LATERALISATION OF CATEGORICAL PERCEPTION OF 
COLOUR

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Abstract

The debate over language and thought has traditionally been framed by two opposing approaches: Universalism and Relativism. Universalism holds that language is shaped by universals of human cognition. In contrast, Relativism holds that language shapes thought. Colour categorical perception has been the main area in which the two theories are tested. The current thesis presents a series of experiments examining the nature and origin of colour categorical perception. The focus is on the categorical perception (CP) of colour defined as better discrimination of colours that straddle a category boundary than that of colours within categories. It has recently been argued that colour CP is represented in the left hemisphere and this reflects explicit language processes. The current thesis tests this account in a series of experiments using a task that loads heavily on perceptual processes. The results show that there is a predisposition for colour CP in pre-lingual infants and that is based in the right hemisphere. In contrast, in adults, colour CP is represented in the left hemisphere. A cross-cultural approach allowed for a further test of the role of language in colour CP comparing speakers of languages that make different categorical colour distinctions. CP effects were found only in marked boundaries and it was lateralised to the left hemisphere. Finally, using a learning paradigm, the findings showed that learning to categorise stimuli alters their perception at an early stage of visual processing and this is restricted to the left hemisphere. Overall, the results presented in this work suggest that colour CP is neither strictly perceptual nor strictly language dependent. Instead, the findings suggest that a subtle interplay between the two positions is required to explain the nature of colour CP. Colour CP is present in the absence of language, but language may modulate the location of categorical perception as colour terms are acquired.
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Introduction to the thesis

Even though humans are able to discriminate a large number of wavelengths, many are categorised together. Over the decades, research into the nature of colour perception and colour categorisation has unveiled much about how humans perceive chromatic stimuli, how they categorise colour and how language has an impact on colour categorisation. The nature and origin of perceptual and linguistic categories has been traditionally investigated within two fundamentally different approaches. On the one hand, according to Universalism, perceptual categories are “hardwired” into the visual system and language exploits these discontinuities in perceptual colour. Innate perceptual categories imply that the neural mechanisms involved in categorisation are genetically determined. Categorical perception is biologically constrained: biological colour vision generates a set of colour categories and these categories reflect perceptual processes. Thus, language is a matter of learning labels for existing categories and there is no influence of language on category formation (e.g., Berlin and Kay, 1969; Franklin and Davies, 2004). As Pinker argues: “The way we see colour determines how we learn words for them, not vice versa” (Pinker, 1994, p. 63). On the other hand, according to Relativism, language is required for perceptual categorisation. Language and its underlying conceptual framework act as a complex adaptive system, which plays an active causal role in perceptual development. Thus, perceptual categories are constructed through language, and colour perception varies as languages vary (e.g., Roberson, Davies & Davidoff, 2000; Kay & Kempton, 1984).

Despite abundant research, there is no clear consensus in the literature as to which approach best explains colour categorisation. The aim of this thesis is to contribute to the debate about the nature and origin of colour CP addressing the relationship between colour perception, colour categorisation and language. Previous research has not investigated the representation of colour categories in the brain, thus, the focus in this thesis is on the categorical perception of colour (hereafter CP) in relation to the functional organisation of the brain.
This thesis addresses fundamental issues in colour CP, such as:

- Whorfian effects and colour CP
- The development of colour CP
- Colour language and colour experience
- Underlying mechanisms in acquired CP

Initially, to investigate Whorfian effects and colour CP a series of experiments focused on the functional organization of the brain. Furthermore, a series of experiments investigated the development of colour categories in infants and toddlers while focusing on hemispheric differences. Additionally, to investigate the effect of colour language on colour CP, speakers of languages that segment the colour space differently from each other were compared. Finally, the underlying mechanisms in acquired CP were investigated focusing on the flexibility of learning to form new colour categories. This was addressed using a category-learning paradigm. It is hoped that the thesis will contribute to a better understanding of the origin and nature of CP.

The first chapter presents a brief summary of the physiological basis of colour vision. In addition, a detailed outline of issues considering the nature and origin of colour CP is given, while arguing on competing theories and relevant research findings.
Chapter 1

1.1. Colour Psychophysiology

The colour of objects improves object identification (Zaidi, Yoshimi, Flanigan & Canova, 1992), helps in the organizing of a scene (Abramov & Gordon 1994), and offers an aesthetic component to visual experience, which is fundamental to our perception of our surroundings (Gegenfurtner, 2003). The early stages of colour vision are well understood: the light enters the eye, passes through the cornea, lens, aqueous and vitreous humour, and then reaches the retina where is initially encoded by three cone photoreceptors (Engel, 1999). Young (1801/1948) suggested the threefold character of colour perception, and speculated that there were three different types of colour sensitive receptors in the eye tuned to different but overlapping regions of the visible spectrum. Three numbers, which specify the photon catches in each of the three photoreceptors, represent colour in the nervous system. These three cone photoreceptors form the basis of what now is known as trichromatic colour vision (in Lennie, 2000).

Helmholtz (1909/1962) argued that these receptors correspond roughly with the red, green and blue sensation, whereas the yellow sensation is achieved through equal activation of red and green receptors. Hering in the late 19th century challenged the Young-Helmholtz theory arguing that the "trichromatic theory" could not explain the phenomenon of afterimages, i.e., negative-coloured images seen after extended viewing of a coloured object (e.g., red after green, or yellow after blue). Hering based his work on the subjective appearance of colours and wondered why certain colours could never be seen or even described, such as bluish-yellow or reddish-green, in contrast to greenish-blue. Hering proposed that the visual system generated signals in opposing pairs (i.e. yellow-blue, red-green), and argued that the resulting chromatic sensation depended on the inhibition and excitation of these two processes (in Wooten & Miller, 1997). Hurvich and Jameson (1957) used a hue cancellation procedure, where participants had to adjust the intensity of one coloured light until the hue of another light was no longer perceived. It was found that when pairs of hues corresponding to Hering’s opponent primaries were presented simultaneously, they cancelled each other. It was argued that red and green cancel each other, as do yellow and blue: i.e. when red and green are mixed together, they produce yellow, not reddish green. Therefore, if one started
with a colour such as bluish green it should be possible to mix this colour with a unique yellow to cancel out the blue content leaving only green. Thus, these hue cancellation techniques provided strong psychophysical evidence for colour opponent process theory.

However, it was not until much later in the twentieth century that early visual processing combined trichromatic and opponent stages. It is now well known that retina contains rod and cone photoreceptors with colour vision primarily sub served by the cone photoreceptors, with each cone cell containing one out of three different types of visual pigment. The three cone-types are sensitive to different ranges of wavelengths: long (L) medium (M) and short (S) with peak sensitivities at 560 nm 530 nm 430 nm respectively (Boynton, 1979). This initial trichromatic coding is followed by opponent process coding in the ganglion cells, where the cone signals are combined into two chromatic channels (L-M and S-[L+M]) and a luminance channel (L+M).

The visual system can distinguish between 1 million (Kaiser & Boynton, 1996) and 7 million (Zeki, 1993) colours, yet the number of basic colour terms in various languages studied is relatively small. Over the decades, research into the nature of colour perception and colour categorisation has aimed at explaining how humans perceive chromatic stimuli, how colour is categorised and whether language influences colour categorisation, or whether colour categories are “hard wired” in the human brain. The picture is complicated by the fact that the representation of colour in the cortex is not well understood (Engel, 1999). Several researchers suggest that colour processes take place at different localities in the cortex, such as in areas V1 and V2, and V4 and V4a (e.g., Engel, 1999; Engel & Fumanski, 2001; Engel, Zhang & Wandell, 1997; Zeki, 1980, 1983). Ratliff (1976) suggested that basic colour terms are linked to spectrally opponent physiological mechanisms, and Kay and McDaniel (1978) argued for the wavelength selective opponent cells in the lateral geniculate nucleus (LGN). Some report evidence of opponent processing cells in ganglion cells and in the LGN (e.g., De Valois, Abramov & Jacobs, 1966; De Valois & De Valois, 1975).

For instance, DeValois and DeValois (1975) showed a contribution of neural substrates to colour categorisation identifying four classes of colour-sensitive cells in the lateral geniculate nuclei (LGN) of the maque monkey. These colour-sensitive cells were excited by yellow
wavelengths and inhibited by blue (+Y-B), or excited by red and inhibited by green (+R-G), showing a connection of opponent cells to the three cones, i.e. a +R-G cell would receive activation from an L cone but inhibition from M cones. However, direct physiological recordings give no support for direct correspondence between opponent cells in the LGN and perception. Research suggests that wavelengths, which cause peak activity in the cells in the LGN correspond to 'cherry/bright red, chartreuse/greenish yellow, teal/greenish blue, and violet/deep purple, thus, the opponent end point do not correspond to the red, green, blue and yellow Hering’s primaries (Jameson & D’Andrade, 1997). As Abramov and Gordon (1994) point out, knowledge of the physiological mechanisms of colour and their properties alone does not explicitly explain how visual information provides the experience of colour. Thus, it is generally agreed that colour processes take place at different localities to form colour experience.

1.2. Categorical Perception

The question of how organisms arrange the objects of the world into categories is one of the most essential queries of cognitive science as categorisation plays a critical role in thinking, perception, language and possibly in motor performance too (Hamad, 1987). Categorisation is important because ‘the world consist of an infinite number of potentially different stimuli’ (Heider & Lloyd, 1978, p.1). Categorisation is ‘thus construed as conceptualisation and taken to be a single central function of an organism in which distinguishable stimuli are understood and responded to as if they were identical’ (Nolan, 1994, p.223)

Hamad (1987) argued that when a continuous stimulus dimension is perceived as a number of discrete segments or categories, with the members of categories resembling each other more than the members of other categories, categorical perception occurs. The signature of CP is faster and/or more accurate discrimination between stimuli that belong to different categories than stimuli that belong to the same category, despite the hue difference for same- and different-category stimuli being equated. This can be demonstrated quantitatively as a perceived discontinuity in a continuous physical dimension in discrimination and identification performance. In Figure 1.1, stimuli A and A1 belong to the same category, while stimulus B1 belongs to a different category. The three stimuli are equally separated in
colour space, but if they are perceived categorically, discrimination of A-B1 is faster/more accurate than discrimination of A-A1.

![Figure 1.1](image)

**Figure 1.1.** Categorical perception here is demonstrated by faster and more accurate discrimination for pair A1-B1 than for pair A-A1.

CP was first demonstrated in speech perception where it was found that a continuum of speech sounds varying in equal steps between phonemes, e.g., from /pa/ to /ta/, was more discriminable for sounds across the category boundary than within category phoneme boundary, even when the difference for the within- and between-category phonemes was equated (Liberman, Harris, Hoffman, & Griffith, 1957). Also, it has been demonstrated in various other domains, such as facial expressions (Calder, Young, Perret, Etcoff, Seth & Rowland, 1996; De Gelder, Teunisse & Benson, 1997; Etcoff, & Magee, 1992; Young, Rowland, Calder, Etcoff, Seth & Perret, 1997), gender of faces (Campanella, Chrysochoos & Bruyer, 2002), faces of different species (Campbell, Pascalis, Coleman, Wallace & Benson, 1997), facial actions (Campbell, Woll, Benson & Wallace, 1999), familiarity of faces (Beale & Keil, 1995; Rossion, Shiltz, Robaye, Pirenne & Crommelinck, 2001), race of faces (e.g., Levin & Angelone, 2002) and colour spaces (e.g., Roberson, Davies & Davidoff, 2000).

Tasks that are used to measure colour CP include successive 2-AFC tasks where a target stimulus is presented, followed after an interval and then by two test stimuli, the target and a foil. The foil is either physically different to the target, but from the same category, or physically different and categorically different; the task is to choose which of the test stimuli is identical to the target (e.g., Pilling, Wigget, Özgen & Davies, 2003; Roberson and Davidoff, 2000). Furthermore, same-different tasks are used, where a target stimulus is shown for a limited time, removed and after an interval, a test stimulus is shown. The task here is to decide if the test and target stimuli are same or different (e.g., Bornstein & Korda, 2000).
1984; Boynton, Fargo, Olson & Smallman, 1989). In addition, simultaneous 2-AFC tasks are used, where participants are presented with three stimuli, two of them belong to the same category and one belongs to a different category, and participants are asked to choose the most different stimulus (e.g., Kay & Kempton, 1984, Laws, Davies & Andrews, 1995, Roberson, Davidoff & Braisby, 1999). Further evidence of colour CP comes from various target detection tasks, for instance, colour visual search tasks where a specific target appears among distractors (Daoutis, Pilling, & Davies, 2006; Gilbert, Regier, Kay & Ivry 2006, Yokoi & Uchikawa, 2005). Alternatively, a target colour may be embedded against a uniform background of a different colour (Franklin, Pilling & Davies, 2005).

In all tasks, pairs of stimuli belong to the same category, or straddle a category boundary. CP is shown when discrimination/memory for between-category pairs is faster and/or more accurate than discrimination/memory for within-category pairs, even though the pairs are equally separated in colour space (e.g., Gilbert et al., 2006; Franklin et al., 2005).

1.3. Colour language and Colour categorisation

1.3.1. Early work on colour language

Various scholars in classical philology considered the study of colour to be of special importance. As early as 1557, Scaliger pointed to the puzzling vagueness of the colour words in the ancient writers and Doering followed in 1788. Similarly, Goethe discussed the Greek colour terms at some length and, around the middle of the nineteenth century, writings appeared, which were mainly concerned with use of colours in Classical antiquity (in Sigmund, 1946). In the mid-nineteenth century, William Gladstone (1858) pointed out the absence of certain colour shades in Homer compared to modern poetry. The debate entered a wider stage around 1870 when the hypothesis was adopted by L. Geiger (313-314), who noted the lack of separate colour terms for certain hues in some ancient texts, e.g., in the Hebrew scripts of the Bible, the Vedic scripts in India, and Homer from ancient Greece. He then argued that the perception of colour had developed relatively recently in humans, following a certain sequence in the evolution of perceptual sensations. Although this theory arguing for perceptual evolution leading to lexical evolution in the colour domain was
challenged (e.g., Hugo Magnus; 1877; 1880), the notion of a universal evolutionary sequence in colour naming dominated the nineteenth century scientific thought (in Rivers, 1901).

As the twentieth century progressed and anthropologists and linguists increasingly encountered languages and cultures that appeared to be as systematic as the familiar European ones, the notion of cultural and linguistic relativity began to take hold, in contrast to the traditional approach of universal evolutionary progress. Sapir (1964/1931) argued for a strong relationship between language and thought, and his student Benjamin Lee Whorf furthered this view. Whorf (1956/1940) compared lexical and structural features of European languages with the Indian language Hopi, and found evident differences among them. He argued that the way speakers of different languages think are not similar. He notes that: ‘we dissect nature along the lines laid down by our native language……the world is presented in a kaleidoscopic flux of impressions, which have to be organized in our minds…. largely, by the linguistic system in our minds’ (Whorf, 1956, pp.213-214). Whorf was credited with the emergence of the linguistic relativity hypothesis sometimes referred as the Whorfian hypothesis. Based on a strong version of the linguistic relativity, language has a strong influence or fully determines concept formation and perception, whereas a weaker version points to an influence of linguistic categories on perception (Penn, 1972).

The newly proposed idea captured the attention of anthropologists, psychologists and linguists, leading to a shift from the universal approach to the linguistic relativity approach. This was the starting point of much empirical research for the following decades. The initial data collected from different languages pointed to a variation of their colour term inventories (e.g., Rivers, 1901; Woodworth, 1910). Ray (1952, 1953) was one of the prominent followers of the Whorfian approach, arguing for a strong relationship between colour language and colour perception. He claimed that because the Eskimo language Atka does not mark the blue-green boundary, they also do not distinguish this boundary perceptually; i.e. they perceive blue-green as one colour. The equivalent argument was put forward for Sanpoil speakers, who have a single term for yellow and orange. Ray suggested that what colour categories each language possessed was completely arbitrary; he notes that: ‘each culture has taken the spectral continuum and has divided it upon a basis, which is quite arbitrary’ (Ray, 1953, p. 104).
However, the early findings suggesting variation in colour inventories across languages could not provide a strong case for linguistic relativity. Evidence for linguistic relativity would be based on differences across languages reflected in perception, memory or thought among speakers of different languages. Research by Brown and Lenneberg (1954) was the first to test the linguistic relativity hypothesis empirically. They investigated the codability of colour terms (measuring numbers of syllables and words needed to name a colour, reaction time and agreement), and found correlations between codability and recognition accuracy on a colour-memory task. A later study by Lenneberg and Roberts (1956) reported similar findings. Zuni Native Americans, who have the same term for yellow and orange in their language, tended to confuse yellow and orange colours in a recognition memory task.

In summary, even though the notion of a universal evolutionary sequence in colour naming dominated scientific thought for almost half a century, the influential work of Whorf and his followers suggested that language affected perception and memory, consistent with linguistic relativity. Early research on colour perception suggested that the ways in which languages segmented the colour spectrum into linguistic categories was arbitrary. But, in 1969 Berlin and Kay revolutionised research in the field, proposing that there are colour universals across languages and languages do not encode colour 'without constraint'.

1.3.2. Universalism

The Berlin and Kay theory

The universal character of colour categories was first proposed by Berlin and Kay (1969) in their pioneering work *Basic Colour Terms: Their Universality and Evolution*. Their theory assumes that colour naming and cognitive processing of colour appearances are linked to the "cognitive salience" of both colours and the terms used to label them, which in turn emerges from the underlying neurophysiology of colour perception. They asked native speakers of 20 different languages to first 'list' the main colour terms in their language. They then 'mapped' which colours were covered by each term, in an array of 220 Munsell colours, and finally asked the informants to choose the best example of each term from the array. Berlin and Kay claimed that there was considerable agreement in the choice of the best example of colour
terms. If languages had equivalent basic colour terms, then the same or very similar colours were chosen as best example across languages. While best examples varied little across languages, colour-category boundaries differed markedly.

Furthermore, based on an examination of more than 78 languages through literature searches, they argued that there are eleven universal colour categories: white, black, red, yellow, green, blue, brown, purple, pink, orange and grey, which are ‘pan-human perceptual universals’ (p.109). They proposed that even though languages varied in their numbers of BCTs (‘basic colour terms’ – the most salient and general terms), from two to eleven, nevertheless, all languages drew their BCTs from just these eleven universal categories. Moreover, the likelihood of a language having a given term varied across the eleven universals. The higher in the hierarchy shown in Figure 1.2, a term is, the more likely a language is to have that term. Thus, all languages have terms for black and white, most have terms for red, with terms at the bottom of the hierarchy being the least common. The hierarchy was also proposed to describe the order in which languages acquired colour terms. Languages having only two colour terms divide colour based on brightness, thus, having terms for black and white (Stage I). If a language had three colour terms, they would always include a single chromatic term, red (Stage II). The next colour that follows is either green followed by yellow, or yellow followed by green (Stage III), then blue (Stage IV) and brown (Stage VI). Finally, purple, pink, orange and grey follow in any order (Stage VII) (see Figure 1.2).

![Figure 1.2. Berlin & Kay’s (1969) evolutionary colour-naming sequence.](image)

Kay and McDaniel (1978) further developed the original 1969 theory by incorporating the study of perceptual physiology to explain the universality of basic colour categories. Fuzzy
set theory and the formalism of fuzzy logic were used to explain the way in which languages acquired their basic colour terms. Fuzzy logic is based on a theory of continua rather than discrete mathematics. They distinguished between ‘primary’ and ‘derived’ basic colour terms. Kay and McDaniel related the universal semantics of colour to the neurophysiological results of Russell De Valois and his associates. Primary terms, i.e. white, black, red, green, yellow and blue are perceptually and neurologically independent of one another. Derived terms – brown, orange, pink, grey and purple – were fuzzy unions (perceptual blends) of two primaries. For instance, orange is a blend of the two primaries, red and yellow. The revised theoretical model allowed for increased variation in the order of acquisition of the colour terms, as well as acquisition of more than eleven basic colour terms. There is room for at least fifteen BCTs, for instance fuzzy intersection of blue and green allows development of ‘turquoise’ (Zollinger, 1984).

Rosch Heider’s study: the Dani

Berlin and Kay’s conclusion about the perceptual universals of the basic colour categories was supported by Rosch Heider’s study (1972). She proposed that even though languages varied in their numbers of basic colour terms, mental representations of colours were basically the same for all people with normal colour vision; thus, focal colours should be remembered and named more readily than non-focal colours, even in cultures where focal colours were not individually named. She tested American English and the Dani (a native tribe in New Guinea), which had only two basic colour terms, mili to describe ‘dark and cool’ colours and mola to describe bright ‘warm and light’ colours. Participants were tested on a recognition memory task for three types of colour: focal colours, internominal colours (non-focal exemplars of chromatic universals), and boundary colours, which were colours between focal and internominal regions. Subjects were presented with a Munsell colour chip for 5 sec, and after a 30 sec delay they were asked to find the chip in an array of 160 maximally saturated Munsell colour chips arranged in terms of hue and lightness. Rosch reported that focal colours were remembered better than both internominal and boundary colours by both Americans and Dani, even though Dani lacked basic hue terms. Further experiments showed that focal colours were more easily retained in long-term and short-term memory for the Dani even though their language lacked basic hue terms. Therefore, Rosch concluded that
perception determines language, as 'the colour space would seem to be a prime example of
the influence of underlying perceptual-cognitive factors on the formation and reference of
linguistic categories' (p.20). In a second paper, Rosch and Olivier (1972) investigated the
recognition memory for desaturated colours in American English and the Dani. They focused
on the differences in the structure of colour memory across the languages, looking at the
analysis of the errors made by the two groups. It was found that the pattern of errors for the
two groups was very similar, even though the Dani made significantly more errors than the
Americans did. It was then argued that rather than language determining perception,
perception determines language.

Evaluation of Berlin and Kay’s, and Rosch’s work

Berlin and Kay’s work has been criticised with regard to both the representativeness of the
data and the definition of ‘basicness’ and ‘focality’. Their original data were gathered in the
USA and many languages were represented only by a single bi-lingual speaker. Crawford
(1982) and Saunders and Van Brakel (1997) argued that methodologically one bilingual
speaker per language is not empirically adequate and not in accordance with linguistic
principles. Criticism of ‘focality’ has focused on the use of the Munsell colour array to elicit
BCTs. For instance, some support that the results are predetermined by the nature of the
array (e.g., Lucy, 1997) as the Munsell array was not ecologically representative (e.g.,
Weirzbicka, 1990). In addition, Saunders & Van Brakel (1997) argued that as 17 of the 20
studied languages were spoken in industrialised societies, languages from non-industrialised
cultures were under represented. Finally, the notion of BCTs is problematic as it disregards
most of the world’s colour vocabulary (Levinson, 2001; Saunders & Van Brakel, 1997).

The findings of Rosch (Heider, 1971; 1972) have been widely interpreted as clearly
supporting the notion that a particular set of colour categories might be pan-human cognitive
universals that transcend terminological differences and might be innately specified (e.g.,
Bornstein, 1985; Rosch, 1975a; Soja, 1994). However, Rosch-Heider’s series of
investigations of cognition and colour salience have been criticised for inadequate stimulus

\[1\] See Saunders & Van Brakel (1997) and Levinson (2001) for a detailed criticism on definition of basic colour
terms.
control and with regard to her experimental design (Lucy & Schweder, 1979) and could not be replicated by other researchers (e.g.; Roberson et al., 2000). Lucy & Schweder (1979), using the Rosch (1972) array of 160 tiles in a perceptual search task, found that Rosch's focal colour could be identified more accurately and more quickly than non-focal colour. This lead to the argument that the saliency of focal colours in Rosch's memory task was due to the greater discriminability of these colours within the array, rather than due to any inherent advantage for these colours, as Rosch initially claimed. Furthermore, when a new array was produced by randomising the ordering of the colour in the array, and by deleting colour chips that were frequently selected in error as targets in their search task, it was found that the advantage of focals over non-focals in short-term memory recognition was no longer significant. Finally, it was argued that linguistic measures of colour codability, rather than focality, count for more variance in the recognition memory of different colours. Furthermore, some researchers have argued that Rosch Heider's original results may also be consistent with linguistic relativity, as one can consider that the lack of lexical terms made the memory task extremely difficult. For instance, Davies (1997) and Saunders and van Brakel (1997) argued that Dani memory performance (5%) was extremely low compared to that of English speakers (28%).

Recently, work of Kay and colleagues (Kay, 2005; Kay and Regier, 2003; Regier, Kay and Cook, 2005), largely based on data collected by the World Colour Survey from 110 unwritten languages in non-industrialised societies, addressed issues in Berlin and Kay's original work. The locations of colour category centroid (the location calculated to represent the centre of a given colour category) were analysed and the results suggested that these languages share colour category centroid with each other as well as with centroids for terms from industrialised languages much more than it was initially predicted to occur by chance (Kay & Regier, 2003). In addition, Regier et al. (2005) found that focal colours representing the best examples of named categories show a similar tendency to cluster around particular points in colour space.

In summary, Berlin and Kay suggested that languages do not encode colour space in an arbitrary way; instead, there are consistent/hierarchical patterns in the ways that languages express basic colour terms. Their empirical research provided ground for a methodological
investigation of colour terms while both emphasising the importance of basic colour terms and their emergence across languages. The work of Berlin and Kay was influential in that it shifted the dominance of the Relativism stance to that of Universalism. Subsequent research of Rosch-Heider on the Dani provided support for the Berlin and Kay theory. The findings were consistent with the universal salience of focal colours, as Dani's colour cognition reflected the cognition of these foci although their language lacked these foci. However, both Berlin and Kay and Rosch Heider's work received considerable criticism over the years on both methodological grounds and representativeness and interpretation of the data. The work of both Berlin and Kay and Rosch Heider has been influential in arguing for universal perceptual categories. At the same time, it attracted further cross-cultural research resulting in a stronger linguistic relativity-universality debate with the aim to provide insight into the structure of colour language and cognition.

1.4. Cross-cultural evidence challenging universalism:

1.4.1. Evidence for Linguistic Relativism

According to the Sapir-Whorf hypothesis, our subdivisions of the spectrum are arbitrary, learned and vary across cultures and languages. Whorf argued that language is a categorical system fundamental to the formation of perceptual attributes. Evidence for an influence of language on colour CP comes from cross-cultural studies showing that language has an impact on colour judgment. These studies are based on the assumption that if a language has two colours that are called by the same name, speakers of that language judge those colours to be more similar in similarity judgements tasks and are more likely to confuse them in memory compared to speakers of languages that have different names for those two colours. Kay and Kempton (1984) investigated whether differences in colour terms of English for blue and green and of Tarahumara - a Uto-Aztecan language of northern Mexico, produced a difference in subjective distance between colours on a triad task. Tarahumara speakers lack blue and green lexical distinction, having instead the term siyóname describing green or blue. It was found that English speakers showed CP across the blue-green boundary, whereas Tarahumara speakers showed no CP. The authors argued that as Tarahumara speakers do not lexicalise the blue-green contrast, they could not use a naming strategy to facilitate cross-category judgment.
Other cross-cultural studies suggest that although colour categorisation is largely universal, linguistic influences can moderate its dominance (e.g., Davies, Corbett, Laws, McGurk, Moss & Smith, 1991; Davies, Sowden, Jerret, Jerret & Corbett, 1998; Laws, Davies & Andrews, 1995). Davies (1998) and Davies and Corbett (1997, 1998) reported comparisons of English (11 BCTs), Russian (12 BCTs) and Setswana (5 BTCs) speakers on a colour grouping task. The three languages differ in the location of colour category boundaries. Sixty-five stimuli evenly sampled from colour space were used. The grouping patterns were largely similar for English and Russians speakers. Subjects in the two groups tended to form separate blue and green groups. In addition, Russian speakers, who have two terms for blue sinyj to describe ‘dark blue’ and goluboj to describe ‘light blue’, were no more likely to form two separate blue groups than English speakers. However, the Setswana speakers, who use a single basic term botala to describe blue or green, were more likely to group blues and greens together than English speakers were. The results point towards a moderate case for linguistic relativism.

