Synchronising the Senses:
The Impact of Embodied Cognition on Communication, Explored in the Domain of Colour

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> "Why did I study Linguistics instead of Celestial Mechanics?
> Linguistics got me into this excellent mess - only physics can get me out."
> Neal Stephenson, *Anathem*

Abstract

Colour terms divide the visual spectrum into categorical concepts. Since Berlin & Kay’s (1969) cross-cultural study of colour terms, there has been debate about the extent to which these concepts are constrained by innate biases from perceptual hardware and the environment. This study shows that concepts can affect perception in the domain of colour (e.g., reading the word ‘yellow’ causes us to *see* yellow). An experiment was run in which participants were asked to adjust the font colour of colour terms to appear grey. In fact, participants adjusted the font colour to perceptually oppose the colour the word described (e.g., the word ‘yellow’ was adjusted to be blue). This is interpreted as over-compensating for a perceptual activation caused by the comprehension of the word. These results are used to argue that cross-cultural patterns in colour term systems do not necessarily imply strong innate biases. It is argued that the most efficient way of converging on, maintaining and transferring a conceptual system is for shared categories to re-organise perception. This re-organisation will converge to optimally fit the perceptual and environmental biases. Therefore, an Embodied, Relativist explanation of cross-cultural patterns is supported. Furthermore, if the comprehension of language involves the activation of perceptual representations, then there will be a communicative pressure to reduce perceptual differences between speakers.

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1 Introduction

Our understanding of the world begins with perception. When we perceive an object, such as a piece of fruit, our sensory equipment measures features of the world such as pressure (touch), chemical composition (taste and smell) or the spectral intensity of light (vision). Our brains then process this analogue data into meaningful, categorical structures such as 'a banana'. Thus we abstract away from the complexity of the world to create *concepts*. This ability helps us function in the world, and is not unique to humans (Hurford, 2007, p.9-16). However, humans are unique in the ability to attach labels to these concepts using *language*. We can use language to convey our thoughts to other humans and reconstruct the thoughts of others in our own mind. This study is concerned with two approaches to language. Universalism takes the position that language is subject to innate constraints from perception and the environment and therefore all cultures will have fundamentally similar understandings of the world. Linguistic Relativism, on the other hand, hypothesises that the structures of a language affect the way individuals think about the world. In this case, concepts can affect cognition and perception.

Since Berlin & Kay's (1969) work on the World Colour Survey, this debate has been researched through the domain of colour perception. This has made the problem more tractable, since it restricts the domain to one sensory modality and the physiology of colour perception is well understood. However, with essentially no variance across populations in terms of the physiology of vision (Mollon, 1999), different cultures nevertheless seem to have strikingly different approaches to colour. For example, the Mangyans of the Philippines seem to have only 2 colour terms – that of 'fresh' and 'dry' colours (Ball, 2001, p. 15-16). In contrast, speakers of Tzotzil from Mexico appear to have hundreds of grammaticalised forms that describe colour (MacKeigan & Muth, 2006). Neither are colour categories stable across time – the English terms 'yellow' and 'blue' have the same etymological root, reflecting a time when yellow and blue were seen as different shades of the same colour (Ball, 2001, p.264). Nevertheless, universal patterns in colour term systems (e.g., Berlin & Kay, 1969) have been taken as evidence for universal, innate biases (Bornstein, 1973). This study argues that this inference is not valid. It is true that some colours are more functionally salient than others. For example, leaves are green whereas fruit are red-ish. Therefore, it is functionally useful to have labels that separate green and red. Furthermore, some colours are more perceptually salient than others (Jameson & D'Andrade, 1997). It has also been shown that natural colour term systems are optimised for constraints on the hardware of vision (Regier, Kay and Khetarpal, 2006) and for functionally classifying objects (Griffin, 2006). Universalism would argue that these innate biases have lead to universal patterns in cross-cultural colour term systems.

However, cross-cultural patterns could occur without innate biases through the following process: If comprehension is based on perception (the Embodied Cognition hypothesis), an adaptive pressure to improve communication will try to minimise perceptual differences between people. That is, by synchronising perception, people's conceptual understanding of the world becomes closer. This requires a process that can change an individual's perceptions to fit a shared configuration. If categories can affect perception (the Categorical Perception hypothesis), then, since categories can be shared through language, categories can warp perceptual spaces (e.g., Kuhl, 1991, Iverson & Kuhl, 1995) so as to bring people's perceptual experiences closer. Systems are likely to converge on colour terms that optimally allow functional discrimination and that involve the least modification of the average perceptual bias. This will cause colour term systems to become optimised for constraints on the hardware of vision and for functionally classifying objects in the environment. Given similar perceptual hardware and survival pressures, this will lead to universal patterns in colour term systems. However, by this line of argument, the innate biases reflected in the colour terms are not the driving adaptive force, but a *product* of a communicative pressure acting in a cultural system. Therefore, even a Relativist approach to language would expect universal patterns in language. It is concluded that universal patterns do not necessarily support Universalism. Furthermore, an Embodied approach is favoured, since it causes a pressure for colour term systems to become more efficient at describing the real world.

For the argument above to hold, three implications need to be proven: Firstly, comprehension is based on perception (**The Embodied implication**). Secondly, linguistic labels (categories) can affect perception (**The Categorical Perception implication**). Thirdly, there is a mechanism whereby categorical effects on perception can cause colour terms to converge on functionally and perceptually optimal configurations (**The Cultural implication**). Each of these implications will be considered.

The Embodied implication will be considered by reviewing the literature on Embodied Cognition. Embodied Cognition Theory hypothesises that there is no neurological distinction between concepts and perception and that comprehension involves re-creating the motor responses or perceptual impressions associated with that concept (e.g., Barsalou, 1999). For instance, understanding the word ‘kick’ involves motor areas which control the leg (Hauk, Johnsrude & Pulvermuller, 2004). Similarly, hearing the word ‘yellow’ activates perceptions of the colour yellow (Ritcher and Zwaan, 2009). Studies of Categorical Perception have shown that concepts can indeed influence perception (e.g., Gilbert, Regier, Kay & Ivry, 2006).

The Categorical Perception implication will be tested by running an experiment which demonstrates that the comprehension of colour terms activates perceptual representations. Although this has been examined to some extent, the current evidence is conflicting. Most studies of categorical perception involve detecting differences in reaction times to stimuli that match or mismatch primed perceptual representations. The current study will use a different approach that is less reliant on processing speed. This paradigm comes from Hansen, Olkkonen and Walter (2006) who found that natural objects with a ‘typical’ colour retain traces of this colour in perception, regardless of their actual colour. For example, bananas look slightly yellow, even when they are actually achromatic (grey). This study will show that this effect extends to abstract words (e.g., the written word ‘yellow’ activates perceptual representations of the colour yellow). This suggests that the linguistic system is built on top of a system for recognising objects (MacWhinney, 1999). This paradigm also tests the sub-implication that concepts should continuously and persistently affect perception.

The Cultural implication will be explored by showing how linguistic categories can affect other domains of constraint. This will involve defining the domains of constraint and the interactions between them. It will be argued that categorical perception causes a dynamic which fits into Niche Construction Theory (Laland, Odling-Smee & Feldman, 2000). Finally it will be concluded that a Universalist approach is not appropriate.

The next section will cover other areas of the theoretical background. Section three will give an overview of the field of colour categorisation. Hansen et al. (2006) will be explained in section four. Section five will define the constraints on colour categorisation, and consider evidence for the influence of each domain of constraint. Section six draws conclusions from this evidence and summarises the implications for theories of cultural transmission. Two experiments on the effects of categorisation on perception are presented in sections seven and eight. A general conclusion follows.

2 Theoretical Background

In this section, the major theories discussed in this study are outlined, including Universalism, Relativism, Embodied Cognition, Symbolism and Niche Construction. Also, since much of the research on constraints on colour terms involves computational models, the rationale behind using models is explained.

2.1 Universalism and Relativism

Universalism and Relativism are two Structuralist approaches to language. Universalism holds that the variation in language and culture is superficial in the sense that there is one common system of cognition underlying them, based on common constraints from perception or the environment. Linguistic Relativism hypothesises that cognition is determined by the language the individual speaks. The strength of this supposition varies between theorists. Relativism grew from the so-called Sapir-Whorf or Whorfian hypothesis (Sapir, 1929, Whorf, 1940/1956) which holds that the linguistic categories held by an individual can affect the way that individual perceives the world. A strong Whorfian hypothesis assumes that there are no constraints on the way linguistic categories are formed (Kay and Kempton, 1984). Section 5 will show that this is not the case for colour categorisation. Indeed, in the domain of colour, Berlin & Kay's (1969) study of basic colours has been interpreted as strong evidence for Universalism (Bornstein, 1987), although Kay's later studies supported a weak Whorfian theory (Kay and Kempton, 1984, Gilbert, Regier, Kay & Ivry, 2006). Recently, within the field of colour categorisation, it has been suggested that the contradictions between the evidence for Relativist or Universalist theories points to a possible third interpretation, situated in the middle ground between the two (Regier, 2007, Claidière, Jraissati & Chevallier, 2008, Jameson, 2005).

2.2 Categorical perception

Categorical perception is a phenomenon whereby continuous, noisy data from the environment is sorted into discrete categories (Harnad, 1990). For example, the visual spectrum is divided into discrete colour categories such as red, yellow and so on. Furthermore, by creating these categories, stimuli from the same category may be perceptually more alike than stimuli from different categories, regardless of their physical similarity (e.g., Liberman, Harris, Hoffman, & Griffith, 1957). That is, categories can affect perception, which fits with a weak Whorfian hypothesis. For example, two shades of green may appear more similar to each other than to a shade of yellow, even though their wavelengths may be *physically* equidistant (Gilbert, Regier, Kay & Ivry, 2006). This is a categorical boundary effect (Pastore, 1987).

Lupyan (2008) found that verbally labelling a concept enhances the categorical boundary effect. Lupyan also concludes that perceptual spaces can be modulated or warped by context-specific online processes rather than long-term, memory-based processes. In addition to explaining the plasticity and context-sensitivity of language, it also explains how individuals can switch between more than one language. This study considers the origins of the categorical boundaries of colour terms. Are they determined by perception or by language? Universalism would argue that perception is the main constraint – that categories are formed based on the optimal way of partitioning the environment. Relativism, on the other hand, would argue that the concepts within a language are the primary constraint on the boundaries. In this sense, language can affect perception. This study will argue that the Relativist position is supported by adopting the approach of Embodied Cognition.

2.3 Embodied Cognition

Given that the range of constraints on colour categorisation includes perception, cognition and the environment, it makes sense to adopt the approach of Embodied Cognition (e.g., Barsalou, 1999). Embodied Cognition arose as a response to classical cognitive approaches (e.g., Artificial Intelligence, Symbolism) which typically study internal processes in isolation. Embodied Cognition emphasises that cognition originated to serve physical agents competing in a real environment, not to solve high-level planning problems like playing chess (Brooks, 1990). That is, cognition is primarily used for driving action in a real environment to complete low-level goals (e.g., finding food, avoiding predators) in real-time (Brooks, 1986, Thelen and Smith 1994, Thelen 1995).

An idea often linked to Embodied Cognition, and one which is associated with it in this study, is the *perceptual symbols* account of comprehension (Barsalou, 1999, Lakoff & Johnson, 1999). Symbolism assumes that cognition involves the manipulation of abstract symbols. In contrast, perceptual symbols theory, traceable to David Hume (1784/1902), hypothesises that comprehension of language involves the simulation of the perceptual representations involved in perceiving the referent or the motor activity involved in carrying out the described action (Hauk et al., 2004, Pulvermüller, 2001). For example, Zwaan, Stanfield and Yaxley (2002) showed participants sentences which included a target word, but implicitly suggested a particular shape. For example, 'an egg in a carton' (ellipse) and 'an egg on a frying pan' ('sunny side up' - circle surrounded by smooth, curvy line). They were then shown a picture of the object in either a matching or mismatching configuration to the preceding sentence and asked to decide if the object had appeared in that sentence. Matched conditions evoked faster reactions than mismatched conditions. Similar results have been found for orientation (Stanfield & Zwaan, 2001) and motion (Zwaan, Madden, Yaxley, & Aveyard, 2004). Zwaan et al. (2002) argue that this would not happen if comprehension involved only amodal symbols – a symbolic 'egg' would activate all shape configurations equally. Instead, *perceptual representations* are activated that involve shape during language comprehension, and there is a processing cost involved when this representation clashes with the one presented. These findings fit into Embodied Cognition theory because they show that perception and comprehension are inherently linked. For example, comprehending an egg involves a functional comprehension of the use of an egg in context. Neuroimaging studies have shown that the same neural substrates are involved in both perception and comprehension (Hauk et al., 2004). However, this effect appears to be lateralised to the right visual field (the left hemisphere, Gilbert et al., 2006, Drivonikou et al., 2007). This could be linked with the lateralisation of language to the left hemisphere creating strengthened connections between linguistic categories and perceptions (Pulvermüller, 2001).

For colour categorisation, then, Embodied Cognition would predict that the cognitive processes behind colour perception were systematically related to the goals of the perceiver as they attempt to survive and replicate in their environment. This would include, for example, being able to easily distinguish colours used by other organisms for signalling (e.g., typical fruit colours), and having words for colours that could be used to distinguish between objects in the world that were part of different goals (for instance, green leaves versus fruit). The first set of goals suggests that colour systems may be adapted to the environment in which they are used. The second set of goals have a social aspect, and include actions such as being able to describe the difference between an edible and a poisonous berry, or request a particularly coloured thread for weaving. These would be subject to cultural constraints. Furthermore, an Embodied approach predicts that the comprehension of colour terms activates perceptual representations of that colour. For example, reading the word ‘yellow’ would activate perceptions of the colour yellow. The experiments in this study test this prediction.

