original colour are presented. The STD values of the hue are smaller than in case of sky and skin colours. Results of a one sample t-test are shown in the last two columns. The hypothesized value here is the chroma and hue values of each original colour. Bold numbers show significant differences, at the p=0.05 level. In Table 4.2.19 the results of a one sample t-test is shown. The hypothesized value here is the lightness, chroma and hue values of the primary original colour. Significant hue and lightness difference can be observed.

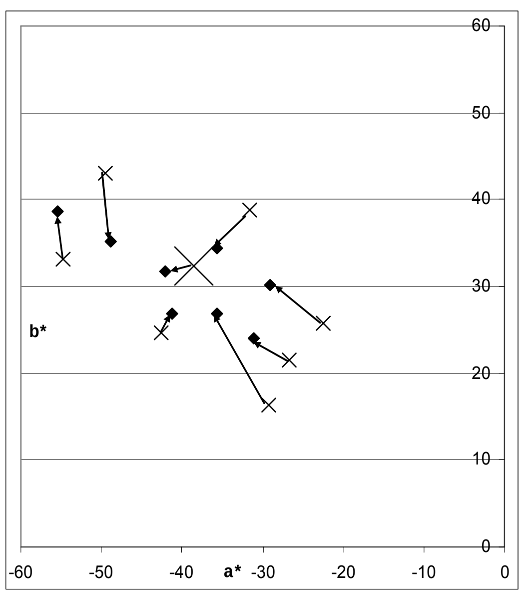


Figure 4.2.18 Chromaticity shifts found for grass colours in the mixing colour patch experiment. “x” – original colour, “♦” – mean of the colours mixed by the observers for an allotted original colour. Arrows show the colour shifts from the original colour to the mean actual colour.

Table 4.2.13 Hue and chroma differences between the original and the mixed mean colours for each original colour in the mixing colour patch experiment for grass colours.

	Original colours		**Mean actual colours**				**STD**		**p**	
	C*	***h***	***C****	***h***	***ΔC***	***Δh***	***C****	***h***	***C****	***h***
1	**34.29**	**141.02**	39.37	142.01	-5.08	-1.00	7.23	3.16	0.146	0.476
4	50.31	139.96	52.84	142.96	-2.53	-3.00	5.41	4.63	0.304	0.174
7	65.72	139.01	60.41	144.27	5.31	-5.26	4.99	5.16	**0.048**	0.055
10	33.55	150.76	44.81	143.22	-11.26	7.54	4.59	4.32	**0.002**	**0.008**
13	49.18	149.88	49.29	147.18	-0.11	2.70	6.54	4.89	0.969	0.234
16	64.09	148.81	67.65	145.30	-3.56	3.51	4.36	3.65	0.102	0.065
19	34.28	131.11	42.01	133.69	-7.74	-2.58	5.85	4.84	**0.023**	0.249
22	50.07	129.19	49.89	136.20	0.18	-7.01	3.93	6.82	0.915	0.053
mean	**47.68**	**141.22**	**50.78**	**141.85**	**-3.10**	**-0.64**	**5.36**	**4.68**		

Table 4.2.19 Significance of the difference between the primary original and actual colours of grass. One sample t-test. Bold numbers show significant differences, at the *p*=0.05 level

	Grass
<L*>	**0.000**
<C_{ab}>	0.752
<h>	**0.040**

4.2.3 Results of the abstract photo experiment

This experiment was not a memory matching experiment, but a preference experiment. The aim of this experiment was to get the preference colours for grass, Caucasian skin and sky objects, and to compare them with the results of the memory matching experiments. Four observers took part in the experiment. In the experimental process the observers saw a greyscale photo-realistic image on the screen. On the images common objects (sky, skin, and grass) were shown. The same greyscale photo-realistic images were applied as in the mixing greyscale photo-realistic images (Bartleson) experiment, except that there were no original colours in the viewing situations. The subjects were asked to adjust the hue, lightness, and saturation of the colour patch on the photo until they got the colour that in their opinion was best suited for the object that was shown on the image. The initial colour of the adjustable colour patch was middle grey. The observers mixed the best suited colours 6-times for each type of greyscale photo-realistic images (Figure 3.2.1).

The mean values of the mixed colours for all observers can be seen in Figure 4.2.10. Mean mixed colours and STD values can be seen in Table 4.2.20-22.

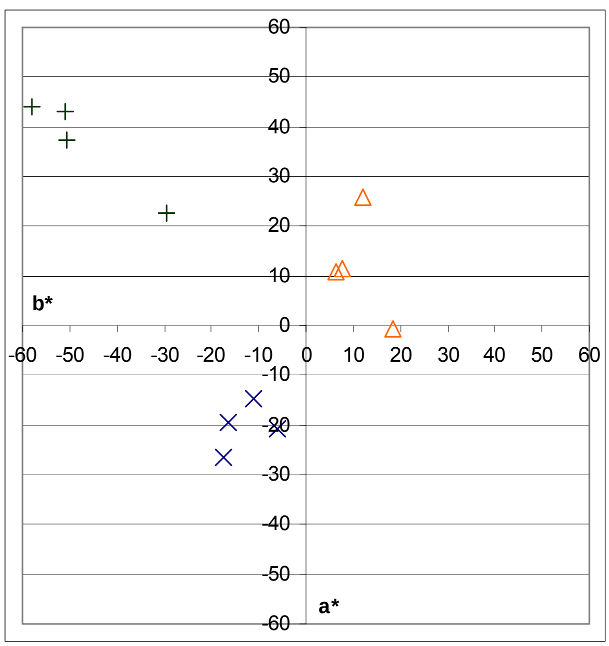


Figure 4.2.10 Results of abstract photo experiment. “x” – sky colours; “Δ” – skin colours; “+” – grass colours.

Table 4.2.20 Mean mixed preferred colours in the abstract photo experiment for each observer for sky colours. Mean for all and standard deviations can be seen in the last two rows.

No. of the observer	Mean			STD		
	*L**	*a**	*b**	*L**	*a**	*b**
1.	83.49	-6.00	-20.76	2.80	1.81	4.07
2.	80.01	-16.51	-19.51	4.69	5.63	5.45
3.	56.86	-17.28	-26.63	4.95	3.88	4.52
4.	65.47	-10.97	-14.56	5.71	8.11	5.68
Mean	**71.46**	**-12.69**	**-20.36**	**4.54**	**4.86**	**4.93**
STD	**12.47**	**5.27**	**4.96**			

Table 4.2.21 Mean mixed preferred colours in the abstract photo experiment for each observer for skin colours. Mean for all and standard deviations can be seen in the last two rows.

No. of the observer	Mean			STD		
	*L**	*a**	*b**	*L**	*a**	*b**
1.	79.54	12.11	25.75	2.70	1.91	4.49
2.	71.45	7.67	11.63	5.17	2.13	3.83
3.	82.43	6.39	10.77	3.60	3.51	3.26
4.	67.96	18.50	-0.77	5.06	4.06	7.03
Mean	**75.35**	**11.17**	**11.84**	**4.13**	**2.90**	**4.65**
STD	**6.77**	**5.47**	**10.86**			

Table 4.2.22 Mean mixed preferred colours in the abstract photo experiment for each observer for grass colours. Mean for all and standard deviations can be seen in the last two rows.

No. of the observer	Mean			STD		
	*L**	*a**	*b**	*L**	*a**	*b**
1.	56.17	-50.88	43.09	5.99	4.09	7.40
2.	50.84	-57.86	44.11	4.35	6.30	3.53
3.	51.50	-50.64	37.22	3.73	4.25	6.36
4.	52.64	-29.40	22.81	5.96	8.74	7.15
Mean	**52.79**	**-47.19**	**36.81**	**5.01**	**5.84**	**6.11**
STD	**2.37**	**12.33**	**9.82**			

For sky colours, the following can be mentioned. The inter-observer variability is large in case of the L^* value. The variability for the a^*, b^* values are not so spread. The intra-observer variability for each observer is smaller than the inter-observer variability for the L^* value. This means that every observer had a nearly precise preferred colour for sky, but this varies between the observers.

For skin colours the inter-observer variability is smaller for L^* values than in case of the sky colours, but for a^*, b^* values these values are larger. The intra-observer variability is also smaller than the inter-observer variability.

For grass colours the intra-observer variability for a^*, b^* values are larger than for skin and sky, but they are smaller than the inter-observer variability values so far. All L^* values are greater than 50 and the inter-observer variability is small.

So, the intra-observer variability is the smallest for skin colours and the largest for grass colours. This observation refers to that the determination of skin colours are the most intensive in mind.

In Table 4.2.23 the results of a one sample t-test is shown. The hypothesized value here is the lightness, chroma and hue values of the primary original colours in the memory matching experiment. Bold numbers show significant differences, at the p=0.05 level.

Table 4.2.23 Significance of the difference between the primary original and preference colours of sky, skin and grass. One sample t-test. Bold numbers show significant differences, at the p=0.05 level

	Sky	**Skin**	**Grass**
$\langle L^* \rangle$	**0.000**	**0.028**	**0.000**
$\langle C_{ab} \rangle$	**0.000**	**0.034**	0.107
$\langle h \rangle$	**0.000**	0.894	**0.000**

The difference between the observers preferred colours can be the effect of the different earlier experiences. The cause of the not so large inter-observer variability is that the observers come from the same cultural and geographical location.

4.2.4 Results of the abstract name experiment

This experiment is the pair of the previous abstract photo experiment. The observers had to mix their preferred colour for the colour names listed on a paper. They saw only a grey patch with black contour, and they had to mix the colours that were written onto a paper. Next to the regular colours (grass, Caucasian skin, sky), there were some other colours enumerated. The reason for applying other colours was to make the experiment less monotonic. The other colours were foliage, banana and orange for two observer and some colours of familiar objects like red apple, plum, carrot, orange and lemon, for the other two observers, but the results of these will not be discussed here.

The mean values of the mixed colours on an *a*, b** diagram can be seen in Figure 4.2.11. Mean mixed colours, intra- and inter-observer variability can be seen in Table 4.2.17-19.

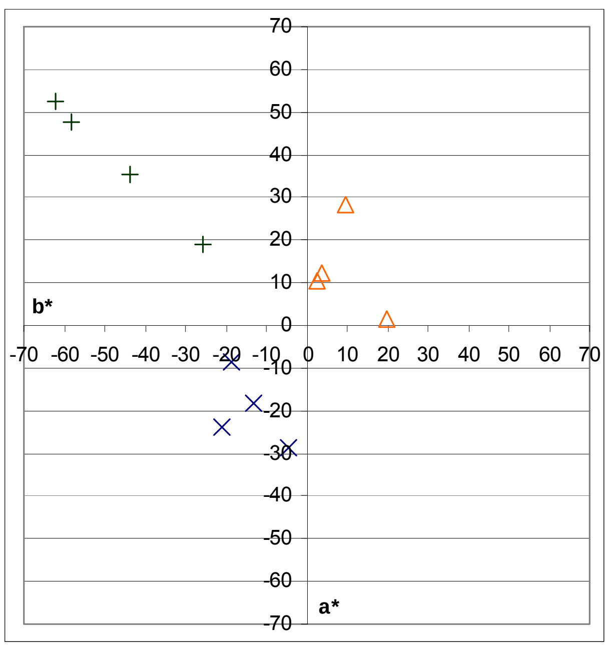


Figure 4.2.11 Results of abstract name experiment. “x” signs – sky colours; “Δ” signs – skin colours; “+” signs – grass colours.

Table 4.2.17 Mean mixed preferred colours in the abstract name experiment for each observer for sky colours. Mean for all and standard deviation can be seen in the last two rows.

No. of the observer	Mean			STD		
	L*	a*	b*	L*	a*	b*
1.	78.23	-4.40	-28.79	2.16	2.22	2.17
2.	79.02	-13.29	-18.21	3.20	3.61	4.29
3.	59.69	-20.80	-23.80	5.80	8.94	7.50
4.	64.88	-18.65	-8.43	4.53	12.26	7.36
Mean	**70.45**	**-14.29**	**-19.81**	**3.92**	**6.76**	**5.33**
STD	**9.67**	**7.31**	**8.73**			

Table 4.2.18 Mean mixed preferred colours in the abstract name experiment for each observer for skin colours. Mean for all and standard deviation can be seen in the last two rows.

No. of the observer	Mean			STD		
	L*	a*	b*	L*	a*	b*
1.	77.38	9.63	28.37	10.01	4.22	8.17
2.	75.58	3.82	12.36	5.07	0.91	4.46
3.	74.26	2.52	10.44	6.04	3.58	4.84
4.	73.42	19.61	1.43	10.90	7.00	5.58
Mean	**75.16**	**8.90**	**13.15**	**8.00**	**3.93**	**5.77**
STD	**1.72**	**7.78**	**11.21**			

Table 4.2.19 Mean mixed preferred colours in the abstract name experiment for each observer for grass colours. Mean for all and standard deviation can be seen in the last two rows.

No. of the observer	Mean			STD		
	L*	a*	b*	L*	a*	b*
1.	56.44	-62.16	52.35	8.15	9.36	8.00
2.	55.15	-58.18	47.65	3.71	7.80	6.58
3.	42.77	-43.65	35.26	6.15	5.18	7.23
4.	49.36	-25.85	18.84	6.07	7.85	15.77
Mean	**50.93**	**-47.46**	**38.53**	**6.02**	**7.55**	**9.39**
STD	**6.25**	**16.46**	**14.97**			

For sky colours the following can be mentioned: the inter-observer variability is larger than the intra-observer variability at the L^* and a^* and b^* values. The reason of this can be the different experiences that the observers had previously.

For skin colour the inter-observer variability of the L^* values is smaller than the intra-observer variability. The mean values of the mixed colours are almost equal for the observers. For the a^* b^* values the regular trend prevails: the inter-observer variability is larger than the intra-observer variability.

The $L*$ values show almost the same deviation between and among the observers at the grass colours. For the $a*$ $b*$ values the regular trend can be observed.

In Table 4.2.24 the results of a one sample t-test is shown. The hypothesized value here is the lightness, chroma and hue values of the primary original colours. Bold numbers show no significant differences, at the p=0.05 level.

Table 4.2.24 Significance of the difference between the primary original and preference colours of sky, skin and grass. One sample t-test. Bold numbers show significant differences, at the p=0.05 level

p	**Sky**	**Skin**	**Grass**
<L*>	**0.000**	**0.031**	**0.021**
<C_{ab}>	**0.000**	0.116	0.397
<h>	**0.000**	0.056	0.122

4.2.5 Comparison of the results in the second experimental series

In the first subsection I will compare the results of the colour matching experiments, in the next the results of the preference experiments and than the results of the colour matching and the preference will be compared. The results showed nearly normal distribution, so applying statistical analysis was available.

4.2.5.1 Comparison of the memory matching experiments in the second series of experiments

The second series of experiments in the theme of colour matching contains the mixing greyscale photo-realistic images (Bartleson) and the mixing colour patch (Bartleson) experiments. The same original colours (Table 4.2.1), the same experimental method, and the same situation were used in the two experiments. The presence or the absences of the greyscale photo-realistic images were the only difference between the two experiments. This means that if any difference exists between the results that can be assigned to the context.

If the original colour was located near to the prototypical colour the following effect could eventuate: the colour itself could revive an object that is in connection with the colour in mind. This effect caused the small hue shift and small standard deviation of hue at the grass colours in case of the mixing colour patch experiment. The results of the mixing greyscale photo-realistic experiment exhibited that the chosen primary colour is near to the prototypical colour, because the hue shift is very small. The same cannot be told for sky and skin colours, because the observers didn't accept these colours as near prototypical colours. The chroma shifts and the hue shifts and the standard deviation of mixed hue and chroma values are large for these colours.