Other cross-cultural studies also support linguistic relativity. Roberson et al. (2000) reported results from experiments with natives from a Papua New Guinean tribe (Berinmo), whose language has five basic colour terms. They do not mark the distinction between blue and green, but they do have a colour boundary between nol ‘greenish’ and wor ‘yellowish’, which has no equivalent in English. Discrimination accuracy across these two boundaries was compared to within-category discrimination using a successive 2-AFC method. It was found that Berinmo speakers showed a cross-category advantage for nol-wor stimuli, but no cross-category advantage for blue-green stimuli, whereas the English speakers showed categorical perception for the blue–green boundary, but not for the nol–wor boundary. However, in successive 2-ACF tasks, cross-category discrimination could (in part at least) have an advantage over within-category discriminations as between-category stimuli have different names, whereas within-category stimuli share the same name. This would be an advantage for English speakers in the blue–green boundary, but not for the nol–wor boundary, whereas the Berinmo speakers would have an advantage for the nol-wor boundary, but not for the blue-green boundary.
A subsequent study by Roberson, Davidoff, Davies and Shapiro (2005) tested Himba
speakers (in Namibia) who live in arid savannah, and their language has only five BCTs, like
Berinmo. Again, Himba participants showed categorical perception for their own linguistic
boundaries, but not for English boundaries, while the English participants showed the
opposite pattern: CP for English boundaries, but no CP for Himba boundaries.

Similar studies using simultaneous 2AFC tasks suggest that categories present in one’s
language can play a role in one’s colour judgments (e.g., Roberson, Pak & Hanley, 2008;
Winawer, Witthoft, Frank, Wo, Wade & Boroditsky, 2007; Witthoft, Winawer, Wu, Frank,
Wade & Boroditsky, 2003). Witthoft et al. (2003) compared English and Russian speakers on
the goluboj-sinyj boundary using a simultaneous 2AFC task. For the Russians, the categorical
relationship of target and foil varied: for within category pairs, both were from the same
category (e.g., goluboj1-goluboj2), whereas for between-category pairs, they were
categorically different as well as physically different (e.g., goluboj1-sinyj1). For English
speakers, the target and foil were always from the same English category (blue). Russian
speakers were better at between-category trials than within-category trials, whereas there was
no difference for the English speakers. However, in such tasks, the most similar stimuli can
be chosen according to perceptual similarity, but the performance could be prone to direct
language strategies. For instance, stimuli could also be chosen according to whether the two
stimuli are named differently to the other stimulus in the triad, or if one judges them to be
more similar when they are given the same name than when they are given different names.

Recent cross-cultural research using a visual search task suggests a language effect on colour
categorisation (Roberson et al., 2008). Roberson et al. tested English and Korean participants
on the boundary between the Korean categories yeondu (yellow–green) and chorok (green).
This boundary is obligatory for Korean speakers, who have no single term that covers both
yeondu and chorok; however, it falls within the green category for English speakers. A strong
CP effect was found only for the Korean speakers. In this task, memory components are
removed, however, the response times were large (over 1000ms), and this may have given
sufficient time for explicit verbal labelling during performance. The CP seems to have been a
result of an advantage for Korean speakers due to the use of verbal labelling since they have
colour terms to distinguish the boundary. This will be discussed further in section 4.1.
In summary, findings from cross-cultural research suggest that colour categories are influenced by linguistic categories. This challenges universalism, as CP effects are found only across boundaries marked in the speaker’s language (e.g., Roberson et al, 2000; Witthoft et al, 2003; Roberson et al, 2005; Winawer et al, 2007; Roberson et al, 2008). However, whilst claims that CP is induced by language may be true, it is also possible that the observed effects are not perceptual effects at all; in other words, the term ‘categorical perception’ may be inappropriate. Instead, the categorical effects could result from the online use of language, rather than language indirectly producing CP by affecting perception during language learning.

1.4.2. Further evidence for linguistic relativism

Based on linguistic relativism, labelling theories take a rather moderate position arguing that language through lexical codes influences rather than determines categorical perception (Kay & Kempton, 1984; Roberson & Davidoff, 2000). It is argued that the discrimination between stimuli are made in part by comparison of verbal labels, thus stimuli belonging to different categories are given different labels, e.g., blue-green. Several studies have shown that prevention of accessibility to colour names eliminates CP (e.g., Gilbert et al., 2006; Pilling et al., 2003; Roberson & Davidoff, 2000; Winawer et al., 2007; Witthoft et al., 2003). For example, Roberson and Davidoff (2000) showed that the CP effect was eliminated if a secondary verbal task was presented along with a delayed colour discrimination task. They used a 2-AFC task where a target was presented and after 5 sec ISI the target and a test colour were presented and participants had to identify the target. During the ISI there were either no interference condition in which a blank screen appeared throughout the ISI, visual interference condition in which a multicoloured dot pattern appeared on the screen during the ISI, or verbal interference condition in which participants had to read aloud a list of words presented on the screen during the ISI. The three types of interference were blocked. It was found that CP occurred for different category pairs in the no interference condition and in the visual condition; however in the verbal interference condition the CP was eliminated. The authors argued that since visual interference did not affect CP, between-category advantage relied on verbal coding of the target colour. This in turn suggests that CP was based on...
labelling strategies. When the target and test colour belong to different categories, they have
different verbal codes and their availability may facilitate a correct response. This would lead
to better discrimination for between-category trials than within-category trials. A further
issue in this study is that the accuracy in the interference conditions was not the same.
Additionally, the authors did not measure performance on the secondary tasks. These
limitations make the results open to several interpretations. This will be discussed further in
section 2.3.

Similarly, cross-cultural research also suggests a role for lexical codes in colour CP. As
mentioned in Section 1.4.1, Winawer et al. (2007) used a simultaneous 2AFC task to test
English and Russian speakers for the goluboj-sinyj boundary. Participants performed the task
either with no interference, verbal interference (remembered a number sequence), or spatial
interference (participants remembered a grid pattern). This method relies on the assumption
that if a colour boundary is present in one language but not in another, then speakers of the
two languages will differ in their perceptual discrimination performance across that specific
boundary. The advantage is eliminated or reduced when verbal interference tasks are
employed. Subjects were asked to complete the 2AFC task, and then to type the number
sequence (verbal interference) or indicate whether one of two visual grids presented was the
same as the one they had to remember. It was found that Russian speakers’ colour judgments
across the goluboj-sinyj boundary were affected by verbal interference, but English speakers’
judgments were not. Finally, the spatial interference task did not influence either the Russian
or English speakers’ performance. The findings suggest that linguistic categories affect CP d
and inability to access those leads to deterioration of performance. The primary task used in
this study was a simultaneous 2AFC task. As already discussed in section 1.4.1 the task itself
is prone to verbal labelling, thus it is no surprise that verbal interference affects the
availability of lexical codes.

In summary, categorical perception may not be independent of language, as verbal
interference suppresses lexically induced colour CP (e.g., Roberson & Davidoff, 2000;
Winawer et al., 2007; Witthoft et al., 2003). Moreover, it seems that CP shown in cross-
cultural studies is task dependent. A strong case for language affecting perception needs to be
based on tasks that isolate perceptual processes and measure perceptual processes directly. If
perceptual processes are isolated, excluding the effects of memory and labelling, and differences in CP between different language groups are still found, this would be strong evidence for language shaping colour perception – an indirect language effect on perception.

1.5. Development of colour categories and colour language

Initial developmental studies suggested that linguistic knowledge of colour terms is related to recognition and matching accuracy (e.g., Dale, 1969; Kimball & Dale, 1972). For instance, Dale (1969) compared children who named colours correctly and children who did not name colours correctly on a matching task and on a recognition task. In the matching task, a single chip was presented and the child was asked to find one colour "just like this one" from an array of 14 colours. The 'namers' were significantly more accurate than 'non-namers'. In the recognition task, a single colour was shown and after five seconds, the child was asked to find 'a colour just like the one shown before' in the array. 'Namers' chose the colour correctly, whereas 'no-namers' did not. Thus, recognition accuracy was significantly related to the children's ability to name colours. However, this differential performance may simply reflect better memory of children who knew the colour terms than those who did not know the colour terms.

Infant categorical responding

Since the mid 1970’s, research suggests that the perception of colour categories in children precedes their acquisition of colour language. Bornstein, Kessen and Weiskopf (1976) showed how 4-month-olds, and thus pre-linguistic children, responded categorically to monochromatic colour stimuli. The infant spectral colour categories matched those generated by adult colour-naming procedures. They habituated infants to a 'standard' light, and then tested for dishabituation with two new lights and the standard. The two test stimuli were either from the same adult colour category as the standard or from an adjacent colour category. For example, if the standard was 480 nm (a blue) then the two test stimuli were 450 nm (another blue) or 510 nm (green). The infants showed no dishabituation to the within-category novel stimulus, but they did dishabituate (look longer) at the between category test stimulus. A similar pattern was shown across the green-yellow and yellow-red
boundaries. It appeared that infant colour categories were remarkably similar to adult categories, and crucially they were present before language.

Franklin and Davies (2004), using a novelty preference method, found a similar pattern of categorical responding to Bornstein et al. in pre-linguistic infants. The authors used separations between habituated and novel stimuli equated in a perceptually uniform metric (Munsell) colour system, rather than in wavelength. Using the novelty preference technique, categorical responding was tested across the blue–green primary boundary and across the blue–purple and red-pink secondary boundaries. Following familiarisation to the original colour, preference for the novel stimulus was shown only if the original and novel stimuli belonged to different categories rather than to the same category. Again, it appeared that colour categories were present before language.

The two studies outline above, clearly show that infants respond categorically before they have learned colour terms. However, as with many of the adult studies, this categorical responding could either be due to between category perceptual distances being ‘stretched’– true CP – or it could reflect memory processes. Both the habituation and novelty preference techniques rely on the infant remembering the standard colour, and thus the categorical effect could arise from unknown memory processes rather than from perception. There is also an important difference between the patterns of adults’ and infants’ categorical responding. Adults show increased sensitivity across a category boundary compared to within-category discrimination\(^2\), but they still are able to detect within-category differences (e.g., Pilling et al., 2003). In contrast, infants showed no dishabituation or novelty preference when the novel colour was from the same category as the standard: they appear to only respond categorically treating within category stimuli as equivalent. However, it appears that this absolute categorical responding may be a product of the habituation/novelty preference methods, as differential within-category responding is found on other tasks. For example, Franklin, Pilling and Davies (2005) tested four- to six-month old infants and adults on a target

\(^2\) Originally, the definition of CP stated that there is no within-category discrimination at all. However, this definition of CP in current research is no longer used. CP is now defined as faster and/or more accurate between-category than within-category discrimination, when between- and within-category separations are equated (for a detailed review on categorical perception see Harnad, 1987).
detection task, where a coloured target appeared on a coloured background. The infant’s and adults visual attention was drawn to a central fixation point on a grey monitor with a flashing bull’s-eye. Following fixation, a coloured target appeared on a coloured background in any of twelve locations forming a circle around the fixation point. The target and the background formed either within- (e.g., green target on green background) or between-category (e.g., green target on blue background) pairs. The time to move gaze from fixation to the target was recorded. Time to fixate between-category targets was faster than time to detect within-category targets for adults and infants. However, importantly, infants did fixate the within-category targets: on this measure, categorical responding was graded rather than absolute.

Colour categorisation in children

Research with older children gives mixed results. Some suggest a role for language in colour CP. Roberson, Davidoff, Davies and Shapiro (2004) showed that children continue to refine their conceptual colour categories for some years after they first show evidence of term knowledge for ‘focal’ colours. In their longitudinal study over three years they tested English children aged 3-4, who were tested initially before they entered pre-school, and a group of Himba children from northern Namibia aged 3-4. Children’s colour term knowledge and memory for colours were tested at six-month intervals over three years. The children completed a colour term listing task (“tell me all the colours that you know”), colour naming (“what colour is this?”), colour term comprehension (“can you find a red one?”) and a recognition memory task. When first tested, both Himba and English children who knew no colour terms, showed a similar pattern of memory errors, which appeared to be based on perceptual distance rather than on a particular set of predetermined categories. Furthermore, there was no advantage in memory for focal stimuli in either language. However, as soon as the children acquired colour terms, an advantage for the set of focal colours became evident. English children showed superior memory for stimuli that are focal in English, but not to Himba focal colours, whereas Himba children showed the reverse pattern. However, as a delayed 2-AFC task was used, the categorical effect could also be due to memory.

However, CP is found in toddlers of 2-3 years-of-age who know no colour terms. Daoutis, Franklin, Riddett, Clifford and Davies (2005) compared British and rural Namibian children
aged from 4-7 years using a visual search task, which consisted of multiple identical targets (coloured circles) among distractors. Neither of the Namibian languages (Otjikwanyama in Experiment 1 and Otjihimba in Experiment 2) marks the blue-green, blue-purple, red-pink, red-orange, or yellow-orange boundaries. The target and distractors could belong either to the same category (e.g., B1 among B2s) or to different categories ((e.g., B1 among G1s). The authors found that CP was present even when toddlers had no knowledge of colour terms. For instance, they found that Otjihimba speakers showed CP to stimuli around the blue-purple boundary, just as English speaking toddlers did, even though they knew no colour terms as the blue-purple is not distinguished in their language. However, the authors note that a labelling strategy may still have occurred giving an advantage to the English speakers for between-category searches.

Furthermore, Franklin, Clifford, Williamson & Davies (2005) compared English and Himba speaking toddlers using a 2-AFC task. The Himba speaking toddlers do not distinguish the blue-purple boundary in their language. Toddlers were shown a test stimulus, after a one second delay the test stimulus was removed, then the same stimulus and a foil, which could belong either to the same or to a different colour category, were shown. Both groups of toddlers showed the same pattern of results even though Himba speaking toddlers knew no colour terms. Both groups made fewer errors when the stimuli straddled the blue-purple boundary than when the stimuli were from the same category, even though the stimuli were equally separated in hue. Additionally, Franklin, Clifford et al. (2005) found that English children who had no linguistic boundary for the stimuli, children who had a correct linguistic boundary and children with a reversed linguistic boundary all showed colour CP. These three groups did not show a difference in the size of the category effect for blue–green, blue–purple, or pink–red boundaries. Therefore, the extent of colour CP did not appear to be affected by the toddler’s ability to name colours. However, the delayed 2-AFC task used in the study is prone to memory influences; thus, the children may have performed the task using a memory code for the colours.

To summarise, research with infants and children, who do not have linguistic terms, suggest a possible innate form of colour CP, or at least CP being present without linguistic categories. Categorical responding in pre-linguistic infants in the absence of linguistic terms
(Bornstein et al., 1976; Franklin & Davies, 2004; Franklin et al., 2005) shows that colour categorisation precedes language acquisition. On the other hand, CP is shown only when the language marks the distinction (Daoutis, Franklin et al., 2005). It seems though that discrepancies between the findings may depend on the tasks used. To conclude that CP is hardwired or results from ‘warping’ of perceptual space caused by language, investigation needs to be based on tasks, which measure perceptual processes directly.

1.6. Induced Categorical Perception

Several studies report improvement in task performance with training or practice in several perceptual tasks, such as stimulus orientation judgments (Shiu & Pashler, 1992), texture discrimination (Karni & Sagi, 1991; 1993) and stereoacuity (Fendick & Westheimer, 1983; Sowden, Davies, Rose & Kaye, 1996). In addition, experimental evidence shows that existing categories are to a certain extent influenced by training (e.g., Zatorre & Halpern, 1979), and through learning new categories (e.g., Goldstone, 1994a; Livingstone, Andrews & Harnad, 1998; Notman, Sowden & Özgen, 2005; Özgen & Davies, 2002). Indeed, research in the area has shown that CP effects can be induced with training. Such effects have been reported for face identity (Beale & Keil, 1996), face perception (Goldstone, Lippa & Shiffrin, 2001), musical pitch (Burns & Cambell, 1994; Burns & Ward, 1978; Zatorre & Halpern, 1979), and sound categories (Pisoni, Aslin, Perey & Hennessy, 1982).

Learning may ‘warp’ the representation of perceptual space, possibly by compression of perceptual space at the centre of categories and/or stretching of perceptual space around categories boundaries (Harnad, 1987). Perceptual change theories, therefore, suggest that the way in which stimuli are mentally represented may be altered through extensive practice or learning to distinguish lexically the stimuli (e.g., Goldstone, 1998; Goldstone et al, 2001). For instance, Goldstone (1994a) trained subjects on one of several categorisation conditions in which one physical dimension was relevant and another was irrelevant. There were two stimulus sets used for the experiment, one consisted of squares varying by the integral dimensions brightness and saturation, and the second consisted of the highly separable dimensions size and brightness. The relevance of each dimension during the training varied across different participants. Then participants were tested on a same-different judgment task.
between pairs of stimuli from the learned set. It was found that performance was improved on the dimension on which the participants were trained. However, they performed worse at discriminating stimuli that differed along the other (non-diagnostic) dimension than controls with no categorisation experience. The acquired CP effects were present for both the easily separated dimensions of brightness and size, as well as the psychologically fused dimensions of brightness and saturation. Thus, perceptual abilities can be sharpened by experience in categorising a set of stimuli along a particular dimension.

Özgen and Davies (2002) also showed that CP could be acquired after category training. Participants were trained to split either blue or green categories into two separate categories, and then tested these new categories in a same-different task. Participants were presented with one colour, after a 1 sec delay a second colour was presented, and they had to decide whether the colour was the same as the one shown previously. The two colours in each pair could be either from the same category or from different categories. A control group also performed the task and performance of both groups was compared. The authors found that the category learners showed a CP effect for the learnt category boundary: i.e., they were more accurate in between-category trials than in within-category trials. However, participants in the control group showed the opposite pattern: they were more accurate in the within-category than in the between-category trials. Therefore, the original perceptual structure of the category had been altered for the category learners. The authors argued that learning colour terms could reorganise the already present colour categories resulting in new category formation. However, experimentally acquired CP does not necessarily imply that it is acquired through learning colour terms. The question is whether linguistic strategies are being used during category training. One possibility is that subjects during category training form a strategy to use some form of linguistic coding to be able to differentiate the stimuli in linguistic terms. For instance, assigning different labels to stimuli that are more dissimilar would be more likely to help differentiate them from stimuli with the same label. If subjects assign labels for stimuli that straddle a boundary in order to learn the new boundary, using linguistic terms must have been powerful enough to change the existing perceptual organisation. However, there is no direct evidence to support the notion that a strategic linguistic coding is active during category training.
Finally, while research clearly shows that CP effects can be acquired through category training, both Goldstone (1994) and Özgen & Davies (2002) tested the CP effects on discrimination of sequentially presented stimulus pairs. This method is vulnerable to influences of memory and the use of labelling. What is lacking is research that investigates whether, following category training, CP is shown in low-level perceptual tasks. This is addressed further in this thesis in Chapter 5.

1.7. Hemispheric asymmetries and colour CP

There is substantial evidence suggesting that the two cerebral hemispheres differ in their processing of information. Studies investigating hemispheric asymmetries suggest left hemisphere (LH) dominance for most linguistic abilities (Hellige, 1993), whereas the right hemisphere (RH) is responsible for tasks such as face recognition (Barton, Press, Keenan, & O’Connor, 2002; Kanwisher, McDermott, & Chun, 1997), and visuospatial processing (Corballis, 2003; Kimura, 1969). The left hemisphere (LH) is typically dominant for a number of important aspects of language (Kimura, 1967; Levy & Trevarthen, 1981) including those involving access to names (Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996), silent word generation (Pujol, Deus, Losilla & Capdevila, 1999) and retrieval of words that belong to distinct conceptual categories (Price, Moore, Humphreys, Frackowiak & Friston, 1996).

Considering the contralateral projection of visual fields to cerebral hemispheres, visually presented stimuli that require verbal processing tend to be advantaged when they are presented in the right visual field (RVF) (Springer & Deutsch, 1997; Gilbert et al., 2006). Such RVF advantages are evident in colour naming (Levy & Trevarthen, 1981; Tokar, Matheson & Haude, 1989), colour discrimination (Wilson, 1987) and colour categorisation (Gilbert et al., 2006). For example, Wilson (1987) found that patients with unilateral LH lesions were less likely to show CP relative to patients with RH lesions on a colour discrimination task.

Hemispheric asymmetries in colour CP had not been examined until a recent study by Gilbert et al. (2006). Participants were given a visual search task that required detection of a single
target colour among eleven distractors (see Figure 1.3). The target could either belong to the same category as the distractors (e.g., blue among blues), or in a different category (e.g., blue among greens). The perceptual difference for each of the target-distractor for between-category discriminations was no greater than for within-category discriminations. The task was to indicate whether the target stimulus appeared in the left visual field (LVF) or in the right visual field (RVF). It was found that a target colour from a linguistic category distinct from that of distractors was detected faster in the RVF than the LVF and, conversely, that a target colour from the same named category as distractors was detected faster in the LVF than the RVF. Each visual field projects to the contralateral brain hemisphere, so a stronger category effect for the RVF indicates a LH bias, and as the LH is predominant for language Gilbert et al. argued that language might be involved implicitly in colour CP.

In their second experiment, participants performed the task either on its own (no interference condition) or together with a concurrent verbal task (retention of an eight-digit number). In the no-interference condition, CP was again shown, but only for RVF targets; however, there was no CP in the verbal interference condition. In a further attempt to investigate whether the interference effect was strictly verbal, they ran a second experiment with a different verbal interference task. In this task an irrelevant colour term (e.g., violet) was presented between search trials and participants indicated when the term was presented on successive trials. A spatial interference task was used as well in which a visual grid with white and black squares was presented and participants indicated when the same pattern was presented on successive trials. Again, it was found that verbal interference eliminated the RVF advantage for between-category trials, but visual interference produced the same pattern that was produced under no interference condition. The authors argued that the verbal interference task, which engaged verbal working memory, disrupted the access to the names of target and distractor colours, eliminating the LH category advantage. The findings suggest that CP is based on lexical categories rather than being perceptual; however, it is not clear how lexical categories may emerge so early in perceptual decisions in a seemingly low-level perceptual task.
In summary, recent research shows that colour CP is lateralised to the LH. These findings are quite fascinating as they direct research towards the functional organisation of the brain, which was neglected in previous research. Gilbert et al. argue that the LH bias suggests implicit language influences on colour CP. However, the interpretations of the findings are not quite clear-cut. Chapter 2 addresses the findings and their interpretations.

1.8. Summary

The work of Berlin and Kay and Rosch Heider suggested a universal salience of focal colours. The findings triggered much further research focusing on whether colour categories are hardwired or learned. A complete explanation of the origin and nature of CP has not yet been provided. For example, colour CP is found in infants in the absence of language (e.g., Franklin & Davies, 2004; Bornstein et al., 1976; Franklin et al., 2005), and in 2-year-old toddlers, who do not have linguistic terms (Franklin, Clifford et al., 2005). Thus, research with infants and children, who do not have linguistic terms, suggests a possible innate form of colour CP, or at least CP being present without linguistic categories. On the other hand, in some cases and some tasks, CP is present only for speakers of the language that marks the
categorical distinction (e.g., Roberson et al., 2000, Daoutis et al., 2005; Witthoft et al., 2003, Roberson et al., 2008), and verbal interference eliminates CP (Roberson & Davidoff, 2000). Furthermore, consistent with linguistic involvement in CP, recent research shows that colour CP is lateralised to the RVF/LH (c.f. Gilbert et al., 2006).

To sum up, it has been more than half a century since Whorf first formulated the idea that language influences the way humans see the world around them. His work was most influential in the debate between universalism and linguistic relativism. Extensive research suggests that there is evidence that favours both universalism and linguistic relativism. Findings are sometimes controversial and there is no agreement on why CP occurs, but the controversy in the findings seems to be task dependent.

1.9. Outline of experimental chapters

1.9.1. Is the observed CP a truly perceptual effect?

It seems that the findings depend heavily on the tasks that are used to investigate CP. Most tests involve a memory component and are prone to direct language strategies (e.g., Kay & Kempton, 1984; Pilling, et al., 2003; Roberson & Davidoff, 2000). These findings are usually interpreted as supporting linguistic relativism through the language providing effective codes for remembering particular stimuli. However, CP effects found with such tasks imply an 'on-line language' effect rather than a perceptual effect. The benefit arises from labelling the target colour and retaining the available colour name facilitating recognition. This direct language account of CP was supported by Roberson & Davidoff (200) where the between-category advantage was eliminated by verbal interference in the ISI.

The previous findings point to a need to use a task that loads heavily on perceptual processes to investigate colour CP. As mentioned in Section 1.5, Franklin et al. (2005) developed a simple detection task to investigate the development of colour categorisation. On each trial, a single circular target appeared on a chromatically different, uniform background. The target and the background could belong either to the same category, e.g., blue1 on blue2, or to different categories, e.g., blue1 on green1. The main aim of the thesis is to explore what
parameters affect lateralisation of colour CP using the target detection task that Franklin et al.
used as the task is suitable to investigate lateralisation of colour CP.

Laterality effects are often studied using hemifield presentations, in which stimuli are rapidly
presented for about 150-250 ms in either left visual field (LVF) or right visual field (RVF).
Information in each visual field travels unilaterally to the opposite hemisphere based on the
anatomy of the human visual system. As both hemispheres are connected to each other, the
information presented to one hemisphere will be transmitted to the other hemisphere within a
few ms (Brizzolara, Ferretti, Brovedani, Casalini, & Sbrana, 1994). However, using rapid
presentations ensures that the ipsilateral hemisphere obtaining information directly will have
at least initial preferential access.

The target detection task has several advantages over other tasks that have been used to
investigate CP, such as 2AFC tasks. For instance, if the target appears for a very short time
(e.g., 250 ms), lexical access and name generation/stimulus labelling is unlikely to be a
beneficial strategy (Flowers & Dutch, 1976). In addition, memory components are removed
as the target and the background are represented simultaneously. Furthermore, as the task has
been used successfully in research with infants (Franklin et al., 2005), the task can be used
for adults and infants, thus it allows investigation and comparison of findings
developmentally. Also, it can be easily used for cross-cultural investigation of colour CP.
Finally, as mentioned in Section 1.7, Gilbert et al. (2006) using a visual search task found a
LH bias for colour CP. However, in the Gilbert et al. study the target and some distractors
have a separation of up to 6°. Such large spatial separation between the target and distractors
means that they do not fall into single-cell receptive fields. The task may not reflect low-level
perceptual processes. The stimuli in the target detection task are juxtaposed, thus it is more
likely that they fall in receptive fields of units in V1 where receptive fields are small (e.g.,
0.5°) (Kastner, Weerd, Pinsk, Elizondo, Desimone & Ungerleider, 2001; Smith, Singh,
Williams & Greenlee, 2001). Thus, as awareness is absent in V1, or at least weaker than in
other cortical areas, and performance is automatic and relies on pre-attentive processes
(Zhaoping, 2008), the task seems to isolate perceptual processes.
In summary, the target detection task appears to be immune to labelling strategies and memory components and on the face of it, it also appears to isolate perceptual processes. Thus, the task seems more appropriate than tasks that have been used previously to investigate the origin and nature of colour CP.