2.4 Niche Construction

This study notes that the domains which affect the origins of categories (e.g., genes, the environment, culture) are not causally separate. For example, an individual’s genes will affect its perceptual hardware, and the range of colours this hardware can detect will have an effect on the categories that are formed. The Embodied Cognition hypothesis predicts that there is a causal link between language and perception. This study will show that this causes a feedback loop between different causal domains which creates a dynamic similar to *Niche Construction* (Laland, Odling-Smee & Feldman, 2000). Niche construction theory observes that some organisms change their environment in a way that influences the pressures to which they must adapt. For example, spiders spin webs and those spiders that are best adapted to life on a web will survive and reproduce. Over time, offspring become better suited to living on a web and better at building a web. Thus, the spider has constructed its own evolutionary ‘niche’ to which it has adapted. Humans change their environment more than any other organism, and so are the ultimate niche constructors. This study suggests that the categorical perception of colour has Niche Construction dynamics. For instance, the range of colour terms you share with your decorator may influence the colour of your walls, which in turn will strengthen the link between that colour term and the perception through exposure.

2.5 Modelling

Such is the complexity of the interactions of constraints governing colour categorisation that many studies have used computational models to investigate the influence of each pressure. Modelling is advantageous because it clarifies the theory and can generate dynamic interactions that are too complex to imagine otherwise. From these interactions, novel predictions can be formed that can be tested in the real world. These models typically involve many computational agents which interact. These agents can learn to associate lexical items with a particular range of the colour spectrum. They typically play two ‘games’ in order to acquire categories. The first is a ‘discrimination game’ wherein agents try to form categories that uniquely identified a given colour (that is, one where any given colour only belongs to only one category). The second type of game takes place in models of cultural transmission. Agents play a ‘communication game’ which models the acquisition of colour terms. This involves associating a category with a lexical item. One agent describes a colour in the environment according to its lexical categories and another agent attempts to pick out that colour according to its own categories. Agents adapt their categories so that, over time, their categories converge to a common configuration. That is, having the same words which refer to the same range of the colour spectrum.

3 Colour Categorisation

This section outlines the field of colour categorisation. First, however, its relation to broader field of modern linguistics is summarised. About 100,000 years ago, a genetic change occurred in the ancestors of humans which resulted in the ability to label concepts and express them in meaningful ways. Modern linguistics has focussed on researching this change. Nativists have focussed on describing the innate ‘principles’ that all languages share (e.g., nouns and verbs) and the set of ‘parameters’ that can lead to differences in the surface forms of languages (e.g., right- or left-headed grammar, e.g., Chomsky & Lasnik, 1993). The ‘change’ for Nativists involved the ability to detect and set those ‘parameters’. Empiricists argue that the innate ‘principles’ are actually rooted in the structure of the world (e.g., principles of processing efficiency). The ‘change’ for Empiricists was an improved ability to process this structure (e.g., recursion, Hauser, Chomsky & Fitch, 2002). Culturalists, on the other hand, argue that the ‘change’ involved the way information is transmitted (e.g., Kirby, 2007). Before language, information could be gained by genetic inheritance or from individual learning. Language allows rapid, multi-agent, cumulative information transmission. The big question of modern linguistics, then, centres on the role of genes (Nativism), the environment (Empiricism) and culture (Culturalism).

The first individuals with the ability to label concepts and share these labels still had a long way to go before communication was possible. Imagine that you want to communicate a piece of knowledge to another person, namely that a particular type of fruit is poisonous. You decide that the best way to distinguish the fruit is by its colour, but have not yet developed a naming system for colours. The main problem to overcome is not necessarily establishing a sign, but establishing the referent. This is because, unlike structural features (size and shape), there is much less certainty about whether the colour percept you experience while looking at the fruit will be the same as the colour percept that somebody else experiences. This is because colour is a 'secondary object property' – one that can only be sensed with one modality (Locke 1690/1975, Jackson, 1977). Also, there are variations between individuals' perceptual hardware (Jameson, Highnote, & Wasserman, 2001) and an object's exact spectral intensity is not stable over time.

Luckily, there are several factors that lead to sensible partitions of the visible spectrum. Firstly, people share the same sensory equipment (cones and rods) and cognitive processes (opponent colour processing). Secondly, the perceptual space is non-uniform, meaning that there are more and less optimal ways of describing this space (Jameson & D'Andrade, 1997). Thirdly, the sensory equipment and the colour of the fruit have co-evolved so that the fruit is easily detectable (Regan, Julliot, Simmen, Viénot, Charles-Dominique and Mollon, 2001). Also, people have plasticity of mind which allows them to adapt and learn. Finally, you live in a community of people who have been faced with this problem before. A system of signs for colour can use constraints from genes, the environment and culture to anchor an otherwise arbitrary pairing of colours and signs. This is essentially the theory used by Steels and Belpeame (2005). However, they reached this conclusion by adopting a Universalist approach to colour categorisation. This study will show that a Relativist approach can also reach this conclusion. This study will argue that the most efficient way of converging on, maintaining and transferring a system for describing colours is for shared categories to be able to influence perception. That is, instead of synchronising information about how each individual maps perceptions onto signs (Symbolism), we synchronise our perceptions so that each individual's mapping is the same (Embodied Cognition).

3.1 Colour Perception

This section outlines the basic physiology of colour perception and introduces the perceptual colour space used in the experiments. Colour is the perceived spectral intensity of light. Energy at various wavelengths is emitted from objects such as the sun or electric lamps. Part of this spectrum of energy is perceivable by human eyes – roughly the range 380 to 750 nm

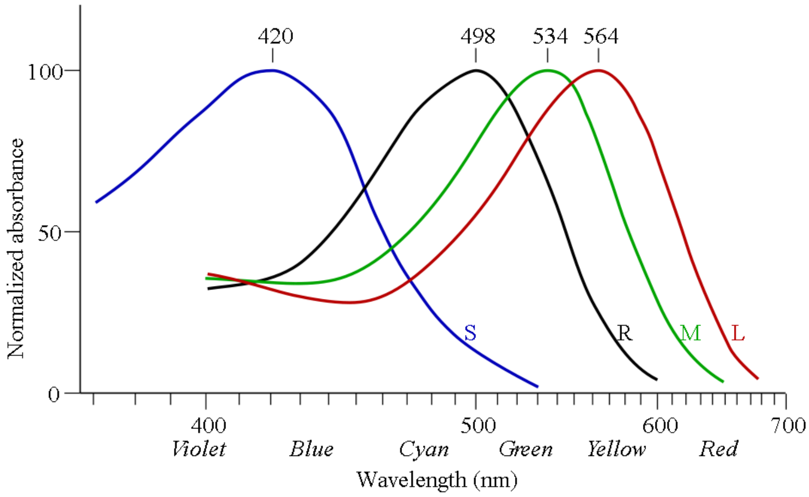

Figure 1: Spectral absorption curves of rod cells (R) and the short (S), middle (M) and long (L) wavelength pigments in cone cells. Image from http://en.wikipedia.org/wiki/File:Cone-response.svg, adapted from Bowmaker & Dartnall (2005, p.505).

(Starr, 2005). Objects may absorb or reflect certain wavelengths of light. Colour results from differing intensities of energy at specific wavelengths. For example, a light with high energy at high wavelengths and low energy at low wavelengths will be perceived as red. Light is detected in the eye by cone cells and rod cells. These contain opsin proteins which are sensitive to light. The rod cells have a broad range and used to detect low-level information about shape and movement. Cones are used for perceiving colour. In a typical eye, there are three cone types which have different peak sensitivity to different portions of the spectrum, those being Short-wave (blue), Middle-wave (green) and Long-wave (red) (abbreviated to S, M and L). The relationship between wavelength and absorbance for a cone type is Gaussian and the ranges of cone types overlap (Figure 1).

To generate perceptions of colour, two types of cells in the Parvocellular lamine – Midget Ganglion and Small Bistratified Ganglion – compare different classes of cone (Regan et al., 2001). The Midget Ganglion cells calculate the ratio between the excitations of the Long and Middle cones (L–M), and the Small Bistratified Ganglion cells calculate the relative excitation of the Short cones compared to the Long and Middle cones ((L+M)–S) (Regan et al., 2001). These two measurements motivate the Derrington Krauskopf and Lennie (DKL) perceptual colour space (Derrington Krauskopf & Lennie, 1984) used in the current study. This is a spatial mapping of colour. Moving along the x axis changes the L and M cone activations independently from the S cone activation. Moving along the y axis changes the S cone activation independently from the M and L cone activations. There is a third axis which alters the luminance (brightness). Any cross-section perpendicular to this axis will be an

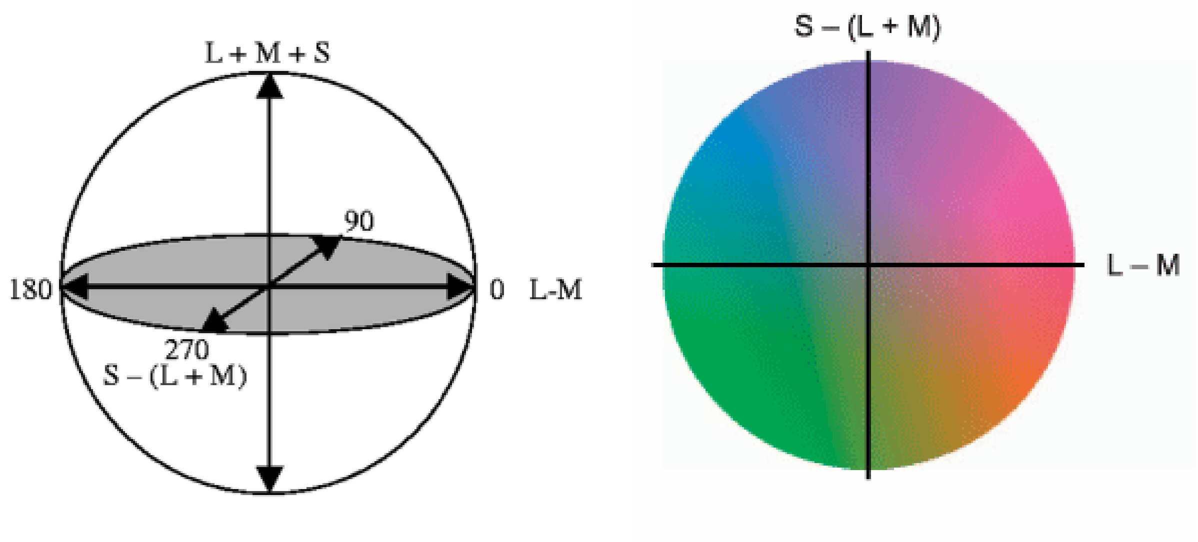

Figure 2: The DKL colour space (Mandelli & Kiper, 2005) (left)
and an isoluminant plane (Hansen & Gegenfurtner, 2006, p. 241) (right).

isoluminant plane, that is, all colours will be perceptually the same luminance (see Figure 2). The centre of an isoluminant plane is called the *adaptation point*. This will appear as completely achromatic (grey) to the average eye. This colour is used for the background in the experiment (participant's eyes adapt to it, hence 'adaptation point'). A participant's idea of 'grey' – their *subjective white point* – may differ from this (white does not mean brilliant white, only an achromatic shade). There is no such thing as a universal 'grey point' that all people will see as achromatic. The adaptation point in Hansen et al. and in this study is set to the colour of the Munsell chip English speakers choose as the best example of 'grey' (Berlin & Kay, 1969).

3.2 Colour Terms

This section introduces the early research on colour terms across cultures. Berlin and Kay (1969) compiled the World Colour Survey (WCS) – a database of how different languages partition the visual spectrum into colour terms. Observing cross-cultural patterns, Berlin and Kay adopted a Universalist approach to colour terms, assuming that there were certain universally salient colours and universally salient categories of colour. These universal categories are mapped onto 'basic colour terms' in each language. These were defined as words which describe colours that were monolexemic (they do not contain modifiers like 'dark red') and psychologically salient (perceptually and socially salient in everyday situations, for instance 'red' has important symbolic roles in cultures and is easily sensed by the perceptual system). However, they cannot be hyponyms (for instance 'crimson',

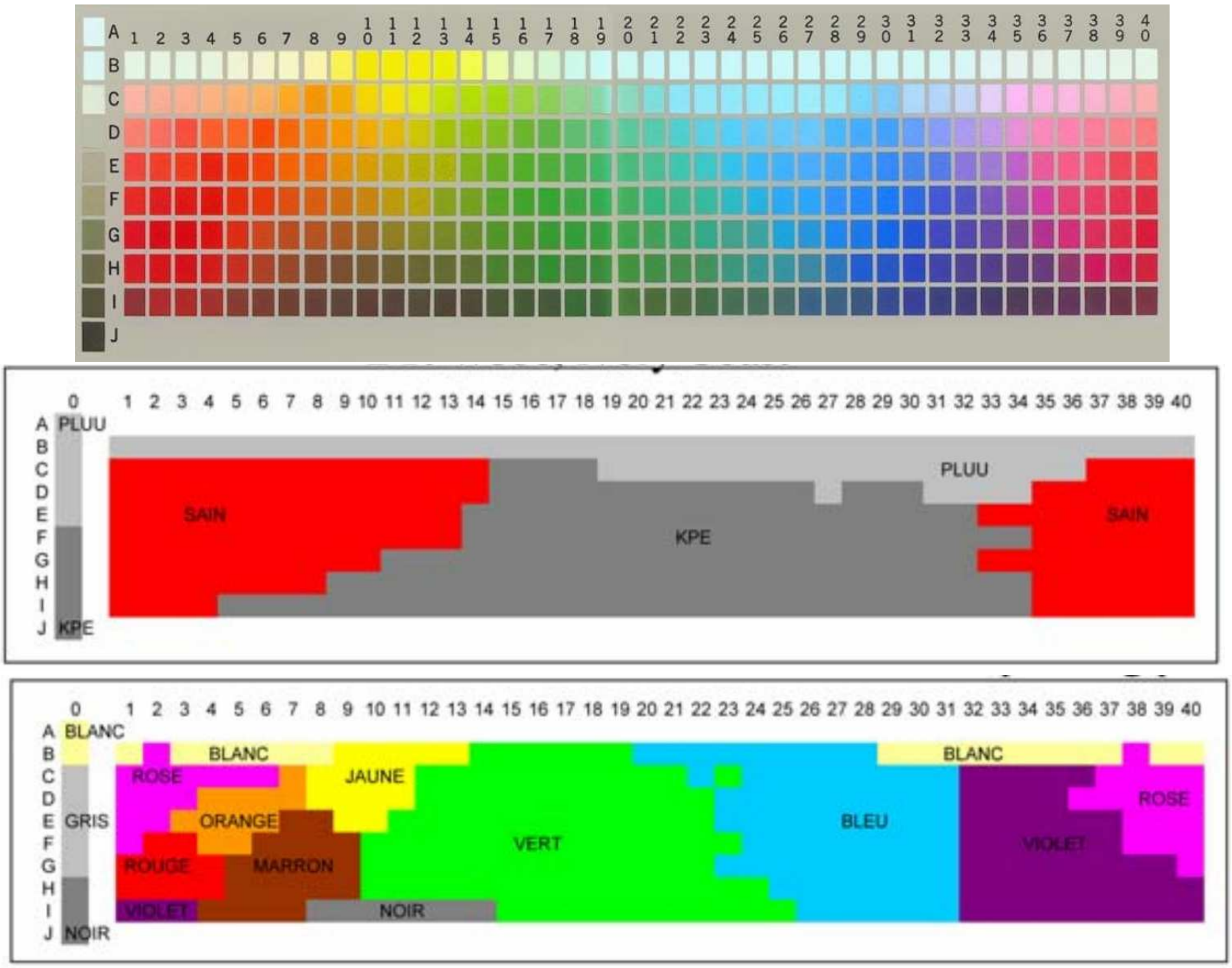

Figure 3: A space representing the Munsell chips used in the WCS (top, from http://www.icsi.berkeley.edu/wcs/data.html) and the partitioning of that space in Wobé (middle) and French (bottom, both from Claidière, Jraissati & Chevallier, 2008).