A general chroma and lightness increase can be observed for all colours. This was also observed in most colour memory experiments in literature. That means that all of the observers mixed more saturated colours for all examined colours. The degree of the increase is differing for the different types of colours.

The mixed colours of the memory matching experiments can be seen in Figure 4.2.12. Results of a t-test are shown in Table 4.2.25. Bold numbers show significant differences. L* values of skin and grass show significant differences.

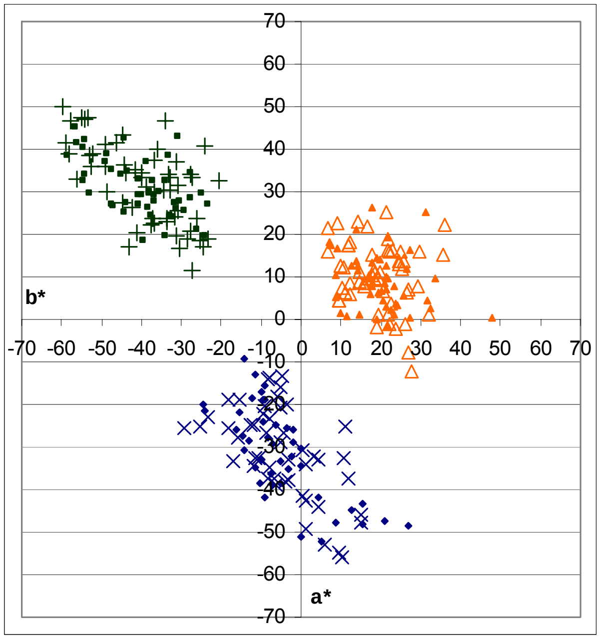


Figure 4.2.12 Results of the memory experiments. “x” – sky colours of mixing photo-realistic images; “♦” – sky colours of mixing colour patch; “Δ” – skin colours of photo-realistic images; “▲” – skin colours of mixing colour patch; “+” – grass colours of photo-realistic images; “■” signs – grass colours of mixing colour patch.

Table 4.2.25 Significance of the differences between the actual colours of mixing greyscale photo and mixing colour patch experiment. T-test. Bold numbers show significant differences, at the p=0.05 level

	Sky	Skin	Grass
<L*>	0.728	**0.000**	**0.000**
<C_{ab}>	0.782	0.378	0.986
<h>	0.764	0.449	0.628

4.2.5.2 Comparison of the preference experiments in the second series of experiments

Except one case (*L** values of sky colour) the intra-observer variability is smaller in the results of the abstract picture experiment. This means that the presence of the greyscale photo-realistic image on the picture helped the observer to determine the preference colour of the object.

The *L** values of the mixed preference colours in the two experiments are close to each other. The *a** and *b** values are not so close, but at the grass colours some similitude can be observed. If we compare the results of one observer for the two experiments, the same tendencies can be seen. The mixed colours in the two experiments are close to each other, so the colours tend to the prototypical colour of the observer. Some differences between the observers exist, which is the consequence of the observers' different remembrances and tastes. These results can be seen in Figure 4.2.13. Results of a t-test are shown in Table 4.2.26, where the significance of the differences between the actual colours of the preference experiments can be seen. Bold numbers show significant differences. The difference between the C_{ab} and h values at sky and L* values at grass are significant.

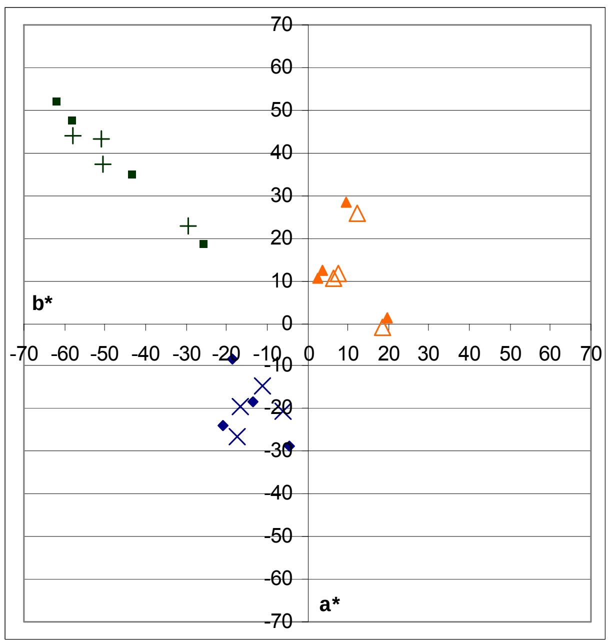


Figure 4.2.13 Results of the preference experiments. "x" – sky colours of abstract picture; "♦" – sky colours of abstract name; "Δ" – skin colours of abstract picture; "▲"– skin colours of abstract name; "+" – grass colours of abstract picture; "■" – grass colours of abstract name.

Table 4.2.26 Significance of the differences between the actual colours of abstract photo and name experiment. T-test. Bold numbers show significant differences, at the p=0.05 level

	Sky	**Skin**	**Grass**
<L*>	0.803	0.718	**0.000**
<C_{ab}>	**0.028**	0.838	0.764
<h>	**0.007**	0.099	0.405

4.2.5.3 *Comparison of the memory matching and preference experiments in the second series of experiments*

If we compare the original colours for sky in the colour matching experiments and the mixed preference sky colours the difference between the L^* values is conspicuous. The L^* values of the mixed colours in the colour matching is larger than the original colours. This means that the observers' prototypical colours are lighter than the original colours in the colour matching experiment.

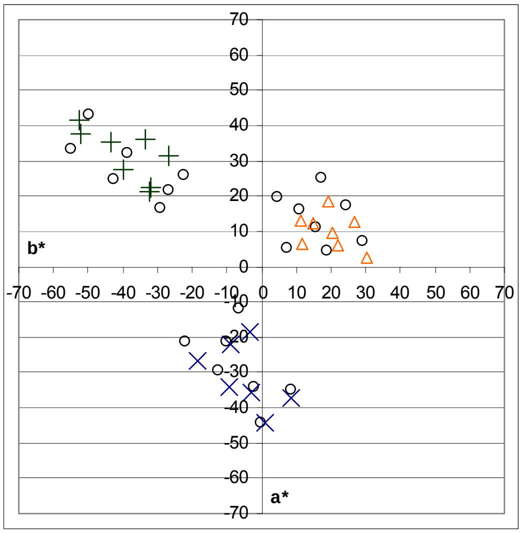
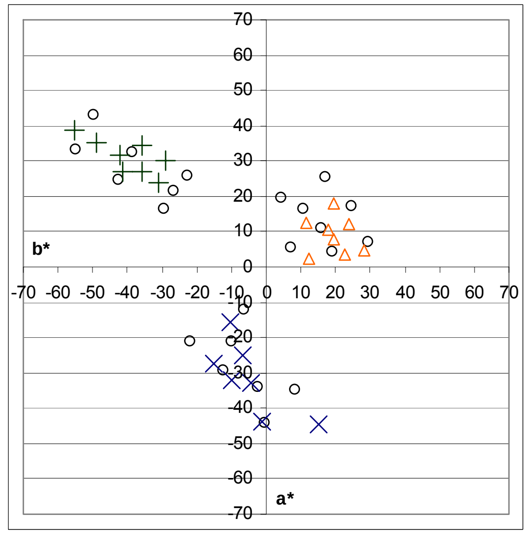
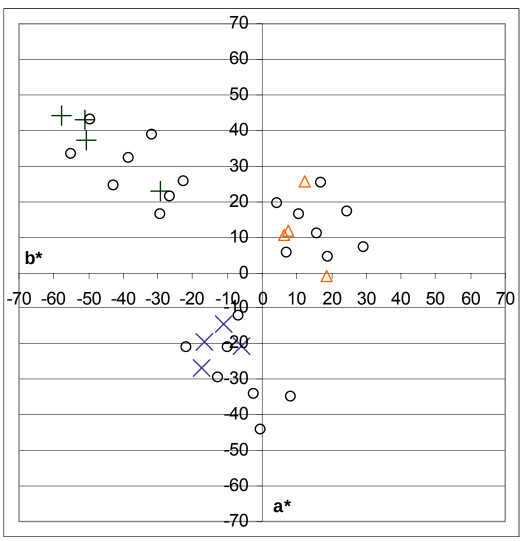
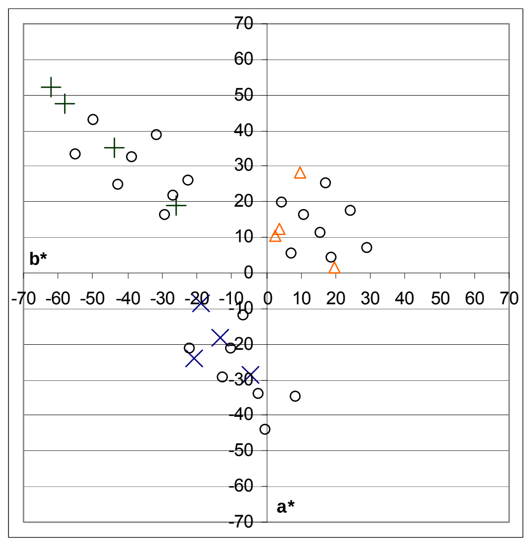
In Figure 4.2.14 the original colours in the memory matching experiment, and the mean mixed colours can be seen for all experiments in a^*, b^* plane. Some hue shift can be seen for one direction for the grass colours. This shift is toward the prototypical colour. The tendency is the same for the mixing greyscale photo-realistic images experiment and for the preference experiment. At the results of the mixing greyscale photo-realistic images experiment the observers tended to accept the primary original colour as a prototypical colour, and at the preference experiment the nearly the same colours are mixed as preference colours. For sky colours the mixed preference colours are similar to the mixed memory colours but not as nearly as in case of grass colours. For skin colours the preference and the mixed memory colours are alien from each other. The position of one observer's preference colour's in the a^*, b^* plane is very close to the set of mixed memory colours, but the other observers' results are far away. These results affirm that the primary original colours of skin and sky, used in the memory matching experiment cannot be used as prototypical colours.

Results of an ANOVA analysis can be seen in Table 4.2.27. The procedure can be used to test the hypothesis that the means of two or more groups are not significantly different. Bold numbers show significant differences, at the p=0.05 level. No significant differences are shown at hue and chroma values of grass colour.

Table 4.2.27 Significance of the differences between the actual colours of abstract photo, abstract name, mixing greyscale photo and mixing colour patch experiment. ANOVA. Bold numbers show significant differences, at the p=0.05 level

	Sky	**Skin**	**Grass**
<L*>	**0.000**	**0.000**	**0.000**
<C_{ab}>	**0.000**	**0.000**	0.689
<h>	**0.000**	**0.004**	0.418

Figure 4.2.14 Original colours and mixed colours in the second experimental series. "o" - original colours in the memory matching experiments, "x" – mixed sky colours, "Δ" – mixed skin colours, "+" – mixed grass colours

	Mixing greyscale picture	**Mixing colour patch**
Memory matching		
Preference		

4.3 Results of the third series of experiments

The experimental method in the third series has a big advantage: it is very easy for the observer to apply. The method is a deciding method, where the observers just had to make a binary decision about the colour they saw in the second viewing situation. The description of the method can be found in Section 3.3.

This experimental series contains three experiments: deciding photo, deciding colour patch, and simultaneous experiments.

The CIELAB values of the original colours that were used in this experiment can be seen in Table 4.3.1 and in Figure 4.3.1 in an a^*, b^* plane. The colours in the diagram have different L^* values, so the aim of the diagram is just to represent the position of the colours in an a^*, b^* plane. The actual or decision colours were chosen as random colours so that the colour difference between the colour centres and the actual colours were less than 20 and $\Delta L^*=0$. The decision colour was allowed to be the same as the original colour (or colour centre). The observer had to decide whether the just seen actual colour is equal to the original colour or not.

The original colours of this series were selected as prototypical colours from previous memory matching experiments[29]. My aim was with this series to prove that these colours are eligible as prototypical colours. The selection method of the original colour was the following: in the mentioned experiment constant hue intervals and medians of the constant hue intervals were determined. Taking the hue values of the median colours into consideration, on a colour monitor sky, Caucasian skin and grass colours were mixed empirically.

Table 4.3.1 Original colours in the third series of experiments.

	L^*	a^*	b^*	C_{ab}	h
sky	53.99	-16.92	-28.02	32.73	238.87
skin	79.54	16.12	10.26	19.11	32.48
grass	50.10	-33.90	29.75	45.10	138.73

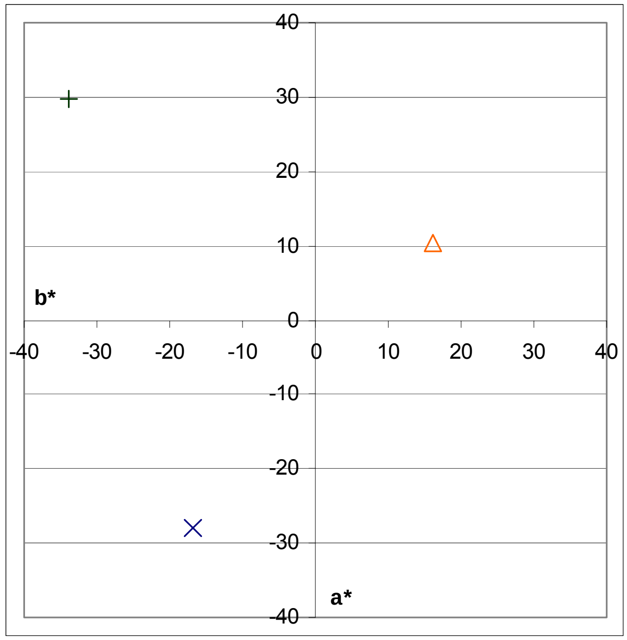
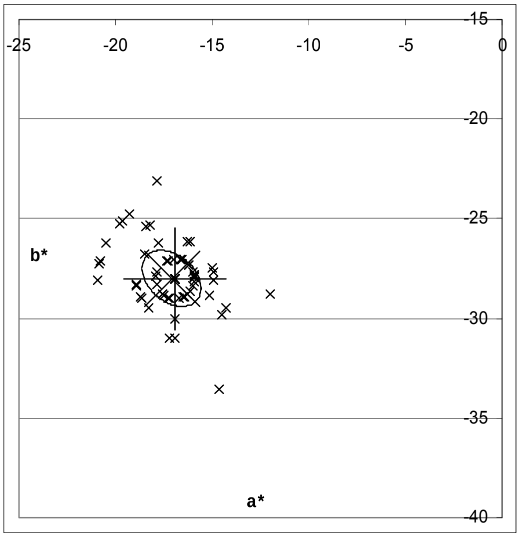


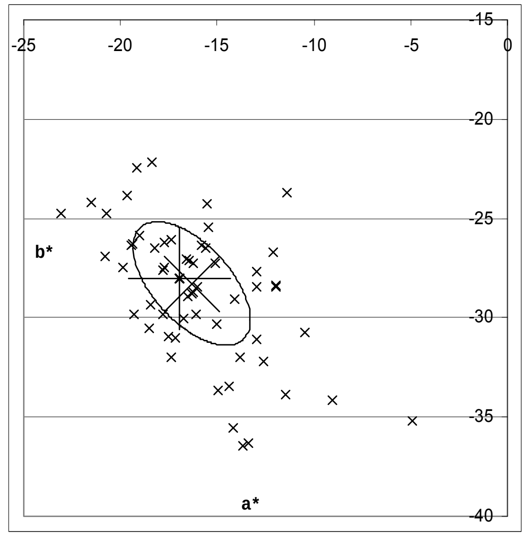
Figure 4.3.1 Original colours of third series of experiments. “x” – sky colour; “Δ” – skin colour; “+” – grass colour.