1.9.2. Research questions in the following chapters.

The main aim of this thesis is to explore whether language affects colour cognition. The emphasis is on the underlying mechanisms of lateralisation of colour CP. Testing laterality effects with the target detection task provides a possible way of investigating the nature of CP and the potential involvement of language. The LH advantage for CP can indicate a direct language effect: linguistic processes represented in the LH may facilitate between-category trials. Another possibility is that the LH advantage for between-category trials represents an off-line language effect: linguistic codes have resulted in ‘warping’ of perceptual space influencing early perceptual processes. These possibilities are investigated in the following experimental chapters.

The thesis is organized as follows: in Chapter 2 the reported experiments replicate and extend recent findings that suggest a LH bias in CP. In Experiment 1 the target detection task was used to investigate whether CP is lateralised to the LH testing the blue-green boundary. Franklin et al (2005) measured eye-movements to the target to investigate colour CP, whereas here the measure was reaction times. In Experiment 2 a secondary boundary not tested previously was tested. In Experiment 3 it was investigated whether verbal or visual interference influences colour CP.

Chapter 3 takes a developmental approach to investigate further the nature and origin of CP. The performance of infants, toddlers and adults was compared on the target detection task.

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Kay and McDaniel (1978) distinguished between ‘primary’ and ‘derived’ basic colour terms. Primary terms refer to colours that are neurologically independent of one another, such as white, black, green, red, yellow and blue. Derived terms refer to colours that are a perceptual blend of two primary colours, such as brown, pink, orange, grey and purple. For instance, purple is achieved blending red and blue. In this thesis, the term ‘secondary boundary’ is used to indicate colours that straddle a primary colour region (e.g., blue) and a derived colour region (e.g., purple).
The research questions were: is infant CP, like adult CP, lateralised to the LH? Does learning colour terms influence the lateralisation of colour CP?

Colour vocabularies vary considerably cross-culturally. For instance, English speakers use 11 basic terms to describe colours, Greek speakers use 12 basic terms, whereas speakers of languages spoken typically by non-industrialised societies, e.g., the Berinmo of Papua New Guinea, use only five basic terms to describe colours. As the number of terms used to describe colour space varies across languages, so does the distribution of category boundaries. In Chapter 4, a comparison of speakers with different colour language structures assessed the potential influence of colour language on colour perception, and whether CP is always lateralised to the LH.

In Chapter 5, participants were trained to distinguish a new colour category boundary. If colour categories are acquired through learning colour terms, resulting in a warping of similarity in colour space, than learning could reorganise categorical boundaries. Indeed, evidence suggests that CP can be acquired after category training (Özgen & Davies, 2002). Following successful learning of a new category boundary, categorical effects were assessed using the target detection task.

Finally, the last chapter concludes by highlighting the main findings, presenting new questions that arise from this work and suggesting some directions for future research.
Chapter 2

Lateralisation of Colour Categorical Perception

2.1. Introduction

As mentioned in section 1.7 Gilbert et al. (2006) using a visual search task reported that CP for the blue-green boundary for English speakers is lateralised to the LH. Gilbert et al. suggested that the LH bias is based on implicit language influences. In addition, a recent study by Tan, Chan, Kay, Khong, Yip and Luke (2008) showed that colour naming of easily accessible linguistic colour terms in a brief discrimination task activates regions that contribute to word-finding processes. In a colour discrimination task it was found that identification of easy-to-name (e.g., red, green) and hard-to-name colours activated largely overlapping brain areas, however, ‘easy to name’ colours were more related to activation of the left posterior temporal-parietal circuits. However, the study did not test for categorical perception, nor were the colours equally separated in colour space. Furthermore, it is not clear that word-finding regions are activated in perceptual tasks that measure CP directly.

Summary of research questions and the following experiments

1. Is lateralised CP to the LH found using the target detection task?
2. Is CP for a secondary boundary (blue-purple) lateralised?
3. What effect do verbal and visual concurrent tasks have on lateralised CP?

Experiment 1

Experiment 1 investigated further the restriction of the lateralisation effect to the LH using the target detection task. The main aim in this experiment was to test that lateralised CP is found with the target detection task.

Experiment 2

The second question that this chapter addresses considers lateralisation effects for a secondary boundary. For this purpose, the same task used in Experiment 1 was used to investigate the laterality effects in the blue-purple boundary.
Experiment 3

Several studies show that when the LH is engaged in a verbal task (e.g., Gilbert et al., 2006; Roberson & Davidoff, 2000; Winawer et al., 2007; Witthoft et al., 2003) CP effects disappear. The last experiment in this chapter uses a similar interference paradigm to investigate this further again using the target detection task.

2.2. Experiment 1: Lateralised CP for blue-green assessed by the target detection task

2.2.1. Introduction

Consistent with the definition of CP, previous research has shown that CP is found for a range of perceptual distances but the size of the category effect does not vary with perceptual distance (Franklin, Clifford et al., 2005). It might be the case that the difference in the two chromatic separation sizes may have not been large enough to produce a difference in the size of the category effect. The perceptual distance of the stimulus pairs in the following experiment was varied. If the category effect is constant when perceptual distance varies (as in Franklin, Clifford et al.), and if the categorical status is all that matters, perceptual distance should be irrelevant.

Participants were tested for CP around the blue-green boundary. A colour naming task established the exact location of the boundary. Several colours within the blue and the green colour region were used at constant chroma and value. Following establishment of the boundary, laterality effects were tested using the target detection task. Pairs of colours were chosen so that some belonged either in the same category (e.g., blue1 on blue2 background) or from different categories (e.g., blue1 on green1 background). The pairs of colours were presented either to the left or to the right visual field, and participants had to decide whether the target appeared on the left or right.

Summary of research questions

1. Is the LH bias for colour CP found using the target detection task?
2. What is the effect of perceptual distance on CP?
2.2.2. Colour naming task: Establishing the blue-green boundary

Bornstein and Monroe (1980) have reported that the blue-green boundary lies at 7.5BG Munsell hue. The purpose of the following naming study was to establish the exact boundary for stimuli at specific value and chroma. Participants were shown colours from the blue and the green colour regions, and asked to name each colour using either green or blue colour terms.

Method

Participants

Ten participants (five males and five females, Mean Age = 24 years, SD = 3.15) participated in the naming task. They were English native speakers studying at the University of Surrey, and received course credits for their participation. They had normal or corrected-to-normal vision, and normal colour vision as assessed by the City University Colour Vision Test (Fletcher, 1980).

Stimuli

The stimuli were measured with a Cambridge Research Systems (Rochester, U.K.) ColourCal colourimeter, and were displayed on a calibrated Sony Trinitron CRT monitor (model GDM-F520). The stimuli were selected from the Munsell system, and emulated on the monitor. The stimuli were in the range 5B to 10G, at constant value (7) and chroma (8).

Procedure and Results

The stimuli were rectangular (50 mm²) and were presented in the centre of the monitor on a grey background. Each stimulus was presented until a response was made. Participants had to respond to each stimulus as blue or green by typing on a keyboard the initials 'g' for green and 'b' for blue. There were four repetitions of each stimulus and the 32 trials were in random order.

Figure 2.1 shows the percentage of responses to the stimuli being blue. It can be seen that the switch from predominantly blue responses to predominantly green responses occurs

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4 See Appendix A for information about the Munsell colour space.
5 This information applies to participants in all the experiments in this thesis unless otherwise stated.
somewhere between 10BG and 5BG. For the purposes of the target detection task, 7.5BG (half way between 8.75BG and 6.25BG) was taken as the blue-green boundary. This agrees with Bomstein and Monroe (1980), and many others (e.g., Franklin et al., 2005, Franklin, Clifford et al., 2005).

![Figure 2.1. Percentage of blue responses to each stimulus.](image)

### 2.2.3. Target detection task

#### Method

**Participants**

Twenty-four participants (17 females and 7 males, Mean Age = 23 years, SD = 1.99) took part in the study.

**Stimuli and Design**

Stimuli were displayed on the same calibrated monitor used in the naming task. There were eight stimuli that varied only in Munsell hue at value 7 and chroma 8 in the range 5B to 10G as shown in Figure 2.2 (See also Table 1.1. for the CIE co-ordinates). The stimuli were
chosen so that half of the stimuli fell in the blue category and the other half in the green category with the boundary at 7.5BG. The relationship between the target and background was manipulated in two ways. First, the two colours were either from the same category or from different categories. Second, the perceptual distance varied. In the ‘near’ condition, the separation was 2.5 Munsell hue steps, and in the ‘far’ condition the separation was 5 Munsell hue steps. As Figure 2.3 shows, for each of the perceptual distances there were three pairs of stimuli: one pair was between-category, one was within the green region, and one was within the blue region of colour space.

Figure 2.2. Munsell codes of the stimuli in the blue-green boundary in the near- and far-conditions. Dashed line represents the boundary between the green and the blue colour region.
Table 2.1. CIE (1931), Y, x, y chromaticity co-ordinates of the stimuli. White point of monitor as measured on screen: \( Y = 72.60 \, \text{cd/m}^2 \). The stimuli emulated a reflectance of 43.06.

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Y (cd/m²)</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25B</td>
<td>31.26</td>
<td>.222</td>
<td>.294</td>
</tr>
<tr>
<td>8.75BG</td>
<td>31.26</td>
<td>.226</td>
<td>.309</td>
</tr>
<tr>
<td>3.75BG</td>
<td>31.26</td>
<td>.239</td>
<td>.342</td>
</tr>
<tr>
<td>10G</td>
<td>31.26</td>
<td>.251</td>
<td>.364</td>
</tr>
<tr>
<td>5BG</td>
<td>31.26</td>
<td>.235</td>
<td>.334</td>
</tr>
<tr>
<td>10BG</td>
<td>31.26</td>
<td>.223</td>
<td>.301</td>
</tr>
<tr>
<td>5B</td>
<td>31.26</td>
<td>.220</td>
<td>.273</td>
</tr>
</tbody>
</table>

**Design**

On each trial, a single circular target (30 mm diameter and ~3.5° when viewed from a distance of 50 cm) appeared on a chromatically different, uniform background. One colour was used for the background that filled the monitor, and the other colour was used for the target. The categorical relationship (within-category/between-category) between the target and background was manipulated so that the two colours were either from the same category or from different categories. Both stimuli in a pair appeared equally often as the target and as the background. As can be seen in Figure 2.3, the target could appear in one of 12 equally separated (30°) locations on a notional circle of 110 mm diameter around the fixation cross at the centre of the monitor (~12.5° from fixation). In clock face terms, six locations were in the RVF from 12:30 to 5:30 at hourly intervals and six were in the LVF (6:30 to 11:30). The target could appear either in the left or in the right visual field. For both within- and between-category pairs, the location of the target was randomised, with the constraint that the target appeared equally as often on the left and right. This gave four kinds of display for each of the near and far sets: within-category left, within-category right, between-category left and between-category right.
Procedure

The experiments were conducted in a dark room. Participants sat at a distance of about 50 cm from the screen. The instructions were: 'Please concentrate on the fixation point at the centre at the screen whenever that appears. On each trial, you will be presented with pairs of colours on the screen: a coloured circle will appear somewhere on the screen on a coloured background. Your task is to decide whether the target is to the left or right of the fixation cross. On your joystick press button 7 if the target is in the left visual field, or button 8 if the target is in the right visual field. Please respond as fast and as accurately as possible as your speed and accuracy will be measured'. A trial sequence consisted of a white fixation cross on a black background for 1000 ms, followed by the test display with the target appearing for 250 ms, but, the coloured background remained until response. The cycle then repeated. Responses were made on a games pad (PCL RP100) with the left index finger indicating left, and the right index finger indicating right. Using the joystick for response allows more accurate timing than response on a mouse or keyboard. A high-resolution timer DLL (ExactTics) ensured accurate event timing. Reaction times were measured from the onset of the target display until a response was made. Figure 2.4 shows the sequence of events. Each stimulus in a pair served for half the trials as the target, and half as the background. For each pair, the target appeared on the left for half the trials, and on the right for half the trials in randomised order. No feedback was given during either practice or experimental trials. There
were 96 experimental trials made up from 16 trials of each of the six colour pairs. Target locations were chosen at random, but, with the overriding constraint that each location was used equally often across each set of 48 trials for near and far conditions. There were 24 practice trials consisting of randomly chosen stimulus-pairs, followed by the 96 experimental trials.

Figure 2.4. Sequence of events in the target detection task. Participants fixated the central cross, and then the target and the background appeared. The target disappeared after 250 ms, while the background stayed until a response was made.

Results

There were 3.6% incorrect responses in total. There were no significant effects of visual field and category on error rates (maximum \( F(1, 23) = 3.50, p = .07, \eta^2 = .13 \)). Median response times (RTs) for correct trials were calculated for each combination of category (within/between), perceptual distance (near/far), and visual field (LVF/RVF) for each observer. From Figure 2.5 it appears that between-category trials are faster then within-category trials and this seems to be more pronounced in the RVF, however there seems to be no difference between the two perceptual distances.
Figure 2.5. Mean RT for within-category and between-category trials in the RVF and the LVF for the two perceptual distances. Error bars represent 95% within-subject confidence intervals calculated by using the error term from the three way interaction.

Looking at Figure 2.6, it appears that the target was detected faster when it appeared on a different-category background (e.g., blue1 target on green1 background) than when it appeared on a same-category background (e.g., blue1 target on blue2 background). Between-category RTs were approximately 60 ms faster than within-category RTs, indicating an overall category effect. Moreover, this category effect is about 60 ms larger for the RVF than for the LVF.

---

5 When analysing the data one is interested in the pattern of population means across conditions. In a within-subject design, analysis of variance tests whether there are any differences among the population means. The within-subject confidence interval is appropriate as it tests whether the two sample means are significantly different (for more details see Loftus and Masson, 1994). Thus, the error bars represent the within-subject confidence limits estimated with the Loftus and Masson formula.

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6 When analysing the data one is interested in the pattern of population means across conditions. In a within-subject design, analysis of variance tests whether there are any differences among the population means. The within-subject confidence interval is appropriate as it tests whether the two sample means are significantly different (for more details see Loftus and Masson, 1994). Thus, the error bars represent the within-subject confidence limits estimated with the Loftus and Masson formula.
Figure 2.6. Mean RT for within-category and between-category in the RVF and the LVF. Error bars represent 95% within-subject confidence intervals calculated by using the error term from the two way interaction.

The data were subjected to a category (within/between) x visual field (RVF/LVF) x distance (near/far) repeated measures ANOVA to investigate further the differences between within-category and between-category presentations in the two visual fields, as well as the difference between the two perceptual distances. The only significant main effect was for category \([F (1, 23) = 58.83, p < .001, \eta^2 = .72]\). A strong interaction between category and visual field \([F (1, 23) = 26.85, p < .001, \eta^2 = .54]\) was observed. LVF targets were detected more quickly than RVF targets for within-category targets \([t (23) = 1.98, p = .06]\). For between-category targets, RVF targets were detected more quickly than LVF targets \([t (23) = 4.95, p < .001]\). As can be seen in Figure 2.6, there was a category effect for both visual fields \([\text{minimum } t (23) = 3.72, p < .001]\) however, the size of the category effect was greater for the RVF than for the LVF \([t (23) = 5.18, p < .001]\). This was the case for 22 out of the 24 participants. This difference also reflects a RVF disadvantage for within-category trials.

Looking at the perceptual distance, as Figure 2.7 shows, when the target-background were separated by 5 Hue steps (far-separation) the targets were detected 13 ms faster than those with 2.5 step separations (near-separation). Considering the visual field presentations, targets in pairs having a 5 hue step separations were detected about 25 ms faster than targets in pairs having a 2.5 hue steps separations for the RVF, whereas mean RTs for the two separations
were virtually identical for the LVF. The above pattern was supported by the main analysis. The perceptual distance effect was marginally significant \[ F(1, 23) = 3.58, p = .07, \eta^2 = .14 \]. Nevertheless, distance did interact with visual field \[ F(1, 23) = 4.49, p < .05, \eta^2 = .16 \]. Five hue step separations were faster than 2.5 hue steps for the RVF \[ t(23) = 2.48, p < .025 \], however, mean RTs for the two separations did not differ significantly for the LVF \[ t(23) = 0.08, p = .94 \]. The three-way interaction between category, visual field and perceptual distance was not significant \[ F(1, 23) = 2.38, p = .14, \eta^2 = .09 \].

![Figure 2.7](image.png)

**Figure 2.7.** Mean RT for near- and far- perceptual separations in the RVF and the LVF. Error bars represent 95% within-subject confidence intervals calculated by using the error term from the two way interaction.

### 2.2.4. Discussion

Participants were faster at detecting the target when the target-background chromatic difference was between-category than when it was within-category. Between-category RTs were approximately 60 ms faster than within-category RTs. There was also a strong interaction between category and visual field. Between-category target detections were faster than within-category target detection in both visual field, however, the size of the category effect (between- faster than within-) averaged 60 ms greater for the RVF than for the LVF.
In addition, participants were not noticeably faster when the target-background chromatic
difference was 5 Munsell hue steps than when the chromatic difference was 2.5 Munsell hue
steps. It might be the case the difference in the two chromatic separation sizes (2.5 Munsell
hue steps) was not large enough to produce a difference in target detection time. However,
distance did interact with visual field, five hue step separations were about 25 ms faster than
2.5 hue steps for the RVF, but they did not differ for the LVF. The three-way interaction
between visual field, distance and category was not significant.

Gilbert et al. (2006) found significant category effects in the RVF but not the LVF. In the
current experiment significant effects were found in both visual fields – but the effects were
stronger in the RVF. It is not clear what the source of this weaker LVF category effect is. It
is possible that the degree of LH colour CP is a function of the opportunity for trans-callosal
transfer. For instance, a patient whose corpus callosum had been surgically severed showed
clear colour CP in the LH but not in the RH (Gilbert et al, 2006). Reaction time responses in
the Gilbert et al. study were about 450 ms on average, whereas here, response times were
about 500 ms. Information presented to one hemisphere is transmitted to the other
hemisphere within a few ms (Brizzolara et al., 1994). It is possible that colour CP is based in
the LH, but perhaps even very short times, such as 50 ms, allow enough time for trans­
callosal transfer of information, thus, CP is shown for LFV targets, as well as for RVF
targets.

2.3. Experiment 2: Laterality effects for the blue-purple boundary.

2.3.1. Introduction

Experiment 1 showed a LH advantage for colour CP. If the LH bias for colour CP applies to
all colour regions, then lateralised CP should be found for all category boundaries. Thus far,
however, only the blue-green boundary has been tested. An issue of particular interest is
whether there are differences in lateralised CP across a boundary dividing primary and
secondary categories, such as blue and purple. This possibility was investigated in the next
experiment, again using the target detection task. As in the previous experiment, a
preliminary naming experiment was conducted to confirm that the blue-purple boundary was
around 10PB (Franklin, Clifford et al., 2005). As Experiment 1 showed no interaction for separation size, category and visual field, suggesting that perceptual distance is irrelevant in low-level perceptual decisions, such as those required in the target detection task, the separation size was not varied in the following experiment.

Main research question

- Is CP lateralised to the LH for a secondary boundary?

2.3.2. Establishing the blue-purple boundary.

Franklin, Clifford et al. (2005), using adult naming and similarity judgments have reported that the blue-purple category boundary for English speakers is around 10P Munsell hue. The stimuli for the naming in this experiment were chosen so that half of the stimuli fell in the blue category, and the other half in the purple category. Participants were asked to name the stimuli to establish the blue-purple boundary at specific chroma and value, so that stimuli could be chosen for the target detection task.

Method

Participants

There were 10 participants (five males and five females, Mean Age = 24 years, SD = 2.35).

Stimuli, Design, Procedure and Results

Stimuli were displayed on the same monitor as used in Experiment 1. Co-ordinates of the stimuli were in Munsell colour space at constant value 5 and chroma 10. The stimuli varied in 1.25 hue steps from 5PB to 7.5P. The design and procedure were as in section 2.2.2, except that participants were required to respond to each stimulus as blue or purple by typing on a keyboard ‘p’ for purple and ‘b’ for blue. The results established that the blue-purple category boundary is around 10PB. As Figure 2.8 shows, the most frequent responses to stimuli labelled blue were for stimuli 5PB to 8.75PB, while the rest of the stimuli were labelled purple.
2.3.3. Target detection task

Participants

Thirty-four participants (26 females and 8 males, Mean Age = 22.05 years, SD = 2.95) took part in the experiment.

Stimuli, Design and Procedure

Figure 2.9 shows the four stimuli that were selected, two blues and two purples with separations of 2.5 Munsell hue steps between adjacent pairs at constant value 5 and chroma 10. Target-background pairs were either within-blue, within-purple or between blue-purple. The design and procedure was the same as in Experiment 1, except that there were 96 experimental trials, but this time there were 32 trials for each stimulus pair (within-blue, within-purple and between-blue-purple).
Table 2.2. CIE (1931), Y, x, y chromaticity co-ordinates of the stimuli. White point of monitor as measured on screen: $Y = 90.5 \text{ cd/m}^2$. The stimuli emulated a reflectance of 19.77.

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Y (cd/m²)</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.25PB</td>
<td>17.89</td>
<td>0.218</td>
<td>0.203</td>
</tr>
<tr>
<td>8.75PB</td>
<td>17.89</td>
<td>0.238</td>
<td>0.203</td>
</tr>
<tr>
<td>1.25PB</td>
<td>17.89</td>
<td>0.258</td>
<td>0.205</td>
</tr>
<tr>
<td>3.75P</td>
<td>17.89</td>
<td>0.275</td>
<td>0.211</td>
</tr>
</tbody>
</table>

Results

There were 3.8% incorrect responses in total. Analysis of error rates showed that participants were more accurate on between-category trials than within category trials [$F(1, 33) = 16.92, p < .001, \eta^2 = .34$], however the effect of visual field and the interaction between category and visual field on error rates was not significant (maximum [$F(1, 33) = 1.73, p = .19, \eta^2 = .05$]. Median response times (RTs) for correct trials were calculated for each combination of category (within/between), and visual field (LVF/RVF) for each observer. As can be seen in Figure 2.10, it appears that the target was detected faster for between-category trials (e.g., blue target on purple background) than for within-category trials (e.g., blue

Figure 2.9. Munsell codes of the blue and purple stimuli. Dashed line represents the boundary between the blue and purple colour regions.
target on blue2 background). Between-category search was about 30 ms faster than within-category search, indicating an overall category effect. The between-category advantage seems to be greater in the RVF than in the LVF by about 34 ms.

The data were subjected to a category (within/between) x visual field (RVF/LVF) repeated measures ANOVA. The results supported the above impressions. The category effect was significant \[ F(1, 33) = 25.8, p < .001, \eta^2 = .44 \], but the visual field effect was not \[ F(1, 33) = 2.01, p = .17, \eta^2 = .06 \]. The interaction between visual field and category was also significant \[ F(1, 33) = 5.94, p < .025, \eta^2 = .15 \]. As can be seen in Figure 2.10, the category effect was present only in the RVF. The difference between within- and between-category trials for the RVF was significant \[ t(33) = 6.07, p < .001 \], whereas the LVF difference was not significant \[ t(33) = 1.23, p = .23 \].

![Figure 2.10](image.png)

**Figure 2.10.** Mean RT for within-category and between-category trial in the RVF and the LVF. Error bars represent 95% within-subject confidence intervals calculated by using the error term from the two way interaction.

### 2.3.4. Discussion

Participants were faster at detecting the target when the target–background chromatic difference was between-category than when it was within-category. Between-category RTs were approximately 30 ms faster than within-category RTs. There was also a strong
interaction between category and visual field. Between-category target detections were about 45 ms faster than within-category target detections in the RVF, but, they did not differ significantly in the LVF. This pattern contrasts with the results of the previous experiment, where the category effect was present for both visual fields. Thus, a stronger LH bias for colour CP is shown for the blue-purple boundary than for the blue-green boundary.

2.4. Experiment 3: The effect of concurrent verbal and visual tasks on lateralisation of colour CP

2.4.1. Introduction

Experiment 1 and 2 provided further support for the LH bias for colour CP. Testing the blue-green and the blue-purple boundary using a simple perceptual task it was found that, the RVF/LH has an advantage for between-category stimuli (e.g., blue target on purple background) over within-category stimuli (e.g., blue target on blue background).

The LH bias for colour CP is consistent with the possibility that even performance of an apparently low-level perceptual task, as used here, could still be vulnerable to language influences. If that is so, then interfering with deployment of language should reduce CP and reduce the LH advantage. The next experiment tested this conjecture by running the target detection task combined with visual and verbal concurrent tasks. The general methods follow previous studies (Gilbert et al., 2006; Roberson & Davidoff, 2000; Witthoft et al., 2003). Participants performed the primary task (the target detection task) and two types of secondary (interference) tasks. The target detection task was performed with either no-interference, verbal interference or visual interference. In the verbal-interference condition, the secondary task was to remember a target-list of four nonsense words presented prior to the primary task. Following completion of the primary task, participants were shown a single nonsense word and they had to decide whether it had appeared in the target-list or not. In the visual-interference condition, the secondary task was a visual-spatial memory task. Participants had to remember a black and white 'checker board', which appeared before the target detection display. After responding to the primary task, a test-grid appeared, and participants had to decide whether it was the same as the target-grid or not.
Main research question:

- What effect do verbal and visual concurrent tasks have on lateralised CP?

2.4.2. Method

Participants

Seventeen participants (15 females and two males, Mean Age = 22 years, SD = 2.77) took part in the experiment.

Stimuli and design

Primary task

The apparatus and basic design and method were as for Experiment 1 apart from the addition of the concurrent tasks. The stimuli only varied in Munsell Hue at value 7 and chroma 8\textsuperscript{7}. Target-background pairs differed by 2.5 Hue steps as illustrated in Figure 2.11.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{blue-green-boundary}
\caption{Munsell codes of the stimuli in the blue-green boundary. Dashed line represents the boundary between the green and the blue colour region.}
\end{figure}

Secondary tasks

Visual interference

The visual interference stimuli are illustrated in Fig. 2.12. Each display was a five by five black and white grid presented centrally. Each square was 10 mm\textsuperscript{2}, and 13 of the squares

\textsuperscript{7} See Table 2.1 for the CIE Yxy chromaticity co-ordinates of the stimuli.
were black and 12 white. Grey lines separated the white and the black squares to make the squares visible against the black background.