'vermillion' are hyponyms of 'red') nor contextually restricted (for instance, 'blonde' is usually restricted for hair colour).

The number of basic colour terms in a language varied between 3 (e.g., for Wobé) and 12 (for Russian). Once these basic colour terms were defined for a given language, a Munsell-chip task was administered to a speaker of that language. In this task, participants are given a large number of coloured chips whose colours are (physically) uniformly spaced (although not psychologically uniformly spaced, see section 5.2.3). Participants are asked to choose the 'best example' or 'focus' of a given colour term. They are then asked to sort all the chips into groups based on the basic colour terms. These define the range of each colour term (the boundaries). Figure 3 shows a colour space where each point is one of the Munsell chips used in the WCS experiments. Also, the partitioning of that space by a speaker of Wobé (3 basic colours) and French (11 basic colours) are shown. For the latter two, a different colour indicates a different colour term (note that the space warps around horizontally, so that the chips in the first column are as close to the second column as the final column on the far right).

Berlin and Kay noted that certain basic colour terms were more likely to exist in a language, for example, most colour systems have a term for black and white, but not all have a distinction between red and pink. From this they formulated a universal order of colour-term evolution. Figure 4 summarises the order. In the first stage (leftmost) the system only differentiates between light and dark hues (black and white). In the second stage, an additional red term emerges, then a green or yellow term emerges in the next stage. This process continues until all basic colours have their own term (for a more in-depth analysis, see Kay & Maffi, 2009).

Stage I	**Stage II**	**Stage III/IV**	**Stage V**	**StageVI**	**Stage VIII**
		Green			Purple
Black	+ Red	*or/and*	+ Blue	+ Brown	+ Pink
White		Yellow			Orange
					Gray

Figure 4: Evolutionary stages of colour terms (from Berlin & Kay, 1969, p.4).

This approach of deriving a universal set of constraints on the structure of language from comparative studies has parallels with Universal Grammar (e.g., Chomsky, 1957). However, the methodological approach has been criticised (e.g., Saunders & van Brakel, 1997, Saunders, 2000, MacKeigan & Muth, 2006). More fundamentally, it has been demonstrated that weak innate biases can be amplified by cultural transmission (Kirby, Dowman & Griffiths, 2007), showing that cross-cultural patterns do not imply strong innate biases. The current study will argue that Kirby et al's point applies to colour terms.

4 Memory Modulates Colour Perception

This section reviews the motivational paper for this study. Hansen et al. (2006) measure subjective perceptions of colour as modulated by semantic information, testing the Embodied implication. This paradigm also tests whether the perceptual symbol hypothesis is supported by more than just a short-term processing effect. Hansen et al. (2006) (reported in more detail and extended in Olkkonen, Hansen & Gegenfurtner, 2008) conducted an experiment to see whether the knowledge that an object has a 'typical' colour, for example bananas are yellow,

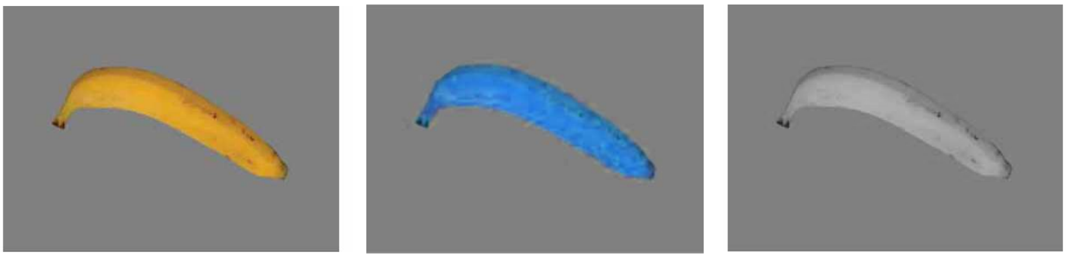

Figure 5: A ‘typical’ yellow banana (left) and the same image manipulated to appear (saturated) blue (middle) and achromatic (right).

affects the perception of that object. To do this, an experimental setup was employed whereby pictures of coloured fruit could be manipulated by the participant to any hue, maintaining a constant brightness. This was done with four buttons which moved the locus of the hue distribution in a perceptually motivated colour space (DKL space, explained in section 3.1). Participants were shown the pictures in a random hue (e.g., green banana) and asked to adjust it to appear naturally coloured (i.e. yellow banana). These were the ‘typical’ settings. Participants were then asked to adjust the hue of pictures of coloured fruit until they appeared achromatic – that is, grey or completely colourless. These were the achromatic settings. The ‘true’ grey was defined in reference to the adaptation point - the colour of the background on which the stimulus was presented, and to which the participants eyes adapted. The adaptation point was set to the hue of the Munsell chip English speakers choose as the best example of ‘grey’ (Berlin & Kay, 1969). Hansen et al. found that the achromatic settings were slightly removed from the adaptation point in the direction opposite to the typical setting in an opponent-colour space. For example, a banana would be adjusted to be slightly bluer than grey. This was interpreted as a ‘compensation’ for the previous experience of seeing yellow bananas. For all 7 fruit tested (carrot, orange, banana, lemon, cabbage, grapes, courgette), this trend held, while achromatic settings for random patches of colour were no different from the adaptation point. To quantify this effect, the Memory Colour Index (MCI) was used (see section 7). Briefly, this value is large when the vector between the typical setting, the adaptation point and the achromatic setting is straight and long. That is, the MCI is large when the achromatic setting is adjusted into the directly opposing colour to the typical one. This involved a consideration of participants’ subjective white points, calculated by asking the participants to adjust control stimuli (uniform patches with no semantic structure) to appear achromatic.

Figure 6 shows a graph summarising the results. The settings of the participants are set out in a perceptual colour space, with the adaptation point in the centre (explained in section 7.3). A line is drawn for each fruit type from its mean typical setting (yellow banana, topmost points), the achromatic settings for control stimuli (‘true’ grey, points within the black circle) and the fruit’s mean achromatic setting (grey banana, bottom-most points). The line for the banana passes from yellow, past the adaptation point (true grey) into the opposite side of the colour space (blue).

Olkkonen et al. suggest that low-level processes in the lateral occipital complex are responsible for the memory colour effect and that a mechanism such as modulatory feedback (Grossberg, 1980) can integrate bottom up visual data with top-down expectations. Olkkonen et al. (2008) expanded the study to look at the importance of surface texture and shading. It was also found that the memory colour effect was robust under different illuminations. That is, the effect was independent of colour constancy. However, images without texture (e.g., a uniformly coloured banana with shadows) and without shading (e.g., a uniform outline of a banana) elicited less of a memory-colour effect. While the participants still recognised the outline of a banana as a banana, the identity of the object only affected perception when *all visual cues were present* (outline + shading + texture). This weakening of the effect was used

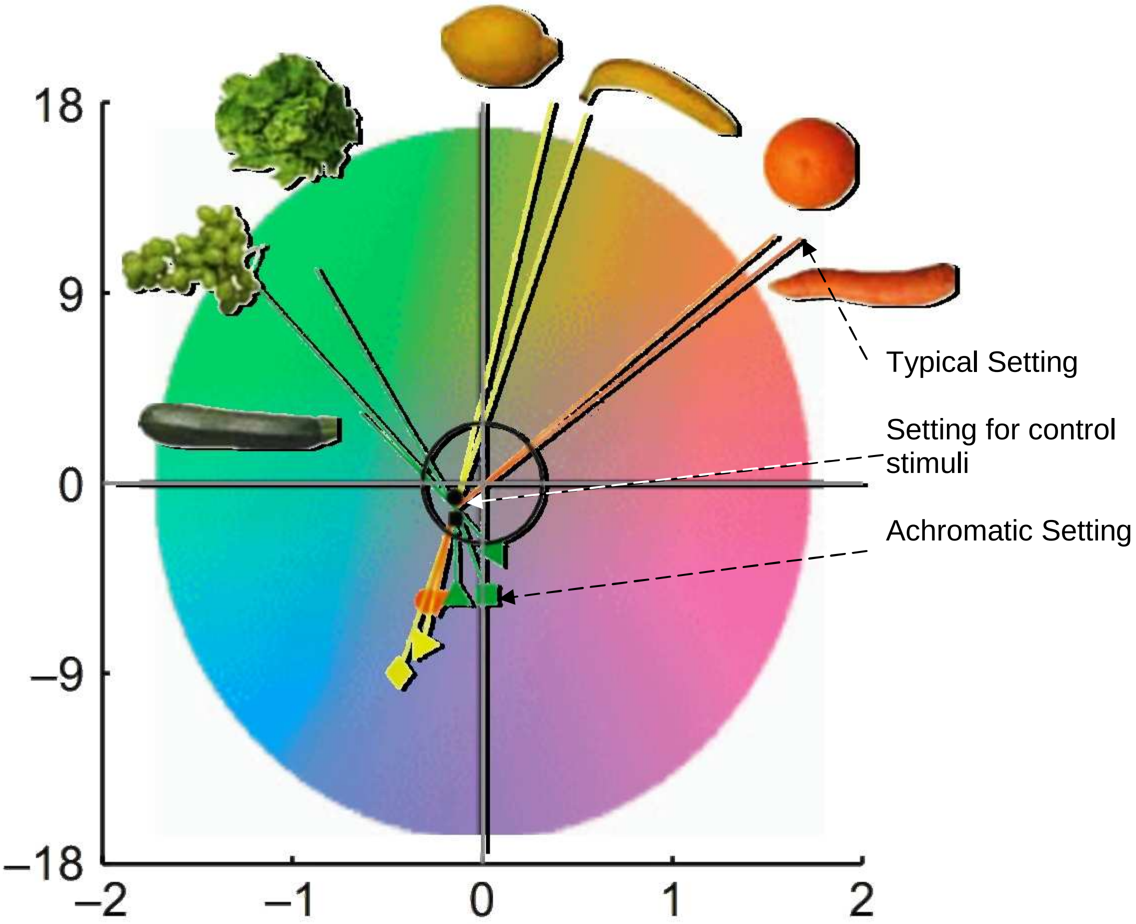

Figure 6: Results from Hansen et al. (2006). The typical and achromatic settings for fruit stimuli. Axes are percentages of DKL space.

to argue that the effect was genuinely perceptual and not due to high-level semantic priming (i.e. knowing it is a banana).

The results of this study are compatible with a perceptual symbol approach, since recognising a banana involves the perception of the colour yellow. However, it does not address the Whorfian hypothesis, since there is no language involved. Hansen et al.'s paradigm will be adapted to test whether perceptual representations are activated by colour terms rather than pictures of fruit. It is predicted that participants will adjust the colour of a colour term beyond their subjective white point in the opposite direction to the one the word describes. For example, the word 'yellow' displayed in an achromatic colour will still appear yellow, and so participants will compensate by adding a blue tint. This will show that reading the word 'yellow' triggers the activation of perceptual representations of the colour yellow (and so on for the other colours). However, Olkkonen et al.'s finding that pictures with less structure elicited less of an effect would predict that colour terms, which are a further abstraction, would have a small perceptual effect. If an effect is found, this will support an Embodied approach to language comprehension. Furthermore, if the comprehension of words is based on the same system as the recognition of natural objects, an Embodied approach to the emergence of language is supported (MacWhinney, 1999).

This paradigm differs from those in other Categorical Perception studies. To begin with, it does not belong to either of Harnad's (1990) methods for researching Categorical Perception. That is, it does not involve discrimination – indicating whether a pair of stimuli are the same or different. Neither does it involve identification – the labelling of stimuli by the subject. Furthermore, other paradigms involve matching colours which are separated spatially or by temporal intervals. Hansen et al.'s paradigm allows simultaneous matching and a fine granularity of colour manipulation which does not rely on short term memory. Also, Hanson et al's paradigm has no time constraints, showing that perceptions are continuously and persistently affected by the properties of the perceived object. Furthermore, inferences in previous Embodied Cognition experiments were drawn from differences in high-level task performance (e.g., confirming the presence of an object or judgements of similarity). Since the stimuli in the current study are manipulated in a perceptually motivated space, and therefore any adjustment by the participant can be quantified in terms of mean Small, Medium and Large cone activations, the results of the current study come from direct, low-level neurological representations of the participant's perceptions. This is seen as an advantage.