In the next Figures (Figure 4.3.2-4.3.4) in *a*, b** plane those colours can be seen that were decided equal to the previously seen original colour. The results of the simultaneous, deciding colour patch and deciding photo experiment can be seen below. The CIELAB values of the colours decided to be the same with the original colour can be seen in Appendix 8 for sky, Appendix 9 for skin and Appendix 10 for grass colours. Variability ellipses are also presented for the colours in Figures 4.3.2-4.3.4, where the observer said “yes, it is the same colour”. The small “x” depicts the “yes, the same” answers, the big “X” depicts the mean of these colours and big “+” depicts the original colour. Results of a one sample t-test can be seen in the last row for C_{ab} and h_{ab} values. The results showed nearly normal distribution, so applying statistical analysis was available. The hypothesized value here is the chroma and hue values of the original colours. Bold numbers show no significant differences, at the p=0.05 level.



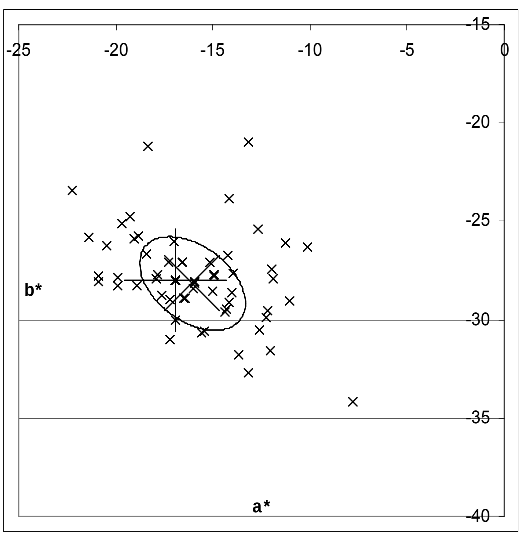
Simultaneous experiment

	*a**	*b**	C_{ab}	*h*
Mean	-17.10	-27.99	32.85	238.56
STD	1.52	1.41	1.19	2.96
p			0.303	0.291



Deciding colour patch experiment

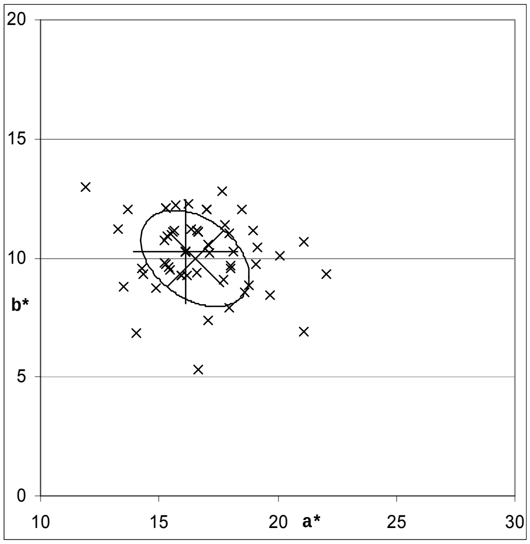
	*a**	*b**	C_{ab}	*h*
Mean	-16.32	-28.28	32.86	239.85
STD	3.03	3.11	2.26	6.40
p			0.468	0.054



Deciding photo experiment

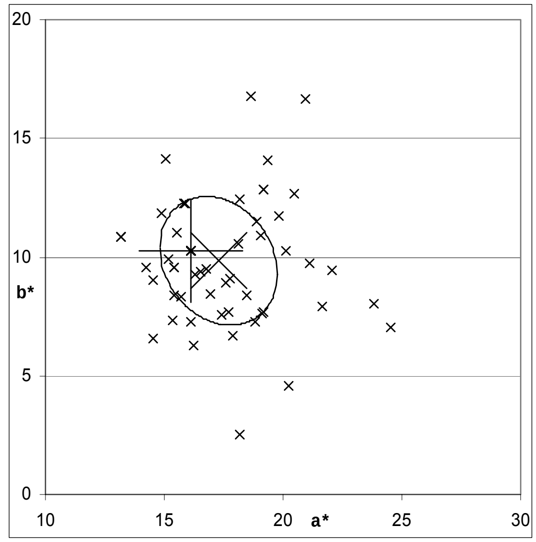
	*a**	*b**	C_{ab}	*h*
Mean	-15.79	-28.23	32.60	240.64
STD	3.45	3.09	2.24	7.09
p			0.471	**0.003**

Figure 4.3.2 Variability ellipses for sky colour for the third experimental series. The original colour is depicted by a large "+", the mean decision colour of the "yes, the same" subset of 10 observers x 50 decision colours is depicted by a big "x". The "yes, the same" subset is depicted by small "x". The mean and standard deviation values are presented. Results of a one sample t-test in the last row



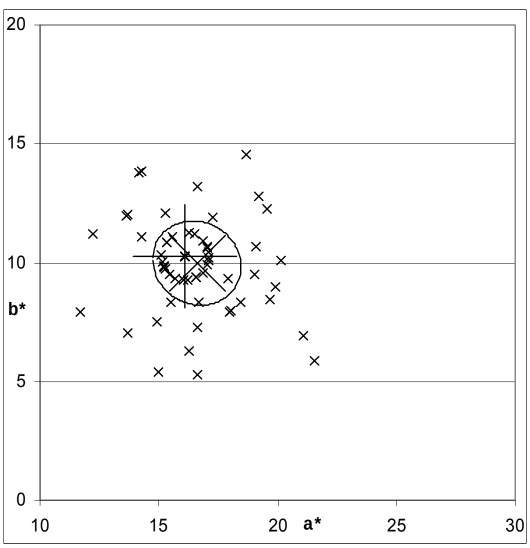
Simultaneous experiment

	*a**	*b**	C_{ab}	*h*
Mean	16.51	9.98	19.41	30.43
STD	2.29	2.02	2.24	10.05
p			0.230	0.068



Deciding colour patch experiment

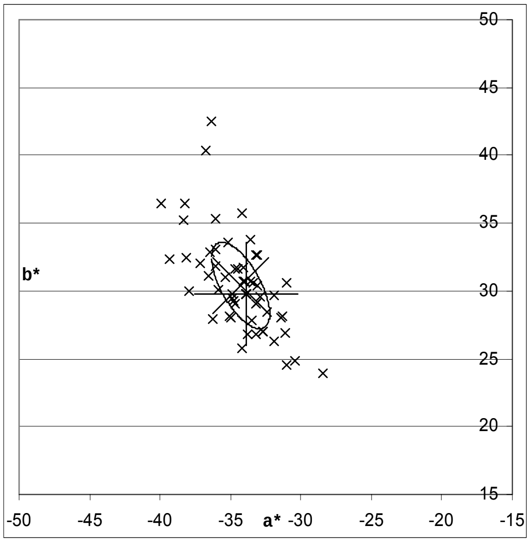
	*a**	*b**	C_{ab}	*h*
Mean	17.29	9.84	20.04	29.52
STD	2.47	2.71	2.75	7.05
p			**0.001**	**0.000**



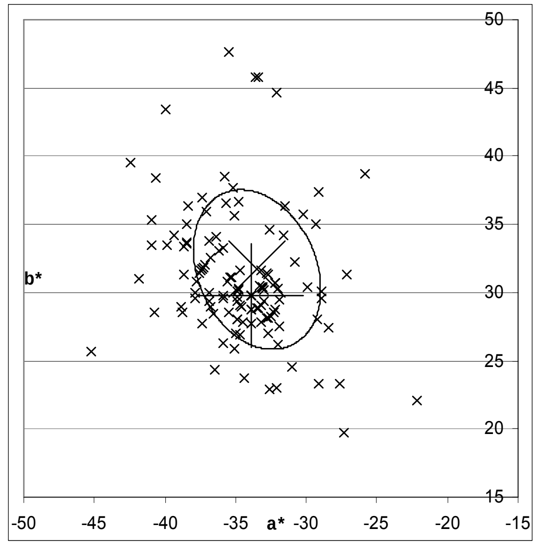
Deciding photo experiment

	*a**	*b**	C_{ab}	*h*
Mean	16.74	10.44	19.88	31.76
STD	2.40	2.87	2.83	7.15
p			**0.014**	0.357

Figure 4.3.3 Variability ellipses for skin colour for the third experimental series. The original colour is depicted by a large “+” sign, the mean decision colour of the "yes, the same" subset of 10 observers x 50 decision colours is depicted by a big “x”. The "yes, the same" subset is depicted by small “x”. The mean and standard deviation values are presented. Results of a one sample t-test in the last row



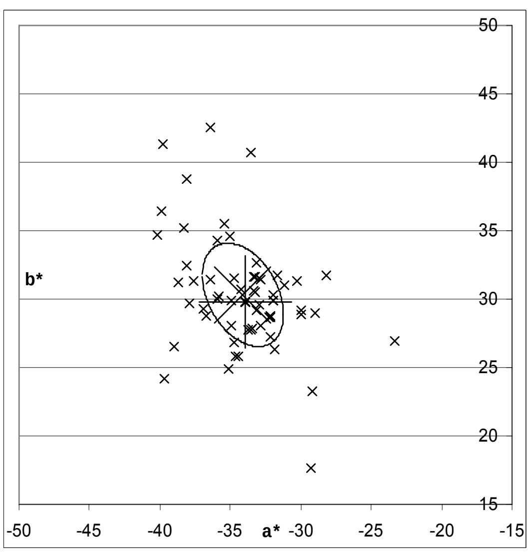
Simultaneous experiment



Deciding colour patch experiment

	*a**	*b**	C_{ab}	*h*
Mean	-34.27	30.39	45.84	138.52
STD	2.05	3.18	3.35	2.14
p			0.068	0.457

	*a**	*b**	C_{ab}	*h*
Mean	-34.52	30.95	46.49	138.24
STD	3.37	4.46	4.43	4.11
p			**0.000**	0.159



Deciding photo experiment

	*a**	*b**	C_{ab}	*h*
Mean	-34.33	30.42	45.97	138.51
STD	3.50	3.96	4.31	3.79
p			**0.021**	0.507

Figure 4.3.4 Variability ellipses for grass colour for the third experimental series. The original colour is depicted by a large “+” sign, the mean decision colour of the "yes, the same" subset of 10 observers x 50 decision colours is depicted by a big “x”. The "yes, the same" subset is depicted by small “x”. The mean and standard deviation values are presented. Results of a one sample t-test in the last row

The *a**, *b** diagrams in Figures 4.3.2-4.3.4 contain all "yes, the same" answers of all observers for a given familiar object (sky, Caucasian skin and grass) and for a given experiment (simultaneous, deciding colour patch and deciding picture). In Figures 4.3.2-

4.3.4 the original colour (or colour centre) is depicted by a large “+” sign, the mean decision colour of the "yes, the same" subset of 10 observers x 50 decision colours is depicted by a big “x”. The "yes, the same" subset is depicted by small “x”. The variability ellipse of latter subset is also shown. Standard deviations (STDs) of the a^* and b^* values of the "yes, the same" subset are listed in tables next to the diagrams in each of the Figures 4.3.2-4.3.4

As can be seen from Figures 4.3.2-4.3.4, the scatter of the yes answers is largest for the deciding colour patch experiment; it is smaller for the deciding photo experiment and smallest for the simultaneous series except for Caucasian skin colours where the photo experiment has the smallest scatter. The reduced scatter of the deciding photo experiment may be a cognitive colour effect: as already mentioned all 3 original colours chosen resulted from previous experiments as colour prototypes. In the photo experiment, in the presence of the photo-realistic greyscale image depicting a familiar object around the original colour and the decision colour, the tendency to categorize the original colour may be extremely strong. Therefore, observers tend to remember a category only i.e. to remember a cognitive colour. Observers may remember the expression “Caucasian skin” and accept or not accept the decision colour as "Caucasian skin" long-term memory colour. The tendency seems to be weaker in case of the deciding colour patch series hence scatters tend to increase.

In previous experiments, the “original” colour stimulus and the selected “actual” colour stimulus were significantly and systematically different. The memory colour shift was usually directed towards a basic colour or a colour prototype. In the present series, the original colour was a colour prototype, and, as expected, memory shifts were statistically not significant. The original colour (or the colour centre) is well within the variability ellipses in Figures 4.3.2-4.3.4.

The effect of presenting or not presenting the visual context of a photo-realistic greyscale image has turned out to be significant. As expected, the mean short-term memory colour was not significantly different from the original colour.

Results of an ANOVA analysis can be seen in Table 4.3.2. The procedure can be used to test the hypothesis that the means of two or more groups are not significantly different. Bold numbers show significant differences, at the p=0.05 level. Significant differences can be seen at hue values of sky colour. This caused by the difference between the mean value and the difference of the standard deviation of the decision colours in case of the simultaneous, deciding colour patch and deciding picture experiments. For skin and grass colours smaller difference in standard deviation and mean values can be seen.

Table 4.3.2 Significance of the differences between the results of simultaneous, deciding colour patch and deciding photo experiment. ANOVA. Bold numbers show significant differences, at the p=0.05 level

	Sky	Skin	Grass
$\langle C_{ab} \rangle$	0.463	0.259	0.460
$\langle h \rangle$	**0.026**	0.180	0.782

From the results of the experiments the following main inference can be drawn: the original colours can be regarded as prototypical colours because they are located inside the variability ellipses which were created to be analogous to the MacAdam variability ellipses. These variability ellipses denote the accuracy of remembering so the original colour is a prototypical colour if it is located inside the ellipsis. The significant differences that were detected by the one-sample t-tests are not relevant from the point of view of prototypical colours.

The variability ellipses of memory colours can be defined as follows: if the original colour is inside this ellipsis then the memory colour is still considered as prototypical but if the original colour is located outside this area then a cognitive effect can be observed during the memory matching. This cognitive effect also begins to act inside the area of the ellipsis and the appearance of the effect is continuous. This is the explanation of the significant differences found in the one-sample t-test. On the basis of the previous discussions, the length of long and short axes of the variability ellipses can be considered as an important characteristic of memory matching. These lengths are listed in Table 4.3.3.

Table 4.3.3 Length of the long and short axes of the variability ellipses in CIELAB units

	Long axis	Short axis
sky	6.2	3.8
skin	3.8	3.4
grass	8.0	5.0

4.4 Results of the fourth experimental series

4.4.1 First Hungarian series

Four lines of four constant colour patches (4x4=16 colour patches called choice colours) were displayed on a middle grey background. The 16 choice colours were shown to the observer on one screen for each of the six colour names. The observer indicated his/her choice for the colour name shown. 30 repetitions have been carried out with a random array of choice colours for each of the 6 memory colours. Therefore the output of each observer was a set of 30 choices per memory colour. The colour centres and the random choice colours can be seen in Figure 3.4.1.

A computer program was used to calculate random choice colours. Most of the random choice colours were chosen from spheres around the colour centres shown in Table 4.4.1, within the tolerance values, i.e. the radii of these spheres given in CIELAB ΔE^* colour difference units, as shown in Table 4.4.1. Thus the choice colours varied in hue, lightness, and chroma around the colour centres. To define the colour centres in the first series of observations, I started from long-term memory colours of literature (Table 4.4.1.1) with slight modifications according to the actual visual impression on the colour monitor used in the experiment. Tolerance values were estimated visually. For missing data, own visual estimate were used as a starting point.

Table 4.4.1 Colour centres and tolerance values from which the random choice colours were calculated, used in the first series of Hungarian observations

Colour name	L^*	a^*	b^*	tolerance radii
Skin	79.5	16.1	10.4	10
Sky	54	-17	-28.1	15
Grass	55	-33.7	29.8	15
Foliage	36	-18.5	12.8	20
Banana	70	0	65	30
Orange	71.6	26.7	69.72	15

The colour stimuli corresponding to the long-term memory colours were quantified as CIELAB L^*, a^*, b^* values. Mean L^* values are listed in Table 4.4.2 and mean a^*, b^* values are plotted in Figure 4.4.1.