![Example representing the visual display used in the interference condition.](image)

**Figure 2.12.** Example representing the visual display used in the interference condition.

**Verbal interference**

For the verbal interference condition, a list of 288 four letter pronounceable non-words – ‘nonsense’ words – was used. Ten people agreeing unanimously that all of the words were nonsense words verified their non-word status. The to-be-remembered word list consisted of four different nonsense words selected at random from the 288 candidates, with the following constraints. Each word was used four times, but was not repeated in any target display, or on successive trials. The words were in white lower-case font against a black background (Times New Roman, 36) presented in a column in the centre of the monitor.

**Procedure**

The basic procedure for the primary task was the same as in Experiment 1. Each target-distractor pair was presented 32 times under each of the three interference conditions, giving 288 trials in total. The interference type was selected randomly on each trial with the sole constraint that there were 96 trials of each type in total. The instructions for the secondary task were as follows: ‘In some of the trials a list of four nonsense words or a black and white

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8 See Appendix B for the list with the words that were used in the verbal interference condition
checker board will appear before the coloured target. You have to remember the words or the grid. A coloured target will then appear on a coloured background, and you have to decide as quickly and accurately as possible, whether the target was to the left or right of fixation. When you have made your response, you will be tested on the memory task, if there was one. For word trials, a single ‘probe’ word will appear, and you have to decide if it was included in the target list. On grid trials, a test-grid will appear and you have to decide if it is identical to the target grid or not. For positive trials, press button 9, and for negative trials press button 10.’

For both interference tasks, the probe stimuli matched the test stimuli on half the trials. The probe word was chosen at random from the list of 288 words. For visual interference, on different trials, two randomly chosen white squares were changed to black, and two black squares chosen at random were changed to white. Thus, the proportion black and white squares did not differ from the target grid (See Figure 2.13).

![Figure 2.13](image)

**Figure 2.13.** Example of a different trial in the visual interference task. Participants had to remember grid *a*. After completing the primary task, they had to decide if the test grid (*b*) was the same as visual grid *a*, or different. Grid *b* differs from *a* as two white squares have been change to black, and two black squares have been changed to white.

Figure 2.14 illustrates the sequence for each kind of trial. Trials began with the onset of the white central fixation cross on a black screen for 500 ms. Then a warning ‘beep’ occurred, and the fixation cross disappeared, leaving a blank screen for 500 ms. Next, either a blank
screen, indicating a no-interference trial, or a checker board, or a word list appeared for 1250 ms. This was followed by a blank screen with a fixation cross for 1250 ms, indicating that the primary task was about to begin. Then the target appeared on the coloured background for 250 ms. After the target had disappeared, the background remained visible until a response was made. After the response, the test stimuli for the concurrent task were presented until a response was made, which initiated the next trial. In the no-interference condition after the 500 ms interval, the next trial was initiated automatically.

Figure 2.14. Sequence of events in the experimental trials for the three types of interference (no interference, verbal interference and visual interference).
Before performing the experimental trials, participants were given 18 practice trials to familiarise them with the different tasks in the experiment. If participants were not comfortable after this, then the practice trials were repeated. The trials consisted of randomly chosen stimulus-pairs where participants were presented with trials for each of the conditions (within-between, left-right, verbal-visual-none and the combinations of these). Following successful practice, the experimental trials were started. No feedback was given in either practice or experimental trials. The time taken to complete the experiment was approximately 30 minutes.

2.4.3. Results

Performance on the two secondary tasks in terms of both reaction time and accuracy is reported first. Analyses of the primary task performance follow. As participants were asked to respond based on speed and accuracy, RT and accuracy are reported as separate performance measures. The reported ANOVAs are three-way with three factors as repeated measures. In all cases, the three factors are category, visual field and interference type. Category has two levels (within and between), visual field has two levels (RVF and LVF), and interference type has three levels (no-interference, verbal interference and visual interference). Analysis of each interference type is reported under separate sub-headings analysed with two-way repeated measures ANOVA: in each case, the two factors are category (within and between), and visual field (RVF and LVF).

Secondary task performance

Accuracy

The percentage of correct responses for each interference type was calculated for each subject. The mean scores across subjects were essentially the same for the two interference types (89.00% and 88.94% for verbal and visual interference respectively [$t(16) = 0.09, p = .93$].
For each subject, the mean of median RTs for correct trials was calculated for each interference type. Mean RTs across subjects did not differ across interference type (1019 ms and 1030 ms for verbal and visual interference respectively; \( t(16) = 0.16, p = .88 \).

**Primary task performance**

*Accuracy*

The mean for correct responses for participants was calculated in the no-interference, verbal interference and visual interference conditions. Figure 2.15 shows the percentage of correct responses for between- and within-category trials under each of the interference types in the two visual fields. It can be seen that percentage of correct responses for within- and between-category trials were similar, 91.81% and 91.69% respectively, and this was also the case for trials in the LVF and in the RVF, 91% and 91.81% respectively. However, it appears that participants were more accurate in the no-interference condition (96.25%) than both verbal (89.06%) and visual interference (89%). Further statistical analysis investigated possible significant differences for each combination of category, visual field and interference type.
Analysis revealed that accuracy was not affected by category \(F (1, 16) = 0.84, p = .37, \eta^2 = .05\) or visual field \(F (1, 16) = 0.11, p = .74, \eta^2 = .01\). However, the effect of interference type was significant \(F (1, 16) = 34.32, p < .001, \eta^2 = .68\). Planned comparison showed that accuracy was higher in the no-interference condition than in the verbal interference condition \(F (1, 16) = 55.97, p < .001, \eta^2 = .78\), and that accuracy did not differ in the verbal and visual interference conditions \(F (1, 16) = 0.20, p = .66, \eta^2 = .01\). As Figure 2.15 shows, the percentage of correct responses in the no-interference condition was higher than both verbal and visual interference conditions [minimum \(t (16) = 7.1, p < .001\), but verbal and visual interference did not differ \(t (17) = 0.44, p = .66\]. None of the interactions were significant, maximum \(F (2, 32) = 1.78, p = .186, \eta^2 = .10\).

**RT**

Trials with errors on either the interference or primary task were not included in the RT analysis. For each participant, median RTs for correct trials in the target detection task, for each combination of category, visual field and interference type were calculated.
Between-category (642.8 ms) trials were about 25 ms faster than within-category (666.4 ms) trials. From Figure 2.16, it appears that RTs in the no-interference condition (~ 633 ms) were faster than in the verbal interference condition (~ 679 ms) and RTs in the visual interference condition were faster than RTs in the verbal interference condition (~ 650 ms). Verbal interference slowed performance by about 46 ms and visual interference was about 17 ms slower than no-interference.

![Figure 2.16](image)

**Figure 2.16.** Mean Reaction Time for between-category and within-category target detection for the two visual fields for each interference type. Error bars represent 95% within-subject confidence intervals.

The above impression was supported by the ANOVA: an overall category effect was revealed with between-category trials being significantly faster than within-category trials \[F(1, 16) = 4.68, p < .05, \eta^2 = .23\]. The effect of interference was also significant \[F(2, 32) = 48.59, p < .001, \eta^2 = .75\]. Planned comparison showed that RTs in the no-interference condition were faster than in the verbal interference condition \[F(1, 16) = 71.36, p < .001, \eta^2 = .82\] and RTs in the visual interference condition were faster than RTs in the verbal interference condition \[F(1, 16) = 34.67, p < .001, \eta^2 = .68\]. Thus, RTs were faster in the no-interference condition than in both the verbal and the visual interference conditions. The overall effect of visual field was not significant \[F(1, 16) = 0.57, p = .46, \eta^2 = .04\] and
neither were the category and visual field interaction \[ F(1, 16) = 3.07, p = .09, \eta^2 = .16 \] or the category and interference type interaction \[ F(1, 32) = 0.02, p = .98, \eta^2 = .002 \].

There was a significant interaction between visual field and interference type \[ F(2, 32) = 8.52, p < .001, \eta^2 = .35 \]. From Figure 2.17 it can be seen that while the verbal interference condition was slowest in both visual fields, the size of the difference is larger in the RVF than in the LVF. Comparison of the difference between verbal and visual interference in the two visual fields shows that the difference averaged about 35 ms larger in the RVF than in the LVF \[ t(16) = 3.08, p < .01 \]. The same was the case for the difference between verbal and no interference: this was about 30 ms larger in the RVF than in the LVF \[ t(16) = 3.91, p < .02 \]. In contrast, although the visual interference condition was slower than the no interference condition in both visual fields, the size of the difference did not differ across fields \[ t(16) = 0.31, p = .76 \].

Additionally, the 3-way interaction between category, visual field and interference type was significant \[ F(2, 32) = 5.74, p < .025, \eta^2 = .26 \]. As can be seen in Figure 2.16, the no-interference and visual interference show essentially the same pattern. There is a category effect in the RVF but not in the LVF. In contrast, in the verbal interference condition, there is no category effect in either visual field. This impression was investigated further with separate analyses on the three interference types.
Figure 2.17. Mean RTs for no-interference, verbal and visual interference in the RVF and in the LVF. Error bars represent 95% within-subject confidence intervals calculated by using the error term from the two way interaction.

No-interference condition

There was no significant effect of visual field \( F(1, 16) = 2.54, p = .13, \eta^2 = .14 \), but between-category was almost significantly faster (~ 25 ms) than within-category \( F(1, 16) = 4.14, p = .059, \eta^2 = .21 \). From Figure 2.16a, this difference appears to be almost entirely due to the RVF. However, the interaction between category and visual field only approached significance \( F(1, 16) = 3.46, p = .081, \eta^2 = .18 \). As can be seen in Figure 2.15a, between-category targets were detected about 37 ms faster in the RVF than in the LVF \( t(16) = 3.37, p < .025 \), whereas RTs for within-category targets did not differ across visual fields \( t(16) = 0.61, p = .95 \). Reinforcing this, there was a reliable category effect (~ 40 ms) in the RVF \( t(16) = 2.74, p < .05 \) but not in the LVF \( t(16) = 0.40, p = .69 \).

Verbal interference condition

Although between-category trials were about 20 ms faster than within-category trials, the difference was not significant \( F(1, 16) = 1.86, p = .19, \eta^2 = .10 \). Mean RTs did not differ across visual field (686 ms and 672 ms for LVF and RVF respectively \( F(1, 16) = 0.91, p = \))
.35, $\eta^2 = .05$. Nor was the interaction between category and visual field significant [$F (1, 16) = 0.20, p = .89, \eta^2 = .001$; see Figure 2.16b].

**Visual interference condition**

Between-category trials were about 30 ms faster than within-category trials [$F (1, 16) = 5.03, p < .05, \eta^2 = .24$], but there was no effect of visual field [$F (1, 16) = 2.74, p = .12, \eta^2 = .15$]. Importantly, the interaction between category and visual field was significant [$F (1, 16) = 7.53, p < .025, \eta^2 = .32$]. RVF targets were detected about 55 ms faster than LVF targets for between-category targets [$t (16) = 3.14, p < .025$], whereas RTs for within-category targets did not differ across visual field [$t (16) = 0.51, p = .62$]. Moreover, there was a reliable category effect (~ 55 ms) in the RVF [$t (16) = 4.14, p < .025$] but not in the LFV [$t (16) = 0.28, p = .79$; see Figure 2.16c]. Thus, CP survived in the RVF/LH, showing the same pattern as in the no interference condition.

### 2.4.4. Discussion

The category effect was influenced by the type of interference: there was a category advantage under both the no interference and the visual-interference conditions, but not under the verbal interference condition. In addition, there was a significant interaction between visual field and interference type. In the LVF, RTs in the verbal interference condition and visual interference did not differ, whereas RTs in the no interference condition were faster than both RTs in the verbal interference condition and in the visual interference condition. Looking at the RVF, RTs in both no interference condition and in the visual condition were faster than RTs in the verbal interference condition. Moreover, the 3-way interaction between category, visual field and interference was also significant. In the no-interference condition there was a reliable category effect only in the RVF. The same pattern was observed in the visual interference condition, however, in the verbal interference condition, CP was eliminated.

The effect of verbal interference on CP could not be attributed to the differences in the difficulty level in the two secondary tasks, or unequal attention being given to the tasks.
Accuracy in the non-interference condition was higher than both verbal and visual interference conditions, 96.25%, 88.43% and 89.06% respectively, but verbal and visual interference did not differ. Median reaction time in the secondary tasks was 1019 ms and 1030 ms for verbal and visual tasks respectively. Additionally, accuracy in the secondary tasks was almost identical, 89% and 88.94%, in the verbal and visual conditions respectively.

In summary, participants show a LH advantage for between-category discrimination in this task under normal viewing and visual interference, but under verbal interference, CP is eliminated.

2.4.5. General discussion Experiments 1, 2 and 3

Experiments 1 and 2 showed a LH advantage for between-category discrimination. This was replicated in Experiment 3 in the no-interference and the visual interference conditions. As the left hemisphere is the locus of most aspects of linguistic processing, it is possible that colour language has shaped perceptual organisation 'warping' perceptual space, resulting in the left hemisphere bias for colour categorisation even on a low-level perceptual task.

However, under verbal interference the category effect was eliminated. In several studies a category advantage was observed in simple perceptual tasks, yet the category advantage was selectively eliminated or reduced by verbal, but not spatial interference (e.g., Roberson & Davidoff, 2000; Winawer et al., 2008). Nonetheless, as discussed in Section 1.4.2, these studies suggest a direct language influence on colour CP. However, in the Gilbert et al. study and in Experiment 3 of this chapter the tasks were presumed to be immune to direct language influences, thus the picture gets more complicated. Another possibility is that an interaction of both lower-level perceptual processing and language processes results in perceptual decision. Existing verbal codes facilitate discriminations of colours straddling category boundaries, but, this is of no help when the stimuli belong to the same linguistic category. This is in line with findings that report larger activation for language areas in discrimination of colours that are easy to map to lexical codes than colours that are difficult to map to lexical codes, even though the colours were presented only for 100 ms (e.g., Tan et al., 2008).
In summary, the results from the three experiments in this chapter show that discrimination of colours with different names is faster in the RVF than in the LVF. Even though it is clear that the CP is much stronger for RVF targets, it is not clear from these data whether this advantage reflects direct or indirect language effects. If language has shaped perceptual organisation, a permanent change in perceptual processing is assumed to have taken place. Temporarily disabling access to linguistic representations with verbal interference should not have changed the pattern in perceptual performance if a permanent change has already occurred. Even though the LH bias disappears when verbal interference is added to the task, it is not clear whether verbal codes are activated. Further studies using neuroimaging techniques should investigate whether language areas are activated during both primary and secondary tasks, i.e. under verbal interference and primary perceptual tasks.
Chapter 3

Developmental changes in lateralised colour categorical perception

3.1. General Introduction

In Chapter 2, using a target detection task, it was found that between-category discrimination (e.g., blue on green) was faster in the RVF than in the LVF. Within-category discriminations did not differ in the two visual fields. This was found for both green-blue and blue-purple boundaries. On the other hand, this advantage was eliminated under verbal but not visual interference when the blue-green boundary was tested. Assuming that the task demands rely on low-level processing it is not easy to understand why this advantage was eliminated under verbal interference. It was suggested that perhaps rapid access to verbal codes may occur during the task and this facilitates categorical perception. When accessibility to these verbal codes represented in the LH is disrupted, the nature of the early visual response to the colours may be altered. Some clarification of the role of language may be obtained by exploring possible hemispheric asymmetries in CP before language is present and as it is acquired. By testing infants and toddlers using the target detection task it should become clearer whether the LH bias reflects a general predisposition of the LH for categorical information, or whether it reflects a genuine language influence on CP.

The following experiments

The following experiments use an eye-movement version of the target detection task to test for lateralisation of colour CP in infants, toddlers and adults. Franklin et al. (2005) showed colour CP in infants using the target detection task using time to target fixation as the measure. However, target fixation time is not ideal measure if interested in lateralisation, as stimulus lateralisation is lost as soon as the eyes move. Short stimulus presentation to one visual field ensures that direct projections of the stimulus are confined to the contralateral hemisphere, however, free-viewing of stimuli is problematic as once the stimulus is fixated it will no longer be lateralised. Latency measures allow for lateralisation of the stimulus, as the latency to initiate a saccadic eye movement to a visual stimulus can be measured as the total time (in ms) elapsed from the onset of the stimulus's display until the onset of the first gaze.
Furthermore, the reaction time measure used in Chapter 2 cannot be used to test infants. One of the experiment in this Chapter tests infants, thus, latency measures are appropriate to investigate laterality effects in infants. Infants, toddlers and adults were tested using the same procedure and method but chromatic separation size was varied due to changes in chromatic sensitivity (c.f. Knoblauch, Vital-Durand and Barbur, 2001).

Experiment 4
Experiment 4 tested laterality effects in adults using the eye-movement latency measure. If this yields the same pattern of lateralisation of CP as in the experiments in Chapter 2 that measure reaction time, then this would provide converging evidence for the LH bias in colour CP. Also, it would confirm the suitability of both the RT and the latency measures in testing for laterality effects.

Experiment 5
Experiment 5 investigated CP and laterality effects in 4-6 month-old infants to investigate whether CP is also lateralised in pre-linguistic infants.

Experiment 6
Experiment 5 compared performance of toddlers, who either know colour terms, or are learning colour terms, to investigate whether lateralisation of CP changes with language learning.

Summary of research questions

1. Do adults initiate eye-movements to the target faster for between-category targets than for within-category targets, and if CP is found, is it lateralised?

2. Can colour CP in infants on a target detection task (Franklin et al., 2005) be replicated using an eye-movement latency measure rather than target fixation times, and if CP is present in infancy, is it lateralised?

3. Does the pattern of lateralisation of CP differ between children who are learning colour terms, and those who know colour terms?
3.2. Experiment 4: Laterality effects in colour CP in adults assessed by eye-movement latencies.

3.2.1. Introduction

Gilbert et al. and the experiments in Chapter 2, using reaction times measures, showed that colour CP is lateralised to the LH. The following experiment investigated whether the LH bias in colour CP is still found when using an eye-movement latency measure.

Participants were tested on a version of the target detection task. A coloured target was embedded on a coloured background that was either from the same colour category (within-category) or from a different category (between-category) to the target. The within- and between-category hue separations were equated using the Munsell colour system. Targets for the within-category (e.g., green1-green2) and between-category trials (blue1-green1) were presented to the LVF or RVF for four seconds. Participants' eye-movements were recorded and the time that elapsed between central fixation at target onset, and the initiation of an eye-movement to the target was measured. Although participants were presented with free-viewing of the stimuli, they were centrally fixated up until the initiation of the eye-movement to the target, thus, there were no eye-movements during the measure of performance.

If CP was present, it would be evidenced by faster between-category latencies than within-category latencies. Laterality effects would be evidenced if the category difference was greater for targets in one visual field than the other. If reaction time and eye-movement latencies are more or less equivalent measures (c.f., Zelinsky & Sheinberg, 1997), adults should show stronger CP in the LH than the RH, as for the experiments of Chapter 2.

Main research questions

1. Do adults initiate eye-movements to the target faster for between-category targets than for within-category targets?
2. If CP is found, is it lateralised?
3.2.2. Method

Participants

Eighteen adults (seven males and eleven females) took part in the study (Mean Age = 21.83 years, SD = 3.85).

Apparatus and Experimental Set Up

The experiment was conducted in a dark room. Stimuli were displayed on a calibrated Sony Trinitron CRT monitor (model GDM-F520). Eye-movements were recorded using an ASL 504 pan/tilt eye-tracking camera, tracking at 0.5° accuracy, placed under the monitor recording at 50 Hz. The eye-movement output gave a video recording of what the participant was shown with ‘cross-hairs’ indicating point of gaze super-imposed. The output was digitised using an analogue to digital video converter (Canopus ADVC-300). The digital video was analysed using the i-Movie 2.1.2 software.

Stimuli and Design

Target and background were separated by 2.5 Munsell hue units, and straddled the blue-green boundary (7.5BG). Two stimuli were green (3.75BG, 6.25BG) and the third was blue (8.75BG; see Figure 3.1 for Munsell co-ordinates and Table 3.1 for CIE, 1931, Y, x, y chromaticity co-ordinates). There were 64 experimental trials made up from 16 trials for each combination of visual field (LVF or RVF) and category (within- or between-category). The trials occurred in a different random sequence for each subject.

Table 3.1. CIE (1931), Y, x, y chromaticity co-ordinates of the stimuli. White point of monitor as measured on screen: Y = 64.80 cd/m^2. The stimuli emulated a reflectance of 30.05.

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Y (cd/m^2)</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.75BG 6/8</td>
<td>19.47</td>
<td>0.214</td>
<td>0.304</td>
</tr>
<tr>
<td>6.25BG 6/8</td>
<td>19.47</td>
<td>0.220</td>
<td>0.322</td>
</tr>
<tr>
<td>3.75BG 6/8</td>
<td>19.47</td>
<td>0.228</td>
<td>0.342</td>
</tr>
</tbody>
</table>
Adults’ eye-movements were calibrated using a nine-point procedure: a black and white attention getter was shown consecutively at nine points. Adults were instructed to look at the attention-getter, and the corneal reflection and pupil signal were recorded for each point. The accuracy of calibration was then assessed by asking participants to look at a further five randomly chosen points on the screen, and if the crosshairs indicating point of gaze hit each of these five points, then calibration was deemed accurate. If calibration was not accurate, the procedure was repeated. Figure 3.2 shows the sequence of events in the experimental trials. Each trial began with the presentation of the attention-getter in the centre of the grey screen (see Table 3.1. for Y, x, y chromaticity co-ordinates). This was presented until eye-movement cross-hairs indicated that the participant was fixating the central point. A blank grey screen was then presented for 250 ms, followed by the presentation of the target and background for four seconds. Initiation time was measured from fixation to the eye-movement towards the target. Participants were told to “Fixate the flashing bulls-eye when it is shown, but other than that, just look at the screen, keeping your head as still as possible”. No other instructions were given. All experimental trials were presented in a random sequence for each subject.
Figure 3.2. Sequence of events. Lines represent cross-hairs. Dashed lines represent eye-movement cross-hairs centrally fixated. Initiation time was measured from fixation to the onset eye-movement towards the target.

Results

Trials were excluded if the eye-movement signal was lost [mean = 2.39 trials; SD = 3.16]. Or if multiple eye-movements were made before the eye-movement to the target [mean = 5.11 trials; SD = 3.5], or if the target was not fixated at all [mean = 0.22, SD = 0.24]. This left on average 56.28 trials per participant [SD = 5.81], and all participants had at least ten trials per condition. There were no significant effects of visual field and category on error rates: maximum \( F(1, 17) = 3.68, p = .07, \eta^2 = .18 \).

The initiation time was calculated as time from target onset up until the start of the eye-movement to the target. Figure 3.3 shows the mean of median latencies across subjects for each combination of visual field and category (within- between-). It seems that between-
category initiation times were about 110 ms faster than within-category initiation times, (means: 352 ms and 460 ms respectively). Initiation times in the LVF were just 15 ms faster than in the RVF (means: 398 ms and 413 ms respectively). In addition, initiation times for between-category trials seem to be faster than within-category trials in both visual fields. In the RVF, between-category trials were about 130 ms faster than within-category trials. In the LVF, this difference was about 90 ms. The size of the category effect seems to be larger in the RVF than in the LVF.

![Figure 3.3](image)

**Figure 3.3.** Mean of median eye-movement latencies for within- and between-category in the RVF and LVF. Error bars represent 95% within-subject confidence intervals calculated by using the error term from the two way interaction.

A category (within/between) x visual field (LVF/RVF) repeated measures ANOVA revealed a category effect with between-category initiation time being faster than within-category time \( [F (1, 17) = 130.02, \ p < .001, \eta^2 = .88] \), but there was no main effect of visual field \( [F (1, 17) = 2.70, \ p = .12, \eta^2 = .14] \). The interaction was also significant \( [F (1, 17) = 9.14, \ p < .01, \eta^2 = .35] \). Although between-category initiation times were faster than within category for both visual fields (minimum \( [t (17) = 8.18, \ p < .001] \), the RVF category effect (between – within) was about 40 ms greater than for the LVF \( [t (17) = 3.02, \ p < .01] \). The greater RVF
category effect was due to within-category target detection being slower in the RVF than in the LVF \[ t(17) = 2.58, p < .05 \], whereas between-category target detection did not differ in the two visual fields \[ t(17) = 0.49, p = .62 \].

### 3.2.3. Discussion

Adults were faster to initiate an eye-movement to a target if it was on a different-category than same-category background. A significant category effect was found in both visual fields; however, the category effect was significantly larger when targets appeared in the right visual field than left visual field. The findings are consistent with the experiments in Chapter 2, which used the target detection task and measured RTs to a briefly presented target. Reaction time and eye-movements showed a reliable correspondence between the measures, i.e., the pattern of results was essentially the same. This indicates that when latency measures are not available, reaction time measures can easily be used to investigate laterality effects. The following experiment investigated whether CP in infants is also lateralised.

### 3.3. Experiment 5: Is colour CP lateralised in infants?

#### 3.3.1. Introduction

**Hemispheric asymmetries in infants**

The lack of functional integration of visual information across the corpus callosum during early infancy ensures that the lateralization effects are more absolute for infants than for adults. The corpus callosum, which is the main interhemispheric pathway, is not functional before the age of 2 years. Cortically mediated transfer of visual information between the hemispheres via the corpus callosum is not present, therefore input to the right hemisphere comes primarily from the left visual field, and input to the left hemisphere comes primarily from the right visual field (de Schonen & Mathivet, 1990; Liegeois & de Schonen, 1997; Liégeois, Bentejac, & de Schonen, 2000). However, hemipsheric communication via subcortical pathways remains a possibility; for instance, de Schonen and Bry (1987) showed that subcortical co-ordination in the case of face-like versus non-face-like patterns is present at the age of 3-6 months.
Although there have been no studies of the lateralisation of colour CP in infants, there is evidence for pre-linguistic hemispheric asymmetries in other domains, such as the processing of visual and auditory information (Catherwood, Cramm, Foster, 2003; Catherwood, Freiberg, Grenn & Holt, 2001; Dehaene-Lambertz & Dehaene, 1994; Deruelle & de Schonen, 1995; De Schonen & Mathivet 1990; Mills, Coffey-Corina & Neville, 1997; Gathers, Bhatt, Corbly, Farley & Joseph, 2006; Pegg and Werker, 1997; Werker, & Tees, 1984). For instance, a RH advantage in face processing is found at 18 to 42 weeks (De Schonen & Mathivet, 1990), whereas a LH advantage in auditory processing is found at 4 months (Dehaene-Lambertz, 2000).

Catherwood et al. (2001) investigated hemispheric asymmetries for colour recognition in six-month old infants using the novelty preference technique. Infants were familiarised to a set of three colour stimuli (e.g., red, green and yellow) presented for 250 ms to either the RVF or LVF. Following familiarisation, a novel colour (e.g., blue) was paired with one of the familiar colours. Comparing looking times for the novel and familiar stimuli, it was found that infants showed novelty preference when colours were familiarised in the LVF, but not in the RVF. It was argued that at six months, there is a right hemisphere bias for colour recognition. However, as colour pairs were always in different categories, it is unclear whether the RH advantage reflects CP, or just better colour discrimination.