5 Constraints on Colour Terms

This section defines the constraints on colour terms in a cultural system, and how they relate. By considering the importance of each domain, conclusions will be drawn about the Universalist/Relativist debate and whether the Cultural implication is supported. Explanations of the cross-cultural variation in colour terms have considered the effects and interrelationships of genetics, culture and the environment. For example, Bornstein (1973) first pointed out that the number of colour terms in a language is likely to be higher if that language is spoken further from the equator (quantified by Ember, 1978). However, the explanations of this pattern have included genetic, cultural and environmental constraints. For example, greater Ultraviolet radiation nearer the equator leads to changes in the eye which favour fewer colour terms (Lindsey & Brown, 2002, see section 5.2.1). This environmental constraint will lead to a genetic adaptation (Bornstein, 1973, Lindsey & Brown, 2002). On the other hand, it has been argued that cultures near the equator tend to be less technologically advanced, leading to less of a requirement for exact specification of colour (Magnus, 1880, Regier & Kay, 2004).

Under conventional interpretations, Universalism and Relativism differ with respect to the pressures that they predict will have the greatest effect on colour categorisations. Universalism predicts that linguistic categories are constrained primarily by perception (Nativism) and environment (Empiricism). Relativism predicts that linguistic categories are primarily constrained primarily by language and culture (Culturalism). I argue that if one takes an Embodied approach which emphasises the functional role of cognition, a different prediction is made for Relativism which allows it to explain more of the variation in cross-cultural colour term systems.

In order to do this, the relationships between the constraints on colour terms in a cultural system need to be outlined. First, the entities and processes involved with colour categorisation are identified (entities are in bold and processes are italicised): **Genes** produce **Phenotypes** through *Ontogeny.* This phenotype is immersed in an **Environment**. The Phenotype passes on its genes through *Genetic Inheritance* (e.g., sexual reproduction), dependent on *Natural Selection* pressures from the environment. The phenotype has sensory organs which interact with the environment to activate a perceptual space by a process of *Perception*. According to Embodied cognition, this space is also used for comprehension, so it is a **Conceputal/Sensory Space**. Motor control is also included in this space. This conceptual/sensory space converts sensory data into categorical concepts through *Cognition*. This cognition can affect the behaviour of the phenotype so as to change the Environment through *Action*. With an ability for **Language**, labels can be learned for concepts through *Learning*. These labels are also learned from other people by a process of *Cultural Transmission*.

Each of the processes above constrains the configuration of colour naming systems:

- Genetic inheritance constrains which genes an entity has.
- Genes constrain the sensory organs that can develop.
- Both the sensory organs and the environment constrain the range of stimuli that are perceived.
- Learning mechanisms and cultural transmission constrain which concepts are labelled.

Figure 7 shows this relationship diagrammatically. Two entities in a genetically and culturally related population are shown. Boxes denote entities and arrows denote processes. From this, we can see that some domains are linked by chains of causality, but others are causally separate. For instance, genes influence the phenotype, and so the perceptual constraints by extension. For example, having genes which produce two or three cone types will influence the physiology of the phenotype and the perceptions it is able to perceive. However, an individual’s genes are not affected by a phenotype’s physiology or perceptions (removing the eyes or turning off a light does not change an individual’s genes).

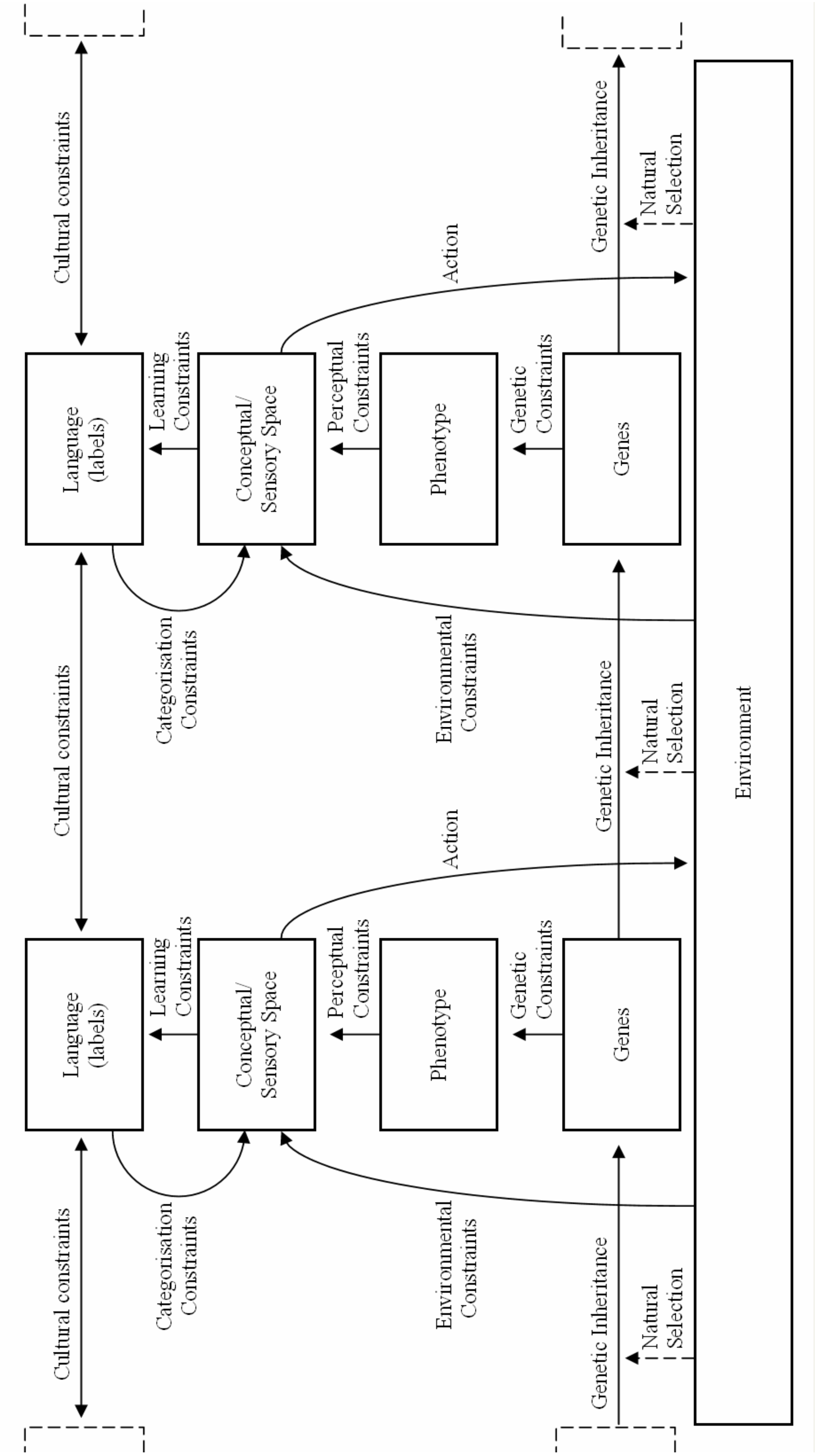

Figure 7: A diagram showing the relationships between different domains of constraint on colour categorisation.

This study is concerned with the effect language has on perception (labelled 'Categorisation Constraints' in the diagram). If language can re-organise our perceptual spaces, this creates a feedback loop between language and conceptual/sensory areas. This causes two changes in the dynamics of the cultural system. Firstly, labels can be learned from others, leading to a shared labelling system. Sharing the same labels will cause a similar warping of the perceptual space, minimising the differences between the conceptual/perceptual spaces of individuals within a population.

Secondly, the causal dynamic of constraints is vastly complicated if language can affect perception. This can be demonstrated if one follows the arrows around the diagram with and without the 'categorisation constraints' arrow. Including it leads to many more possible routes. For example, the action of an individual is determined through a process of cognition applied to the conceptual/perceptual space. Since language can affect this space, it has an impact on the way an individual changes the environment through action. Changing the environment affects the natural selection pressures on an individual, which affects genetic inheritance (Niche Construction). Therefore, language can have an indirect affect on gene frequencies in a population. Individuals may survive and reproduce better if they are better at communicating through language. From an Embodied perspective, better communication involves minimising the differences between activations in the conceptual/sensory spaces. Therefore, I argue that the Cultural implication of an Embodied account predicts that the evolution of individuals in a cultural system will converge on systems that minimise the differences between perceptions, including perceptual hardware and cognition. Furthermore, since genetic changes to hardware take a long time, the rapid development of language suggests that cognition (e.g., perceptual warping) has adapted to a greater extent. This will be discussed further in section 6.

The current study argues that Symbolist and Embodied approaches would predict that the primary constraints on colour terms come from different domains. Symbolism would predict that primary constraints on colour categorisation come from perception and cognition. On the other hand, the Cultural implication for Embodied Cognition predicts that the constraints on colour terms will not be demonstrably dependent on only one domain of constraint. The next sections will review evidence that linguistic systems for categorising colour are optimised for each domain of constraint mentioned above[1]. I argue that that although categorisation may be optimised for a given domain, is not necessarily *adapted to* that domain, and that cultural and categorisation constraints can explain why linguistic categories appear to be optimised for perceptual, environmental and learning constraints.

5.2 Domains of Constraint

5.2.1 Genetic constraints. Bornstein (1973) first suggested that genetic constraints could influence colour categorisation, hence populations nearer the equator having fewer colour terms. Lindsey and Brown (2002, p. 510) argue that colour terms vary cross-culturally on a "fundamentally biological basis". They showed that the number of colour terms in a language correlated with the amount of UV-B radiation to which speakers were subjected. This 'burnescence' effect increases the density of the lens. Over time, populations would adapt to have denser lenses nearer the equator. Denser lenses skew hues towards green, 'squeezing out' the blue hues and the blue term with it (however, see Hardy et al., 2004 and Regier & Kay, 2004 for counter-arguments)[2]. Models of genetic constraints have found that populations can converge on shared categorisations for colour if reproduction is based on discriminative success (Steels & Belpaeme, 2005) [3]. Jameson and Komerova (2008) found that modelling a heterogeneous population of dichromats and trichromats further constrained the convergence, aiding the emergence of shared categories. In conclusion, genetic constraints seem to interact with other constraints to affect colour categorisation. However,

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[1] This has already been addressed to some extent by Saunders and Brakel (1997), but all the evidence in the current study comes from research carried out after this publication.

[2] Furthermore, Lindsey and Brown (2002) conducted a WCS-style Munsell-chip experiment on a culturally homogeneous population with the stimuli virtually manipulated to simulate the effects of burnescence. This was an innovative solution to controlling for individual differences. It was found that participants' use of "green" extended further into "blue" areas with greater simulated burnescence. However, Hardy et al. (2004) repeated the burnescence experiment with the addition of a condition where older participants were given stimuli virtually manipulated to simulate *less* burnescence. The results did not support Lindsey and Brown's hypothesis.

[3] Steels & Belpaeme (2005) constructed computational models with 10 agents with the ability to categorise colours according to perceptions (radial basis function neural networks for each colour category). The innate biases of these categories were defined by genetic encodings, but the categories did not change over a lifetime. That is, individual learning was not modelled. Agents played the discrimination game 50 times before half of the population was replaced with new agents generated by a mutation of an existing agent (asexual reproduction). The extent of the mutations were based on the inverse of the parent's discriminatory success. That is, genes which facilitated success in the task were less likely to mutate. Category variance between agents and between populations was used to measure the extent to which agents had a common categorisation, a small value meaning that many agents share large parts of their categorisations. With these constraints, systems became totally shared within populations. However, more categories were produced than for individual learning, the synchronisation of categories took longer and the system was less robust against changes in the environment. Also, the systems were not shared across populations.

genetic change happens on a large timescale. Colour terms have evolved in a time span with very little cross-cultural genetic change, suggesting that other processes have a more immediate effect.

5.2.2 Environmental constraints. Regan et al. (2001) show that colour vision co-evolved with the colour of the objects that it was used to identify. Specifically, colour vision facilitated the detection of coloured fruit against a background of leaves. Reciprocally, primates helped disperse the seeds (*zoochory*) so that, over time, the plants adapted to become more detectable (*dispersal syndrome*) [4] (Regan et al., 2001). However, this is a long-term explanation. The particular properties of the immediate environment may affect perception during individual development. For example, focal colours have been shown to vary between populations from distant environments (Webster et al., 2002). This may reflect either a cultural bias or an environmental bias. Laeng et al. (2007) studied individuals from the same town in Norway, that is, a culturally homogenous population. Colour sensitivity in adults varied depending on where they were born. Those born at higher latitudes, where sunlight is shifted towards blue, had reduced sensitivity to yellow-green and blue-green contrasts, but a higher sensitivity to variations in the purple range. Therefore, differences in the environment may have repercussions for the colour term system.

Dowman (2007) ran a cultural transmission model where agents had to converge on categorisations for a uniformly-spaced colour space. However, certain colours in the space were set to be more salient. These ‘universal colours’ were not evenly spaced. The analysis was done by converting the population’s convergent categorisation to the same format as the WCS data. The fit between the model’s outcome and actual attested types in human cultures could then be compared. Dowman found that the emergent systems fitted with attested types in the WCS only with the inclusion of unevenly-spaced ‘universal foci’. This implies that the

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[4] Regan et al. (2001) give a thorough review of the research into the evolution of colour vision. There is a large variation in primate visual morphology, ranging from monochromaticity (Owl monkeys, *Aotus trivirgatus*) to trichromaticity (all old-world monkeys and apes, *catarrhine*) and polymorphism (e.g., dichromaticity in males and a percentage of trichromaticity in females). However, dichromaticity is not necessarily disadvantageous compared to trichromaticity. Trichromaticity does appear to be optimised for the detection of certain fruit at close range (see Regan et al., p 260-262). However, dichromats may be better at breaking camouflage of predators or prey (e.g., edible insects). Therefore, in a society where foraging is done in groups and individuals may *cooperatively signal* to others about the presence of resources, polymorphic colour vision may be advantageous, since different individuals are ‘specialised’ for different tasks (a *frequency-dependent advantage*, see Clarke 1979, Mollon, Bowmaker & Jacobs, 1984).

spacing and frequency of salient colours constrain colour term systems. However, Dowman emphasises that the nature of these foci could be environmental, genetic or cultural[5].