Table 4.4.2. Mean CIELAB L^* values of the mean values of all observers, for all three types of experiments and for all six types of long-term memory colours in the first series of Hungarian experiments

Experiment	**Skin**	**Sky**	**Grass**	**Foliage**	**Banana**	**Orange**
Choice colours	84.3	66.6	49.8	41.0	84.8	71.8
Colour name	76.8	61.3	42.9	42.1	78.0	63.7
Greyscale photo	84.2	68.5	45.4	50.4	85.0	68.6

Table 4.4.3 The standard deviations of all observers' mean L^* values (inter-observer variability values)

Experiment	**Skin**	**Sky**	**Grass**	**Foliage**	**Banana**	**Orange**
Choice colours	1.9	2.2	1.6	1.5	1.9	3.1
Colour name	6.0	10.5	6.0	7.7	9.2	6.1
Greyscale photo	2.7	9.6	7.1	12.1	7.3	3.9

As can be seen from Table 4.4.2 and 4.4.3, the standard deviations of the mean L^* values are comparable to the difference among the mean values from the three types of experiment. Likewise, as can be seen from Figure 4.4.1, the results from the three types of experiment show an overlapping picture in the a^*, b^* diagram. Analyses of variance have also shown that, in general, the type of experiment (choice colours, colour name, or greyscale photo) did not influence long-term memory colours significantly (at the $p=0.05$ level).

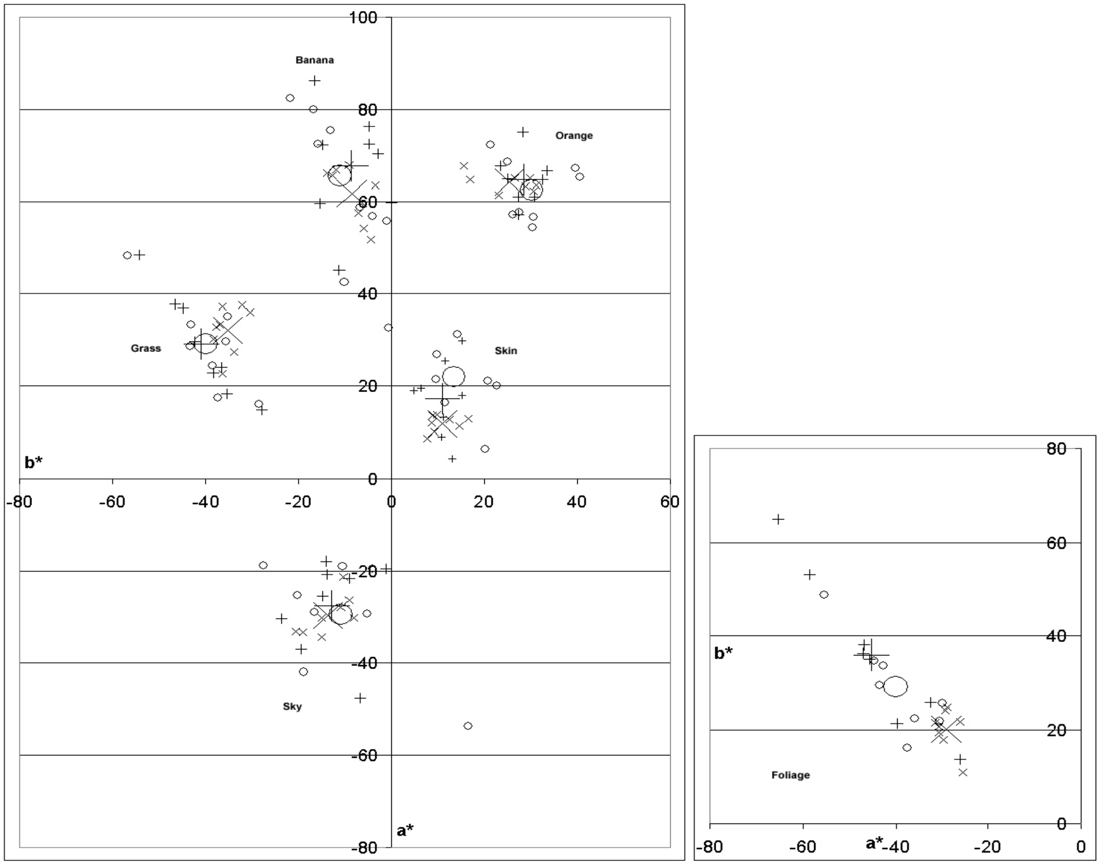


Figure 4.4.1 First Hungarian series. Mean findings of each observer for each type of experiment (small plus signs: choice colours, small circles: reproducing a colour name, and small crosses: greyscale photo). Large signs depict the mean values of all observers for a given type of experiment and long-term memory colour. CIELAB *a**, *b** diagram. Foliage is shown in a separate diagram.

Therefore, the overall mean values as long-term memory colours resulting from the first Hungarian series were used. They were calculated from the mean values of all three types of experiment. They are listed in Table 4.4.4.

Table 4.4.4 Long-term memory colours of the Hungarian first series, calculated from the mean values of all three types of experiment

Name	Skin	Sky	Grass	Foliage	Banana	Orange
L*	81.8	65.4	46.0	44.5	82.6	68.0
a*	11.9	-12.4	-38.6	-38.0	-9.5	28.0
b*	17.1	-28.9	30.2	28.4	65.0	63.8

4.4.1.1 Literature data

Long-term memory colours were extensively studied and quantified in literature. The CIELAB L^*, a^*, and b^* values of six memory colours are summarized in Table 4.4.1.1, under standard illuminant C. The Oriental skin colour is a CIE test-colour sample[97]. In literature, we found a paper dealing with the long-term memory colour for banana[3] but we could not retrieve its colorimetric values.

Table 4.4.1.1. CIELAB L^*, a^*, and b^* values of important memory colours. Caucasian skin, blue sky, green grass, deciduous foliage, and orange (under illuminant C). A test-colour sample used to test light sources[97] and representing Oriental skin is included.

Memory colour	L^*	a^*	b^*	Reference
Caucasian skin	79.5	16.1	10.4	4
Blue sky	54.0	-17.0	-28.1	4
Green grass	50.0	-33.7	29.8	25
Oriental skin	63.9	14.0	16.1	97
Deciduous foliage	33.6	-18.5	12.8	4
Orange	71.6	26.7	75.72	7

4.4.2 Second Hungarian series

The colour centres and tolerance values that were used in the second series of Hungarian observations can be seen in Table 4.4.5.

Table 4.4.5. Colour centres and tolerance values from which the random choice colours were calculated, used in the second series of Hungarian observations

Colour name	*L**	*a**	*b**	tolerance radii
Skin	81.4	10.7	18.2	8
Sky	66.4	-12.5	-26.5	10
Grass	46.8	-41.1	31.4	9
Foliage	44.8	-40.1	29.2	11
Banana	81.5	-10.8	64.7	11
Orange	68.0	26.1	62.7	8

The colour centres of Table 4.4.5 are depicted in Figure 3.5.4 together with a plot of the actual random choice colours calculated from Table 4.4.5 and used in the second Hungarian series.

Similar to the first Hungarian series, the results are shown in Tables 4.4.6-4.4.7, and in Figure 4.4.2. For similar reasons, the overall mean values were considered as long-term memory colours resulting from the second Hungarian series. They are listed in Table 4.4.8.

Table 4.4.6 Mean CIELAB L^* values of the mean values of all observers, for all three types of experiments and for all six types of long-term memory colours in the second series of Hungarian experiments

Experiment	Skin	Sky	Grass	Foliage	Banana	Orange
Choice colours	85.0	69.3	45.6	41.2	87.1	69.8
Colour name	77.9	60.8	43.1	40.7	82.2	66.0
Greyscale photo	82.9	67.9	46.4	43.5	87.5	69.5

Table 4.4.7 The standard deviations of all observers' mean L^* values (inter-observer variability values)

Experiment	Skin	Sky	Grass	Foliage	Banana	Orange
Choice colours	2.1	3.7	2.9	22.6	2.0	1.8
Colour name	5.5	3.2	4.2	7.2	8.4	4.8
Greyscale photo	4.0	4.3	6.6	10	7.6	5.3

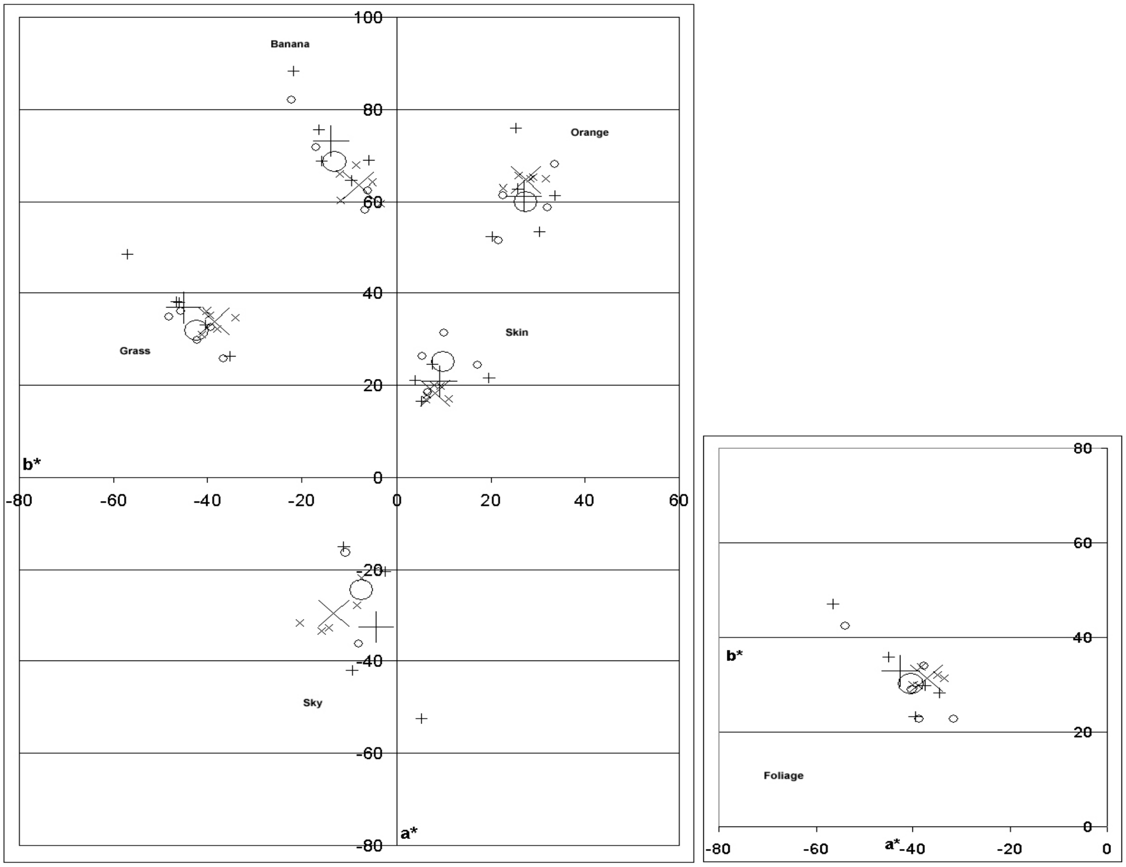


Figure 4.4.2 Second Hungarian series. Mean findings of each observer for each type of experiment (small plus signs: choice colours, small circles: reproducing a colour name, and small crosses: greyscale photo). Large signs depict the mean values of all observers for a given type of experiment and long-term memory colour. CIELAB *a*, b** diagram. Foliage is shown in a separate diagram.

Table 4.4.8 Long-term memory colours of the Hungarian second series, calculated from the mean values of all three types of experiment.

Name	Skin	Sky	Grass	Foliage	Banana	Orange
L*	81.9	66.0	45.0	41.8	85.6	68.4
a*	9.1	-8.4	-42.1	-40.1	-11.7	27.3
b*	21.5	-28.8	34.2	31.5	68.4	61.9

4.4.3 Korean series

Similar to the first and second Hungarian series, the results are shown in Tables 4.4.9-4.4.10, and in Figure 4.4.3. Here again, the overall mean values were considered as long-term memory colours resulting from the Korean series. They are listed in Table 4.4.11. One observer was excluded due to irregular results.

Table 4.4.9 Mean CIELAB L^* values of the mean values of all observers, for all three types of experiments and for all six types of long-term memory colours in the Korean experiments

Experiment	Skin	Sky	Grass	Foliage	Banana	Orange
Choice colours	71.8	62.3	55.5	39.5	90.2	75.3
Colour name	73.5	60.9	55.4	41.2	83.2	71.0
Greyscale photo	74.0	64.5	56.0	40.8	86.3	71.6

Table 4.4.10 The standard deviations of all observers' mean L^* values (inter-observer variability values)

Experiment	Skin	Sky	Grass	Foliage	Banana	Orange
Choice colours	0.5	4.5	7.5	5.0	1.9	2.8
Colour name	7.3	7.4	12.7	9.1	5.2	4.9
Greyscale photo	7.6	10.5	15.1	12.9	3.3	5.4

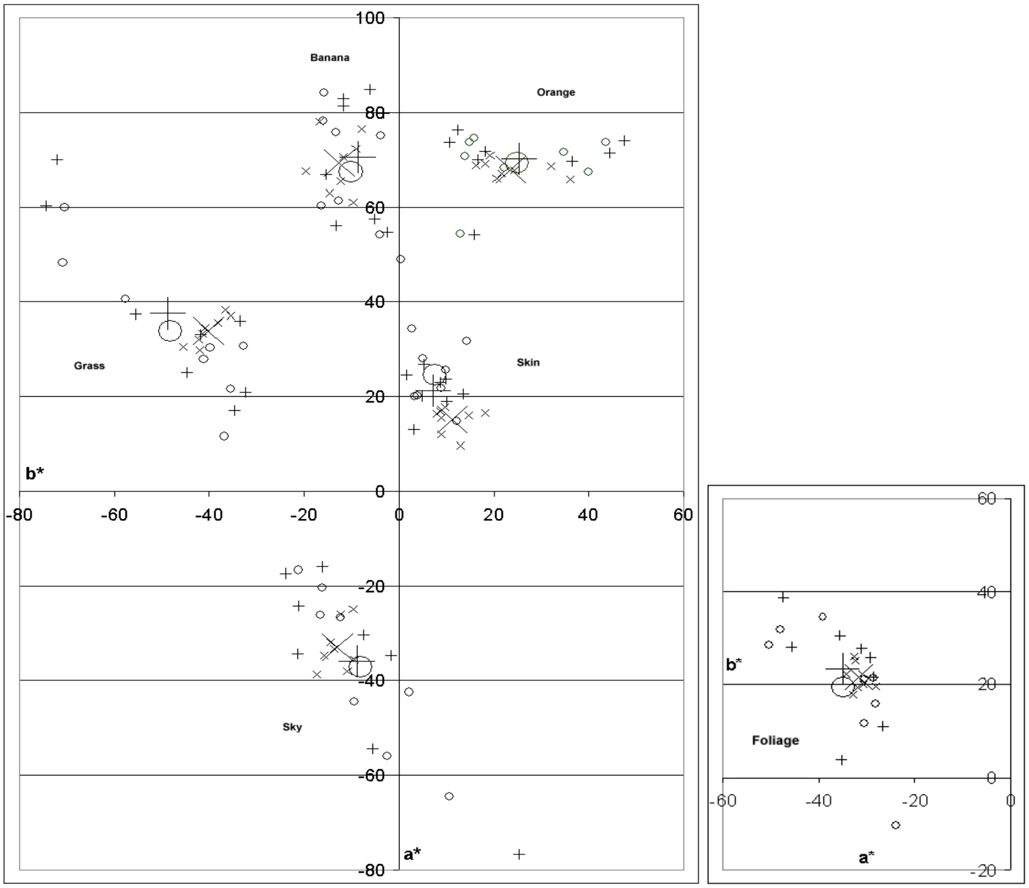


Figure 4.4.3 Korean experiment. Mean findings of each observer for each type of experiment (small plus signs: choice colours, small circles: reproducing a colour name, and small crosses: greyscale photo). Large signs depict the mean values of all observers for a given type of experiment and long-term memory colour. CIELAB *a*, b** diagram. Foliage is shown in a separate diagram.