The following experiment

The following experiment investigated colour CP and laterality effects in infants. The same method was used as in the previous experiment, and the main performance measure was eye-movement latency to the target. CP would be indicated if initiation times were faster for between-category target-background pairs than for within-category pairs. A hemispheric asymmetry in CP would be indicated by a larger CP effect for one of the visual fields. If a left hemisphere bias were found in infants then this would suggest a pre-disposition for colour CP in the LH. It is also possible that infants would show a reversed, right hemisphere bias for CP. If that were the case, then it would suggest that adult colour CP in the LH does not rely on pre-linguistic categories. The left hemisphere bias for colour categorisation in
adults may emerge as the perceptual categorisation becomes linguistically based when the lexical codes for colour become cognitively salient.

**Main research question**

1. Can colour CP in infants on a target detection task (Franklin et al., 2005) be replicated using an eye-movement latency measure rather than target fixation times?

2. If CP is present in infancy, is it lateralised?

**3.3.2. Method**

*Participants*

Twenty-six infants took part in the study. Prior consent was obtained from their parents or guardians. Of these, 13 were not included in the final analysis due to: general fussiness such as crying or excessive head movement (six infants); accurate calibration not achieved (three infants); not enough completed trials for one or more of the conditions (four infants). The mean age of the final sample was 20.61 weeks [SD = 2.66] and there were five females and eight males. The mean birth weight of the sample was 3850 grams [SD = 820].

*Apparatus and Experimental Setup*

Infants were seated and strapped into an infant car seat 50 cm away from, and at eye-level to the monitor. The apparatus was the same as Experiment 4. All other aspects of the experimental setup remained the same.

*Stimuli and Design*

There were three stimuli that varied only in Munsell Hue, with Munsell Value and Chroma kept constant (Value = 6, Chroma = 8). As can be seen in Figure 3.1, the target and background colours were separated by 10 Munsell hue units (also see Table 2 for CIE, 1931, Y, x, y chromaticity co-ordinates). Adjacent stimuli were paired, giving one within-category and one between-category pair. There were 32 experimental trials in total made up from 8 trials for each combination of visual field (LVF or RVF) and category (within- or between-category). The trials were presented in a random order for each participant.
between-category

between-category

within-category

within-category

2B
Blue region

2BG
Green region

2G

Figure 3.4. The Munsell Hues (Value 6 Chroma 8) of the experimental stimuli. The target-background separation was 2.5 Munsell hue steps.

Table 3.2. CIE (1931), Y, x, y chromaticity co-ordinates of the stimuli. White point of monitor as measured on screen: Y = 64.80 cd/m². The stimuli emulated a reflectance of 30.05.

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Y (cd/m²)</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>2B 6/8</td>
<td>19.47</td>
<td>0.209</td>
<td>0.282</td>
</tr>
<tr>
<td>2BG 6/8</td>
<td>19.47</td>
<td>0.235</td>
<td>0.355</td>
</tr>
<tr>
<td>2G 6/8</td>
<td>19.47</td>
<td>0.286</td>
<td>0.431</td>
</tr>
<tr>
<td>Grey</td>
<td>19.47</td>
<td>0.336</td>
<td>0.344</td>
</tr>
</tbody>
</table>

Procedure

Infant eye-movements were calibrated with a two point procedure. A black and white attention getter was shown consecutively at two points (top left, bottom right). The pupil signal and corneal reflection were recorded for each point. The attention getter was shown at a further three randomly chosen points to assess the accuracy of calibration. The calibration was deemed accurate only if the infant was fixated on the attention getter for each of these three points. If calibration was not accurate then the procedure was repeated. Following calibration, infants were shown the 32 experimental trials. The experimental trials were only shown once infants were fixating the central attention getter. If the infant did not fixate the central attention getter, black and white cartoon animals that moved in synchrony with noises were shown in between trials to re-focus the infant on the screen. When the infant was
focused on the screen, the attention getter was shown, and once this was fixated, the next experimental trial began.

Results

Trials were excluded if the eye-movement signal was lost [mean = 7.77 trials, SD = 4.90], or if multiple eye-movements were made before the eye-movement to the target [mean = 3.77 trials, SD = 2.62], or if the target was not fixated at all [mean = 2.9 trials, SD = 1.8]. This left on average 17.56 trials per infant [SD = 5.30], and all infants had at least two trials per condition. There were no significant effects of visual field and category on error rates (maximum $F(1,12) = 0.79, p = .39, \eta^2 = .06$).

The initiation time was calculated as time from target onset until the start of the eye-movement to the target. Mean initiation times were calculated for each infant for each visual field and for within- and between-category conditions. From Figure 3.3 it appears that initiation times were faster to between-category targets than to within-category targets trials (means: 631 ms and 711 ms respectively). Initiation times seem to be faster in the LVF than in the RVF (means: 724 ms and 617 ms respectively). Initiation times were about 210 ms faster for between-category trials than within-category trials in the LVF (means: 815 ms and 606 ms respectively), but the difference in the RVF was only about 5 ms (means: 634 ms and 629 ms respectively).

A two-way repeated measures ANOVA with category (within/between) and visual field (LVF/RVF) was conducted on the mean initiation times. The analysis supported the above pattern. The effect of category was significant with initiation times for between-category trials being faster than for within-category trials [$F(1, 12) = 5.73, p < .05, \eta^2 = .32$]. There was no effect of visual field [$F(1, 12) = 2.38, p = .15, \eta^2 = .17$]. The interaction was significant, [$F(1, 12) = 18.49, p < .005, \eta^2 = .61$]. As can be seen in Figure 3.5, the interaction reflected a significant LVF category effect [$t(12) = 3.71, p < .005$], and no RVF category effect [$t(12) = 7.4, p = .47$]. The visual field difference in CP was due to slower RVF within-category responses than LVF responses [$t(12) = 2.61, p < .05$], while between-category responses did not differ [$t(12) = .078, p = .94$].
Figure 3.5. Mean eye-movement latencies for within- and between-category conditions for the LVF and RVF. Error bars represent 95% within-subject confidence intervals calculated by using the error term from the two way interaction.

3.3.3. Discussion

The analysis of initiation times showed an overall category effect; infants were faster to initiate eye-movements when the target was in a between-category trial than when the target was in a within-category trial. There was no overall visual field effect; initiation time was equally fast for left visual field and right visual field targets. However, there was a significant interaction of category and visual field. Interestingly, there was a category effect for targets presented to the LVF but no category effect for targets presented to the RVF. The results suggest that colour CP in infancy is lateralised, yet with a RH bias, rather than LH bias as in adults.

It is possible that the side of lateralisation changes with colour term acquisition. Changes in side of lateralisation across development are reported for other domains, such as some aspects of language processing. For instance, brain activity for known and unknown words is observed in both hemispheres at 13-17 months, but, it is lateralised to the left hemisphere at
20 months (Mills et al., 1997). Since laterality effects are found in infants, learning to apply different colour terms for different colours may change the locus of the asymmetry. Toddlers who are in the process of learning the colour terms, and toddlers who have already acquired the colour terms, may show different laterality effects for CP. Comparisons with toddlers who are in the process of learning colour terms may lead to a greater understanding of why there is hemispheric specialisation in infant colour CP, and how this changes across development.

3.4. Experiment 6: Does lateralisation of colour CP change with colour term acquisition?

3.4.1. Introduction

Experiment 4 replicated the findings of experiments in Chapter 2 showing a LH advantage for colour categorical perception in adults, measured with eye-movement latencies instead of reaction times. Interestingly, Experiment 5 showed the opposite pattern, a strong lateralisation for CP was found for infants also, but it was lateralised to the RH. A RH bias in infants, but LH bias in adults, suggests that at some point in development, there must be a transition from RH bias to LH bias. Hemispheric changes have shown in other domains (e.g., Mills et al., 1997, Gathers et al., 2006). For instance, Gathers et al showed that 5-11 year old children showed activity in both hemispheres in face and object recognition, whereas adult’s brain activity was lateralised to the right hemisphere. If the LH bias in colour CP for adults is due to the implicit use of language, even in simple visual search tasks, it seems likely that the transition may be driven by colour term learning. The next experiment investigated this hypothesis.

The following experiment

Children know that a set of terms refer to ‘colour’, and can select colour as a property on which to match objects as early as two years of age (Soja, 1994), and they can classify red as a colour before they apply it correctly (Sandhoffer & Smith, 1999). It is estimated that by two years of age children acquire a minimum colour vocabulary (Shatz, Behrend, Gelman & Ebeling 1996; Andrick & Tager-Flusberg, 1986), and at the age of three can identify colour as a feature and use it in an identity match (Kowalski & Zimiles, 2006). Children know the
words for primary colours such as blue, green, red and yellow, but also for secondary colours such as purple, orange, and pink, by roughly three years and three months, however, colour terms for brown and grey come roughly nine months later (Pitchford & Mullen, 2002).

The following experiment examined whether the lateralisation of CP varies with knowledge of colour terms. Competent use of colour terms is shown by success in colour naming and colour comprehension. In colour naming, a colour is shown and the child is asked to name it; this indicates whether children can map a colour term onto a colour. In a comprehension task, the child is asked to point to an instance of a given term in an array of differing colours; this indicates whether children can map a colour onto a colour term. Studies of colour term knowledge typically use both naming and comprehension measures (e.g., Bartlett, 1978; Andrick & Tager-Flusberg, 1986; Shatz et al., 1996; Brasby & Dockrell, 1999; Pitchford & Mullen, 2002), and both were used here.

CP was tested across the blue-green boundary, thus, correct use of blue and green terms was assessed. Competence was assessed by naming and comprehension test for the colours used in the target detection task, plus the best exemplars of blue and green. In addition, to check that the use of these terms was not over-extended to include non-blues or greens, they were also tested with the best examples of the other basic chromatic categories: yellow, red, pink, orange, purple and brown. As competence in using blue and green is achieved at about 37-months (Pitchford and Mullen, 2002), children in the age range of 2-5 years were tested.

It was expected that there would be a sub-sample of toddlers, who were still learning these terms (learners), and a sub-sample of toddlers, who used both terms competently (namers). Thus, toddlers were divided into two groups on the basis of their naming and comprehension ability. Lateralisation of CP as indicated by the target detection task was compared in these sub-samples. The same method was used as in the previous experiment, and the main performance measure was eye-movement latency to the target.

CP would be shown if eye-movement latencies were faster for between-category target-background pairs than for within-category pairs in the target detection task. Laterality effects in CP would be present if a larger CP effect for one of the visual fields were present. If the LH bias in colour CP in adults is language driven, the two groups of toddlers should show an opposite pattern of results: RH CP for learners (toddlers who do not have explicit knowledge
of colour terms), and LH CP for namers (toddlers who have explicit knowledge of colour terms). This pattern of results would suggest that the effect of language is strong enough to overcome an initial right hemisphere bias.

Main research question

• Does the pattern of lateralisation of CP differ between children who are learning colour terms and those that know colour terms?

3.4.2. Method

Participants

Fifty toddlers took part in the study. Prior consent was obtained from their parents or guardians. Of these, 13 toddlers were not included in the final analysis because accurate calibration was not achieved (six toddlers), or not enough trials were completed for one or more of the conditions (six toddlers), and one toddler did not complete the naming and comprehension tasks. The mean age of the final sample was 39.08 months [SD = 9.12] and there were 24 females and 13 males.

3.4.2.1. Target detection experiment

Stimuli, Design and Procedure

The stimuli, design, apparatus and procedure were the same as for the infants in Experiment 4 except the target-background separation was five rather than ten Munsell hue units. Figure 3.6 shows the three stimuli used in the task, and table 3.3 shows the CIE Y, x, y chromaticity co-ordinates of the three experimental stimuli: 5BG, 1OBG, and 10G. The sequence of events in the experimental trials was the same as in Experiment 4.

---

9 Refer also to Figure 3.2 for the sequence of events in the experimental trials.
between-category  within-category

10BG  5BG  10G
Blue region  Green region

Figure 3.6. Munsell Hues (Value 6, Chroma 8) of the experimental stimuli. The target-background separation was five Munsell hue steps.

Table 3 3. CIE (1931), Y, x, y chromaticity co-ordinates of the experimental stimuli. White point of monitor as measured on screen: Y=64.80 cd/m^2. The stimuli emulated a reflectance of 30.05.

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Y (cd/m^2)</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>5BG6/8</td>
<td>19.47</td>
<td>0.224</td>
<td>0.331</td>
</tr>
<tr>
<td>10G6/8</td>
<td>19.47</td>
<td>0.242</td>
<td>0.368</td>
</tr>
<tr>
<td>10BG6/8</td>
<td>19.47</td>
<td>0.212</td>
<td>0.295</td>
</tr>
</tbody>
</table>

3.4.2.2. Colour naming and comprehension tests

The tests of colour term competence took place after the target detection task. Toddlers’ ability to comprehend and name the three experimental stimuli and the best exemplar (focals) was assessed using a Power Point Presentation. The naming tasks were made into a game where toddlers had to name the colour of a cartoon rabbit’s balloon. The comprehension tasks were made into a game where toddlers had to point to the cartoon rabbit that was holding the balloon of a certain colour.

Stimuli

Stimuli were displayed on a calibrated Sony Trinitron CRT monitor (model GDM-F520) and were clear examples of each of the eight chromatic basic colours (red, blue, green, yellow, purple, pink, orange and brown (See Table 3.4 for the CIE Y, x, y chromaticity co-ordinates
of the stimuli). The shape of the stimuli was oval (4 cm width and 6.5 cm long) viewed at a typical distance of 50 cm. The background of the screen was set to grey.

Table 3.4. CIE (1931), Y, x, y chromaticity co-ordinates of the eight focal stimuli and the background.

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Y (cd/m²)</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>9.86</td>
<td>0.556</td>
<td>0.309</td>
</tr>
<tr>
<td>Yellow</td>
<td>48.54</td>
<td>0.464</td>
<td>0.435</td>
</tr>
<tr>
<td>Green</td>
<td>16.24</td>
<td>0.294</td>
<td>0.575</td>
</tr>
<tr>
<td>Blue</td>
<td>9.86</td>
<td>0.202</td>
<td>0.228</td>
</tr>
<tr>
<td>Pink</td>
<td>48.54</td>
<td>0.374</td>
<td>0.325</td>
</tr>
<tr>
<td>Purple</td>
<td>5.38</td>
<td>0.277</td>
<td>0.171</td>
</tr>
<tr>
<td>Orange</td>
<td>35.37</td>
<td>0.525</td>
<td>0.417</td>
</tr>
<tr>
<td>Brown</td>
<td>5.38</td>
<td>0.497</td>
<td>0.391</td>
</tr>
<tr>
<td>Background</td>
<td>19.47</td>
<td>0.336</td>
<td>0.344</td>
</tr>
</tbody>
</table>

Procedure

The experiment was conducted in a dark room. Each child was sat on a chair facing the monitor at a distance of approximately 50 cm to enable the child to touch the screen easily. Comprehension tasks were made into a game about pointing to coloured balloons on a screen (grey background). Naming tasks were made into a game about naming balloons of a certain colour that a cartoon rabbit was holding. First, the naming of the three colours used in the target detection task was assessed. As can be seen in Figure 3.7a, three coloured balloons (B1-10BG6/8, G1-5BG6/8, G2-10G6/8) were shown on a grey background. Toddlers were told the colour name (G1-green, G2-green, B1-blue) and asked to point at the appropriate balloon. For example the child was asked, “Can you show me the blue balloon?” The stimulus remained on the screen until the child had made a response. Then the comprehension of the experimental stimuli was assessed. Figure 3.7b shows the display: all three balloons appeared with the rabbit next to one of the balloons, and toddlers were asked to name the colour of the balloon. This was done for all (B1, G1, and G2) colours. For example, the child was asked, “Can you tell me the colour of the balloon that the rabbit is
holding?". Again, the stimuli remained on the screen until the child had made a response. There were three trials.

Figure 3.7. Schematic illustration of stimulus displays to assess the naming and comprehension of the experimental stimuli. a) To test for colour comprehension each child was told the colour, and asked to point at the appropriate balloon. b) To test for colour naming the child was asked to name the colour of the balloon that the rabbit was holding.

The same procedure was followed to assess the naming and comprehension of the eight focal terms. All focal colours (purple, blue, green, orange, yellow, pink, brown, and red) filling the balloons appeared on the screen (Figure 3.8a), and the toddlers were asked to point at relevant colours on the screen following the same procedure as for the experimental stimuli. Then, they were asked to name each of the colours corresponding to the balloon that the rabbit was holding each time (see Figure 3.8b). There were 8 trials. Each child completed both the naming and comprehension tasks in approximately 10 min\textsuperscript{10}.

\textsuperscript{10} See Appendix C for detailed responses on both naming and comprehension tasks
Figure 3.8. Schematic illustration of stimulus displays to assess the comprehension and naming of the eight chromatic focal colours. a) To test for colour comprehension each child was told each colour, and then asked to point at the appropriate balloon. b) To test for colour naming the child was asked to name the colour of the balloon that the rabbit was holding.

Results

Naming and comprehension

For each child, the number of blue and green experimental stimuli and the blue and green focal stimuli that were correctly named and identified were entered as variables into a principal components analysis. Other focals were not included in this analysis, because the toddlers were tested on the blue-green boundary, and thus competence at using blue and green was the main concern. The analysis revealed a single common factor that explained 70.2% of the variance, to which all variables contributed. Table 3.5 shows the factor loadings. Figure 3.9 shows the distribution of factor scores, and as can be seen there seem to be two separate groups of toddlers, those with negative or marginally positive scores (N = 19), and those with positive scores (N = 18), corresponding to a median-split.

12 Principal component analysis on all the measures gave effectively the same factor loadings.
Table 3.5. Factor loadings derived from the principal component analysis.

<table>
<thead>
<tr>
<th>Factor Loadings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naming experimental stimuli</td>
</tr>
<tr>
<td>Identifying experimental stimuli</td>
</tr>
<tr>
<td>Naming blue and green focals</td>
</tr>
<tr>
<td>Identifying blue and green focals</td>
</tr>
</tbody>
</table>

Figure 3.9. Distribution of factor scores.

Those with low naming scores consisted of eight males and eleven females, and the group with large positive scores consisted of five males and thirteen females. Table 3.6 shows mean accuracy scores for the two groups of toddlers for the naming and comprehension tasks for the four measures, as well as the accuracy scores for naming and identifying the other six focal stimuli. As can be seen in Table 3.6, the higher scoring group were very accurate at naming and identifying the blue and green experimental stimuli; only two toddlers made any mistakes. They were also completely accurate in naming and identifying the blue and green
focal stimuli, never used blue and green to name the other focal stimuli, and did not point to 
blue and green focals inappropriately. They also had largely accurate naming and 
comprehension of focals for other colour categories. These toddlers were classified as 
‘namers’, as they showed a basic competence in usage of the terms blue and green. Toddlers 
with negative or minimal scores made many mistakes when naming and identifying the blue 
and green focals, and the blue and green experimental stimuli. They also did not name and 
identify other focal colours appropriately. These toddlers were therefore classified as 
‘learners’, as they were still learning how to understand and apply blue and green 
appropriately. The mean age of the ‘learners’ was 32-months (SD = 7.5), and the mean age of 
the ‘namers’ was 46-months (SD = 3.8).

Table 3.6. Number of correct responses for the naming and comprehension tasks for 
experimental stimuli and focal blue and green, for toddlers with positive or negative (or 
minimal) factor scores.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Positive scores</th>
<th>Negative scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naming experimental blue and green (max=3)</td>
<td>2.89 (0.32)</td>
<td>0.58 (0.77)</td>
</tr>
<tr>
<td>Identifying experimental blue and green (max=3)</td>
<td>2.89 (0.32)</td>
<td>1.47 (0.96)</td>
</tr>
<tr>
<td>Naming blue and green focals (max=2)</td>
<td>2.00 (0.00)</td>
<td>0.84 (0.60)</td>
</tr>
<tr>
<td>Identifying blue and green focals (max=2)</td>
<td>2.00 (0.00)</td>
<td>1.37 (0.68)</td>
</tr>
<tr>
<td>Naming other focal stimuli (max=6)</td>
<td>5.72 (0.57)</td>
<td>3.58 (1.46)</td>
</tr>
<tr>
<td>Identifying other focal stimuli (max=6)</td>
<td>5.89 (0.47)</td>
<td>2.95 (1.27)</td>
</tr>
</tbody>
</table>

Target Detection Task

Trials were excluded if the eye-movement signal was lost [mean = 4.49 trials, SD = 3.37], if 
multiple eye-movements were made before the eye-movement to the target [mean = 2.84 
trials, SD = 2.36], if the target was not fixated at all [mean = 0.73 trials, SD = 1.17], or if the 
toddlers were not fixating the attention-getter before the test-display appeared [mean = 2.81 
trials, SD = 3.03]. This left on average 21 trials per toddler [SD = 5.11] and all toddlers had 
at least two trials per. Analysis of accuracy showed that there were no significant effects of
visual field, group and category on error rates (maximum $F (1, 35) = 3.11, p = .09, \eta^2 = .08$).

The time taken to initiate an eye-movement to the target was calculated in the same way as for the adults. Median latencies for each combination of visual field (LVF/RVF) and category (within- or between-category) were calculated for each child, and the means across subjects are show in Figure 3.9 for the namers and learners.

From Figure 3.10, it appears that there is an overall category effect (between category = 439 ms; within-category = 536 ms); but most strikingly, for the learners, the category effect is clearly larger in the LVF than in the RVF (~215 ms ~25 ms respectively), whereas for the namers, the category effect is marginally larger in the RVF (~75 ms) than in the LVF (~43 ms).

**Figure 3.10.** Means of median eye-movement latencies for the groups in the two visual fields for each category. Error bars represent 95% within-subject confidence intervals calculated by using the error term from the three-way interaction. Between-subjects 95% CL calculated by using the between groups error term is shown as the separate error bar.
A mixed three-way ANOVA with category (within/between), visual field (LVF/RVF) and group (learners/namers) revealed that responses were faster for between-category targets than for within-category targets \([F (1, 35) = 12.56, p < .002, \eta^2 = .26]\), and there was no effect of visual field \([F (1, 35) = 0.74, p = .39, \eta^2 = .02]\) or group \([F (1, 35) = 0.85, p = .36, \eta^2 = .24]\). None of the two-way interactions were significant (maximum \([F (1, 35) = 1.93, p = .17, \eta^2 = .05]\)). However, the three-way interaction between category, visual field and group was significant \([F (1, 35) = 4.33, p < .05, \eta^2 = .11]\). Separate analyses for the two groups were conducted to investigate this further.

For the learners, latencies were about 35 ms faster for between-category trials (437 ms) than within-category trials (572 ms; \([F (1, 18) = 9.21, p < .02, \eta^2 = .34]\)), but there was no effect of visual field \([F (1, 18) = 0.75, p = .39, \eta^2 = .04]\). In addition, the interaction between visual field and category was significant \([F (1, 18) = 5.31, p < .05, \eta^2 = .23]\). As can be seen in Figure 3.10, the interaction reflects a strong LVF category effect of about 215 ms \((t (18) = 3.14, p < .02)\), but for the RVF, although the means showed an advantage of between-category over within-category of about 50 ms, this was not significant \((t (18) = 1.27, p = 0.22)\).

For the namers, the category effect approached significance: latencies were ~ 500 ms for within-category trials and ~ 441 ms for between-category trials \([F (1, 17) = 3.64, p = .07, \eta^2 = .18]\), but there was no effect of visual field \([F (1, 17) = 14, p = .71, \eta^2 = .01]\), nor was the interaction significant \([F (1, 17) = .27, p = .61, \eta^2 = .02]\). Thus, unlike the learners, the size of the category effect did not differ significantly across visual fields. However, as Figure 3.10 shows, it is important to note that there is a tendency for the category effect to be larger in the RVF (~ 75 ms) than in the LVF (~ 43 ms) – the reverse pattern to the learners: the category effect was significant in the RVF \((t (17) = 2.96, p < .02)\), but not in the LVF \((t (17) = 0.78, p = 0.45)\).

Namers were on average older than the learners, thus, the observed pattern of lateralisation of category effects for the two groups could be due to age rather than colour term knowledge. To assess this, age was included as a covariate in the above ANOVA. Figure 3.11 shows the predicted mean latencies derived from the ANCOVA. It appears that the overall pattern is broadly the same as in Figure 3.7, but if anything, the contrast between the two groups is
even more marked. Now, for the learners, the LVF category effect is about 300 ms compared to about 10 ms in the RVF; for the namers, in the LVF, within-category responses are now faster than between-category responses, while the reverse obtains for the RVF, emphasising the different patterns for the two groups. The ANCOVA supported these impressions with a clearly significant three-way interaction \[F(1, 34) = 12.24, p < .002, \eta^2 = .26\].

**Figure 3.11.** Predicted means of median eye-movement latencies for learners and namers for each combination of category and visual field. Error bars represent 95% within-subject confidence intervals calculated by using the error term from the three-way interaction. Between-subjects 95% CL calculated by using the between groups error term is shown as the separate error bar.

Finally, a follow up ANOVA on the predicted scores showed that the interaction between field and category for learners was strongly significant \[F(1, 18) = 23.09, p < .01, \eta^2 = .56\], and for namers was marginally significant \[F(1, 17) = 5.86, p = .09, \eta^2 = .15\].
3.4.3. Discussion

Toddlers’ eye-movements showed an overall category effect, with faster between- than within-category target fixation; however, there was no overall visual field effect: eye-movement latencies did not differ significantly for LVF and RVF targets. More importantly, while the category effect was much stronger in the LVF than in the RVF for toddlers still learning colour terms, this asymmetry was not present for those toddlers who were competent at using colour terms. If anything, there was a suggestion that the asymmetry had reversed, as the category effect was significant for the RVF but not the LVF for the namers. It therefore appears that, for toddlers who are in the process of learning colour terms, CP is lateralised to the LVF, as with infants. However, the RH bias is lost when toddlers have explicit knowledge of colour terms: instead, they show a trend for LH advantage for colour categorisation.

Franklin, Clifford et al. (2005) found that the extent of the category effect was not affected by linguistic categorisation and did not increase with increased knowledge of colour terms. However, Franklin et al. did not assess whether CP was lateralised. The findings of the current experiments suggest that language may play a role in early development of colour CP after all – not in the extent of CP but in the way in which CP is lateralised. Consistent with language learning inducing a shift from RH to LH CP, CP is lateralised to the RH before colour terms are learned, whereas there is significant colour CP in the LH after colour terms are learned.

3.4.4. General Discussion of Experiments 4, 5 and 6

Experiment 4 investigated laterality effects in adults using eye-movement latencies as the index of discriminability. The results replicated previous findings: CP was found only when the target was presented to the right visual field for adults. Using the same measure as in Experiment 4, in Experiment 5 laterality effects were investigated in 4-6 month old infants. Infants were faster overall at initiating eye-movements on between-category trials than on within-category trials, but this category effect was only significant in the LVF than in the RVF. Experiment 6 tested laterality effects in toddlers and found toddlers who were in the process of learning colour terms showed a much stronger category effect in the LVF than in
the RVF, but there was no such bias for toddlers who had acquired colour terms. Those toddlers showed a trend for a greater LH category effect, with only a significant category effect in the LH.