Griffin (2006) found that linguistic partitionings of the colour spectrum are optimised for the recognition of natural objects. Images of objects were classified based on the distribution of pixels belonging to each colour category (e.g., trees are mainly green and brown while bananas are yellow and brown). Natural colour categories proved to be better at classifying objects than other random categorisations. This implies that colour terms are optimised for functionality, as Embodied cognition predicts. In conclusion, and as expected, the visual environment does seem to impose constraints on colour categorisation.

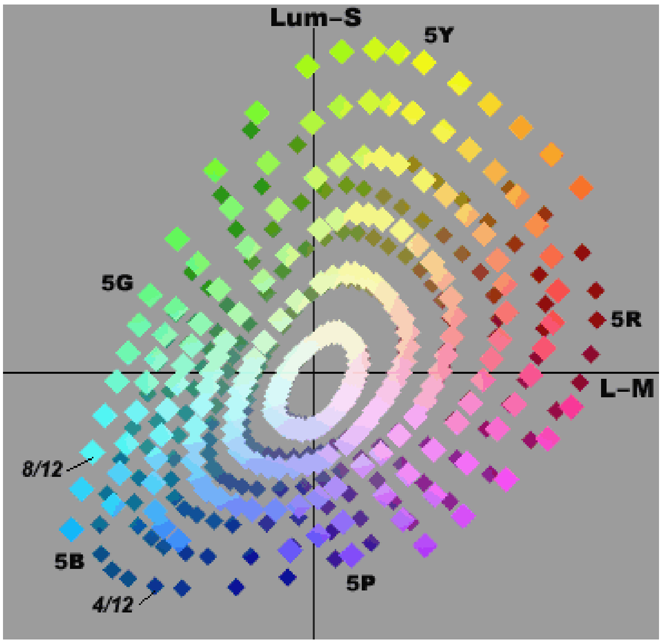

Figure 8: Munsell color samples, although regularly distributed in physical colour space, are irregularly distributed in perceptual opponent space (similar to DKL), from http://www.handprint.com/HP/WCL/color2.html.

5.2.3 Perceptual constraints. The perceptual space that results from the processing of opponent colours is non-uniform (see Figure 8), meaning that there are optimal ways to describe it (Jameson & D'Andrade, 1997). Natural language partitions are optimised for describing the perceptual colour space, suggesting that perception is a primary constraint on

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[5] To achieve this, Dowman (2007) configured the model so that the 'universal foci' were chosen as the topic during communications 20 times more often than other colours, and were 20 times more likely to be remembered, meaning that universal foci were up to 400 times more salient, and not 20 times more salient, as stated in Dowman (2007, p.118).

colour categorisation (Regier, Kay & Khetarpal, 2006) [6]. This mirrors findings in the configurations of vowel spaces (e.g., Liljencrants & Lindbloom, 1972, De Boer, 2000). Taken on its own, this evidence would support a Universalism, although later sections will show more complex interactions.

Buchsbaum and Bloch (2002) found that similar algorithms approximate low-level processing of colour in the striate cortex (red-green and blue-yellow opponent contrasts, by Principal Component Analysis, PCA) and high-level linguistic encodings of colour (colour terms, by Non-negative Matrix Factorisation, NMF[7]). Colour terms also emerge from the latter in a similar order to Berlin & Kay's universal colour order[8]. Although this may be evidence for innate perceptual biases, it also shows that perceptual and conceptual processing are similar, which is predicted by Embodied Cognition. Buchsbaum and Block also point out that participants may be optimally dividing the Munsell chip space rather than describing their natural colour categories, confounding some of the findings for perceptual constraints.

5.2.4 Learning constraints. A memory and learning mechanisms are necessary to acquire colour categories (Komarova, Jameson & Narens, 2007). Models have shown that individual learning alone does not lead to categorisations that are shared within a population, suggesting that individual learning is a weak constraint (Steels & Belpaeme, 2005)[9]. Learning constraints also include storage capacity. However, the number of categories for colours is not typically larger than any other domain, and Tzotsil speakers seem to be able to acquire hundreds of grammaticalised forms (see section 5.2.5).

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[6] Concluded from a model which partitioned the Munsell chip colour set so as to optimise the 'well formedness' of the partitions. Well-formedness is a measure of how the partition of colour space maximises similarity within a category and to what extent words tend to name connected regions. The first constraint biases categories to be regularly shaped rather than cover large ranges of the colour space. The second constraint biases categories to cover a single, connected space, rather than isolated patches. The model's output resembled natural human partitonings (from the WCS). Furthermore, for 82 of the 110 natural languages in the WCS, the well-formedness decreased as their partitions were shifted.

[7] NMF is a factor analysis algorithm like PCA, except that it is designed for values that are inherently positive and cannot be centred. NMF has been applied to pictures of faces and has been shown to isolate features such as noses, eyes, ears (Lee & Seung, 1999).

[8] NMFs can be manipulated to extract any number axes to describe the data (*basis functions*). In this context, the number of basis functions requested is analogous to the number of colour terms in the language. NMFs were derived from the Munsell colour space with 3, 4, 6 and 8 basis functions, then each basis function was translated to an English colour term using data from the WCS. The addition of colour terms as the number of basis functions increased, although not deterministic, generally followed Berlin and Kay's (1969) universal order. That is, labels for colours emerge first for areas of the space which are easier to distinguish cognitively.

[9] Steels & Belpaeme (2005) ran a model where agents could change their colour categories over a lifetime through individual learning. The agents were successful at the discrimination game, but the systems did not become shared between agents or between populations.

Lupyan and Dale (under review) hypothesise that languages spoken by larger, more dispersed groups (e.g., English) favour less morphological complexity (more lexicalised meanings). This is because more dispersed languages may be adapted to greater numbers of adult non-native speakers, who find it easier to learn ‘simpler’ morphology (Lupyan & Dale, under review). Furthermore, contextually restricted terms for colour are more feasible to use in tighter-knit communities. For example, a speaker of Tzotszil, living in a remote village in Mexico described a pink Munsell chip with the name of a flower and the location of the particular flower they hand in mind (MacKeigan & Muth, 2006). This approach is not feasible in a large, dispersed community. Figure 9 shows the current study’s finding that more basic colour terms are found in larger groups (r=0.35, df=87, p<.005) and in ‘simpler’ languages with fewer inflectional forms for verbs (r= -0.51, df=14, p=.04, raw data from Kay & Maffi, 2009, Lewis, 2009, Roberson, Davies, Corbett, & Vandervyver, 2005). This fits with Lupyan & Dale’s hypothesis as well as with Embodied Cognition’s emphasis on the functional role of language. It also predicts that, although cultural processes may synchronise perceptions, there will be less synchronisation in more dispersed language communities.

5.2.5 Cultural constraints. This section reviews evidence of cultural constraints on colour terms. Modelling has shown that cultural transmission can cause individual categorisations of colour space to converge on shared categories, given constraints on perception and the

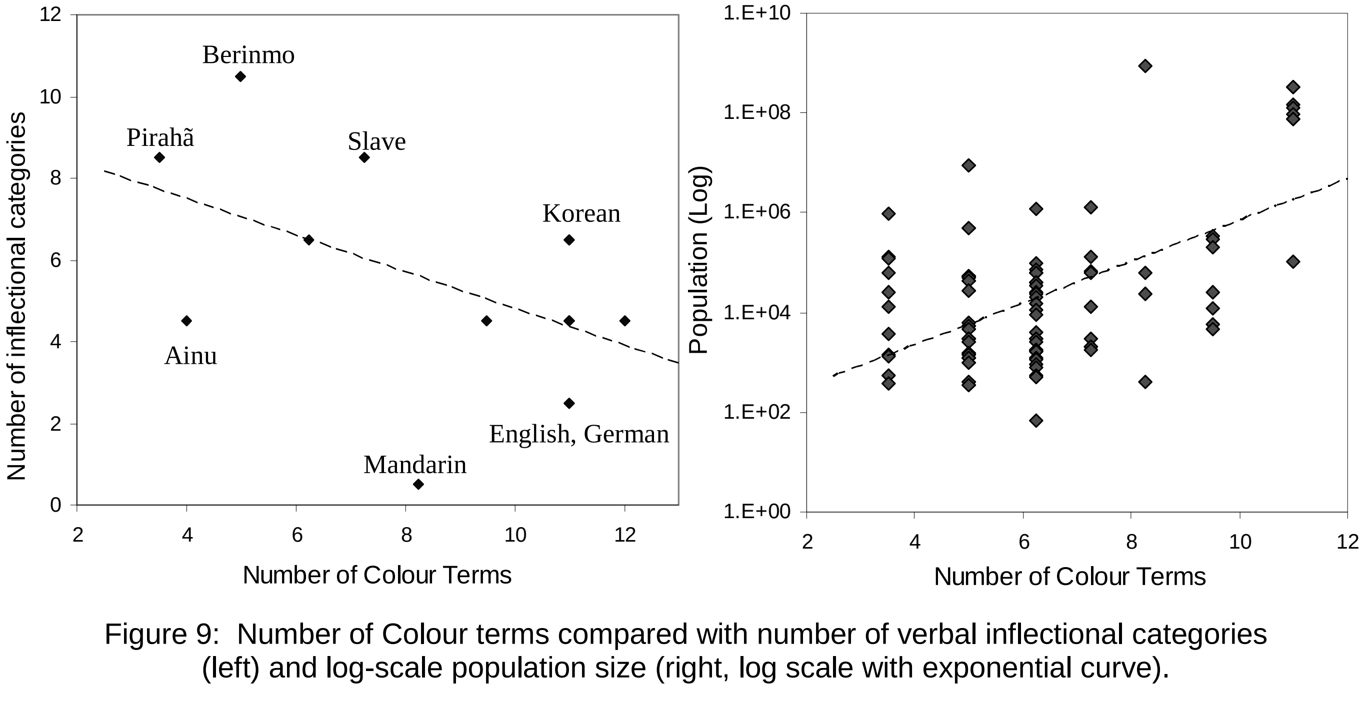

Figure 9: Number of Colour terms compared with number of verbal inflectional categories (left) and log-scale population size (right, log scale with exponential curve).

environment (Steels & Belpaeme, 2005) [10] and also without constraints from the environment (Belpaeme & Bleys, 2005). This has also been demonstrated in human-based experiments (Dowman, Xu & Griffiths, 2008)[11]. However, these studies have not ruled out perceptual constraints as the major cause of cross-cultural patterns. This may not be necessary, however: Kirby, Dowman and Griffiths (2007) have shown that very weak innate biases can be amplified through cultural transmission, leading to universal patterns. Therefore, it's possible that the constraints imposed on colour perception by the sensory organs are actually relatively small, and cultural processes are the main driving forces of colour term evolution. This is supported by showing that simple discrimination rules combined with pragmatic constraints can lead to shared systems, without complex models of the perceptual system (Komarova, Jameson and Narens, 2007).

If culture is a strong influence on colour categorisation, then Relativism is supported, since different cultures can arrive at different ways of comprehending the world, based on their functional needs (e.g., hunting vs. gathering vs. interior decorating). If this is the case, then we would expect the WCS to contain large variance between cultures, contrary to Berlin and Kay's original assumption. There is some evidence for this. Firstly, there are several systems of colour categorisation in the world that are remarkable outliers in the WCS. For example, the Tzotzil language of Chiapas, Mexico, studied by MacKeigan & Muth (2006): Although the WCS lists only 5 basic colour terms for Tzotzil, MacKeigan & Muth argue that there are

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[10] In Steels & Belpaeme's (2005) study, cultural transmission was modelled using agents with categorical networks for discrimination, but also a lexicon which associated a word with each category, similar to other models of emergent categories (e.g., de Boer 2000). No genetic inheritance was modelled. Agents played a communication game. The hearer could adjust its categorical network and lexicon to better fit what had been revealed about the speaker's network and lexicon. This adjustment could involve adopting the speaker's name for a category, creating a new category or adjusting the focus of a category. In this way, language communication stimulates the formation of categories, but also the formation of categories stimulates the language used. This is a model of two way structural coupling between category formation and language (Maturana & Varela, 1998). Steels & Belpaeme found that, although category boundaries were not completely shared, agents did have a common repertoire. Furthermore, agents could be replaced with naive ones without disrupting the communicative success of the population.

[11] This was done using the transmission-chain paradigm (e.g., Kirby, Cornish & Smith, 2008). In Dowman et al. (2008), participants were shown colours with made-up names, and asked to memorise them. The participant was then tested on these names. However, the participant did not see all colour-name pairs during training, imposing a bottleneck on learning. The names shown to the first participant are randomised and randomly assigned to colours. That participant's output – their recalled pairings of colours and colour names – are given to the next participant as their input. This process of iterated learning is repeated down the chain. Chains were initiated with 2, 3, 4 5, and 6 initial colour terms with 13 participants in each chain with. As with other transmission chain experiments (e.g., Kirby, Cornish & Smith, 2008), structure in the categories emerged in response to a pressure to become more learnable. With 2 or 3 initial colour terms, the categories changed to be based either on hue or lightness. With 4-6 categories, categories emerged based on both hue and lightness.

between 900 and 1000 colour compounds. Below is one speaker’s description of a purple Munsell Chip:

> “ *ik’ik’+tik s+k’an+al s+yax+al* … This possessive form instructs the viewer to search the overtones and reflections of the black for hints of yellow and then for dark blue, … This colour term is roughly equivalent to “dark’s yellowness (including orange) and blue-greenness”, showing that a literal translation does not arrive at the required “dark purple”. Clearly, in-depth grammatical analysis is required.”
> (MacKeigan & Muth, 2006, p.27-28)

Note that the system is highly morphologically complex, as predicted by Lupyan and Dale (under review, see section 5.2.4). The complexity is due to the Tzotzil culture being heavily bound-up with colour. The colour system is connected to orientation in the landscape, seasonal cycles and personality. Distinctions are made based not only on hue, saturation and brightness, but also on the size of the object, discreteness, opacity, texture and movement. For Tzotzil speakers, then, concepts of colour should evoke many kinds of perceptual representations. Evidence for this would support Relativism.