Table 4.4.11 Long-term memory colours of the Korean series, calculated from the mean values of all three types of experiment

Name	Skin	Sky	Grass	Foliage	Banana	Orange
L*	73.1	62.6	55.6	40.5	86.6	72.6
a*	8.6	-10.0	-45.7	-33.9	-10.5	24.5
b*	20.3	-35.4	35.1	21.4	69.1	69.1

4.4.4 Comparison of the Korean series and the two Hungarian series

As can be seen from Figures 4.4.1, 4.4.2 and 4.4.3, the variability of the choice colours and the memory colours from reproducing a colour name is greater than the variability of the memory colours from the greyscale photo method. The explanation for this finding may be that the range of choice colours was much more extended than the perceptual variability of the memory colours. In the “colour name” task, the colour name written on the screen may provide a less explicit clue to reproduce the memory colour, compared to the “greyscale photo” situation where a greyscale pictorial image (i.e. “the image context”) provides a more unambiguous hint.

Comparing Tables 4.4.4 and 4.4.8, the maximum colour difference between the long-term memory colours of the two Hungarian series is in the order of 5 CIELAB $\Delta E_{ab}*$ units. This is comparable to the inter-observer variability. T-tests have also shown that the difference between the two Hungarian series was not significant (at the p=0.05 level). Therefore, the two Hungarian series were unified and computed the overall Hungarian long-term memory colours, see Table 4.4.12.

Table 4.4.12. Overall Hungarian long-term memory colours (averages of the two Hungarian series)

Name	**Skin**	**Sky**	**Grass**	**Foliage**	**Banana**	**Orange**
L*	81.8	65.7	45.5	84.1	68.2	43.2
a*	10.5	-10.4	-40.4	-10.6	27.7	-39.1
b*	19.3	-28.9	32.2	66.7	62.9	30.0

Figure 4.4.4 shows a comparison of the long-term memory colours from the Korean series (Table 4.4.11), the two Hungarian series (Tables 4.4.4 and 4.4.8), and their average (Table 4.4.12). Long-term memory colours corresponding to another viewing situation can also be calculated, by using a colour adaptation transformation or the CIECAM02 colour appearance model. Table 4.4.13 shows the result of a statistical analysis about the significance of the differences between the Korean series and the unified two Hungarian series.

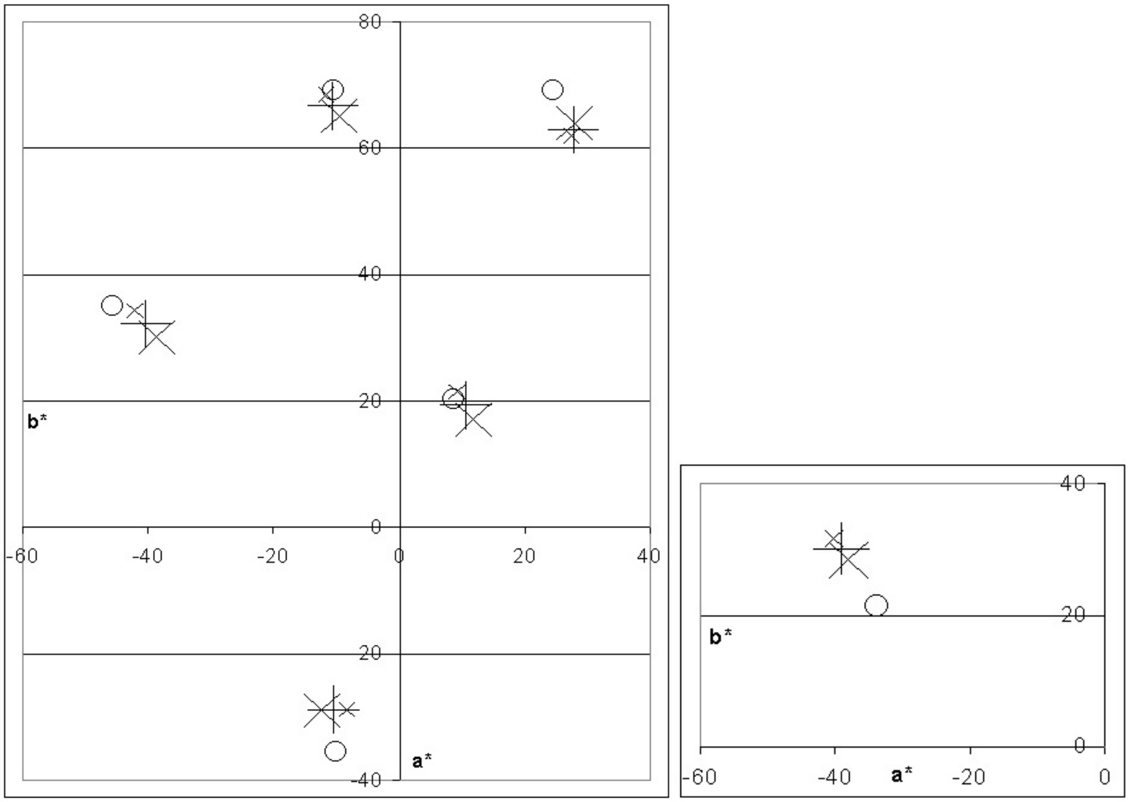


Figure 4.4.4 Long-term memory colours from the Korean series (open circles), the two Hungarian series (first: small crosses, second: large crosses), and their average (plus signs). Foliage is shown in a separate diagram on the right.

Table 4.4.13 Significance of the differences between the long-term memory colours of Korean and Hungarian observers. T-test, the two Hungarian series were unified. Bold numbers show significant differences, at the p=0.05 level.

p	**Skin**	**Sky**	**Grass**	**Foliage**	**Banana**	**Orange**
L*	**0.000**	0.397	**0.000**	0.306	**0.019**	**0.000**
a*	**0.037**	0.835	0.060	**0.038**	0.715	0.150
b*	0.147	0.166	0.240	**0.007**	0.324	**0.000**

Following can be seen from Figure 4.4.4 and from Tables 4.4.11-13. Hungarian grass and foliage long-term memory colours were similar to each other but the Korean ones were different. Korean grass was lighter and much more saturated than Korean foliage. Korean green grass was lighter and more saturated than Hungarian green grass. Korean foliage was less saturated than Hungarian foliage. Oriental skin and Caucasian skin had similar chroma, Oriental skin contained somewhat more yellow hue, and Caucasian skin was found to be significantly lighter than Oriental skin. Korean sky had similar lightness as Hungarian sky but Korean sky was somewhat more saturated than Hungarian sky. Korean banana was somewhat lighter than Hungarian banana. Finally, Korean orange was lighter than Hungarian orange and Korean orange contained more yellow than Hungarian orange.

4.5 Summary of the results

In the previous sections the results of three experiments using different methods were discussed. Each of the experimental methods was built upon the previous one. The aims of the formation of the experiments were: 1. to realize memory matching methods on computer monitor; 2. to examine the results of memory matching experiment.

There are many ways how an experimental method can be built up. This is an evaluation process, during which the best method can be reached. From the first to the third method an improvement was achieved, and the last experimental method fulfils the requirements of a convenient experimental method. The viewing situation is the same during the experiment and the task is easy and not tiring for the observer. With the deciding experimental method correct results can be gain.

Previously, some experimental data dealt with colour memory and some of them observed some colour shift in the memory matching experiments according to simultaneous colour matching. In my experiments, the first aim was to examine these colour shifts in case of sky, Caucasian skin, and grass colours. I found significant shifts, which were due to cognitive effects. Prototypical colours were determined, and proved with the deciding method mentioned in Section 4.3. These colours can be regarded as prototypical colours because they are located inside the variability ellipses, which were created to be analogous to the MacAdam variability ellipses in the third series of my experiments, where the decision method was applied. These variability ellipses denote the accuracy of remembering, the original colour is a prototypical colour if it is located inside the ellipsis.

The presence or absence of the context in the memory matching experiment is important. Significant differences were detected between the results where the only difference was the presence or the absence of the context. From these observations the following can be concluded: the context develops cognitive effects that cause a difference between the results of the experiments. This significant difference can be seen at the first series of experiments, at the mixing photo and mixing colour patch experiments. The t-test between the results of the two experiments shows (Table 4.4.1), that significant difference consists between the results of experiments with and without image context.

No significant difference exists for chroma values. In all experiments significant chroma increase was observed and these results were confirmed by results in literature.

Table 4.4.1 Significance of the differences between the actual colours of mixing photo and mixing colour patch experiment. T-test. Bold numbers show significant differences, at the p=0.05 level

	Sky	**Skin**	**Grass**
<L*>	**0.025**	0.977	0.423
<C_{ab}>	0.633	0.468	0.568
<h>	**0.006**	**0.000**	**0.013**

Previously, it was determined that the observers in the memory matching experiments shift the original colours towards long-term memory colours. In the second experimental series long-term memory colours were used as original colours. In case of grass colour at mixing greyscale photo-realistic images experiment no significant hue difference was found between the primary original and the actual colours (see Table 4.4.2). This colour difference could not be observed in case of the mixing colour patch experiment. The comparison of the two experiments can be seen in Table 4.4.3. Significant difference can be observed between the lightness values of skin and grass but in case of the other values no significant difference was observed.

Table 4.4.2 Significance of the difference between the primary original and all of the actual colours of sky, skin and grass, at mixing greyscale photo-realistic images and colour patch experiments. One sample t-test. Bold numbers show significant differences, at the p=0.05 level

Mixing greyscale photo			
	Sky	**Skin**	**Grass**
<L*>	0.169	0.374	**0.001**
<C_{ab}>	0.333	**0.000**	0.801
<h>	**0.000**	**0.017**	0.233

Mixing colour patch			
	Sky	**Skin**	**Grass**
<L*>	0.069	**0.000**	**0.000**
<C_{ab}>	0.208	**0.001**	0.752
<h>	**0.002**	**0.001**	**0.040**

Table 4.4.3 Significance of the differences between the actual colours of mixing greyscale photo and mixing colour patch experiment. T-test. Bold numbers show significant differences, at the p=0.05 level

	Sky	**Skin**	**Grass**
<L*>	0.728	**0.000**	**0.000**
<C_{ab}>	0.782	0.378	0.986
<h>	0.764	0.449	0.628

The preference colours of sky, skin and grass were also examined. I compared them with the results of the memory matching experiment and with the selected primary original colours. The comparison between the results and the primary colours can be seen in Table 4.4.4. The effect of the absence and the presence of the context are noticeable.

Table 4.4.4 Significance of the difference between the primary original and actual colours of abstract picture and name experiments. One sample t-test. Bold numbers show significant differences, at the p=0.05 level

Abstract picture			
	Sky	**Skin**	**Grass**
<L*>	**0.000**	**0.028**	**0.000**
<C_{ab}>	**0.000**	**0.034**	0.107
<h>	**0.000**	0.894	**0.000**

Abstract name			
	Sky	**Skin**	**Grass**
<L*>	**0.000**	**0.031**	**0.021**
<C_{ab}>	**0.000**	0.116	0.397
<h>	**0.000**	0.056	0.122

Table 4.4.5 Significance of the differences between the actual colours of abstract photo and name experiment. T-test. Bold numbers show significant differences, at the p=0.05 level

	Sky	**Skin**	**Grass**
<L*>	0.803	0.718	**0.000**
<C_{ab}>	**0.028**	0.838	0.764
<h>	**0.007**	0.099	0.405

The significance of the differences between the actual colours of the experiments at the second series can be seen in Table 4.4.6. From the result of an ANOVA analysis it can be seen that no significant difference exist in case of the chroma and hue value of the actual colours of grass, so the observers mixed actual colours close to each other.

Table 4.4.6 Significance of the differences between the actual colours of abstract photo, abstract name, mixing greyscale photo-realistic images and mixing colour patch experiment. ANOVA. Bold numbers show significant differences, at the p=0.05 level

	Sky	**Skin**	**Grass**
<L*>	**0.000**	**0.000**	**0.000**
<C_{ab}>	**0.000**	**0.000**	0.689
<h>	**0.000**	**0.004**	0.418

In the last series of experiments a new experimental method for memory matching was used. In these experiments previously found nearly prototypical colours were used as original colours. In the simultaneous, deciding colour patch and deciding photo experiments the same original colours were used. Significance of the difference between the primary original and subset of yes answers of simultaneous, deciding colour patch and deciding photo experiments in the third series can be seen in Table 4.4.7. No significant differences can be seen between the mean of the subset of the yes answers and the original colour at hue values of skin and grass colours for deciding photo experiment. The results of an ANOVA analysis between the results of the experiments can be seen in Table 4.4.8. The main results of this memory matching experimental series are the variability ellipses of the sky, skin and grass colours in Figure 4.3.2-4.3.4, created analogically with the colour matching ellipses by MacAdam[33].

Table 4.4.7 Significance of the difference between the primary original and subset of yes answers of simultaneous, deciding colour patch and deciding photo experiments in the third series. One sample t-test. Bold numbers show significant differences, at the p=0.05 level

Simultaneous			
	Sky	**Skin**	**Grass**
$\langle C_{ab} \rangle$	0.303	0.230	0.068
<h>	0.291	0.068	0.457

Deciding colour patch			
	Sky	**Skin**	**Grass**
$\langle C_{ab} \rangle$	0.468	**0.001**	**0.000**
<h>	0.054	**0.000**	0.159

Deciding picture			
	Sky	**Skin**	**Grass**
$\langle C_{ab} \rangle$	0.471	**0.014**	**0.021**
<h>	**0.003**	0.357	0.507

The original colours can be regarded as prototypical colours because they are located inside the variability ellipses which were created to be analogous to the MacAdam variability ellipses. These variability ellipses denote the accuracy of remembering so the original colour is a prototypical colour if it is located inside the ellipsis. The length of the axes of the ellipses can be considered as an important characteristic of memory matching. The mean of the length of the long and short axes of the ellipses represents the expansion of the prototypical area. These mean length in a*, b* plane are listed in Table 4.4.9.

Table 4.4.9 The diameter of the prototypical area of the prototypical sky, skin and grass colours

	Sky	Skin	Grass
r	5.0	3.6	6.5

The significant differences that were detected by the one-sample t-tests are not relevant from the point of view of prototypical colours. The emergence of the cognitive effects on instant colours gears to the distance from the prototypical colour. From results of the experiments it can be seen that the distance of the original colour and the long-term memory colour determines if the cognitive effects appear in the colour memory matching process. It is obvious from the previous experiments, that the distance of the original colour and the long-term memory colour determines if the cognitive effects set up in the colour memory matching process. A scheme of such an experimental series can be found in Chapter 5.

As we seen, at the long-term memory colour experiment, literature data were usually different from the experimental findings. One reason is the difference between the viewing conditions that we could not account for when considering the literature data. Namely, literature data were obtained by using reflecting stimuli and not self-luminous stimuli as in the present study.