It appears from the findings that a RH to LH switch in lateralisation of colour CP occurs with acquisition of the relevant colour terms. Children who had learnt the terms for blue and green were generally (although not always) older than those who were still learning the terms. One possibility is that these changes are related to chronological age rather than colour term knowledge. However, when age was considered as a covariate in the analysis, the pattern of lateralisation of CP for the two groups of toddlers did not change. It is also important to note that many important anatomico-functional changes, such as the development of a functional corpus callosum and inter-hemispheric co-ordination, have already occurred by 2 years (Liégeois et al., 2000).

Toddlers showed CP irrespective of their colour term competence colour and the extent of blue-green CP did not differ between the ‘learners’ and the ‘namers’. This supports the findings of Franklin, Cliford et al. (2005), who found that the extent of colour CP in toddlers was not affected by then degree of colour term knowledge. The crucial difference between learners and namers was in the pattern of lateralisation of CP. One possibility is that LH CP starts to develop as colour terms are acquired at around 2-5 years (Bornstein, 1985), but, that it does not reach the adult form until later in childhood, as access to lexical colour codes becomes more automatic.

Comparing the infants’, toddlers’ and adults’ performance on the same perceptual task aids interpretation of the developmental changes. It is highly unlikely that the RH advantage for colour CP found in infants and toddlers, who do not know colour terms, and the reverse pattern, a LH advantage in adults, suggest that CP is strictly perceptual or strictly language shaped. The findings are not necessarily contradictory. Perhaps the best explanation of colour CP needs to combine both influences. It seems that there is a predisposition for CP in infants in the absence of language, and it is mainly represented in the RH. On the other hand, there is a trend towards a LH advantage with the acquisition of colour terms although, the switch over has not yet reached adult level.
In summary, a shift of the locus from the right hemisphere to the left hemisphere suggests that language changes the functional organisation of colour CP in the brain. Finally, it is important to examine whether the RH bias in infancy, and the changes in lateralisation of colour CP around the time of colour term acquisition, also apply to colour category boundaries other than the blue-green boundary.
Chapter 4

Cross-cultural differences in lateralisation of colour CP: Examining the Greek blé-γαλάζjo boundary

4.1. Introduction

Experiment 4 replicated the findings of Chapter 2, showing a LH advantage for colour categorical perception in adults measured with eye-movement latencies instead of reaction times. Interestingly, Experiment 5 showed the opposite pattern; strong lateralisation of CP was found for infants also, but it was lateralised to the RH. Experiment 6 showed a shift of the locus of colour CP from the right hemisphere to the left hemisphere. One explanation put forward in the discussion of findings from the experiments in Chapters 2 and 3 is that the LH bias for colour CP may reflect language influences. In this chapter, possible linguistic influences on the lateralisation of CP were explored by comparing two groups whose languages differ in their category structure. Greek marks a boundary in the blue region (blé-γαλάζjo) that English does not, and English and Greek speakers were tested for lateralised CP across the Greek boundary.

Cross-cultural studies and colour CP

The comparison of colours may be within-category for one language, but cross a category boundary in another language. For instance, Russian speakers make an obligatory distinction between goluboj ‘dark blue’ and sinyj ‘light blue’ (Moss, Davies, Corbett & Laws, 1990), whereas these both fall in the blue category for English speakers. Similarly, Greek speakers divide the English blue category into γαλάζjo [γαλάζjo] ‘light blue’ and μπλε [blé] ‘dark blue’ (Androulaki, Gómez-Pestaña, Mitsakis, Lillo, Coventry & Davies, 2006). Additionally, English speakers have a single term for green, but Korean speakers divide this region with two terms, yeondu ‘yellow–green’ and chorok ‘green’ (Kim, Pak & Lee, 2001; Pak, Kim, Kim & Lee, 2004).

According to the linguistic relativity hypothesis, the language we speak influences the way we think and perceive the world around us. The differences in how languages segment the colour continuum offer the possibility of seeing whether the extent of colour CP covaries
with the position of linguistic boundaries, as the linguistic relativity hypothesis predicts. Consistent with relativism, in adults, CP is only found around boundaries that are marked by the respondent's language. For instance, neither Tarahumara (from Mexico), or Berinmo (from Papua New Guinea), nor Otjihimba (from Namibia), mark the blue-green boundary and adult speakers of these languages do not show blue-green CP, whereas speakers of English do (Kay & Kempton, 1984; Roberson et al., 2000, 2005).

However, as outlined in section 1.4.1, the tasks typically used to assess CP, such as triadic judgements (Kay & Kempton, 1984) and successive X-AB tasks (Roberson et al., 2005) do not isolate perceptual processes. Therefore, the observed behavioural effects could arise from cross-language differences in perception, but, they could also reflect memory processes or direct language effects such as labelling. To try to determine the location of categorical responding more precisely, recent cross-cultural research has used tasks that purport to rely exclusively on perceptual comparisons. For instance, Winawer et al. (2007) tested English and Russian speakers using a simultaneous matching-to-sample task. Three stimuli were displayed, a target and two test stimuli. One of the test stimuli was identical to the target and the other one (the foil) was different. They compared English and Russian speakers using stimuli that straddled the goluboj-sinyj boundary. For the Russians, the foil was either physically different to the target, but from the same category (e.g., goluboj-goluboj), or it was physically and categorically different (goluboj-sinyj). For English speakers the foil was physically different to the target, but always from the same category, namely blue. Russian speakers responded faster when the foil was categorically different to the target than when it was just physically different, whereas there was no difference for English speakers. Winawer et al. (p. 7783) note that ‘These results demonstrate that categories in language can affect performance of basic perceptual colour discrimination’. However, overall reaction times for both English (1110 ms) and Russian speakers (826 ms) were slow enough to allow time to access verbal codes; thus, the attempt to isolate perceptual processes was undermined.

Roberson et al. (2008) used a visual search task, on the assumption that this would not be vulnerable to labelling or memory processes, and sought to test whether the expected CP for Koreans was lateralised to the LH (cf. Gilbert et al., 2006). They compared Korean speakers
and English speakers assessing CP across the yeondu-chorok ('yellow-green' 'green') boundary. The task was to detect a target among distractors, and for the Koreans, it could belong to the same category as the distractors (e.g., yeondul among yeondu2), or to a different category (yeondul among chorok1). Consistent with categorical perception, between-category target detection was faster than within-category detection, but only for the Korean speakers. Roberson et al. did not find laterality effects. However, when the Korean group was separated into 'fast responders' and 'slow responders', CP was stronger in the LH than the RH for the fast responders. They attributed the lack of lateralisation in the slow group to there being sufficient time for information about LVF targets to cross the corpus callosum and access the language centres, resulting in CP for LVF targets.

There are two curious aspects of these results and their interpretation. First, response times for the Korean speakers were very slow, (~1000 ms on average) compared to ~450 ms for Gilbert et al.'s (2006). As with Winawer et al., this potentially undermines the purpose of using the visual search task. For example, this might have been long enough to access to the target name after pre-attentive processes had detected the target. Second, even the Korean fast responders were about 300 ms slower than Gilbert et al.'s (~450 ms and ~750 ms); it might have been expected that this additional 300 ms would have provided sufficient time for the conjectured trans-callosal transmission (Brizzolara et al., 1994), and CP should have been present for both visual fields. Subjects may also have had sufficient time to attend to the signalled target location and access the target name in time for this information to influence RTs. Thus, it is not possible to rule out labelling as the source of the observed category effect.

The following experiments

This chapter consists of a preliminary naming experiment that established where the blé-yalázjo boundary was (8a). This is followed by an experiment (8b) that established that Greek speakers showed blé-yalázjo CP, and that it was lateralised to the LH. For convenience, this was conducted using a laptop display. The following experiment (Experiment 9) compared Greek and English speakers to check that English speakers did not show CP, and to test whether the use of the laptop might have artefactually contributed to the lateralised CP found in Experiment 8b. Accordingly, Experiment 9 was run using a
conventional CRT display. Finally, the performance of Greek speakers from Experiments 8b and 9 were compared to assess whether the differences in display devices could have affected performance. The comparison is potentially important, as if it could be established that the two systems can give equivalent results, it would suggest that with due care, laptops could be used for field work where it was not possible to access CRT monitors.

The Greek blé-yalázjо boundary was examined using the usual logic of the target detection task (cf. also Roberson et al. 2008 as outlined above). Pilot work showed that detection times by Greek speakers were of the same order as those reported in Chapter 2 for English speakers and those reported by Gilbert et al. Thus, it was expected that performance on the task would rely essentially on perceptual processes, avoiding the pitfalls described above in Winawer et al.'s and Roberson et al.'s work. For Greek speakers, the target and distractors could either be in the same category (e.g., blé1-blé2 – ‘dark blue1’–‘dark blue2’) or they could be from different categories (blé1-yalázjol – ‘dark blue1’ ‘light blue1’). For English speakers, target and distractors were all instances of blue. Provided CP occurs across this relatively uncommon boundary, then Greek speakers should be faster to detect targets that are categorically different to the background than targets in the same category as the background, whereas there should be no category effect for English speakers. In addition, with the same proviso about the uncommon category boundary, CP should be lateralised to the RVF for the Greek speakers.

Summary of main research questions

1. Do Greek speakers show CP for the blé-yalázjо boundary? If they do, is CP lateralised to the LH?
2. Is CP present for a non-marked boundary? If it is, is CP lateralised to the LH?
4.2. Experiment 8a. Establishing the blé-yalázjo boundary

Androulaki et al. (2006) reported that the Greek language has twelve BCTs, including two terms for blue. Greek speakers make an obligatory distinction between blé to describe dark blue and yalázjo to describe light blue. In their naming studies, the authors measured basicness of colour terms including frequency, consistency and consensus of use, naming time and ‘necessity’. The two colours fall in the blue region for English speakers. Androulaki et al. found that the blé and yalázjo colour regions have a fuzzy boundary around L* = 50 and L* = 60. A preliminary naming study was conducted to establish the linguistic blé-yalázjo boundary.

Method

Participants

Twenty native Greek speakers, 12 females and 8 males (Mean Age = 27.5 years, SD = 3.65) were tested. They were all right handed, had normal or corrected-to-normal vision and showed no colour deficiencies as tested with the City University colour vision test (Fletcher, 1980). All participants were educated at University level and spoke English as a second language taught at school.

Stimuli, Design and Results

The stimuli were displayed on a LCD 270 mm x 200 mm monitor. The CIE x, y, Y coordinates of the white point were 0.35, 0.37, 80.60 cd/m². Twenty-nine stimuli were chosen to establish the blé-yalázjo boundary, with four presentations of each of the stimuli in 116 randomly ordered trials. The decision time was not limited. The participants were asked to name each stimulus presented as a square stimulus (50 mm²) centrally on a monitor on a grey background with a viewing distance of 50 cm. Greek participants were required to classify each stimulus by using one basic colour term blé or yalázjo. The Commission Internationale de l’Eclairage (CIE) L*u*v* coordinates ranged from 46.46, -20.27, -96.62 to 67.3, -26.55, -70.12 (See Appendix D). The stimuli differed primarily in luminance. Figure

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12 The CIE (Committee International de l’Eclairage) has various systems for describing colour. For the L*u*v* space, L*u*v* are the axes of the colour space, where L* is lightness, u* is a red–green axis, and v* is a blue–green axis. Equal distances (ΔE) are intended to correspond with equal perceptual distances (see Hunt, 1987, for further information). See also Appendix A for information about the CIE colour space.
4.1 shows the percentage of blé responses to the stimuli. It can be seen that the switch from predominantly blé to predominantly yalázo responses occurs somewhere between stimuli with $L^* = 53$ and $L^* = 56^{13}$.

Figure 4.1. Percentage of stimuli labelled blé.

4.3. Experiment 8b: Target detection task

4.3.1. Method

Participants

Sixteen Greek native speakers took part in the experiment. There were five males and twelve females (Mean Age = 28 years, SD = 2.42). They were all educated at University level and were taught English as a second language in high school.

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A preliminary study looked at whether English speakers would use different colour terms to describe the colours tested for the Greek blé-yalázo boundary. All were asked 'What do you call this colour?'. The naming data showed that English speakers labelled all stimuli blue.
Stimuli and Design

The stimuli were displayed on an Acer (TravelMate 240) LCD 270 mm x 200 mm monitor. The CIE x, y, Y coordinates of the white point were 0.35, 0.37, 80.60 cd/m². Four stimuli were chosen for the experimental task so that half of the stimuli fell in the ble category and the other half in the yalázjo category. Separations of 4.20 ΔE* CIE were used between the four stimuli in both within- and between-category pairs. As can be seen in Figure 4.2, three pairs were used for the experiment: two within category (B1-B2, G1-G2) and one between-category pair (B2-G1). Table 4.1 shows CIE (Y, x, y) co-ordinates of the stimuli.

<table>
<thead>
<tr>
<th>L*</th>
<th>u*</th>
<th>v*</th>
<th>B1</th>
<th>B2</th>
<th>G1</th>
<th>G2</th>
</tr>
</thead>
<tbody>
<tr>
<td>49.62</td>
<td>-18</td>
<td>-76.15</td>
<td>53.12</td>
<td>-20.76</td>
<td>-74.89</td>
<td>56.62</td>
</tr>
</tbody>
</table>

Figure 4.2. The co-ordinates of the stimuli in the ble-yalázjo boundary in CIE (L*u*v*) Space. Dashed line represents the boundary between the ble side and the yalázjo side.

14 Small separations were used between the stimuli as luminance differences are detected more quickly than chromatic differences. For instance, time to initiate a saccade to a target is faster for a luminance defined target than a chromatic target [see Satgunam & Fogt (2005) for further details].
Table 4.1. CIE (1931) Y, x, y chromaticity co-ordinates of the stimuli in the blé and yalázjo sides.

<table>
<thead>
<tr>
<th>Colours</th>
<th>B1</th>
<th>B2</th>
<th>Г1</th>
<th>Г2</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>0.205</td>
<td>0.208</td>
<td>0.211</td>
<td>0.214</td>
</tr>
<tr>
<td>y</td>
<td>0.182</td>
<td>0.191</td>
<td>0.199</td>
<td>0.207</td>
</tr>
<tr>
<td>Y (cd/m²)</td>
<td>14.50</td>
<td>17.05</td>
<td>19.79</td>
<td>22.78</td>
</tr>
</tbody>
</table>

Procedure

Procedure was the same as in Experiment 1 with the exception that there were 96 experimental trials made up from 32 trials for each of the three pairs. At the end of the experiment, all Greek participants performed the naming study to confirm their linguistic blé- yalázjo boundary.

Results

The data of four Greek participants were not included, as their linguistic blé- yalázjo boundary did not match the established boundary from the naming study. About 3% of trials of data were not included because of erroneous responses. Error rates were similar for between- and within-category trials, and LVF and RVF trials (maximum [F (1, 15) = 4.02, p = .06, η² = .21]. Median RTs for correct trials were calculated for each combination of category (within/between), visual field (LVF/RVF) for each participant. As can be seen in Figure 4.3, it appears that, the target was detected faster for between-category trials than for within-category trials. Between-category search was 422 ms, whereas within-category search was about 439 ms. Reaction times in the two visual fields seem to be similar, 429 ms in the RVF and 432 ms in the LVF. The category effect seems to be larger in the RVF than in the LVF.

A two-way ANOVA with category (within/between) and visual field (LVF/RVF) showed that between-category search was about 13 ms faster than within-category search [F (1, 15) = 17.22, p < .002, η² = .53]. Visual field was not significant [F (1, 15) = 0.49, p = .49, η² =
RT for within-category targets in the LVF and RVF were similar \( t(15) = 0.75, p = .47 \). The interaction between visual field and category was significant \( F(1, 15) = 8.49, p < .02, \eta^2 = .03 \). As can be seen in Figure 4.3, the category effect is present in both the LVF \( t(15) = 2.21, p < .05 \), and in the RVF \( t(15) = 4.68, p < .001 \). However, as Figure 4.3 shows, the size of the category effect (between- faster than within-) averaged 12 ms greater for the RVF than for the LVF \( t(15) = 2.91, p < .05 \).

**Figure 4.3.** Mean target detection RTs for within- and between-category trials in the LVF and in the RVF. Error bars represent 95% within-subject confidence intervals calculated by using the error term from the two way interaction.

### 4.3.2. Discussion

The results of Experiment 8b indicate that Greek speakers show a clear CP effect across the ble-yalázjo boundary. Target detection times were significantly faster at the ble-yalázjo boundary than at either of the within-category locations. In addition, the CP effect was observed in both the right and the left visual field however, the size of the category effect was larger for the right visual field than the left visual field. The results are in line with the LH bias in adult colour CP found in previous research (Gilbert et al., 2006) and in chapters 2
and 3, and extend the finding to another category boundary, which is defined mainly in lightness change.

4.4. Experiment 9: Greek and English on CRT screen

4.4.1. Introduction

Experiment 8b found that Greek speakers showed CP for the ble- yalázie boundary and this was lateralised to the LH. However, there is a possible technical problem with the findings. The stimuli were displayed on an LCD monitor. Displays on a CRT monitor (cathode-ray-tube) can be viewed from almost any angle, but with an LCD monitor (liquid-crystal-display) this is often a problem as the appearance changes with angle of view. The subjects were instructed to fixate the middle of the screen and not move their heads, but it is possible that some head movements may have occurred. Most psychophysical studies rely on CRT monitors avoiding the use of LCD monitors. The LCD’s display characteristics have not yet been assessed for psychophysical purposes (Elze, Lochman & Tanner, 2007), and for requirements of vision research (Elze, Tanner, Lochmann, & Becker, 2007). The following experiment compared English and Greek speakers on a CRT screen to assess whether the differences in display devices could have affected performance. This is potentially important, as if it could be established that the results were independent of display mode, it would suggest that, laptops could be used (with due care) for fieldwork if there is no possibility of using a CRT screen. Moreover, the inclusion of the English speaking group provides a test of the assumption that the Greek speakers’ CP is related to the boundary marked in Greek but not in English.

4.4.2. Method

Participants

There were 20 native Greek speakers (13 females and six males, Mean Age = 28 years, SD = 2.88) and 20 native English speakers (16 females and four males, Mean Age = 23 years, SD = 2.68). The Greek speakers were all educated at University level and were taught English as a second language in high school.
Stimuli, Design and Procedure

The stimuli were displayed on a Sony Trinitron monitor (model GDM-F520) monitor. The CIE x, y, Y coordinates of the white point were 0.31, 0.34, 68.92 cd/m². Table 4.2 shows the CIE x, y, Y coordinates of the stimuli. The stimuli, design and procedure were the same as in Experiment 8b.

Table 4.2. CIE (1931) Y, x, y chromaticity co-ordinates of the stimuli in the blé and γαλάζjo side.

<table>
<thead>
<tr>
<th>Colours</th>
<th>B1</th>
<th>B2</th>
<th>Γ1</th>
<th>Γ2</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>0.205</td>
<td>0.208</td>
<td>0.211</td>
<td>0.214</td>
</tr>
<tr>
<td>y</td>
<td>0.182</td>
<td>0.191</td>
<td>0.199</td>
<td>0.207</td>
</tr>
<tr>
<td>Y (cd/m²)</td>
<td>12.48</td>
<td>14.58</td>
<td>16.91</td>
<td>19.47</td>
</tr>
</tbody>
</table>

Results

Accuracy

The data of three Greek participants were not included as their blé-γαλάζjo boundary did not match the boundary established by the naming study. The remaining Greek participants made about 5% errors, and the English group made about 4% errors. The percentage of correct trials for each combination of category (within/between), visual field (LVF/RVF) and language (Greek/English) were calculated. Accuracy was similar for between- and within-category trials (95.91% and 95.69% respectively), and for visual field (LVF and RVF: 96.31% and 95.25% respectively). A category (within/between) x field (LVF/RVF) x language (Greek/English) mixed ANOVA showed that the only significant main effect was for language: English participants were more accurate than Greek speakers were \[F (1, 35) = 5.68, p < .05, \eta^2 = .14\]. The interaction between language and category was also significant \[F (1, 35) = 6.69, p < .05, \eta^2 = .16\]. Looking at the two groups separately, the effect of category was not significant for English speakers \[F (1, 19) = 2.15, p = .16, \eta^2 = .10\]. For Greek speakers category approached significance \[F (1, 16) = 4.45, p = .51, \eta^2 = .22\], but this
reflected better accuracy for within-category trials than between-category trials (see Figure 4.4). All other main effects and interactions were non-significant: maximum \[ F (1, 35) = 2.18, p = .15, \eta^2 = .60 \]. Importantly visual field did not interact with category \[ F (1, 35) = 1.11, p = .29, \eta^2 = .30 \]

![Figure 4.4](image)

**Figure 4.4.** Percentage of correct trials for Greek and English speakers in within- and between-category trials. Error bars represent 95% within-subject confidence intervals calculated by using the error term from the two way interaction.

**RT**

Mean RTs for correct trials were calculated for each combination of category (within/between), visual field (LVF/RVF) and language (Greek/English), for each participant. From Figure 4.5, it appears that between-category trials were faster than within-category trials (418 ms and 425 ms respectively). LVF presentations were about 425 ms, whereas RVF presentations were about 418 ms. Looking at the two groups separately, it appears that the Greeks show a clear category effect in the RVF but no such effect in the LVF (see Figure 4.5a). English speakers appear not to show a category effect in either visual field (within- between differences are just a few ms), nor is there any effect of visual field (see Figure 4.5b). However, the English group appear to be slightly faster overall than the Greek group.
A three-way mixed ANOVA showed a significant main effect for category with between-category RTs ~7 ms faster than within-category \[F (1, 35) = 5.42, p < .05, \eta^2 = .13\]. The main effect of visual field, and the two-way interactions between category and language and visual field and language were not significant, maximum \[F (1, 35) = 2.14, p = .15, \eta^2 = .06\]. However, there was a two-way interaction between category and field \[F (1, 35) = 4.58, p < .05, \eta^2 = .12\]. As Figure 4.6 shows, this reflects a category effect in the RVF \(t (36) = 2.39, p < .05\), but not in the LVF \(t (36) = 0.78, p = .44\).
Figure 4.6. Mean target detection RTs for within- and between-category trials in the left (LVF) or right visual field (RVF). Error bars represent 95% within-subject confidence intervals calculated by using the error term from the two-way interaction.

The three-way interaction between category, field and language was also significant \[F (1, 35) = 5.30, p < .05, \eta^2 = .13; \text{see Figure 4.5}\]. Separate analyses for the two language groups were conducted to investigate this further. For Greek speakers the category effect approached significance \[F (1, 16) = 3.31, p = .09, \eta^2 = .17\] and there was no effect of visual field \[F (1, 16) = 0.31, p = .59, \eta^2 = .02\]. The interaction between visual field and category was significant \[F (1, 16) = 4.99, p < .05, \eta^2 = .24\]. This reflects the fact that there was no category effect in the LVF \[t (16) = 0.26, p = .80\], but there was a category effect in the RVF with between-category trials being about 22 ms faster than within-category trials \[t (16) = 2.29, p < .05; \text{see Figure 4.5a}\].

Considering the English speakers, between-category search did not differ from within-category search \[F (1, 19) = 2.69, p = .12, \eta^2 = .12\]. The visual field effect approached significance \[F (1, 19) = 4.35, p = .051, \eta^2 = .19\], with RTs being faster in the RVF than in the LVF by ~ 7 ms. Most pertinent, the interaction between category and visual field was clearly not significant \[F (1, 19) = 0.05, p = .83, \eta^2 = .003; \text{see Figure 4.5b}\]. Thus, CP was stronger in the RVF than in the LVF for Greek speakers, whereas English speakers did not
show CP, and there was no suggestion that the relationship between within- and between-category RTs depended on visual field.

English speakers were on average more accurate than Greek speakers thus, the observed pattern of lateralisation of category effects for the two groups may be due to accuracy rather than colour term knowledge. To rule out accuracy as a confounding variable further analysis was carried out adding accuracy as a covariate to the above ANOVA. The analysis revealed that the pattern and significance of the three-way interaction was still present \( F(1, 34) = 10.51, p < .005, \eta^2 = .24 \). This shows that even when the variation in errors is statistically accounted for, the pattern of lateralisation for the two groups is preserved. Figure 4.7 shows the predicted mean latency times for Greek and for English speakers for each visual field and category when accuracy is added as a covariate.

**Figure 4.7.** Predicted Mean target detection RTs for within-and between-category backgrounds for target in the left (LVF) or right visual field (RVF) for Greek and English speakers. Error bars represent 95% within-subject confidence intervals calculated by using the error term from the three-way interaction. Between-subjects 95% CL calculated by using the between groups error term is shown as the separate error bar.
4.4.3. Discussion

Although there were some significant effects for accuracy, the differences were very small, and none involved visual field effects. The key point in the results was that Greek speakers showed CP, and it was stronger in the RVF than in the LVF. In contrast, English speakers neither showed CP, or any suggestion of a dependency between visual field, and for within and between-category conditions.

The pattern shown by the Greek speakers was essentially the same as that found with the LCD display in Experiment 8 (this is tested formally in the next section). Moreover, the pattern Greeks showed for the blé-yalázjo boundary is essentially the same as earlier findings in Chapters 2 and 3 and by Gilbert et al. (2006). As blé and yalázjo differ primarily in lightness, this shows that laterality effects can occur for either hue boundaries or lightness boundaries.

4.5. Comparison of data from CRT and LCD screens

A comparison of performance of Greek speakers on the two types of monitors was conducted to see whether the performance of the group that performed the target detection task on the LCD monitor, differed from the performance of the group that performed the target detection task on the CRT monitor. As can be seen from Figure 4.8, the data pattern for the two monitors looks remarkably similar both relatively and absolutely. The apparent lack of a monitor effect was confirmed by three-way ANOVA on monitor-type (LCD/CRT), category (within- between) and visual field (LVF/RVF), which showed there were no significant effects involving monitor-type (maximum, \(F(1, 31) = 0.395, p = .53, \eta^2 = .01\)). This suggests that for the target detection task at least, provided angle of view is controlled, LCDs can be reliable and accurate enough to use for data collection, and they could be used when there was no CRT monitor available in field studies.
Figure 4.8. Mean Reaction times for each combination of visual field and category for the two types of monitor. Error bars represent 95% within-subject confidence intervals calculated by using the error term from the three-way interaction. Between-subjects 95% CL calculated by using the between groups error term is shown as the separate error bar.

4.6. General Discussion of Experiments 8b and 9

The experiments presented compared performance of Greek and English speakers on the target detection task, using stimuli drawn from the \textit{blé-yalázjo} region of colour space. Several studies have suggested that colour categorisation arises from language influences (e.g., Kay & Kempton, 1984; Roberson & Davidoff, 2000; Winawer et al., 2008; Witthoft et al., 2003; Roberson et al., 2008). However, as discussed in the general introduction, the tasks that have shown differences in colour categorisation show a direct language effect on colour CP.

Greek speakers, who mark the \textit{blé-yalázjo} boundary, detected targets that were categorically different to the background faster than targets in the same category as the background. The category effect was lateralised to the LH, consistent with findings reported for the blue-purple and blue-green boundaries in adults in this thesis and with the findings of Gilbert et al.
(2006). The blé-yalážjo boundary is not marked in English, and the English group did not show a category effect.