Furthermore, colour terms have often emerged due to economic pressures (e.g., ‘Azure’ comes from Azurite – a very expensive material used in painting in the Middle Ages; Ball, 2001) or artistic invention (e.g., ‘vermilion’ comes from the insect used to make dye or ‘International Klein Blue’ from the work of Yves Klein; Ball, 2001). Language contact can also have an effect. For example, Middle Welsh did not have separate terms for green and blue whereas modern Welsh does, possibly due to a pressure from contact with English, although the original ‘grue’ term can still carry its original connotation (Lazar-Meyn, 2004). Overall, there is much evidence that cultural constraints can affect categorisation, supporting the Cultural adaptation implication. However, in order to support a Relativist account, these differences would have to be more than superficial differences in colour words. The variation caused by cultural processes must reflect fundamental variation in cognition and conceptual approaches to action and the environment.

5.2.6 Categorisation Constraints. This section reviews the conflicting evidence for ability of linguistic categories to affect perception, which is crucial for the Cultural implication.

Section 2 mentioned studies of Embodied Cognition which found evidence that comprehension of size and shape activated perceptual representations. However, colour is not necessarily processed in the same way as spatial properties and is encoded with less stability (Aginsky & Tarr, 2000). Several studies have found fragile links between colour concepts and colour perception. For example, Kay and Kempton (1984) showed that categorisation could affect perception in the domain of colour[12]. However, this effect disappeared when the task was constrained so as to avoid the "name strategy". This strategy involved labelling the chips with colours terms, then basing the decision on those labels rather than the actual spectral properties. Kay and Kempton suggest only a weak form of the Whorfian hypothesis is supported by their study, namely that "Structural differences between language systems will, in general, be paralleled by nonlinguistic cognitive differences, of an unspecified sort, in the native speakers of the two languages" (See Kay & Kempton, 1984, p. 74).

Ritcher and Zwaan (2009) found that perceptual symbols are activated during the comprehension of colour terms using an interference paradigm. Participants were shown two coloured squares in sequence, interrupted by a colour term. The squares were either identically coloured, or very slightly different. The colour term either matched or mismatched the colour of the squares. Participants performed a lexical decision task on the word, and then judged whether the colours were the same or different. Responses for the colour discrimination task were slower when participants saw an intervening colour term that mismatched the colour of the squares. This result held even when the participants were not required to perform the lexical decision task. This implies that, for the current study's experiment, perceptual activation is still expected without a comprehension task. Ritcher and Zwaan interpreted the results as a conflict between the perception of the colour of the first square held in short-term memory and a different colour activated by the mismatched colour word. This supports the theory that perceptual representations are accessed during comprehension.

Returning to the motivational paper for this study, Hansen et al. (2006) found that perceptions are influenced by the knowledge of an object's 'typical' colour (bananas always look yellow).

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[12] Kay and Kempton (1984) measured the subjective distance of green and blue hues of two cultures – one with a separate term for green and blue and one with one term that covered both. Participants were presented with triads of coloured chips and asked to identify the one that was most different ('furthest away') from the other two. The subjective distances of the speakers of the language with two colour terms were warped at the category boundary. That is, their categorisation influenced the way they contrasted colours.

In perceptual symbol processing terms, their comprehension of the structure of the object activated perceptual representations of that object's typical colour. Olkonnen et al. (2008) suggest that this is due to a top-down effect of expectations. In other words, they do not rule out comprehension involving abstract symbol manipulation (contra-Embodied Cognition). However, they do predict that the object must share visual features with its referent in order to effect perception. Indeed, they find less of an effect with objects stripped of shading or texture. This suggests that the perception (of a structure) activates a perceptual 'memory' (of a colour) whereas Embodied Cognition would argue that there is no difference between perceptions and concepts in terms of the neural substrates involved.

However, there is evidence that, although perceptual symbols may be activated by comprehension, they can occur in separate substrates to direct perceptual activation (Connell 2005, 2007). This would be a modification of a strict perceptual symbols theory. Connell (2007) showed participants an image following a sentence that primed the reader to expect a certain colour configuration. For example, a "steak on a plate" primed a cooked (so brown) steak while a "steak in a butcher's window" primed a raw (so red) steak. Participants had to confirm that the image contained the object mentioned in the sentence. There was a significant difference in response times between matching and mismatching conditions, suggesting that the comprehension of colour involves perceptual symbols. Counter-intuitively, however, the *mismatched* condition evoked faster responses (participants primed with a steak on a plate responded faster to a red steak than a brown steak). Connell explains this by suggesting that colour is encoded in a different way to some other object features. A distinction is made between *stable* embodied representations, such as size and shape, which are multimodal and salient in visual field configuration and *unstable* embodied representations such as colour and smell, which are unimodal and not salient in visual field configuration. If shape is more important for recognition than colour, colour can be ignored without incurring a processing cost. Connell argues matched colours are harder to ignore, since the neural substrates that represented it are already active (see nurological evidence in Spalek & Thompson-Schill, 2008).

The conflict between Ritcher and Zwann (2009) and Connell (2007) could be due to separate levels of representation. For example, the perceptual representation for the abstract term 'red' and the one for the more concrete red of a raw steak could belong to different orders of an abstraction hierarchy. Connell and Lynott (2009) suggest that separate representations can be maintained when considering the interactions between typicality and context. Response times were tested for objects presented either in their typical or atypical colour (e.g., red tomato versus green tomato), crossed with matching and mismatching primes (e.g., 'Dan ate the tomato' versus 'Dan tasted the tomato before it was ready to eat'). Responses were fastest both for typically coloured objects and matched primes but there was no additional effect for these conditions combined. This suggests that typical colours (e.g., 'red' for tomatoes) are activated, regardless of context, but a representation of the contextual colour – the 'actual' colour - can be held in parallel[13]. This does not fit with a strict perceptual symbol account, which predicts only one representation for both perceptions and concepts. Neither does it fit with a Symbolist account, which predicts two representations, but one of them being non-perceptual.

Furthermore, it has been suggested that these parallel representations can be driven by different domains of constraint, possibly confounding the Universalist/Relativist debate. Claidière, Jraissati and Chevallier (2008) asked participants who had 11 colour categories in their native language to sort Munsell chips into 4 categories. Participants' choices reflected their native linguistic categories more closely than four-colour-category languages from the WCS, suggesting that participants were using their lexical categories, rather than perceptual ones. This was interpreted as supporting a relativist theory. However, the same results were obtained when participants sorted the chips while doing verbal shadowing (mindlessly repeating sentences played to them through headphones), which has been shown to interfere with lexical access and categorical perception (Winawer et al., 2007). Claidière et al. concluded that colour categories are both language-specific (a cultural constraint supporting Relativism) and perceptually motivated (a perceptual constraint supporting Universlaism). Furthermore, they conclude that the Relativist/Universalist dichotomy is too narrow and restricts research and experimental paradigms. Claidière et al. suggest that the influence of categorisation on cognition is task-dependent and that not all perceptually determined categories may be perceptually grounded (e.g., 'red' vs. 'orange' may be salient, but 'orange'

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[13] An interpretation of Hansen et al.'s findings, in the light of possible dual representations, is that the expected colour of an object (yellow for a banana) can interfere or integrate with the actual colour of an object (a grey banana with a blue tint) when participants are forced to give a single response. Conell and Lynott suggest that holding parallel representations may be advantageous for error-correction, in the same way maintaining many possible parses of a sentence is advantageous (see Mitchell, 1994). However, when required to sequentialise concepts, as for expression in language, a fusion of expected and actual representations is required, causing the 'memory colour' effect.

on its own is not). This runs against the idea of Embodied Cognition, which hypothesises a single process of comprehension.

However, an alternative interpretation of Claidière et al.'s finding is that linguistic and perceptual categories are synchronised. That is, participants in the verbal shadowing task were sorting the colours perceptually without influence from their linguistic categories, but their perceptual space had been warped by their linguistic categories and so the results were the same. This synchronisation of linguistic and perceptual categories is exactly what is predicted by the dynamic outlined at the beginning of this section. That is, a feedback loop between a single conceptual/perceptual space and linguistic labels. Furthermore, the current study will show that people see colour term as achromatic only when they are adjusted to *directly oppose the best exemplar* of that colour term. That is, the concept and the percept align directly. This suggests single, not dual representations. However, the current study does find differences in the strengths of this effect for different colours, potentially agreeing with Claidière et al.'s suggestion of graded perceptual grounding.

5.3 Summary

This section outlined the Cultural implication of Embodied Cognition. Language can be used to acquire shared concepts. If concepts and perceptions rely on the same system, then language can re-organise perceptions. This increases the complexity of the interactions between sources of constraint on linguistic categorisations. This section has reviewed studies that seem to conflict with regards to the primary source of constraint on colour categorisation. There is evidence for both innate biases, supporting Universalism, and cultural influences, supporting Relativism. Furthermore, there is evidence for perceptual and cognitive constraints supporting Symbolist accounts, and cultural constraints supporting Embodied accounts. This study argues that these apparent conflicts have occurred due to the increase in interactions cause by a feedback loop between shared linguistic labels and individual perceptual spaces.

6 Implications of Categorisation Constraints for Cultural Transmission

The last section showed that several domains of constraint, including cultural processes, influence colour categorisation. There is evidence that these categorisations can influence perception, which has been identified as a crucial argument for Relativism. This section considers the Cultural implication, summarised in the last section, in greater depth. First, the idea of perceptual warping is explained and applied to colour categorisation. Next, the impact of a feedback loop caused by an Embodied approach is discussed in terms of Niche Construction. Thirdly, perceptual warping, within a system with Niche Construction dynamics is argued to lead to convergence of perceptual spaces, resulting in better communication. Finally, a note is made on compositionality in language. It is concluded that Embodied Cognition may explain some of the features of the emergence of language.

6.1 Perceptual Spaces

This section explains perceptual warping. Many models of the cultural transmission of denotation systems begin by defining a perceptual space for each individual which is then divided up with loci and boundaries (e.g., deBoer, 1999). Eventually, a kind of 'lookup table' is produced where an individual calculates within which boundary a given stimulus falls in order to classify it. An alternate view would be that each individual alters (warps) the *perceptual space* to suit the categories (Goldstone, 1994; Kuhl, 1994). This is not a controversial theory for the auditory modality. For instance, although born with the ability to detect any meaningful difference in any language, children eventually become unable to detect those differences that do not exist in the languages spoken around them (Eimas, 1978, Miyawaki, 1975, Kuhl, 1983). In other words, humans do not merely categorise areas of the audible spectrum as belonging to particular phonemes, but actually alter their perceptual space to suit the phonemic system. In the visual domain, Kuhl (1994) argues that the perceptual space is permanently changed by exposure to graphemes, although Lupyan (2008) shows that categorical perception can emerge on-line.

Figure 10 is a graphical illustration of warping a perceptual space. The division of the Munsell colour space by speakers of Culina is warped and rotated to optimally encode the colour categories. Formally, the parameterisations are the same. However, warping the perceptual space allows for compression of information. For example, the initial encoding of Figure 10 takes up to 40 x 8 units, while the final encoding takes only 4 units[14]. This can ease processing and storage requirements. Compression reduces the uncertainty between

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[14] The unwarped space could also be compressed, but note that only a uniform compression of the existing axes of the space would be formally different from warping the space.

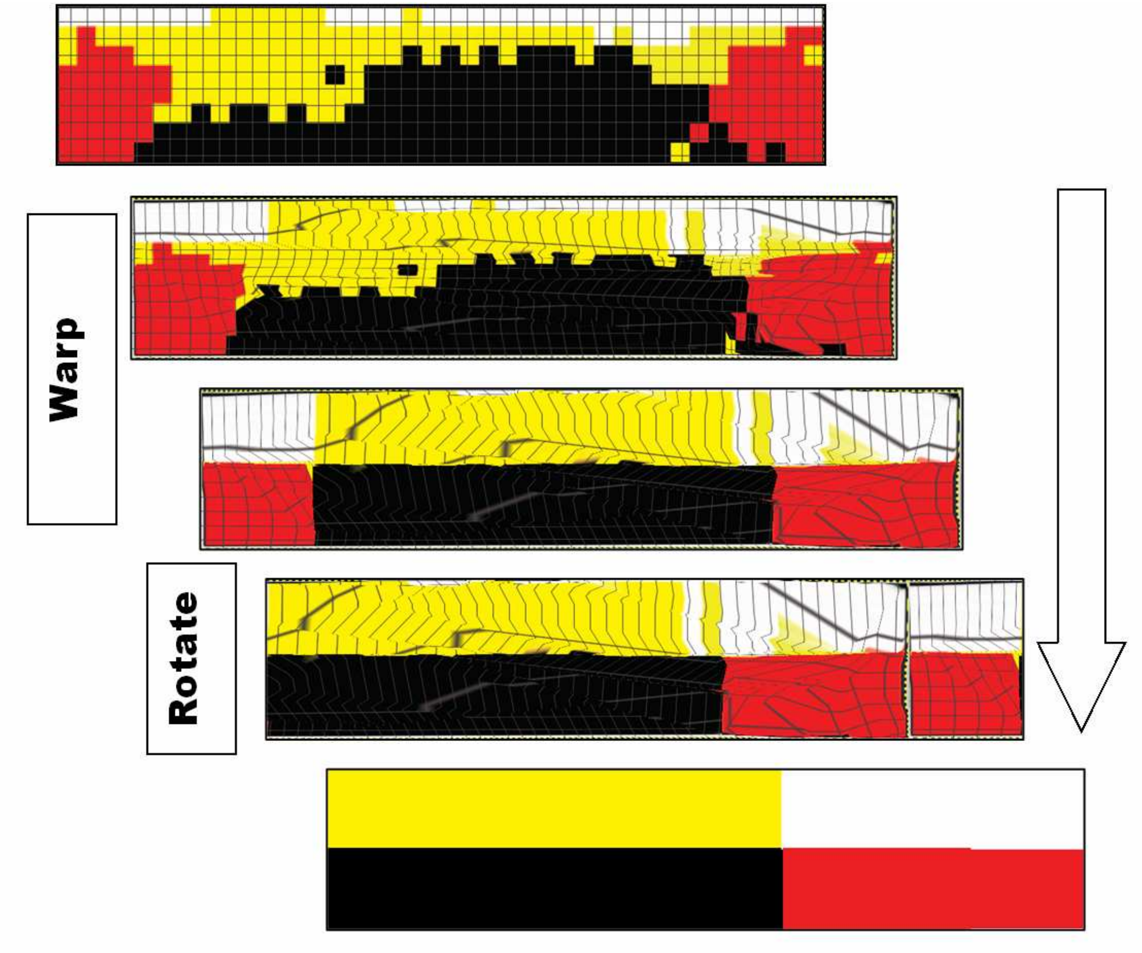

Figure 10: Warping the perceptual space to efficiently encode the linguistic colour categories of Culina. Original image (top) from Regier, Kay & Khertarpal, 2007, p. 1439.

categories (e.g., red vs. green) and the ability for individuals to differentiate within categories (e.g., different shades of red), similar to the effects of categorical perception. This approach has already been suggested. Buchsbaum and Bloch's (2002) study showed that the NMF algorithm approximates colour categorisation in real languages (see section 5.2.3). NMF essentially warps the perceptual space to best describe its limits. The current study suggests that language sets constraints on an NMF-like process which works to alter the perceptual space to suit culturally salient colour contrasts. However, it is suggested that this optimisation is not primarily a response to an adaptive pressure, but a *consequence* of the way we understand language. Indeed, it is only because our perceptions can be aligned with our language system that semantics works at all. This would fit better with an Embodied view than a Symbolist view.