If we compare the Hungarian and the Korean results, the following can be established: Hungarian and Korean grass and foliage long-term memory were different. Oriental skin and Caucasian skin had similar chroma, Oriental skin contained somewhat more yellow hue, and Caucasian skin was found to be significantly lighter than Oriental skin. Korean sky had similar lightness as Hungarian sky but Korean sky was somewhat more saturated than Hungarian sky. Korean banana was somewhat lighter than Hungarian banana. Finally, Korean orange was lighter than Hungarian orange and Korean orange contained more yellow than Hungarian orange. These differences in the results are attendants of the different cultural and geographical aspects. Naturally, in Korea, the flora is not the same as in Hungary. It is possible, that intensity, or the duration of the sunshine are in contrast, and this has an effect on life-long experiences and results from this that the long-term memory colours of familiar objects in the brain differ.

Chapter 5 Future opportunities

As I mentioned at the end of the results section there are some possibilities to examine the influence of the cognitive effect of colour mechanism to the distance from a prototypical colour. The influence of the cognitive effects on colours can be examined by more experiments using the applied deciding method. The prototypical colours (primary original colours) are listed in Table 5.1. These colours were used as original colours in the third series of experiments and proved to be prototypical colours. More original colours can be used in new experimental series as listed in Table 5.2-5.5. The colours locate at determined distances from the primary original colours. The difference between the primary and the other original colours is only a given h_{ab} value. The primary original colours are presented in Figure 5.1 in an a*, b* diagram.

Table 5.1 Original colours used in the third experimental series; primary original colours

Original	**Sky**	**Skin**	**Grass**
L*	53.99	79.54	50.10
a*	-16.92	16.12	-33.90
b*	-28.02	10.26	29.75

Table 5.2 Original colours shifted counter clockwise from the primary original colours with the quoted Δh values

1x - CCW	**Sky**	**Skin**	**Grass**
Δh	15	15	12.5
L*	53.99	79.54	50.10
a*	-9.09	12.92	-39.54
b*	-31.44	14.08	21.71

Table 5.3 Original colours shifted counter clockwise from the primary original colours with the quoted Δh values

2x - CCW	**Sky**	**Skin**	**Grass**
Δh	30	30	25
L*	53.99	79.54	50.10
a*	-0.65	8.83	-43.30
b*	-32.73	16.94	12.63

Table 5.4 Original colours shifted counter clockwise from the primary original colours with the quoted Δh values

1x - CW	**Sky**	**Skin**	**Grass**
Δh	15	15	12.5
L*	53.99	79.54	50.10
a*	-23.60	18.23	-26.66
b*	-22.68	5.73	36.38

Table 5.5 Original colours shifted counter clockwise from the primary original colours with the quoted Δh values

2x - CW	**Sky**	**Skin**	**Grass**
Δh	30	30	25
L*	53.99	79.54	50.10
a*	-28.66	19.09	-18.16
b*	-15.80	0.82	41.29

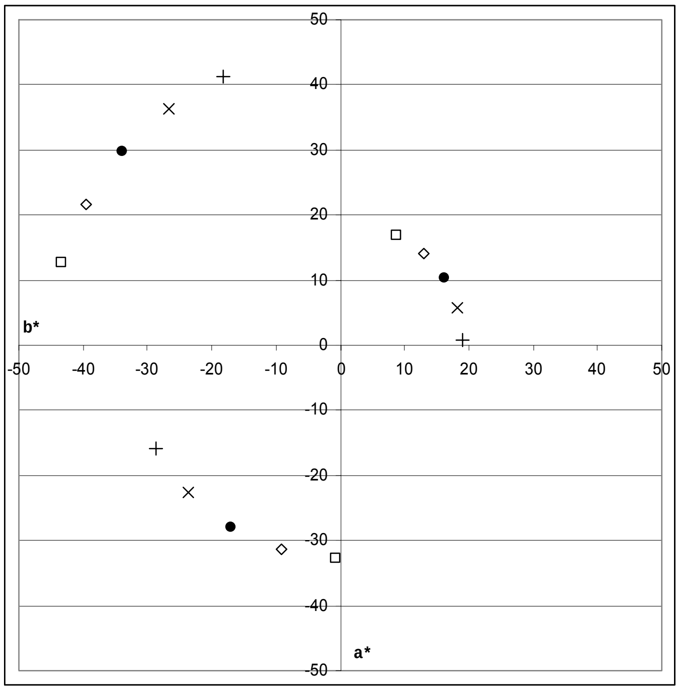


Figure 5.1 Original colours in a*, b* plane. "♦" - primary original colours, "x" – 1x hue shift clockwise, "+" – 2x hue shift clockwise, "◊" – 1x hue shift counter clockwise, "□" – 2x hue shift counter clockwise.

From these attainable experimental series two were performed and the others are progressing now. The results of the experiments will map the surroundings of the prototypical colours, where the cognitive effects influence the colour matching in memory.

Chapter 6 Summary

In the present work, examination of memory colours was implemented. Mapping colour memory is an important work to do because it has an effect on colour matching which is often examined. In literature many articles deal with colour memory matching and memory colours but most of the experiments are implemented with colour chips, like Munsell colour chips. Nowadays computers play an important role in everyday life, so it is obvious to make colour matching experiments on colour monitors. Naturally, these experiments can be colour memory matching experiments.

As I mentioned in the overview of earlier investigations, there are some concepts that are in close connection with colour. These concepts are in mind and their usage is non-conscious in everyday life. The concepts manifest themselves as cognitive effects. Colour memory matching depends on these cognitive effects: exaggeration, focality, and typicality[5].

I applied new experimental set-ups with the following general rule: all experiments must ensure equal viewing situations with equal chromatic adaptation conditions for the memory matching of test colours:

1. In the fist series of experiments, the observers had to memorize the colour of a colour patch in a black frame in a photo-realistic image. After a short delay, the observers had to mix the colour they memorized with the help of three sliders representing hue, lightness and chroma ranges.

2. In the second experiment the image context type on the screen was changed. A greyscale picture represented the image context in this situation. This solution gave the opportunity to select the original colour range as needed. The task of the observer was the same as in the first set-up. Results of a preference experiment were compared to the results of the memory matching experiment.

3. The third type of experimental set-up was created to decrease the concentration load of the observers, and to verify the earlier experimental results. The image context was the same as in the second experimental set-up but the task of the observer was a simple decision making. The subject had to make a decision about the identity of the colours in the memorization and the memory matching phase.

Previously, some experimental data dealt with colour memory and some of them observed some colour shift in the memory matching experiments compared to simultaneous colour matching. In my experiments, the first aim was to examine these colour shifts in case of sky, Caucasian skin, and grass colours. I found significant shifts, which were due to cognitive effects. Prototypical colours were determined, and proved with the deciding method. The deciding method is a new experimental method in examining colour memory matching.

The presence or absence of the context in the memory matching experiment is important. Significant differences can be detected between the experiments where the only difference is the presence or absence of the context. These observations assume that the context develops a cognitive effect that causes a difference between the results of the experiments.

The observed colour memory effects were most intense in case of Caucasian skin colour. Similar to the MacAdam ellipses, the accuracy of memory matching was depicted by ellipses determined during the colour memory experiments. Variability ellipses of „green grass", „Caucasian skin" and „blue sky" prototypical colours for given lightness values were determined.

It is obvious from the performed experiments, that the distance of the deciding colour and the long-term memory colour determines whether the cognitive effects occur in the colour memory matching process. Some experiments were done and more have to be carried out to examine the emergence of the cognitive effects geared to the distance from the prototypical colour.

New scientific results

Developing new experimental methods to examine colour memory effects

Ensuring equal adaptation conditions for colour memory experiments performed on computers

1. *Applying blurred images in the memory matching phase of psychophysical colour memory experiments to ensure equal chromatic adaptation conditions of the observer in the observation/memorization phase and in the memory-matching phase* [25,29,85,88] *and thus to eliminate the perceptual artefact influencing the memory colours.*

2. *Applying greyscale background images to examine colour memory effects in order to ensure equal chromatic adaptation conditions in case of employing arbitrary number of original colour.* [91, 93, 94, 95]

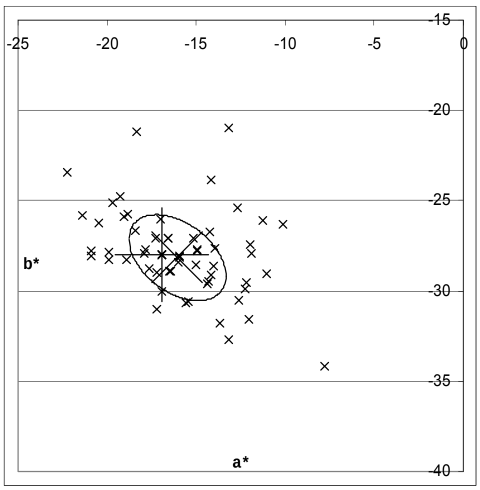
Developing new computerized experimental methods to ensure more precise examination of the colour memory effects

3. *Developing a computerized colour mixing method changing hue, lightness and saturation components of the colours (i.e. according to the perceptional attributes of colours) in the memory colour mixing phase of the psychophysical examination of the memory colour shift to enable a more precise action of observing the memory colour shifts in the memory colour-mixing phase.* [25,29,85,88, 93, 94, 95]

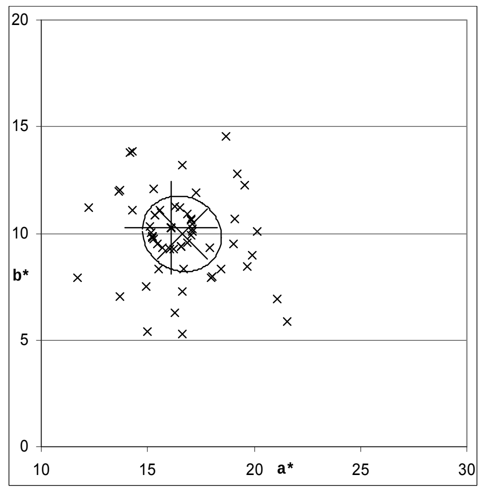
4. *Applying the simple decision rating experimental paradigm during colour memory experiments on computers to get fast, unambiguous results by eliminating the observer's fatigue.* [89, 91, 93]

New experimental results for short-term memory colours

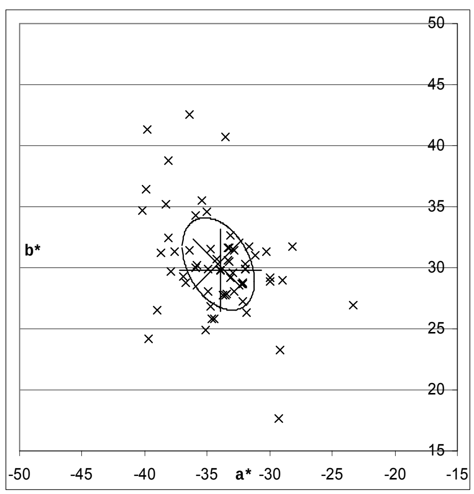
5. *Based on the new paradigm of the accuracy of the memory - the variability ellipses of the most important sky, skin and grass colours can be determined, analogous to the fundamental MacAdam ellipses - describing just perceptible simultaneous colour differences - as shown in the following figures* [89, 91, 93,98,99]*:*



Sky L^*=54



Skin L^*=80



Grass L^*=50

Figure 1. Variability ellipses for sky, skin and grass colours in CIELAB a^*, b^* plane for memory experiment with image context. The original colours are depicted by a large plus sign, the mean decision colours of the "yes, the same" subsets is depicted by big crosses. The "yes, the same" subset is depicted by small crosses.

Table 1. Length of the long and short axes of the variability ellipses in CIELAB units

	Long axis	Short axis
sky	6.2	3.8
skin	3.8	3.4
grass	8.0	5.0

6. *The unambiguous proof of cognitive effect in colour memory: the shift towards prototypical colour is the strongest in case of Caucasian skin colour* [89, 91, 93] *as could be proved by determining the length of the axes of the variability ellipses obtained during the psychophysical experiments applied for examining the accuracy of the memory.*

Table 3. Mean of length of the axes of the variability ellipses of the simultaneous, the colour patch and the photo experiments at the simple decision method

	Simultaneous	Colour patch	Photo
sky	3.0	5.8	5.0
skin	4.2	5.2	3.6
grass	4.8	10.4	6.5

New experimental result for long-term memory colours

7. *A comprehensive three stage experimental method for determining long term memory colours is based on the following two paradigm, built one on the other:*
    1. *First Stage: applying the method of constant stimuli where the memory colour is selected from several constant colour patches,*
    2. *Second Stage: applying the method of constant stimuli once more for more exact results,*
    3. *Third Stage: applying the mixing method to find the long-term memory colours of the subjects,*

    through this method the mean of the results of the three series provides the accurate long-term memory colours of the observers. [92]

8. *Significant differences exist between long-term memory colours of European and Far-Eastern observers, illustrated by the following tables and figures* [92]*:*

Table 4. CIELAB values of long-term memory colours of Hungarian (H) and Korean (K) observers

	Skin		Sky		Grass		Foliage		Banana		Orange	
	H	K	H	K	H	K	H	K	H	K	H	K
L*	81.8	73.1	65.7	62.6	45.5	55.6	84.1	40.5	68.2	86.6	43.2	72.6
a*	10.5	8.6	-10.4	-10.0	-40.4	-45.7	-10.6	-33.9	27.7	-10.5	-39.1	24.5
b*	19.3	20.3	-28.9	-35.4	32.2	35.1	66.7	21.4	62.9	69.1	30.0	69.1

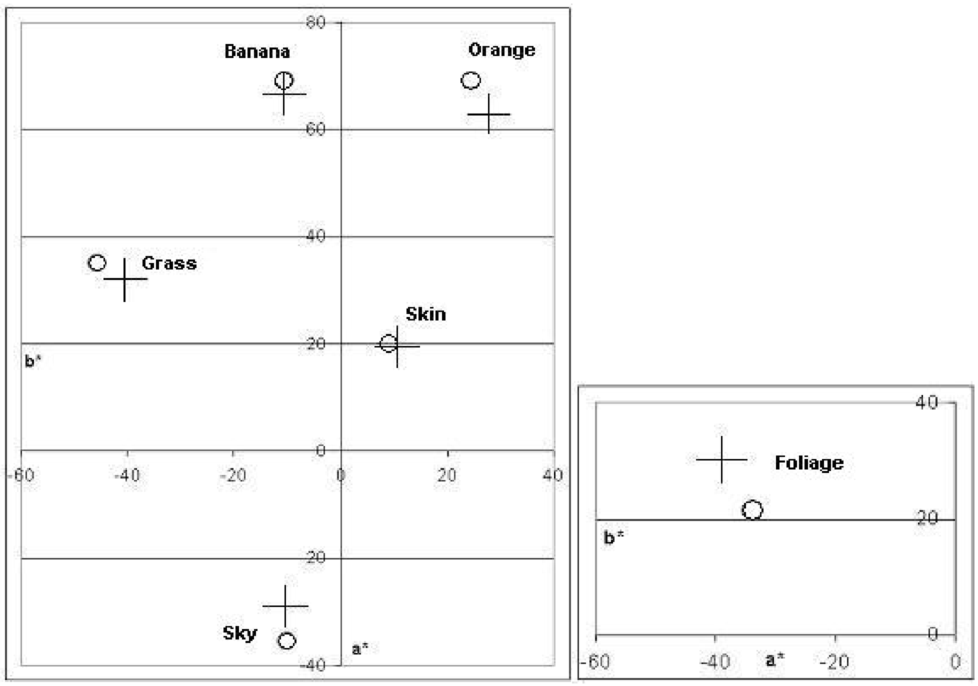


Figure 2. Long-term memory colours from Korean observers (open circles) and Hungarian observers (plus signs); in CIELAB a^*, b^* plane. Foliage is shown in a separate diagram on the right.