The findings presented in this chapter suggest an indirect language influence on colour CP. The two distinct colour terms may have resulted in a warping of perceptual space, such that equally spaced blé and yalážjo stimuli closer to the blé-yalážjo category boundary are perceived as being different, whereas equally spaced blé stimuli in the blé colour region and equally spaced yalážjo stimuli in the yalážjo colour region are perceived as being similar.
Chapter 5
Induced colour CP and laterality effects

5.1. Introduction

So far, hemispheric asymmetries have been found for infants, toddlers, and adults. Prelinguistic infants and toddlers, who are in the process of acquiring colour terms, show a RH advantage for colour CP. In contrast, adults and toddlers who have acquired colour terms show a LH advantage for colour CP. The above findings suggest that the shift of colour CP from RH to LH may happen when colour term are acquired. It was shown in Chapter 4 that Greek speakers showed CP across the ble-yalâzjo boundary, whereas English speakers, whose language does not mark the distinction, did not. Moreover, CP for Greeks was stronger for RVF targets than for LVF targets.

Perceptual change theories suggest that the way in which stimuli are represented mentally may be altered through extensive practice or learning to distinguish stimuli lexically (e.g., Goldstone, 1998; Goldstone et al., 2001). These theories argue that learning ‘warps’ perceptual space, increasing the perceptual distance among objects in different categories, leading to CP. Specifically, it is argued that ‘warping’ of similarity space as specified by similarity judgments, causes members of the same category to move closer together (within-category compression; Kurtz, 1996), or members from different categories to move further apart (between-category expansion; e.g., Goldstone, 1994a; Levin & Beale, 2000), or both (Livingston et al., 1998). Learning colour terms may highlight the similarities among colours given the same term and highlight the differences among colours given different terms. This process could cause within-category compression and between-category expansion of perceptual space in the LH. If the foregoing account is true, it may be possible to study the development of CP by investigating the effects of learning to split a known colour category, such as blue into two new categories, such as greeny-blue and purply-blue (c.f., Özgen & Davies, 2002). Such an investigation is reported in this chapter.
New categories can be acquired through learning or training (e.g., Goldstone, 1994a; Livingstone et al., 1998; Notman et al., 2005; Zatorre & Halpern, 1979; Pisoni et al., 1982; Özgen & Davies, 2002). For instance, it has been found that the categorical boundaries for voice onset time (VOT) continua differ between native, monolingual speakers of Spanish and English (Williams, 1977). A sound difference that crosses the boundary between phonemes in a language is more discriminable to speakers of that language than to speakers of a language in which the sound difference does not cross a phonemic boundary (e.g., Repp & Liberman, 1987). Training to split a pre-existing phonemic category (e.g., phonemic variation along a continuum of VOT) can produce categorical perception around the newly learned boundary (Pisoni et al., 1982). Furthermore, category training of non-speech stimuli, in which subjects learn to identify stimuli within a particular frequency range as members of the same category, can lead to a decrease in sensitivity to stimuli in that category (Guenther, Husain, Cohen & Shinn-Cunningham, 1999).

Categorical perception is not limited to low-level perceptual continua, but can occur at higher levels, such as face perception, and may also be acquired through experience. Beale and Keil (1995) noted that the ability to recognise specific individuals must be learned. To investigate whether individual faces are perceived categorically, they generated linear continua of "morphed" faces between individual exemplars of familiar faces produced by morphing John Kennedy's face into Bill Clinton's and Pete Townsend to Sylvester Stallone. Participants viewed pairs of faces/stimuli from either the Kennedy/Clinton or Townsend/Stallone continuum. In separate categorisation, discrimination and "better-likeness" tasks, participants were more accurate at discriminating when face-pairs straddled category boundaries than when face-pairs were from the same continuum. It was concluded that individual faces are perceived categorically and these categorical perception effects can be acquired through experience.

As mentioned in Section 1.6, Goldstone (1994a) trained participants to categorise stimuli on perceptual dimensions, such as size, saturation and brightness. The relevance of each dimension during the training varied across participants. Then participants were tested on a
same-different judgment task. Between-category expansions were found only for the dimension on which participants were trained.

Practice may lead to shifting, sharpening or broadening in the tuning of the sensitivity functions of the relevant neurons resulting in perceptual learning changes (Fine & Jacobs, 2002). Learning can reorganise less dedicated structures to generate similar categorical boundaries *de novo* during category learning, as categorically perceived boundaries can be generated with dedicated neural structures (Livingston et al., 1998). Neuro-physiological evidence shows changes as a function of practice at early stages of visual processing. For instance, small changes have been observed in the slope of neural tuning within VI as a function of practice using an orientation discrimination task (Schoups, Vogels, Qian, and Orban, 2001). In addition, there is more rapid (or less effortful) visual processing of the categorical patterns in cortical areas correlated with the category judgement task after the category is learned (Reber, Stark & Squire, 1998).

**Induced colour CP**

Learning may ‘warp’ the representation of perceptual space, possibly by compression of perceptual space at the centre of categories, and/or stretching of perceptual space around categories boundaries (Harnad, 1987). It is possible that colour boundaries can be modified because of learning and weaker secondary boundaries can be learned. This was shown by Özgen and Davies (2002). Participants were trained to split either blue or green categories into two separate categories, with the to-be-learned boundaries at the centre of *blue* and *green* around the prototypes. Category training required participants to learn to classify exemplars into two categories – Ca and Cb. Training stimuli were chosen at random from within the continua of each category, and the categories had to be discovered through trial-and-error with feedback. Following training, discrimination was measured using a successive same-different task. The first stimulus colour (the target) was shown for one second and after a five-second delay, the test stimulus was shown. The test stimulus could be either physically identical to the target, or physically different. The task was to decide if target and test were identical or not. Crucial to the assessment of CP, on different trials, the test could be either physically different to the target (e.g., Ca1 - Ca2) or physically and categorically different (e.g., Ca1 - Cb1). Before training discrimination around the new boundaries was the poorest
in the category, but training reversed this pattern: category learners showed peak
discriminability at the old category centre. Thus, the original perceptual structure of the
category had been altered. Learning was also restricted to the trained colour region: trainers
only showed perceptual change for their training region (blue or green) and there was no
transfer to the non-trained region.

The following experiments

It is argued throughout this thesis that tasks involving a delay between target and test appear
to invite the use of verbal labels and memory, rather than just perceptual processing. Thus,
although Özgen and Davies undoubtedly induced novel categorical responding, the origin of
the effect may not have been perceptual. To argue for warping of perceptual space, CP must
arise from low-level perceptual processes. The next experiment replicates Özgen and
Davies's category training phase, but assesses its effect using the target detection task, rather
than a successive same-different task.

As well as testing whether induced CP would be found using the target detection task, the
next experiment also tested whether induced CP (if found) would be lateralised to the LH as
found in all the adult experiments reported for far. The results throughout this thesis have
shown a shift of the locus of colour CP from the right hemisphere to the left hemisphere, and
a LH bias for CP in marked boundaries, suggesting that language may change the functional
organisation of CP in the brain. If LH lateralised CP were found following categorisation
training, it would provide converging evidence supporting the role of language in colour CP.

A training group learned to divide the green region into ‘yellow-greens’ versus ‘blue-greens’
with the category boundary centred on the green prototype (7.5G). Following training, the
target detection task was used to compare discrimination that straddled the newly learned
boundary with within-category discriminations either side of the boundary. Following Özgen
and Davies, it was expected that without training, discrimination would be poorest around the
green prototype (the new boundary) – a form of the ‘perceptual magnet’ effect (Kuhl, 1991).
If category training induced CP around the new boundary, discrimination should become
better around the new boundary than within the new categories. To assess this, the training
group were compared to a control group that only did the target detection task. If category training induced CP around the new boundary, then the training group should show peak discrimination around the new boundary, and the control group should show poorest discrimination at this location. As a test that any difference between trainers and controls was specific to the training region, both groups also performed the target detection task for equivalent points in the blue region. If any differences between the groups were really due to training, then there should be no differences between them for the blue stimuli.

The training group was trained to divide green into two new categories for one session a day for three successive days. On the fourth day, subjects had a short ‘refresher session’ followed by the target detection task for green and blue. The control group just performed the target detection.

**Summary of research questions**

1. Can colour CP be induced? Is it found with the target detection task?
2. If yes, is induced colour CP lateralised to the LH?

**5.2 Method**

*Participants*

Forty-nine participants (Mean Age = 20.2 years, SD = 2.12) were randomly allocated into the training group (16 females and 8 males) and the control group (19 females and 6 males).

*Stimuli*

Stimuli in the training phases were coloured squares (5 cm²). They were displayed at the centre of a Sony Trinitron monitor (model GDM-F520) against a background of neutral grey. Munsell hue varied between 5BG and 10GY and Munsell value varied between 5 and 7. As can be seen in Figure 5.1, the stimuli were generated randomly from this region of colour space: on each trial in training, a random point was selected and the corresponding colour was displayed on the monitor. Stimuli within 0.2 Munsell hue units of the boundary were avoided. The hue boundary fell roughly in the centre of the linguistic category occupying the
green region (7.5G). The maximum possible chroma that could be realised for the training region was used (6).

**Figure 5.1.** Random colour generation area during the training sessions. The values range from 5BG to 10GY in Munsell hue and 5 to 7 in value, maximum value for chroma = 6. Points close to the new boundary were never used as stimuli (shaded area in the range between 7.3G and 7.7G)

**Procedure**

The training group performed categorisation training for three daily sessions. They were seated 50 cm away and at eye-level to the monitor. During training they learned to categorise all stimuli between 5BG and 7.3G in one category, and those between 10GY and 7.7G in the other category. There were two types of category training: ‘context training’ and ‘singleton training’ with context training always occurring first.

**Context training**

Participants made category judgements while being able to see examples of stimuli they had previously categorised correctly. A randomly chosen colour was presented in the centre of the screen, together with sixteen “slots” to be filled with the incoming colours divided into
two groups: eight slots (two columns, four rows) on each side of the test stimulus (see Fig. 5.2). The random test colour could be at any point within a given training area, and thus, fall on either side of the training boundary (avoiding points very close to it). The stimuli varied in lightness as well as in hue, but the training relevant variation was hue. The participant sorted the test stimuli into two groups around this boundary by placing the colour in the centre into an empty slot on the left or right. They had to decide to put the colour in the correct slot, using left-arrow (Ca) or right-arrow (Cb). The participant could place the first colour in a set on either side of the screen. Once it was placed on the left or right side, colours from the same experimental category (those from the same side of the relevant training boundary) as the first colour had to be placed on the same side. Similarly, colours from the other experimental category (other side of the boundary line) had to be placed on the other side of the screen. It was up to the participants on which side of the display were categories a and b to be assigned to. Immediate feedback was given: the colour remained in the slot following a correct response, but disappeared and a sound indicated ‘incorrect’ if the response was incorrect. The number of colours for comparison increased with correct responses in each block (up to the maximum number of slots available: 16). When they correctly filled all sixteen slots, a “block” was complete, and a new one began; the cycle continued until the criteria for successful category learning were met. No instructions on what the categorisation was based on were given.

The instructions given to participants were as follows: “Several coloured squares will appear on the screen. Your task is to sort these into two groups. You must discover the rule that separates these two groups. On every trial, you will see a colour in the centre of the screen. At the beginning of each block, when all slots are empty, you can place the first colour on either side. From the next colour onward, the question is ‘Does this go with the first colour, or does it belong to the opposite group?’ Use the left and the right arrows to place this colour in an empty slot on the left hand side if you think it belongs to one group, and right-hand side for the other group. If your answer is correct, the colour stays where you put it. If you are incorrect, the colour disappears and you hear a sound. You complete a block when you correctly fill all slots, and start a new one until you get sufficiently good at the task to finish”.
The first stage of training finished when at least 20 blocks were completed and there were at least three error free blocks. This stage typically took about 30 minutes.

![Figure 5.2. Representation of context training. Participants had to make a category judgement: they decided to place the randomly generated coloured square presented in the centre of the computer screen, in the slots on either side of the screen.](image)

**Figure 5.2.** Representation of context training. Participants had to make a category judgement: they decided to place the randomly generated coloured square presented in the centre of the computer screen, in the slots on either side of the screen.

**Singleton training**

In the second stage of training, single test colours appeared at the centre of the screen. The participant had to decide which of the two categories it belonged to by pressing “left” or “right” arrows. Incorrect choices were signalled by the word “incorrect” replacing the test colour, accompanied by a sound. The instructions given to the participants in the second stage were as follows. “The task here is the same as before, only this time you see just the coloured square at the centre. Again, you have to decide which group it belongs to by pressing the left arrow for one group, and the right arrow for the other. If your choice is incorrect, you will see the word “incorrect” in the place of the colour and hear a sound. You will be able to finish this part of the experiment when you get sufficiently good at the task.”
The criteria for finishing this stage were completion of at least 250 trials and 25 consecutive correct responses. This stage typically took about 10 minutes.

Refresher phase

The procedure for the refresher phase on the testing day was the same as for the training phase, except that the criteria for completing training were less stringent than on the training days. The criteria for completing context training were that at least 10 blocks were completed, and there was at least one error free block. ‘Context’ training typically took about 10 minutes. The criteria for completing singleton training were completion of at least 100 trials, and 25 consecutive correct responses. This stage typically took about five minutes.

5.2.1. Results and Discussion

Performance change across training

The data of three subjects were not included because they were not able to complete the training phase, or they performed at chance level during the training sessions. Table 5.1 shows the mean number of trials for the two types of training across training days and test day. During the training phase, participants performed between 500 and 1000 context-training trials on each day, and about 250 to 500 single colour trials. On the test day, participants performed about 150 to 250 context-training trials, and about 100 to 250 single colour trials. Overall, participants performed around 2300 trials in the context-training phase and around 1000 trials in the singleton-training phase including the refresher-training day. There appears to be general improvement in the number of context training trials across the days of training, especially in the second day. A similar pattern is present for the singleton training trials; however, the improvement is mainly in the second day. The mean overall number of categorisation trials completed throughout the three training days and the refresher training was around 3300 trials.
Table 5.1. Mean number of trials taken to complete context and single colour training across the three days of training and on the testing day (refresher training).

<table>
<thead>
<tr>
<th></th>
<th>Day1</th>
<th>Day2</th>
<th>Day3</th>
<th>Test Day</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Context Training</strong></td>
<td>844</td>
<td>660</td>
<td>600</td>
<td>197</td>
<td>2301</td>
</tr>
<tr>
<td><strong>Single Training</strong></td>
<td>335</td>
<td>292</td>
<td>268</td>
<td>116</td>
<td>1011</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1179</td>
<td>952</td>
<td>868</td>
<td>313</td>
<td>3312</td>
</tr>
</tbody>
</table>

*Error reduction across training*

Four different error scores were calculated to assess whether categorisation had improved across training.

*Errors in the first and the last 10 blocks in context training across the training days*

For each training day, the percentage of errors (incorrect classifications) in the first 10 and last 10 blocks of context training were calculated and these are shown in Figure 5.3. It appears that percentage error score reduced mainly on the second day. Additionally, errors seem to be lower in the last 10 blocks than in the first 10 blocks.

A day (day 1, day 2, day 3) x block (first 10 blocks, last 10 blocks) repeated measures ANOVA was conducted on the percentages of incorrect classifications. The analysis supported the above pattern: there was a main effect of days \(F(2, 40) = 43.41, p < .001, \eta^2 = .69\). Planned contrasts show that error scores were lower on the second day than on the first day \(F(1, 20) = 47.41, p < .001, \eta^2 = .70\), however there was no significant reduction on the third day \(F(1, 20) = 2.27, p = .15, \eta^2 = .10\). In addition, the main effect of blocks was significant, there were less errors in the last 10 blocks than in the first 10 blocks \(F(1, 20) = 5.20, p < .05, \eta^2 = .21\). The interaction between days and blocks was also significant \(F(2, 40) = 4.69, p < .025, \eta^2 = .19\). There were significantly less errors in the last 10 blocks than in the first 10 blocks in the first day of training \(t(20) = 3.85, p < .002\), however there was
no difference between the first 10 blocks and the last 10 blocks on the second and the third day of training (minimum \[t(20) = 1.92, p = .07\]).

**Figure 5.3.** Percentage errors in first and last blocks each day for the context training for the three training days. Error bars represent within-subjects 95% confidence intervals.

**Error in the first 10 blocks in context training including the testing day**

Figure 5.4 shows the percentage of errors (incorrect classifications) on the first 10 blocks of context training. It appears that error scores fell mainly on the second day with little improvement on the following days. Within-subjects ANOVA on the first 10 block errors for all 4 days revealed a main effect of blocks \([F(3, 60) = 37.48, p < .001, \eta^2 = .65]\). Planned contrasts showed that there were less errors on the second day than on the first day \([F(1, 20) = 36.62, p < .001, \eta^2 = .65]\), but the reduction in errors on the third day only approached significance \([F(1, 20) = 3.74, p = .07, \eta^2 = .16]\).
Figure 5.4. Percentage errors in the first 10 blocks for the three days of training and ‘refresher’ training on the testing day. Error bars are within-subjects 95% confidence intervals.

Errors including all blocks in context training across the training days

The percentage of incorrect context training classifications across all blocks for all three training days was calculated for each subject and these are shown in Figure 5.5. Errors seem to reduce across the training days. One-Way within subjects ANOVA on the total errors showed that the errors reduced across days \( F(2, 40) = 35.88, \ p < .001, \eta^2 = .64 \). Planned comparison showed that performance was better on the second day than on the first day \( F(1, 20) = 33.06, \ p < .01, \eta^2 = .62 \) and it continued to improve on the third day \( F(1, 20) = 8.89, \ p < .01, \eta^2 = .31 \).
Figure 5.5. Total percentage errors across the three days of training. Error bars are within-subjects 95% confidence intervals.

**Errors in singleton training across the three training days**

The percentage of incorrect classifications for each day on the ‘singleton’ training trials were calculated for each subject and these are shown in Figure 5.6. It appears that participants made fewer errors on the second day than on the first day; however, there is no much improvement on the third day. This was supported by a One-Way ANOVA on the singleton training across the three days: errors reduced across the days \( F(2, 38) = 17.77, p < .001, \eta^2 = .48 \)\(^{15} \). Planned contrasts showed that performance on the second day of category training was better than on the first day \( F(1, 19) = 13.89, p < .05, \eta^2 = .42 \), however, error reduction on the third day only approached significance \( F(1, 19) = 3.55, p = .075, \eta^2 = .16 \).

\(^{15}\) One subject is missing hence the dfs are different. The subject did not complete the ‘singleton’ training on the third day due to personal reasons.
5.3. Method for target detection task

Apparatus, Stimuli, Design and Procedure

Stimuli were displayed on a calibrated Sony Trinitron CRT monitor (model GDM-F520). These were two within- and two between-category pairs for the green region (Figure 5.7). Also, two within- and two between-category pairs for the equivalent blue region were used (Figure 5.8). Participants were not trained to divide the blue region into two new categories; nonetheless, for consistency and ease in the analysis of data, the equivalent pairs in the blue region are called within- and between-category pairs. Target-background separations were 5 hue Munsell steps, with value and chroma being constant at 6 and 6 respectively (See Table 5.2 for CIE Y x Y chromaticity co-ordinates). For each group (trained and control) half the participants performed the target detection task with one within- and one between- pair, and the other half with the other within- and between- pair. The order in which the blue or the green region was tested was randomised. There were 168 trials for each region (84 within-category trials and 84 between-category trials). The procedure and design were the same as in Experiment 1.

Figure 5.6. Error percentages on 'singleton' training across the three training days. Error bars are within-subjects 95% confidence intervals.
**Figure 5.7.** The pairs of the stimuli used in the green colour region. Dashed line represents the new boundary (7.5G): there are two within-category pairs, and two between-category pairs. The range of the trained region was from 5BG to 10GY.

**Figure 5.8.** The pairs used in the blue colour region.

**Table 5.2.** CIE (1931), Y, x, y chromaticity co-ordinates of the stimuli. White point of monitor as measured on screen: Y=64.80 cd/m². The stimuli emulated a reflectance of 30.05.

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Y (cd/m²)</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>4PB</td>
<td>19.47</td>
<td>0.251</td>
<td>0.257</td>
</tr>
<tr>
<td>1PB</td>
<td>19.47</td>
<td>0.243</td>
<td>0.263</td>
</tr>
<tr>
<td>9B</td>
<td>19.47</td>
<td>0.233</td>
<td>0.276</td>
</tr>
<tr>
<td>6B</td>
<td>19.47</td>
<td>0.231</td>
<td>0.283</td>
</tr>
<tr>
<td>4B</td>
<td>19.47</td>
<td>0.233</td>
<td>0.297</td>
</tr>
<tr>
<td>1B</td>
<td>19.47</td>
<td>0.294</td>
<td>0.575</td>
</tr>
<tr>
<td>4BG</td>
<td>19.47</td>
<td>0.245</td>
<td>0.332</td>
</tr>
<tr>
<td>1BG</td>
<td>19.47</td>
<td>0.257</td>
<td>0.351</td>
</tr>
<tr>
<td>9G</td>
<td>19.47</td>
<td>0.262</td>
<td>0.360</td>
</tr>
<tr>
<td>6G</td>
<td>19.47</td>
<td>0.271</td>
<td>0.375</td>
</tr>
<tr>
<td>4G</td>
<td>19.47</td>
<td>0.281</td>
<td>0.386</td>
</tr>
<tr>
<td>1G</td>
<td>19.47</td>
<td>0.303</td>
<td>0.409</td>
</tr>
</tbody>
</table>
5.3.1. Results

There were far more errors made in the blue region (~30%) than in the green region (~2%) by both groups, and therefore the data for two regions were analysed separately. Analysis of the green region is reported first followed by the analysis of the blue region. Because error rates were so high in the blue region, accuracy and RT were analysed. For comparison and consistency, the same was done for the green region. The initial analyses are three-way ANOVAs: category (within/between) by visual field (LVF/RVF) by group (trained/control), with the first two factors being repeated measures. Separate follow-up two-way ANOVAS (category by field) for each group were conducted if the three-way interactions were significant, and they are reported under separate sub-headings.

5.3.1.1 Green region

Accuracy

The percentage of correct responses was calculated for each subject, for each combination of category and visual field and the means across subjects are shown in Table 5.3. It appears that the percentage of correct responses was very high on average, and the means were very similar for the two groups (97.81% and 98.83% for the control and training groups respectively). There were no significant effects in the ANOVA (maximum \(F(1, 44) = 2.44, p = .13, \eta^2 = .05\)).

Table 5.3. Percentage of correct responses for the control and trained group in the two visual fields for within- and between-category trials.

<table>
<thead>
<tr>
<th></th>
<th>Within</th>
<th>Between</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LVF</td>
<td>RVF</td>
</tr>
<tr>
<td>Control</td>
<td>98.00</td>
<td>98.19</td>
</tr>
<tr>
<td>Trained</td>
<td>99.31</td>
<td>98.62</td>
</tr>
</tbody>
</table>
RT

Median response times (RTs) for correct trials were calculated for each combination of category (within/between) and visual field (LVF/RVF) for each observer, and Figure 5.9 shows the mean RTs across subjects for each group. Overall, the trained group appears to have responded faster than the control group (means 451 ms and 481 ms respectively), and within-category responses tended to be faster than between-category responses (460 ms and 472 ms respectively); this appears to be rather like a 'reverse category effect'.

![Figure 5.9](image)

**Figure 5.9.** Green region: mean RTs for target detection for the control and the trained group for each combination of visual field and category. Error bars represent 95% within-subject confidence intervals calculated by using the error term from the three-way interaction. Between-subjects 95% CL calculated by using the between groups error term is shown as the separate error bar.

Analysis supported the apparent reverse category effect \( F(1, 44) = 11.22, p < .01, \eta^2 = .20\); within-category responses were about 13 ms faster than between-category responses. The group effect only approached significance \( F(1, 44) = 2.69, p = .11, \eta^2 = .06\). RTs in the two
visual fields also did not differ \[ F (1, 44) = .27, p = .61, \eta^2 = .01 \]. None of the two-way interactions were significant (maximum \[ F (1, 44) = .33, p = .57, \eta^2 = .01 \]). However, there was a strong 3-way interaction between visual field, category and group \[ F (1, 44) = 14.22, p < .001, \eta^2 = .24 \]. From Figure 5.9, this appears to be due to the category effect for the trained group in the LVF differing from all the other group by visual field combinations.

Specifically, in all combinations there appears to a reverse-category effect (within-< between-category), whereas for the training group in the LVF within- and between-category conditions are virtually identical.

**Control group**

Analysing the groups separately showed that for the control group, RTs in the two visual fields did not differ \[ F (1, 24) = 0.002, p = .97, \eta^2 = .00 \]. However, there was a significant reverse category effect \[ F (1, 24) = 12.75, p < .01, \eta^2 = .35; \text{means: 472 ms and 491 ms for within- and between-category respectively} \]. In addition, the field by category interaction was significant \[ F (1, 24) = 8.91, p < .01, \eta^2 = .27 \]. As can be seen in Figure 5.9, this appears to be due to the larger reverse category effect for the RVF than for the LVF: the reverse category effect was on average 17 ms larger in the RVF than in the LVF \[ t (24) = 2.99, p < .01 \].

**Trained group**

For the trained group, the within-and between-category RTs did not differ significantly \[ F (1, 20) = 1.38, p = .25, \eta^2 = .07 \]. In addition, RTs in the two visual fields did not differ \[ F (1, 20) = .569, p = .46, \eta^2 = .28 \]. However, there was a two-way category by field interaction \[ F (1, 20) = 5.81, p < .025, \eta^2 = .23 \]. As Figure 5.9 shows, the interaction reflects a reverse category for the LVF \[ t (20) = 2.20, p < .05 \], but no such effect for the RVF \[ t (20) = .39, p = .70 \]. Training has nullified the strong RVF reverse category effect shown by the control group.

**5.3.1.2. Blue region**

**Accuracy**

The percentage of correct responses was calculated for each combination of visual field (LVF v RVF), category (within/between) and group (trained/control) and these are shown on
Table 5.4. As can be seen, error rates were much higher than for the green region. The difference between the two groups approached significance (percentage of correct responses: control group = 66.38%, trained group = 72.90% [F (1, 44) = 3.01, p < .09, \(\eta^2 = .06\)]). There was also a significant reverse category effect: participants were more accurate on within-than between-category trials (73.09% versus 66.19% respectively [F (1, 44) = 16.58, \(p < .001, \eta^2 = .06\)]. All other main effects and interactions were not significant, (maximum [F (1, 44) = 1.19, \(p = .28, \eta^2 = .03\)]).

### Table 5.4. Percentage of correct responses for the control and trained group in the two visual fields for within- and between-category trials.  