However, humans *are* able to perceive gradients in colours within categories. There are two explanations for this. Firstly, there may be two separate, competing perceptual and 'categorical' colour spaces, similar to Connell and Lynott's (2009) hypothesis. Since the categorical system is shared and can quickly adapt to immediate environmental pressures, one would expect agents with two systems to increasingly rely on the categorical system, especially for communication (see code duality theory, e.g., Hoffmeyer & Emmeche, 1991). In contrast, novel tasks which involved no communication (e.g., comparing colours and choosing an 'odd one out') may rely more on the true perceptual system. A second explanation for the flexibility of categories is suggested by Lupyan (2008) who shows that perceptual spaces can be warped, but by context-specific, *online* processes rather than long-term, memory-based processes. This would allow a single conceptual/perceptual system (as Embodied Cognition hypothesises), as well as explaining the plasticity of language.

6.2 Embodied Relationships

A further adjustment to the assumptions about perceptual space is suggested. The assumption that all perceptual spaces are the same may be unrealistic and may favour Universalism (see Levinson, 2000). To begin with, colour vision and colour concepts develop during ontogeny (Bornstein, Kessen & Weiskopf, 1976, Roberson, Davidoff, Davies & Shapiro, 2004). Secondly, there may be an underestimation of the variation in colour term systems across cultures (see section 5.2.5). Going back to the example of Tzotzil, colour terms seem to be intricately related in a way that, for example, 'blue' and 'green' in English seem not to be. This prompts a third way of approaching the formation of colour categories. An individual begins with no conceptual space, but learns *relationships* between colour terms and perceptions. For example, learning that 'yellow' and 'blue' are *as different* as light with 640nm and 450nm wavelengths. By using an embodied, relational approach to colour categories, one can construct relationships between terms based on *any* perceivable feature. This could include brilliance, reflectance or the physical structure of the object. Therefore, a banana looks yellow because its colour is understood in terms of its structure, as well as its spectral properties. This is a more stable approach to object identification, since structures are usually stable, while colour is not. It would also fit with the grammaticalisation of colour terms to extend to other domains. For example, the Tzotzil *sak-vilan*, meaning 'pastel' originates from the fading of colours on fabric from fraying (MacKeigan & Muth, 2006). Constructing relationships between words based on the relationships between the perceptual properties of their referents would then be part of a general learning mechanism which facilitated the learning of all concepts.

6.3 Niche Construction

This section reiterates how a link between linguistic categories and perception fits into Niche Construction Theory. If concepts can influence perception, and people share the same concepts, their perceptions will become synchronised. This would render them more effective at communication, since referents would be perceived as similar (‘red’ can refer to the same domain of entities for each individual). Furthermore, it may render them more able to co-operatively build a better model of the actual environment (for instance, describing an unseen danger, or researching physics). However, this will only be true if language is grounded in constraints that come from the actual environment. If this were not the case, apart from being inefficient at describing the actual environment, a language may drift to influence the perceived environment in a way that results in a *worse* fit with the actual environment.

Returning to the constraints diagram (section 5), note that the influence of categorisation continues, through action, to change the environment. In other words, if language influences the perceived environment and facilitates communication, then it may also facilitate the way we change the actual environment. In this sense, language’s influence on perception can be regarded as a form of Niche Construction (Laland, Odling-Smee & Feldman, 2000). Therefore, not only does language become better at describing the actual environment, but the environment becomes better suited to being described by language. This creates a better fit between perceived and actual environments and possibly increases the fitness of language users. Essentially, then, this study presents evidence for language-specific niche construction where language can influence the environment. This dynamic would be a consequence of an Embodied system, and more efficient as part of an Embodied system than a Symbolist account. I therefore argue that the Embodied account is supported.

As an example of this dynamic, Hansen et al. (2006) showed that perception is affected by semantic knowledge, specifically that achromatic bananas look yellow. However, bananas are domesticated (Heslop-Harrison & Schwarzacher, 2007). The link between a banana’s structure and colour, therefore, is a constructed niche – cultivators fertilise the ‘best’ bananas, which go on to influence the way they perceive bananas, which affects which bananas they fertilise, and so on. This means that the effect found in Hansen et al. cannot be innate, since the colour and structure of a banana have changed (see Figure 11). Modulating perception with flexible, high-level categories is a way of keeping up with rapidly changing environments.

Less anecdotally, Griffin's (2006) model, which classified objects using colour (see section 5.2.2), found that natural colour categories optimally aid the identification of objects. Furthermore, the model performed equally well for natural and manufactured objects. That is, manufactured objects have been coloured to be maximally classifiable by colour, according to linguistic colour categorisations. This would be an intuitive and efficient tactic if, as Embodied Cognition suggests, comprehension is scaffolded onto systems of object recognition (MacWhinney, 1999). There would be no advantage in doing this in a Symbolist system where perceptions and concepts have arbitrary connections.

Figure 11: Differing structures and colours of six species of banana, all ripe. Top left: Musa balbisiana, ancestor of modern cultivated bananas. Top right: Pink Banana (Musa velutina). Bottom, from left to right: Plantains (Musa paradisiacal), red bananas (Musa rutilus), Bananito (Musa acuminate) and Cavendish bananas (Musa cavendishii). Images from Wikimedia Commons, http://commons.wikimedia.org.

6.4 Drift in cultural systems

An important point which has not been highlighted in the literature is the drift introduced by cultural transmission. Perceptual systems are noisy, and change over lifetimes. Therefore, systems of categorising these perceptions may drift over time. However, if concepts are shared, this drift is influenced by more than one system. This may cause a different kind of drift from a stand-alone system for self-thought. Communication has an additional semantic bottleneck which self-though does not have. Using language for self thought, if you don't know a label, you can make one up. However, for communication, this won't work. For example, in models of cultural transmission (e.g., Steels & Belpaeme, 2005) agents do create new labels but, importantly, accept the speaker's label when available. That is, communicative systems are more flexible than systems for self-thought (communicators must be more willing to change their minds), and so are more subject to drift. The drift allows the system to move around the possible space of coding efficiency and object categorisation efficiency. Peaks in these landscapes will attract the drift, hence environmental and perceptual constraints being projected into language. That is, although systems of colour categorisation for self-thought may be more efficient if they were constrained by the environment, shared cultural systems are more likely to reflect constraints in the environment because they are more flexible. That is, perceptual constraints have projected themselves into language because of a communicative pressure, rather than a perceptual or environmental pressure.

I suggest that this drift, together with an ability for categories to warp perceptual spaces, would mean that individuals converge on a shared perceptual system. If comprehension involves the activation of perceptual representations, then communication involves individuals reaching similar perceptual representations or, in a perfect world, activation of the same neural substrates. Therefore, a population with a shared perceptual system would be able to communicate much more effectively. In this sense, Embodied systems improve communicative success, whereas the same effect is not necessarily true of Symbolist systems. Furthermore, this drift means that populations can still converge on similar solutions, without having to assume that Universal biases are the main driving force. It has been argued that the similarities in colour categorisation between cultures contradicts Relativism, which would predict a large variation in colour categorisation between cultures (e.g., Belpaeme & Bleys, 2005). I argue that this inference is not necessarily valid.

6.5 Compositionality

A note is now made on a possible link between categorical perception and compositionality. Kirby, Cornish and Smith (2008) show that humans impose compositionality onto random systems in the presence of a semantic bottleneck. The modulation of perception by categories may allow compositionality to operate by re-organising perception according to shared linguistic labels so that the features picked out by those labels are categorically salient. This does not necessarily oppose Kirby et al.'s conclusion that cultural transmission alone can cause the emergence of compositional structure. Rather, categorical modulation of perception may be the *process* which causes the emergence of compositionality. Compositionality emerges when an object's meaning is broken up into sub-meanings (Wray, 2000). If meanings are perceptual representations, then compositionality involves breaking up the perceptual representation to more abstract parts. An efficient way to do this would be to break the representation up by modality. A testable hypothesis would be that compositional meanings would emerge quicker for stimuli that differed in two modalities than stimuli that differed in only one.

6.6 Summary

Categorical perception and Embodied Cognition cause dynamics in a cultural system that leads to a drive for better communication and a better coherence between concepts, the environment and perception. This would explain cross-cultural patterns in colour term systems, as well as allowing radically different outliers. In this sense, universal patterns do not necessarily support Universalism. Furthermore, an Embodied approach to cognition can help explain the process of cultural transmission by providing a driving force for better communication.

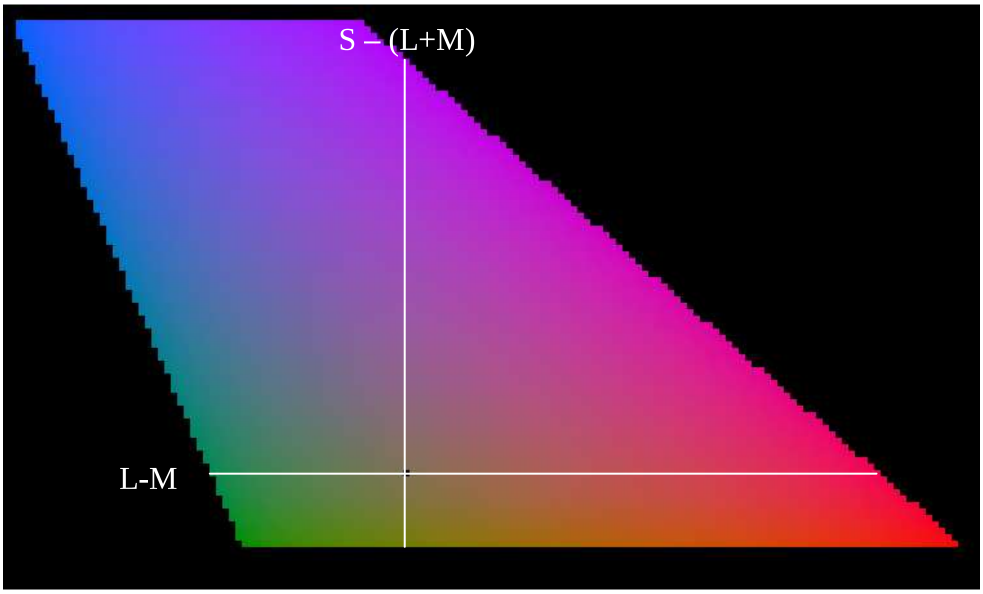

Figure 12: The gamut of the monitor used in the experiment in DKL colour space.

7 Experiment 1

In this experiment, participants changed the colour of colour terms to appear achromatic (grey). It was predicted that the participants would adjust each word *beyond* grey into the opposite colour space to the colour it described. For example, the word ‘yellow’ would only look grey to the human eye if it was actually tinted blue. This would suggest that reading colour terms triggers the perceptual experience of the denoted colour. In other words, when we read “yellow”, we *see* yellow.

7.1 Apparatus

This experiment uses computer controlled stimuli displayed on a monitor. Monitors create the impression of a range of colours using groups of 3 phosphors which emit varying strengths of light at red, green and blue wavelengths. The three phosphors correspond roughly to the S, M and L cone sensitivities in the eye. However, a way is needed to map from the colour the computer intends to display and the actual cone activations in the eye. The CIE colour space is based on the average viewer's cone activations, and can be used to create this mapping. Using a spectroradiometer, a monitor’s phosphor emissions were measured to create a conversion matrix which mapped between the program’s digital representation of phosphor emissions and a CIE representation of cone activations. The cone activations were then converted to DKL colour space. In this way, colours of the stimuli could be manipulated in a perceptually motivated colour space and experimental measures could be taken that would approximate closely and systematically to the actual activation of cones in the participant’s eyes. Figure 12 shows the monitor gamut in DKL space.

The stimuli were displayed on an LG Flatron F900P monitor with a spatial resolution of 1280x1024 pixels and a refresh rate of 60Hz. The monitor was calibrated using a spectroradiometer and specialised calibration software (Woolf, 2001). The error of the predicted values was 2.65Δe (a perceivable difference begins at about 3Δe). The CIE chromaticity of the phosphors were Red=(0.56,0.34), Green=(0.29,0.57), Blue=(0.15,0.08). The CIE chromaticity of the white point of the monitor was set to the adaptation point used in Hansen et al. (2006): x=0.32, y=0.34 with a luminance of 29cd/m². This chromaticity is equal to the one chosen by participants in Berlin & Kay (1969) as the focal point representing grey. It is also the colour of the background for the stimuli in both Hansen et al. (2006) and this study.