Table 5. Significance of the differences between the long-term memory colours of Korean and Hungarian observers. T-test, bold numbers show significant differences, at the p=0.05 level.

p	Skin	Sky	Grass	Foliage	Banana	Orange
<L*>	**0.000**	0.397	**0.000**	0.306	**0.019**	**0.000**
<a*>	**0.037**	0.835	0.060	**0.038**	0.715	0.150
<b*>	0.147	0.166	0.240	**0.007**	0.324	**0.000**

Application

The customers of colour imaging products often prefer long-term memory colours or colour prototypes of familiar objects frequently seen in the past. Therefore, it is important to determine the prototypical colour of frequently seen (or used) objects, like sky, grass, or skin. This is also important in everyday life. Just think about the advertisements on TV, or posters in the streets. Prototypical colours are the best-remembered colours (with the smallest shifts and the lowest inter-observer variability). If an object is displayed in colour shades within the prototypical colour region, its perceived naturalness is high. The advertised object has greater influence on the customers if its colour is more natural. Therefore it is recommended to include in the imaging software's palette special "sky-blue", "grass-green" and "Caucasian complexion hue" patches to help novice image processing engineers to select pleasing colours for their jobs. In the future further special patches should be added.

Új tudományos eredmények

Új kísérleti módszerek kifejlesztése a színi memóriahatások vizsgálatához

Azonos adaptációs állapot biztosítása számítógépes színi memóriavizsgálatok számára

1. *Elmosott képek alkalmazása a memóriaegyeztetési kísérleti fázisban a színmemóriára vonatkozó pszichofizikai kísérleteknél a memóriaszínek befolyásolásának kiküszöbölésére annak érdekében, hogy a megfigyelő színi adaptációs állapota azonos legyen a megfigyelési/memorizálási és memóriaegyeztetési kísérleti fázisban.* [25, 29, 85, 88]

2. *Szürkeárnyalatos háttérkép alkalmazása a színi memóriahatások vizsgálatához az azonos színi adaptációs állapot megtartása érdekében tetszőleges számú színinger esetén.* [91, 93, 94, 95]

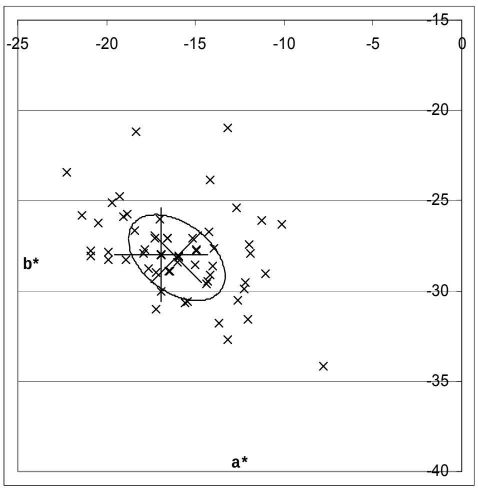
Számítógépes kísérleti módszerek kialakítása, a színi memóriahatások pontosabb vizsgálatának biztosítására

3. *A színezet, világosság és színdússág összetevők (az intuitív színészlelet-jellemzők tengelyeinek irányában való állíthatóság) alapján történő színkeverés, mint új számítógépes módszer alkalmazása a memóriaegyeztetési (vagy a memóriaszín kikeverés) fázisban a színi memóriavizsgálatokhoz alkalmazott pszichofizikai kísérletek esetében a színi eltolódások pontosabb megfigyelése érdekében.* [25, 29, 85, 88, 93, 94, 95]

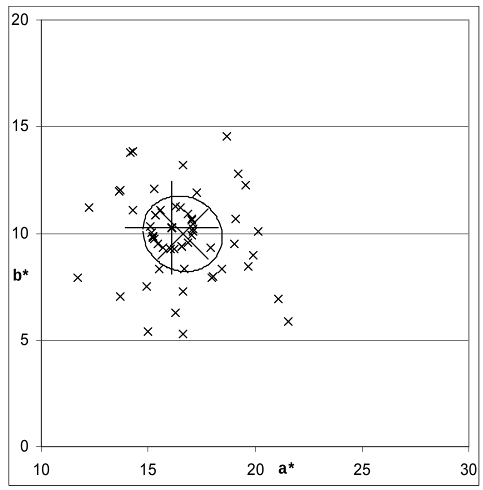
4. *A számítógépes színi memóriavizsgálatok során az egyszerű döntésen alapuló paradigma alkalmazása gyors és megbízható eredmények biztosításához, melynek segítségével kiküszöbölhető a kísérleti személyek elfáradása, amely a kísérletek során gyakran fellép.* [89, 91, 93]

A rövid-távú színmemória vizsgálatára vonatkozó új kísérleti eredmények

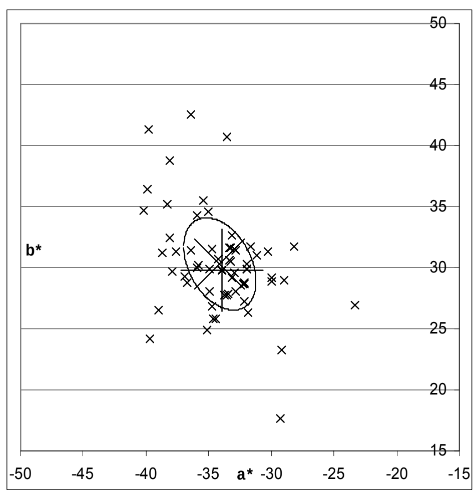
5. *A memória pontosságra vonatkozó új paradigma alapján rövid-távú színmemória a legfontosabb ég-, bőr- és fűszínek esetében az alábbi ellipszisekkel írhatóak le (az irodalomban alapvető, MacAdam által vizsgált, éppen érzékelhető színkülönbségeket ábrázoló ellipszisek analógiájára)* [89, 91, 93,98,99]*:*



Ég, $L^* = 54$



Bőr, $L^* = 80$



Fű, $L^* = 50$

1. ábra: Az ég-, bőr- és fűszín szórási ellipszisei CIELAB a^*, b^* síkban képi kulcsos színegyeztetési kísérlet esetén. Az eredeti színek nagy pluszjellel, az eredetivel azonosnak talált színek átlagai nagy kereszttel, míg maguk az eredetivel azonosnak talált színek kis kereszttel vannak jelölve.

1. táblázat: A szórási ellipszisek hosszú és rövid tengelyeinek hossza CIELAB egységekben

	Hosszú tengely	Rövid tengely
ég	6,2	3,8
bőr	3,8	3,4
fű	8,0	5,0

6. *A színmemóriában a kognitív hatások egyértelmű bizonyítása: (a pszichofizikai kísérletek alapján) a prototipikus szín felé történő eltolódás a kaukázusi bőrszín esetén a legerősebb, miként ezt az emlékezet pontosságának vizsgálatára alkalmazott kísérletek eredményeként kapott szórási ellipszisek tengelyeinek hossza igazolja*[89, 91, 93]*:*

3. táblázat: A szórási ellipszis hosszú és rövid tengelyeinek átlaga a szimultán, valamint a színmintát és képi kulcsot alkalmazó egyszerű döntéses kísérletek esetén

	Szimultán	**Színminta**	**Színes fotó**
ég	3,0	5,8	5,0
bőr	4,2	5,2	3,6
fű	4,8	10,4	6,5

A hosszú-távú színmemória vizsgálatára vonatkozó új kísérleti eredmények

7. *A hosszú távú memóriaszínek meghatározására szolgáló, hatékony számítógépes módszer a következő két alapvető pszichofizikai módszer egymásra épülő alkalmazásaiból alakul ki:*

    1. *szakasz: konstans stimulusok módszere, ahol a kísérleti alany feladata több megjelenített szín közül saját hosszú távú memóriaszínének kiválasztása, majd a*

    2. *szakasz alkalmazása, amelynek célja az eredmények pontosítása a konstans stimulusok módszerével és a*

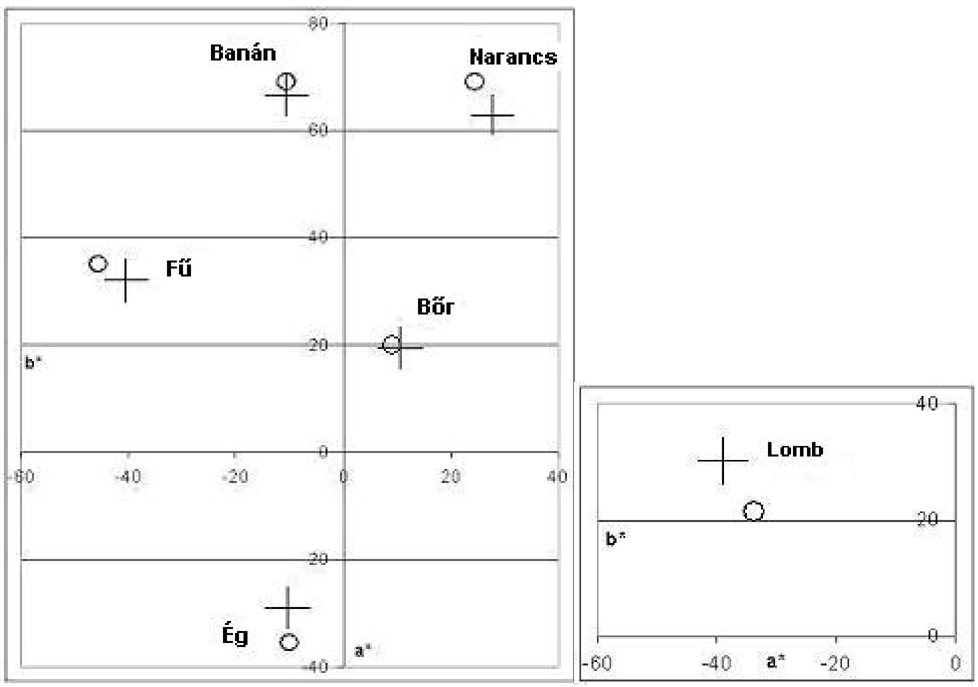
    3. *szakaszban a színkeverési módszer alkalmazásával a memóriaszínek kiválasztása,*

    majd ezután a kísérleti szakaszokban az egyes színekre kapott eredmények átlaga adja meg a hosszú távú memóriaszíneket[92]*.*

8. *Az európai és távol-keleti megfigyelők hosszú távú memóriaszíneiben szignifikáns eltérések vannak, melyeket az alábbi táblázatok és ábra szemléltet*[92]:

4. táblázat Koreai (K) és magyar (H) megfigyelők hosszú-távú memóriaszíneinek CIELAB értékei

	Bőr		**Ég**		**Fű**		**Lomb**		**Banán**		**Narancs**	
	H	**K**	**H**	**K**	**H**	**K**	**H**	**K**	**H**	**K**	**H**	**K**
L*	81,8	73,1	65,7	62,6	45,5	55,6	84,1	40,5	68,2	86,6	43,2	72,6
a*	10,5	8,6	-10,4	-10,0	-40,4	-45,7	-10,6	-33,9	27,7	-10,5	-39,1	24,5
b*	19,3	20,3	-28,9	-35,4	32,2	35,1	66,7	21,4	62,9	69,1	30,0	69,1



2. ábra Koreai (körök) és magyar (plusz jel) megfigyelők hosszú-távú memóriaszínei CIELAB a^*, b^* síkban. Lomb eredmények külön diagramban a jobb oldalon.

5. táblázat Magyar és a koreai megfigyelők által meghatározott hosszú-távú memóriaszínek közötti szignifikáns különbségek CIELAB *L**, *a** és *b** értékekre. T-teszt, a félkövérrel szedett értékek szignifikáns különbségeket mutatnak a p=0.05 szinten.

p	Bőr	Ég	Fű	Lomb	Banán	Narancs
<L*>	**0,000**	0,397	**0,000**	0,306	**0,019**	**0,000**
<a*>	**0,037**	0,835	0,060	**0,038**	0,715	0,150
<b*>	0,147	0,166	0,240	**0,007**	0,324	**0,000**

Alkalmazás

Képmegjelenítő eszközön megjelenő kép esetén a megfigyelők jobban kedvelik a képet, ha azon az ismert tárgyak hosszú távú memóriaszínei láthatók. Ezért fontos feladat meghatározni a gyakran látott vagy használt eszközök, tárgyak prototipikus színeit, mint például az ég, a bőr és a fű hosszú távú memóriaszíneit. Ez fontos szerepet tölt be a mindennapi életben is. Gondoljunk csak a reklámokra a televízióban vagy a plakátokra az utcákon. A prototipikus színek a legkönnyebben megjegyezhető színek. Ezek esetében az eltolódás és a megfigyelők közötti szórás a színi memóriaegyeztetési kísérletekben a legkisebb. Ha egy szín a prototipikus tartományon belül helyezkedik el, a színt a megfigyelő természetesnek értékeli. A reklámok nagyobb hatást érnek el, ha a látott képeken megjelenő színek természetesek. Ezért ajánlott a képfeldolgozó programokban olyan színek, mint például az „ég", a „fű" vagy a „kaukázusi bőr" prototipikus színeinek alkalmazása, hiszen ezek nagymértékben megkönnyítik és gyorsítják az ezekkel a programokkal dolgozó emberek munkáját. A jövőben további speciális színminták hozzáadását kellene biztosítani.