<table>
<thead>
<tr>
<th></th>
<th>Within</th>
<th></th>
<th>Between</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LVF</td>
<td>RVF</td>
<td>LVF</td>
<td>RVF</td>
</tr>
<tr>
<td>Control</td>
<td>68.38%</td>
<td>72.14%</td>
<td>62.57%</td>
<td>63.43%</td>
</tr>
<tr>
<td>Trained</td>
<td>77.21%</td>
<td>75.50%</td>
<td>72.21%</td>
<td>66.67%</td>
</tr>
</tbody>
</table>

**RT**

Figure 5.10 shows the mean RTs for each combination of visual field (LVF v RVF), category (within-between-category), and group (trained v control). Overall, the trained group responded similarly to the control group (means: 721 ms and 746 ms respectively), however within-category responses tend to be faster than between-category responses (689 ms and 778 ms respectively) - a 'reverse category effect'. A group (trained/control) x visual field (RVF/LVF) x category (within/between) ANOVA performed on the median correct RTs showed that the only significant effect was for category \([F (1, 44) = 9.03, \ p < .005, \eta^2 = .17]\]. As can be seen in Figure 5.10, this reflects a large reverse category effect of about 90 ms. Nothing else approached significance: all \(F (1, 44) < 1\).
Although there was no significant difference in RT between the two groups, the trained group were more accurate than the control group in the blue region, albeit not quite significantly. To check that the similar RTs for the two groups were not due to different speed-error trade off functions for the two groups, the above ANOVA was repeated with accuracy as a covariate. Figure 5.11 shows the predicted mean RTs for each combination of group, visual field and category. The analysis revealed essentially the same pattern as the ANOVA with category being the only significant effect. Within-category trials were still about 90 ms faster than between-category trials \( [F (1, 43) = 9.03, p < .005, \eta^2 = .16] \). Nothing else approached significance: maximum \( [F (1, 43) = 1.36, p = .251, \eta^2 = .03] \).
Figure 5.11. Blue region: predicted Mean RT for target detection for the control and the trained group for each combination of visual field and category. Error bars represent 95% within-subject confidence intervals calculated by using the error term from the three-way interaction. Between-subjects 95% CL calculated by using the between groups error term is shown as the separate error bar.

5.4. Discussion

The trained group were making approximately 10% classification errors at the end of training. All performance measures converge to indicate that categorisation improved significantly. However, the largest change occurred between day 1 and day 2 with relatively little change between day 2 and day 3. A prominent feature of the results was that, as expected, there was a clear pre-existing reverse-category effect: discrimination around the category prototypes was worse than discrimination either side of the prototype. This was true for both colour regions. Thus, as in Özgen & Davies (2002), if training were to induce CP around the newly learned boundary, the reverse-category effect had itself to be reversed. Moreover, the reverse-category effect for the controls was primarily present in the LH; if induced CP were to be lateralised to the LH as expected, the scale of the required reversal would be particularly severe. In fact, the training group did not show CP around the new boundary after training. However, there are strong indications that the induction of CP was
underway. The reverse category effect was eliminated in the RVF for the training group, consistent with between-category expansion and acquired distinctiveness. It seems likely that with more training, full CP may have been induced. Performance in the blue region indicates that the partially induced CP resulted from category learning rather than some odd pre-existing difference between the two groups. All combinations of visual field and group showed a clear reverse-category effect, and there were no differences between the control and training groups. Additionally, the results for the blue region show that the effects of training were restricted to the training region, as with Özgen & Davies (2002).

The target detection task has been used throughout this thesis, as on the face of it, performance should rely primarily on early visual processes. As discussed in section 2.1, the task is likely to reflect visual processes as early as in V1. Neuro-physiological evidence shows changes resulting from practice at early stages of visual processing. For instance, small changes have been observed in the slope of neural tuning within V1 resulting from practice on an orientation discrimination task (Schoups et al., 2001). Moreover, on the target detection task, there is no memory load and target-pop-out is unlikely to be influenced by labelling. On these grounds, it appears that genuine perceptual change must have occurred. Nevertheless, labelling may have been used during categorisation training. Although not required to, participants may have generated labels to help them learn the new categories, and these personal labels could have been available to them to affect performance (somehow) on the target detection task. The LH lateralisation of the learning effect is consistent with the possibility that language (albeit implicitly) may be involved even in these seemingly low-level tasks. Alternatively, learning, possibly guided by labelling, could have induced changes in perceptual representations in the LH that were different to changes produced in the RH. There is nothing in the current results that can distinguish between these two possibilities.

As Özgen & Davies (2002) argued, category training could provide an intensive version of the category learning undergone by children learning colour terms. The fact that the learning effect was restricted to the LH is consistent with the results earlier in this thesis, showing that LH lateralisation of CP only occurs if the boundary is within the linguistic repertoire of the individual. Experiment 6 in this thesis showed that only children who have explicit knowledge of colour terms show a LH advantage for colour CP. In addition, Experiments 7
and 8 showed that CP is lateralised to the LH only if the boundary is marked in the speaker's language: Greek speakers showed CP across a Greek boundary, whereas English speakers who do not mark that boundary, showed no CP. However, further research is needed to investigate this further.
Chapter 6
General Discussion

This thesis aims to build on the debate over the relationship between language and thought by examining colour categorical perception. According to Universalism, categories are built on universals of human cognition, where language exploits existing categories: categories are universal regardless of whether these are encoded in one’s language. In contrast, Relativism holds that language shapes semantic distinctions in an arbitrary way, thus linguistic differences influence human cognition. The domain of colour has been one of the main areas of empirical research to test the two positions. The colour continuum is continuous, yet it is perceived as discontinuous: people use different colour terms to describe colour, e.g., blue, green, orange etc. The phenomenon of "categorical perception", in which a continuous stimulus dimension is perceived as a number of discrete segments or categories, with the members of categories resembling each other more than the members of other categories (Harnad, 1987), has been reported in numerous studies. Thus, the study of the colour CP effect has become the focus in the debate regarding the effect of language on thought.

Research findings on colour CP support both positions. Consistent with Universalism, CP effects are found in pre-linguistic infants (Bornstein et al., 1976; Franklin et al., 2005) and in toddlers with no colour term knowledge (Franklin, Clifford et al., 2005; Daoutis et al., 2006). Both toddlers with no colour terms and pre-linguistic infants show better discrimination for colours that straddle a category boundary than for colours that belong to the same category. On the other hand, consistent with Relativism, other findings indicate a role of language, suggesting that CP arises from availability of colour terms (e.g., Kay & Kempton 1984; Gilbert et al., 2006; Roberson & Davidoff, 2000; Winawer et al., 2007). For example, comparing stimulus labels facilitates discrimination for between-category pairs, and/or hinders discrimination for within-category pairs (Roberson et al., 2005). This is supported also by cross-cultural research showing that CP is found if the category boundary is marked in the participant’s language (Kay & Kempton, 1984). In addition, CP disappears when a concurrent task that places strong demands on specifically verbal resources is introduced (Roberson et al., 2000; Winawer et al., 2008).
This thesis investigated colour CP and possible language influences by examining laterality effects. Four main research questions were examined throughout the experimental chapters. The first experimental chapter investigated the lateralisation of colour CP in adults. The second experimental chapter examined whether pre-linguistic CP is also lateralised to the LH, and the development of the LH bias. The third experimental chapter investigated the lateralisation of colour CP comparing speakers of a language that mark a specific boundary and speakers of a language that lacks that boundary. The last experimental chapter builds on the findings from the previous experimental chapters, and investigated underlying mechanisms in CP induced by category training. The aim of the current chapter is to discuss the impact of the findings, to draw attention to unresolved issues, and to suggest possible directions for future research. The chapter ends with a summary of the main findings.

6.1. Summary of research questions and findings

6.1.1. Laterality effects in colour CP and Whorfian effects.

Two experiments presented in Chapter 2 suggest that colour CP is lateralised to the LH\(^{16}\). The findings support and extend previous research suggesting a LH bias for colour CP (e.g., Gilbert et al., 2006). However, in the experiments in Chapter 2, discrimination was measured using a target detection task, which was more perceptual in its demands than tasks that have been used in previous lateralisation of CP studies. It was found that colour CP across the blue-green and blue-purple boundary was stronger in the LH than in the RH. In the last experiment of Chapter 2, the target-detection task was accompanied by a concurrent interference task, and CP was eliminated under verbal interference but it survived visual interference. This is in accordance with previous research showing that when the LH is engaged in a secondary verbal task CP is eliminated (e.g., Gilbert et al., 2006; Pilling et al., 2005; Roberson & Davidoff, 2000; Winawer et al., 2008).

\(^{16}\) These experiments were published in PNAS: Drivonikou, G. V., Kay, P., Regier, T., Ivry. T. R., Gilbert. A. L, Franklin. A. & Davies. I. R. L (2007). Further evidence that Whorfian effects are stronger in the right visual field than the left. Proceedings of the National Academy of Sciences, 104, 1097-1102. (See Appendix E for the full paper).
6.1.2. Laterality effects in colour CP in infancy and changes in lateralisation of colour CP.

To investigate the development of the LH bias in colour CP, the experiments presented in Chapter 3 compared performance in four different age groups.

Infants show categorical responding (e.g. Franklin et al., 2005), but previous research has not investigated whether CP is lateralised in infants. If the LH bias for colour CP derives from language learning, then it should not be present in pre-linguistic infants or in young children before they have learned their colour terms. To investigate this possibility, the target detection task was adapted for use in infants and young children; it exploited the fact that infants automatically moved their eyes to a singleton coloured target against a uniform background. For all groups, eye-movement latencies were used to assess speed of target detection, and latencies to within- or between-category target-background pairs were compared. The eye-movement latency measure showed the same pattern of results for adults as the reaction time measure used in previous studies. Furthermore, eye-movement latencies on between-category trials were faster than on within-category trials for infants and toddlers - consistent with previous research showing that CP is present in infants and that it is not affected by degree of colour term knowledge in toddlers (Franklin, Clifford et al., 2005). However, a striking difference in the lateralisation of CP emerges across development. CP in infants is lateralised to the RH, whereas in adults, as already described, it is lateralised to the LH.

6.1.2. Cross-cultural differences in lateralisation of colour CP.

Experiments 8b and 9 in Chapter 4 examined the relationship between colour language and colour perception. This was examined by comparing two populations whose language segments the colour space differently. Greek speakers showed categorical effect across the blé-yalážo boundary, which is marked in their language, and this was lateralised to the LH.


English speakers, who lack this linguistic distinction, did not show CP. Moreover, as with the studies in Chapter 2, the nature of the target-detection excludes memory processes or explicit use of colour names as the origin of CP. The cross-cultural differences in the category effect could have not been due to strategies to complete the task as memory, and labelling components are excluded due to the nature of the task.

6.1.3. What are the underlying mechanisms in CP induced by category training?

Experiment 10 sought converging evidence for the conjectured plasticity of CP by seeing if CP that was newly induced by category training was lateralised to the LH. Özgen & Davies (2002) showed that category learning induced CP around the newly learned boundary, as indicated by performance on a successive same-different task. Experiment 10, partially replicated this result, but importantly, CP was evidenced by faster between- than within-category target detection. Most pertinently, the changes suggesting that CP was being acquired were clearly restricted to RVF targets.

6.2. Implications of the present work for the main Theoretical Approaches

The main approaches, Universalism and Relativism are fundamentally different in explaining the experience of colour perception. Naturalist theories within Universalism argue that perceptual categories are hardwired (e.g., Bornstein, 1985). In contrast, labelling theories (e.g., Roberson & Davidoff, 2000), and perceptual change theories (e.g., Özgen & Davies, 2002) within Relativism argue that perceptual categories are acquired. The following section discusses the implications of the present work and considers the extent to which answers to the main research questions are given.

6.2.1. LH bias for colour CP and Whorfian Hypothesis

As discussed in Chapter 2, recent research has shown that colour CP is based in the LH (e.g., Gilbert et al., 2006) suggesting that this supports a Whorfian effect in colour CP. Experiments in Chapter 2 investigated the robustness of these findings. Beside a primary boundary (blue-green), a secondary boundary (blue-purple) was tested using a target detection task that measures low-level perceptual processes. Category effects were found for both boundaries; however, the LH contribution was not absolute: for the blue-green boundary
CP was present for both the LH and the RH, however, the contribution of the LH was larger. The findings may imply, as Gilbert et al. (2006) suggested, that language could influence performance even in the target detection task — a seemingly low-level perceptual task. The last experiment in Chapter 2 included a concurrent interference task and in accordance with previous research (e.g., Gilbert et al., 2006; Winawer et al., 2008), CP was selectively eliminated under verbal interference. The discussion of Chapter 2 considered whether the findings support a Whorfian effect resulting in a permanent change of perceptual organisation. However, the fact that verbal interference eliminated the category effect suggests that an interaction of both low-level processes and language processes results in the perceptual decision.

6.2.2. Laterality effects in colour CP in infancy and changes in lateralisation of colour CP

Evidence suggests that colour CP depends on access to lexical codes for colour (Kay & Kempton, 1984; Pilling et al., 2005; Roberson & Davidoff, 2000; Roberson et al., 2000; Winawer et al., 2008). On the other hand, colour category effects are found in pre-linguistic infants and toddlers (Franklin et al., 2005; Franklin, Clifford et al., 2005; Franklin & Davies, 2004). Experiment 4 investigated laterality effects in adults using eye-movement latencies rather than manual RTs. The results replicated previous findings (e.g., Drivonikou et al., 2007); CP was found only when the target was presented to the right visual field. Experiment 5 investigated laterality effects in 4-6 month old infants using the same measure. CP was present at 4-6 months of age, consistent with previous research (Franklin et al., 2005). Infants were faster at detecting the target on between-category trials than on within-category trials and this effect was only significant for targets presented to the left visual field.

One possibility put forward in the introduction to Chapter 4, was that the LH CP develops as colour terms are acquired at around 2-5 years (Bornstein, 1985). This was supported by the results of Experiment 6. Toddlers who were in the process of learning colour terms relevant to the category boundary showed the same pattern as infants, then a RH bias for colour CP. However, there was no such bias for toddlers who have already acquired the colour terms relevant to the category boundary. In turn, this suggests that the acquisition of the colour terms relevant to the category boundary drives this shift in lateralisation, and this conjecture
was supported by the results of Experiment 6 that showed the switch from RH to LH CP coincides with the learning of colour terms.

In the discussion of Chapter 4, it was suggested that language might modulate the location of categorical perception as colour terms are acquired. However, it is not clear whether the RH to LH "switch" in lateralisation of colour CP when colour words are learned, results in a permanent loss of colour CP in the RH. The findings of Experiment 2 in Chapter 2 show a RH colour CP as well in adults, albeit weaker than LH CP. In addition, the RH CP is stronger with long reaction times (e.g., Roberson, et al., 2008) suggesting that the cross-callosal transfer from the LH is responsible for the RH CP. Moreover, the lack of RH CP in callosotomy patients (Gilbert et al., 2006) suggests that the RH CP after colour term acquisition is not present.

In summary, the findings from the experiments presented in Chapter 4 appear to provide evidence for a presence of linguistic and prelinguistic colour categories. Colour categories are present in infancy prior to acquisition of colour terms and these are represented in the RH, however the hemispheric lateralisation appears to change during development: colour categories are represented in the LH in adulthood when colour terms are cognitively salient. The findings indicate that learning colour terms may change the lateralisation of the colour categories in the brain, however further research is needed to clarify the mechanisms underlying the loss or suppression of the RH CP after colour terms are acquired and/or have become cognitively salient.

6.2.3. Cross-cultural differences in lateralisation of colour CP

Evidence of better between-category than within-category colour discrimination has been attributed to underlying perceptual mechanisms resulting in ‘warping’ of perceptual space (e.g., Bornstein & Korda, 1984, Boynton et al., 1989). Roberson and Davidoff (2000) have argued that comparison of verbal labels leads to the advantage for the between-category discriminations. Other cross-cultural studies have also suggested that linguistic categories influence performance on different tasks usually used to measure colour CP (e.g., Kay & Kempton, 1984; Winawer et al., 2008; Witthoft et al., 2003). Caution though is needed in
interpreting the findings with tasks, such as simultaneous and delayed 2-AFC tasks, due to their vulnerability to memory and labelling strategies.

Experiments in Chapter 4 deal with this problem using a low-level perceptual task to examine colour CP. Using the target detection task, it was found that category effects were found only at a marked boundary, and they were represented in the LH. CP was found for the Greek ble- yalazjo boundary for Greek speakers, but not for English speakers. The Whorfian hypothesis predicts that speakers of languages, which differ in the way that they divide colour space, should also show relative differences in their colour discrimination. Discriminability show local maxima around the boundaries marked in the respective speaker's language. Previous studies have shown that CP is restricted to boundaries marked in the observer's language (e.g., Roberson et al., 2000; Winawer et al., 2008; Witthoft et al., 2003), but this was the first study to also show that when CP was found, it was lateralised to the LH. The findings from the experiments in Chapter 4 suggest that the two distinct categories in Greek may have become perceptually salient because of linguistic emphasis on the distinction between ble and yalazjo. This in turn suggests some support for indirect language influences in colour perception. The results suggest that some colour categories at least, may be created through learning colour terms, and CP arises from category learning.

6.2.4. What are the underlying mechanisms in acquired colour CP?

Findings from previous research suggest that colour CP is flexible, and that new category boundaries can be learned (e.g., Özgen & Davies, 2002). Özgen and Davies showed that through learning to subdivide a pre-existing basic colour category (green or blue) a new colour boundary could be learned. Using the target detection task, the control group showed faster discriminations in the pre-existing within-category regions, and this was stronger in the RVF than in the LVF. In category learners, there was no difference between within- and between-category RT in the RVF, but there was in the LVF. Thus although new CP was not induced, it appears that the induction process had begun. However, learning was stimulus-specific (e.g., Özgen & Davies, 2002).

It is possible that labelling may have been involved in the process of category learning, modifying the location of categorical perception and reorganising the representation of
perceptual colour space. This is in accordance with perceptual change theories, which suggest that learning to distinguish stimuli lexically, or extensive practice, may result in a change of perceptual categories (e.g., Goldstone, 1998; Goldstone et al., 2001). Furthermore, category training could provide an intensive version of the category learning undergone by children learning colour terms (Özgen & Davies, 2002). Neither of these possibilities can be ruled out. Moreover, the learning effect was restricted to the LH, consistent with the results earlier in this thesis, indicating that LH lateralisation of CP only occurs if the boundary is within the linguistic repertoire of the individual. This provides further support for the conjecture, that colour categories are mutable, and that CP may be an inevitable consequence of categorisation, whether hard-wired, learned through language, or learned through intensive 'artificial' category training.

6.3. Unresolved issues and further research

The findings from this work replicate and extend findings in the research field. The focus has been the investigation of laterality effects in colour CP, and the main implication of the work is the understanding of the effect of language acquisition on the brain. Colour CP was lateralized to the "language dominant" left hemisphere (LH) in adults, as in Gilbert et al. (2006), and LH CP was eliminated by verbal but not visual interference, in accordance with (Gilbert et al., 2006; Winawer et al., 2008). Moreover, categorical perception (CP) of colour occurred only at the boundary of linguistically encoded basic colour terms: only Greek speakers showed CP for the ble-galazio boundary, consistent with findings reported from other researchers (e.g., Kay & Kempton, 1984; Roberson et al., 2000; Winawer et al., 2008), and again a LH bias was observed. In a nutshell, these findings imply linguistic involvement in CP.

Despite the overwhelming evidence that colour CP in adults depends on language, there is also research showing that colour CP can be language independent. Work in this thesis showed that CP was found to occur in the absence of colour terms in infants and in toddlers that have not acquired colour terms. Previous developmental studies have also found that infants as young as 4 months respond categorically to colour on several tasks and across a range of colour category boundaries (Bornstein et al., 1976; Franklin & Davies, 2004;
Franklin et al., 2005). However, research in this thesis found that this prelinguistic CP, in contrast to the LH-lateralised colour CP in adults, appears to be lateralised to the right hemisphere (RH).

Furthermore, previous research with toddlers at the stage of colour term acquisition have shown that CP is present irrespective of colour term knowledge (Franklin, Clifford et al., 2005), and this was also found in this work, though the extent of CP did not appear to change with colour language learning, only the lateralisation of CP changed. The RH bias found in infants and toddlers, who were in the process of acquiring colour terms, was not present in toddlers, who had explicit knowledge of colour terms, instead a trend towards LH advantage for colour CP was found for these toddlers.

Finally, employing a category training paradigm, findings in the last experimental chapter showed that the learning effect was restricted to the LH, consistent with the results earlier in this thesis, indicating that LH lateralisation of CP only occurs if the boundary is within the linguistic repertoire of the individual. This shows further support for the conjecture, that colour categories are mutable (Özgen & Davies, 2002).

In summary, this work has shown that there are two forms of CP: a prelinguistic CP, which is lateralised to the RH, and a linguistic CP, which is lateralised to the RH. However, the available data are not sufficient to conclude that the linguistic CP is a product of direct or indirect linguistic involvement. Several issues have emerged from the present work and these are outlined below, together with suggestions for how they might be addressed.

**Issues arising from experiments in Chapter 2 and future directions**

The left hemisphere shows an advantage for colour CP, and even though it is generally accepted that the left hemisphere is responsible for most aspects of language processing, it is not clear whether this advantage reflects direct or indirect linguistic influences. Several studies are proposed to investigate this further:
Study 1: Does the LH advantage for colour CP reflect attentional preferences?

Colour categorical perception is lateralised to the left hemisphere. It might be the case that this bias reflects processing differences between the two hemispheres. But, additionally, it may reflect attentional preferences for the right visual field. A study is suggested where a locational pre-cue would be combined with the standard target detection task, alerting the observer to the probable location of the target. On 80% of the trials, the cue would be valid and it would be invalid on 20% of the trials. If lateralised CP were found to be present on invalid trials, it would suggest that CP is not due to attentional preferences.

Study 2: The effect of verbal interference on CP in low-level perceptual tasks.

Verbal interference eliminated CP even though a seemingly low-level perceptual task was used. It is not clear why and how linguistic processes can influence early perceptual decisions. One way to investigate how language influences CP under verbal interference conditions is to find a better way of integrating behavioural data and neuroimaging data. Additional experiments using neuroimaging techniques will help to clarify the relationship between performance responses in early stages of visual processing and higher cognitive level processing. More emphasis has to be given to the localisation of regions that are active during both secondary tasks, i.e. under verbal interference, and primary perceptual tasks. It might be the case that language has resulted in warping of perceptual space, as indicated by the LH bias for colour CP as found using a task that isolates perceptual processes, yet perhaps verbal codes emerge even during low-level perceptual tasks, and language areas are activated during the task.

Issues arising from experiments in Chapter 3 and 4 and future directions

Study 1: Colour CP in infancy for other colour boundaries.

Experiment 4 investigated lateralisation of CP for the blue-green boundary; however no other boundaries have been investigated yet. Further studies should test for laterality effects at other boundaries, such as purple-blue, green-yellow, etc., as well as between colours that change also in lightness, such as the red-pink boundary. If the same pattern of findings were observed in such studies, this would provide further support for a RH bias in colour CP.
Study 2: Colour CP in infancy: a cross-cultural study.

Experiment 4 showed that infants with English speaking parents show a RH bias in colour CP for the blue-green boundary. In addition, Experiment 7 showed that CP is lateralised to the LH in adults at linguistically marked boundaries. There is no previous cross-cultural infant research investigating the ble-yalá żjo boundary. Such a study would investigate whether infants with Greek parents also show a RH bias for this boundary, and how this develops with the acquisition of the distinct ble and yalá żjo terms. Second, such a study would investigate whether infants with English parents show CP for this boundary, and if CP is present at what age it is lost.

Study 3: Changes in lateralisation of colour CP; a cross-cultural study.

The age of colour term acquisition is variable across cultures (Bornstein, 1985). A study could compare toddlers of similar age but from different cultures, and with different levels of colour term knowledge. This study would help investigate when laterality effects occur, and whether age is a significant factor in changes in lateralisation of colour CP.

Study 4: Change in lateralisation of colour CP in secondary colour terms.

Some colour terms such as brown and grey are usually acquired around 9-months later than the other colour terms (Pitchford & Mullen, 2002). It would be interesting to test for laterality effects within an individual looking at these colours; for instance, a study could test the brown-orange boundary. A change in lateralisation of colour CP may occur later than for the blue-green boundary. Such a study would provide further evidence to suggest that the switch in lateralisation of colour Cp depends on colour term acquisition rather than age.

Issues arising from experiments in Chapter 5 and future directions

Study 1: Do explicit verbal instructions given during category training influence induced CP?

One possibility put forward in the discussion is that the nullified ‘reverse’ category effect in the LH may reflect language processes. For instance, participants may have used labelling strategies during the course of learning to classify the exemplars into the new categories.
This possibility may be investigated further using explicit instructions for category formation, i.e., during categorisation training explicit instructions may be given to classify the colours based on two lexically distinguished colour terms. It might be the case then that a clear CP effect can be found.

Study 2: Category training and pronounced/long-term CP effects.

The nullified ‘reverse’ effect was shown after three days of training. One experiment in such a study could test participants on the target detection task at different periods to check when/whether the performance would change. Additionally, even though the ‘reverse effect’ was nullified in the RVF, a clear CP effect was not present. Thus, another experiment would test whether more training is needed in order to show a clear CP effect. For instance, training would be more intense and/or longer, e.g., 10 days or two weeks, and then performance on the target detection task would be measured. Such a study would shed light on the mechanisms underlying long-term effects of training measured with low-level perceptual tasks.

Study 3: Can CP effects be induced through category training in other colour regions?

Özgen and Davies (2002) trained participants to divide the blue and green region into new categories, and the study reported in Chapter 3 trained participants to divide the green region into two new categories. So far, there has been no other research investigating other colour regions. A study is proposed where participants can be trained to divide several other colour regions into new categories. This would suggest a generalisation of findings showing categorical effect following category training in a range of colours in the colour spectrum.

Study 4: Can CP effects be induced by unlearning basic existing categories?

Chapter 5 investigated CP effects following category training dividing existed colour categories. It would be interesting to train participants to form new categories combining existing categories, e.g., green and blue, purple and blue, orange and brown etc. If new categories can be formed, than this would support further the notion that colour categories are flexible, and can be learnt and unlearnt.
Conclusion

This thesis investigated the nature and origin of colour CP addressing the question of whether colour CP is perceptual or dependent on language. The nature and origin of colour CP was investigated in a series of experiments focusing on the functional organisation of the brain. Investigations took a developmental, and a cross-cultural approach, as well as a learning paradigm. The results of the first experimental chapter showed that colour CP is stronger in the LH of adults, and that this bias disappears with verbal interference. The second experimental chapter investigated lateralisation of colour CP at different ages, and showed that pre-linguistic CP is lateralised to the RH, whereas once the colour terms relevant to the category boundary are learned then the RH bias in colour CP disappears. The third experimental chapter showed that CP in adults, and the LH bias in this CP, is present only when the category boundary is linguistically marked by the adult speaker. The final experimental chapter showed that category training also produces discrimination changes based in the LH for between-category discriminations. The main contribution of this thesis is that it suggests ways of reconciling Universalist and Relativist accounts of colour CP. Both universal constraints and the influence of colour language on colour categorisation are supported. There appear to be two forms of CP: one which is RH lateralised and is found before colour term acquisition, and another form which is LH lateralised and is found in adults, but only when adults mark the category boundary linguistically. Future research should focus on establishing whether the observed LH bias for adult colour CP arises because of language indirectly producing CP by affecting perception during colour word learning, or the online, albeit 'implicit', use of language during target detection.
REFERENCES


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