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Glossary

1st viewing situation	observers memorize an original colour
2nd viewing situation	observers may modify the colour until it matches the memory colour
abstract memory colour	the experimenter says only the name of a familiar object, and the subject has to choose or mix a colour which seems to him to best represent the colour of the object
adaptation hypothesis	explains the colour shifts by the difference of the state of adaptation between viewing the original colour and viewing the choice figure
back-calling	the 2nd viewing situation, when the observer determines his memory colour
basic colour term	the basic colour terms of a language are the smallest set with which a speaker can name any colour
brightness	attribute of a visual sensation according to which an area appears to emit more or less light
chroma	chromaticness, colourfulness, of an area judged as a proportion of the brightness of a similarly illuminated area that appears white or highly transmitting
chromaticity	property of a colour stimulus defined by its chromaticity coordinates, or by its dominant or complementary wavelength and purity taken together.
chromaticity coordinates	ratio of each of a set of three tristimulus values to their sum
chromaticness	attribute of a visual sensation according to which the perceived colour of an area appears to be more or less chromatic.
cluster analysis	encompasses a number of different algorithms and methods for grouping objects of similar kind into respective categories
cognition	subsequent higher-order processes of semantic and verbal classification of the perceptions
cognitive colour	the result of the colour module of early visual processing is perceived colour with its three continuous perceptual attributes, hue, colourfulness, and brightness. After the early visual processing stage, the colour perception is classified into a (semantic) category if required by the visual task. Cognitive colour means one from the discrete set of these categories.
cognitive effect	possible cause of colour shifts in human short-term colour memory. There are three cognitive effects: exaggeration, focality, and typicality
color combination theory	mental model for the formal description of the perceptual colour attributes that characterize a Colour Gestalt
colour category	colour categories decompose the colour space in partially overlapping subsets. Colour categories are prototype categories
colour constancy	refers to the invariance of the perceived colour of surfaces under changes in illumination, for example, from the blue-grey

	of North-sky light to the orange-red of the setting sun
colour emotion	colour plays an important role for customers, making decisions on what they like and dislike. They evoke various emotional feelings such as excitement, energy, and calmness. These feelings, evoked by either colours or colour combinations, are called colour emotions.[74]
colour harmony	harmony is widely thought of as a description of similarity, arrived at subjectively, on the grounds of appearing to be pleasing. In fact, harmony is a function of balance and equilibrium
colour shift	the difference between the mean perceived colour and the mean remembered colour
colourfulness	attribute of a visual sensation according to which the perceived colour of an area appears to be more or less chromatic.
context	a visible familiar object in addition to a colour patch to memorise (in an experiment focusing on colour memory)
corresponding colour	the result of the modification of the actual colour
CRT	cathode ray tube monitor
decision colour	the actual colour in the second viewing situation about which the observer had to decide whether it is equal to the memorized colour
deuteranomalous trichromat	according to the traditional theory deuteranomalous people have normal S and L cones and anomalous M cones whose spectral sensitivity is shifted to longer wavelength (closer to the L cone spectral sensitivity)
exaggeration	a cognitive effect: a tendency to avoid storing “medium” brightness or saturation in short-term colour memory
experimental series	some experiments that have a common attribute like same original colours
FAN effect	the FAN effect is Anderson's explanation for the brain's ability to optimize memory retrieval by keeping better access to memories that are more likely to be relevant
focal colour	a colour most frequently chosen from many similar colours for a monolexemic colour term, e.g. “blue” (Boynton & Olson, 1987) the focal colours are those that for the observer are ideal representatives of a given basic colour name
focality	a cognitive effect: focal colours shift the perception toward themselves in short-term colour memory
geometric image	a uniform colour patch standing alone on a grey background
hue	attribute of a visual sensation according to which an area appears to be similar to one, or proportions of two, of the perceived colours red, yellow, green, and blue (Hunt, 1995)
instant memory colour	the original colour in the observers mind in the memorization part

lightness	the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting (Hunt, 1995)
long-term colour memory	memory about the colour of an object in the observer's mind, which rests on the observer's previous experiences during their life
MacAdam ellipses	determine a series of boundaries around several color targets (x, y coordinate) on the CIE chromaticity diagram, illustrating how much one can "stray" from the target (along various colour axes) before perceiving a difference from the target color
maximum likelihood estimation	maximum likelihood estimation is a totally analytic maximization procedure. A method of point estimation, that uses as an estimate of an unobservable population parameter the member of the parameter space that maximizes the likelihood function.
memorizing phase	memorization part of the experiment
memory colour	refers to colours that are recalled in association with familiar objects in long-term memory
memory shifts	the difference between later memory colour and the instant memory colour is the memory shift
memory task	subjects have to remember previously seen colours
monochromatic stimulus	a stimulus consisting of a very small range of wavelengths which can be adequately described by stating a single wavelength
monolexemic	consisting of only one simple word
Munsell Atlas	a colour atlas displaying coloured specimens of a range of values and chromas for ten hues
Munsell colour chip	a colour chip in Munsell Atlas, uniquely identified by a code indicating value, hue and chroma
naturalness	a colour of an object is natural to us if the colour resembles to the colour we keep in our remembrances from the object
NCS colour space	a logical color system, which builds on how the human being sees colour
original colour	the colour presented at the beginning of an experiment focusing on colour memory; the colour to be memorised by the observer
Ostwald hues	red, orange, yellow, yellow-green, green, blue-green, blue, purple
perceived naturalness	a term of Yendrikhovskij et al. (1998): the degree of correspondence with reality. A perceived attribute of displayed images.
perception	immediate mapping of objects or events of the real world into the brain
photo	a photo-realistic image displayed on the monitor

photoreceptor hypothesis	the colour recalled from memory "reproduces" the light absorbed by each type of cone
preference task	subjects have to rate actually seen colours on a rating scale according to their judgement about how they like them or they have to decide which colour is better, more beautiful, etc.
preferred colour – preference colour	the observer has to compare different colours and to choose the one he/she prefers for a reproduction of a familiar object, e. g. a human face
primary original colour	the original colour from which the other original colours arise
protanomalous trichromat	a according to the traditional theory protanomalous people have normal S and M cones and anomalous L cones whose spectral sensitivity is shifted to shorter wavelength (closer to the M cone spectral sensitivity)
prototypical colour	the mean of the prototypical colour region
prototypical colour region	the region of original colours for which no significant colour shift is found in short-term colour memory with the context present in the field of view
prototypical hue	the mean of the prototypical hue range
prototypical hue range	the range of hues of those original colours for which no significant hue shift is found in short-term colour with the context present in the field of view
prototypical lightness	the mean of the prototypical lightness range
prototypical lightness range	the range of lightness of those original colours for which no significant lightness shift is found in short-term colour memory with the context present in the field of view
retention hypothesis	it is stated that colour memory was a selective resultant of the relative impressiveness of the various aspects of stimulation. Selection occurs during perception. More dominant, characteristic, and attractive aspects tend to be more impressive and more prone to survival in short-term memory.
saturation	chromaticness, colourfulness, of an area judged in proportion to its brightness.
short-term colour memory	memory about the colour of an object in the observer's mind, when the original colour was seen short time before
simultaneous or perceptual colour matching	two simultaneously presented colour stimuli to make it visually match each other
successive or delayed matching	colour matching with some delay between the memorization and the back-calling part of the experiment
surface-reflectance hypothesis	the colour recalled from memory is based on an inferred spectral reflectance of a surface that does not depend on the spectral distribution of the illuminant

Meaning of symbols

CIELAB	CIE $L^*a^*b^*$ is theoretical colour space developed by the Commission Internationale de l'Eclairage (CIE).
C^*	CIELAB chroma
C_{mixed}	CIELAB chroma of mixed colour
C_o	CIELAB chroma of original colour
h	CIELAB hue angle
h_{mixed}	CIELAB hue angle of mixed colour
h_o	CIELAB hue angle of original colour
L^*	CIELAB lightness
ΔC^*	CIELAB chroma difference
Δh	CIELAB hue angle difference
ΔL^*	CIELAB lightness difference
a^*	In CIELAB coordinate system a* represents the difference between green $(-a^*)$ and red $(+a^*)$
b^*	In CIELAB coordinate system b* represents the difference between yellow $(+b^*)$ and blue $(-b^*)$

Appendix

APPENDIX 1 Photo-realistic images presented in mixing photo experiment, Section 3.1.1.

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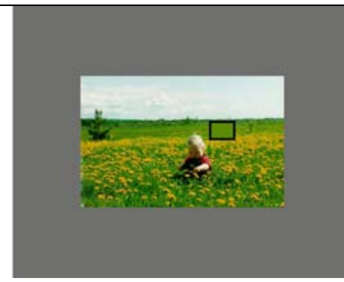

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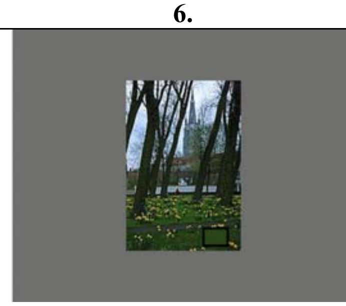

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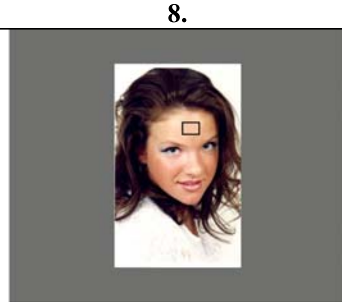

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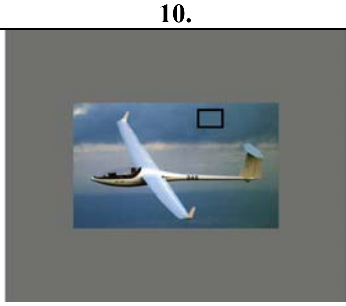

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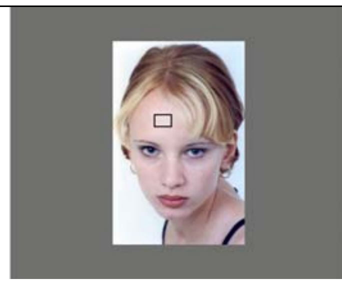
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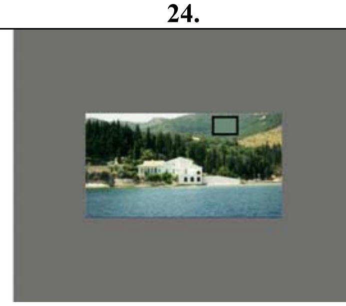
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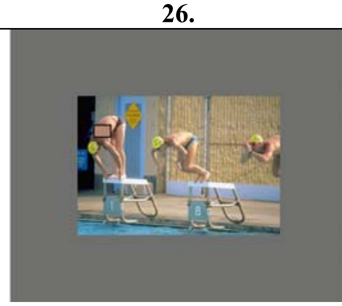
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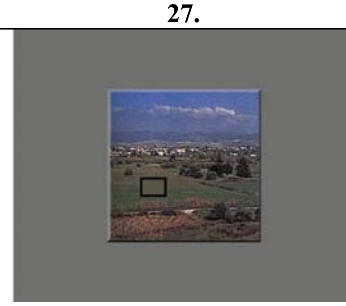
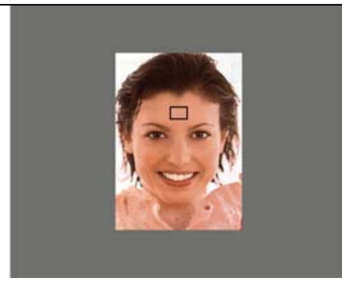
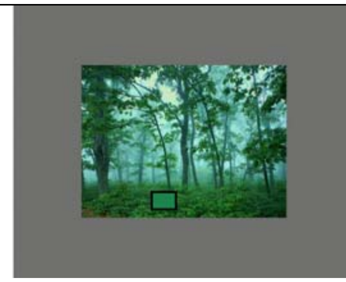
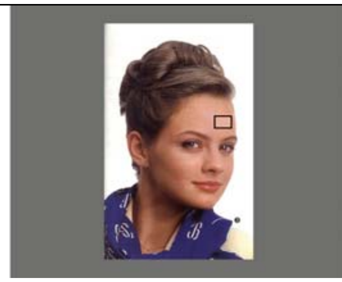
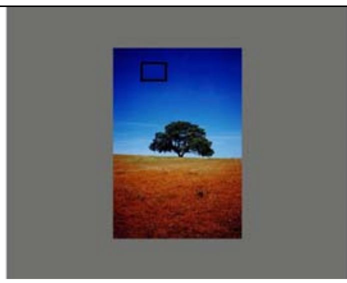
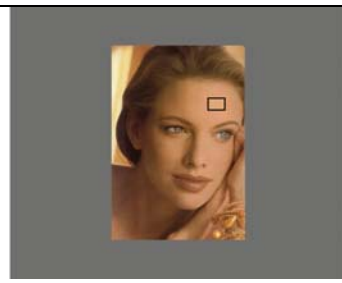
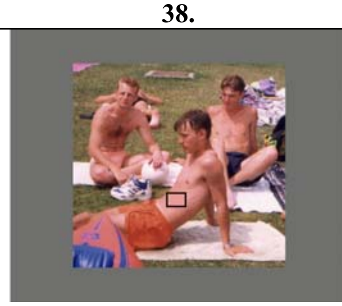
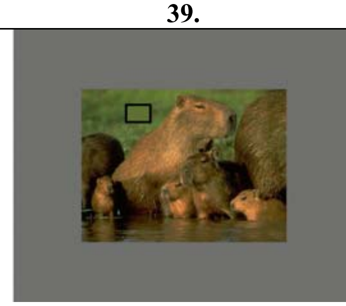
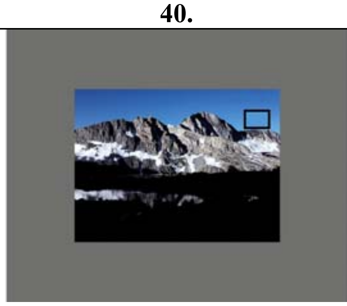
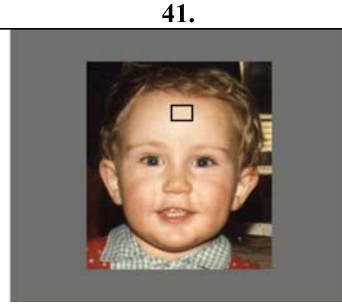
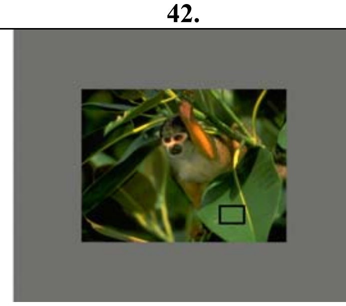

30.

 **31.**	 **32.**	 **33.**
 **34.**	 **35.**	 **36.**
 **37.**	 **38.**	 **39.**
 **40.**	 **41.**	 **42.**
 **43.**	 **44.**	 **45.**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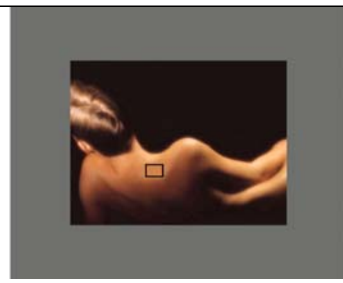
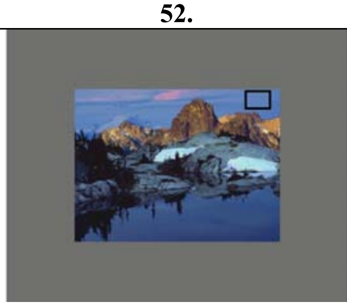
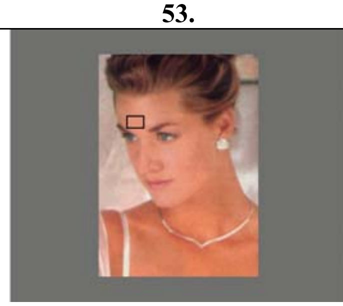

53.


54.


55.


56.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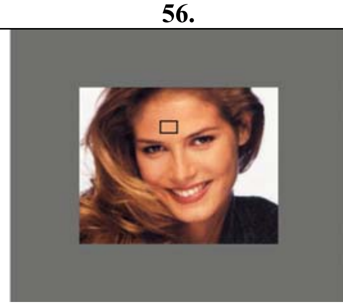
59.


60.

APPENDIX 2 Instruction to the observer

Please read this short description attentively. Your task will be simple. You will be able to do it easily based on this description. Please do not ask any other questions.

There are three basic properties of colour: lightness, hue, and saturation. The meaning of lightness is evident. Hue is the type of the colour, e. g. red, orange, yellow, green, blue, or purple, or the mixture of the previous colours. Example: Is there a bit less or a bit more purple in the colour of a flower? What do you think: is it purplish or rather a bit like the red of fire? Saturation means how much the colour contains from its hue, how strong the colour is. E. g. in a "rose-coloured" rose there is less purple and more white but in the colour of a vivid purple dress there is more purple, it is more saturated.

During the experiment, you will have the following task: Memorise the colour of that part of the image being in the black frame. After 4 seconds of pause, try to find the colour in your mind in another black frame by adjusting three "slides" at the top of the screen corresponding to lightness, hue, and saturation. The three "slides" adjust the colour of the field in the black frame. First, try to set a lightness. Then search for a hue. Then try to find a saturation. Look at the colour now and compare it with the colour in your mind. Amend lightness, hue, and saturation if necessary. Compare the colour with the colour in your mind again. Amend lightness, ... etc. Continue this process until you have got the colour in your mind.

Phase 1: Practice. You can practice by using two images. Memorise the colour in the black frame and push the "Next" button. After 4 seconds, another image will appear. Try to find the colour in your mind by using the "slides". Push "Ready" when you are ready. 2 minutes per image is suggested.

Phase 2: Experiment. This phase consists of 60 images. Your task is similar to what you have just done.