7.2 Methods

7.2.1 Participants. Eighteen participants were recruited, all of whom had normal or corrected-to-normal vision and normal colour vision.

7.2.2 Stimuli. The stimuli consisted of five basic colour terms in English ('red', 'green', 'blue', 'orange', and 'yellow'). These were chosen because they approximate most closely with Hansen et al.'s (2006) stimuli. 'Blue' was added as a test case and so as to cover a wider portion of the visual spectrum. The control stimuli were uniform coloured squares, each with an area equal to the average surface area of the words (subtended 1.25^o x 1.25^o), and adjectives matched for colour term length and frequency (were 'six', 'total', 'fine', 'sudden' and 'humane'; control word mean count=1772, sd=1343, colour term mean count=1503, sd=925, paired sample Wilcoxon signed rank test, W=11, p=.84) using CELEX (Baayen et al., 1995) and normed for colour association. The words were presented centred in the middle of the screen in an Arial font and subtended a maximum of 6.3^o x 2^o. The mean surface area of the words was 22,578 pixels or 1.7 % of the total surface of the screen. All stimuli had a constant luminance of 30.8 cd/m^2 (the same as in Hansen et al., 2006), slightly lighter than the background so that an achromatic stimulus would not blend into the background. Stimuli were initially displayed in a random colour that was at least 5% of the total range of the stimulus space away from the centre of the colour space (that is, stimuli were never initially presented in a colour close to true grey).

7.2.3 Procedure. The experiment took place in a light-proofed room with the only source of light being the monitor. Participants were seated 187cm from the monitor and were required to complete three tasks involving the manipulation of the colour of the stimuli. The participants were shown how to use 4 buttons to do this. The four buttons moved the locus of the colour of the stimuli around the colour space along the x and y axes. The buttons were labelled for the participant as 'remove yellow' (up), 'remove blue' (down), 'remove red' (left), 'remove green' (right). This is an approximation of the actual manipulation which increased and decreased the x and y axis values in the DKL colour space. No participant was shown a representation of the colour space. Before the experiment began, the participants spent three minutes in the darkened room with the monitor showing the background colour in order for their eyes to adapt. There were four tasks in this experiment, run in blocks. In task 1, participants saw the colour terms and were asked to manipulate the colour to be 'completely colourless, or grey'. This is the achromatic value or C_a. Task 2 was the same, but for control words. In task 3, participants saw the colour terms and were asked to manipulate the colour to 'match the colour described' (e.g., make “red” appear red). This is the 'typical' value or C_t. In task 4, participants saw the uniform squares and were asked to manipulate the colour to be 'completely colourless, or grey'. This is the achromatic value or S_a. The time taken to adjust each word was recorded. The order of the words within each task was randomised and the order of the tasks for each participant was counterbalanced. Before the experiment, participants completed a training phase where they could practice each of the tasks with random, non-experimental stimuli. The number of trials required and the relative difficulty of the task meant that the experiment was relatively strenuous. For more accurate results, the four tasks were split over two experimental sessions on different days. A participant always had both sessions at the same time of day in order to minimise effects of exposure to daylight.

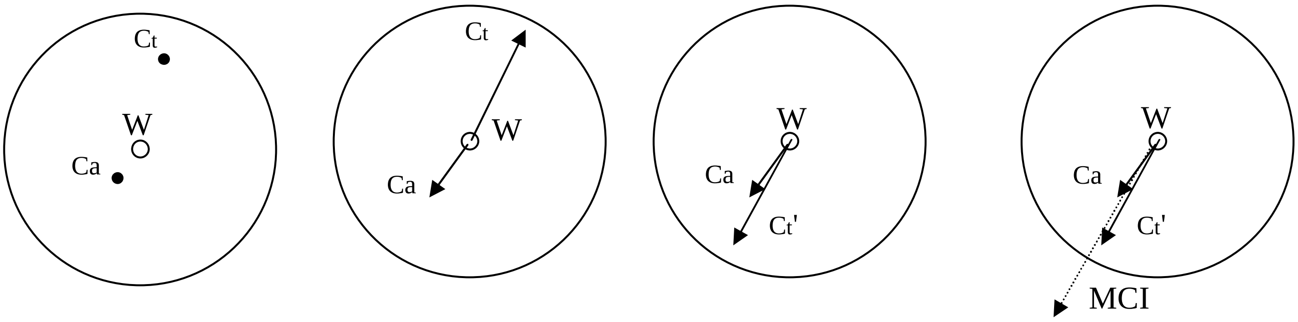

Figure 13: Steps to creating the MCI (left to right): plotting typical and achromatic settings around the whitepoint; converting to vectors; mirroring the typical vector; vector product of the two vectors gives the MCI.

7.3 Measurements. As in Hansen et al. (2006), the main measurement was the Memory Colour Index (MCI). First, each participant’s final settings for each stimulus were re-centred around each participant's subjective white point, W (the mean achromatic setting for control stimuli). The typical settings C_t were mirrored relative to the origin (-180^0) to give C_t'. The memory colour index (Equation 1) was then calculated as the length of the vector product of the vector between the origin and the achromatic setting C_a and the vector between the origin and the typical setting C_t. An MCI will be large if the two vectors are maximally opposing.

(Equation 1) $$MCI = \frac{C_a \cdot (-C_t)}{|C_t|^2}$$

7.4 Data

One trial was removed due to equipment failure. Two participants' data were removed, since they reported difficulties with the task, and took significantly longer than other participants to complete the test (mean total time=29min, mean for outliers=63min, t=-8.70, df=15, p<.001). One participant was removed because the distance of their achromatic settings from the adaptation point were more than 1.96 standard deviations from the total mean. That is, they were unable to successfully complete the achromatic task. Trials where the participant's chosen setting was identical to the initial random setting were removed because this suggests they completed the trial prematurely without adjusting the colour. Trials that were more than 1.96 standard deviations form each participant's mean trial time for each task type (achromatic and typical settings) were removed. Achromatic trials further than 1.96 standard deviations from the mean for each achromatic stimulus type were removed. This left 1068 data points (71%) for 15 participants.

7.5 Results

This study aims to show that the comprehension of colour terms involves perceptual representations of the denoted colour. This experiment found that participants only see a colour term as achromatic when it is tinted with the perceptually opposing colour. There are three key effects:

1. The achromatic settings for colour terms are further from the adaptation point ('grey') than for control stimuli.
2. A colour term's achromatic setting directly opposes its typical setting in the perceptual space (the word 'yellow' is adjusted to a blue tint).
3. A control word's achromatic setting does not directly oppose its typical setting in the perceptual space (the word 'sudden', which has the same length and frequency as 'yellow' is not adjusted to a blue tint).

7.6 Statistics

This section provides statistics to support the key findings outlined in the last section.

(1) The achromatic settings for colour terms were significantly further from the adaptation point than the achromatic settings for the control stimuli (over all trials, mean distance from adaptation point for colour terms=3.6%, for control stimuli=3.1%, $t = 2.9$, $df = 751$, $p<.01$).

(2) Participants adjusted the colour terms to achromatic settings which directly opposed their typical settings (MCI, 2-tailed, by-subjects, one-sample t-test; $t=2.8$, $df=14$, $p=.016$). Participants' Mean MCIs ranged from -2% (no effect) to 5% with a mean of 1.3%. The MCI for each stimulus was as follows: 'red' = -0.03%, 'green' = 1.40%, 'blue' = -0.32%, 'yellow' = 3.74%, 'orange' = 2.00% (by-item, $t=1.8$, $df=4$, $p=.14$).

(3) The MCIs for control words were calculated using their matched colour term's typical settings ('sudden' was given the typical setting of 'yellow'). The MCIs for control words were not significantly greater than zero (MCI, 2-tailed, by-subjects, one-sample t-test; $t=0.8$, $df=14$, $p=.41$). MCIs for colour terms were significantly higher than for control words (2-tailed by-subjects two-sample t-test; $t=2.24$, $df=14$, $p=.04$).

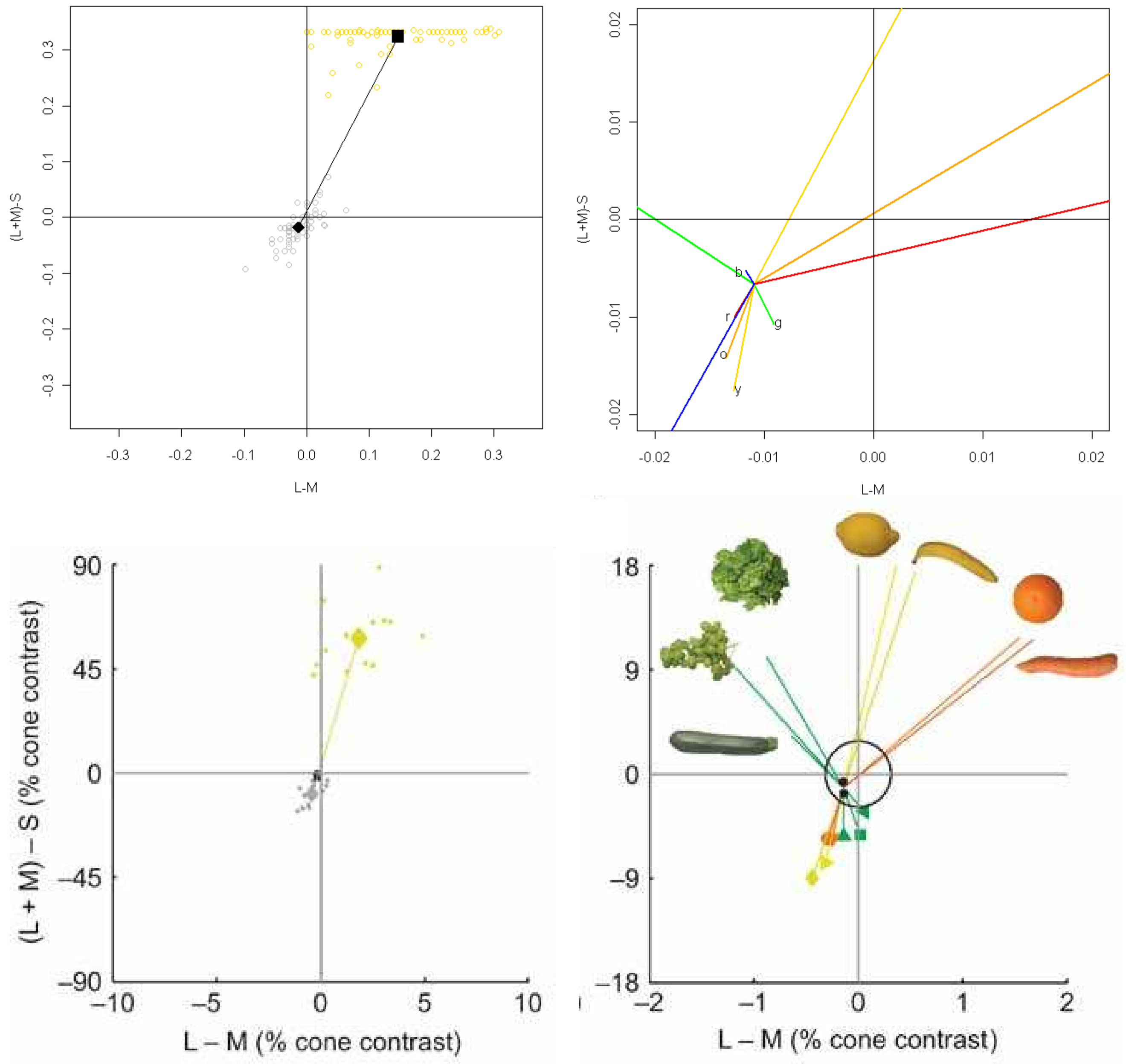

Figure 14: Graphs from the current study (top) and Hansen et al. (2006, p.1368). All graphs are plotted in DKL colour space with axes in percentages of DKL space (e.g., top left x-axis ranges from -30% to 30%, bottom left x-axis from -10% to 10%). Top left: Typical (yellow) and achromatic (grey) settings for the colour term 'yellow', with means for each condition in black. Bottom left: Typical (yellow) and achromatic (grey) settings for pictures of a banana, with means for each condition as diamonds. Top right: Lines connecting typical settings for each colour term, the mean subjective whitepoint and the mean achromatic settings for each colour term. Achromatic settings are labelled with a letter (r = 'red, 'g = 'green', b = 'blue', y='yellow', o = 'orange'). Bottom right: Lines connecting the mean typical setting for each fruit, the mean subjective whitepoint and the mean achromatic settings for each fruit. Typical settings are labelled with a picture of the fruit.

Hansen et al. (2006) includes two other statistics which are replicated for the current study: Firstly, achromatic squares did not significantly differ from the adaptation point, based on the

Y-axis only (2-tailed by-subjects one-sample t-test; t=1.2, df=14, p=.23). Secondly, achromatic colour-terms are significantly different from the adaptation point, based on the Y-axis values only (2-tailed by-subjects one-sample t-test; t=2.5, df=14, p=.03). Another statistic included in Hansen et al. (2006) is that achromatic settings for fruit (colour terms in the current study) were significantly different from achromatic settings for control stimuli. This made sense for Hansen et al., since all their experimental stimuli had typical settings in one hemisphere of the colour space, and so the expected MCI shift for colour terms was in one direction. However, this statistic is not appropriate for the current experiment, since we have experimental stimuli with typical settings in both hemispheres. This means that there is no prediction about the mean settings for experimental stimuli in comparison with control stimuli for the current study.

Figure 14 shows two graphs from Hansen et al. (2006) and the same graphs with the data from the current study. The graphs on the left show the typical and achromatic settings for the experimental stimuli, with the means for each condition highlighted. The line between

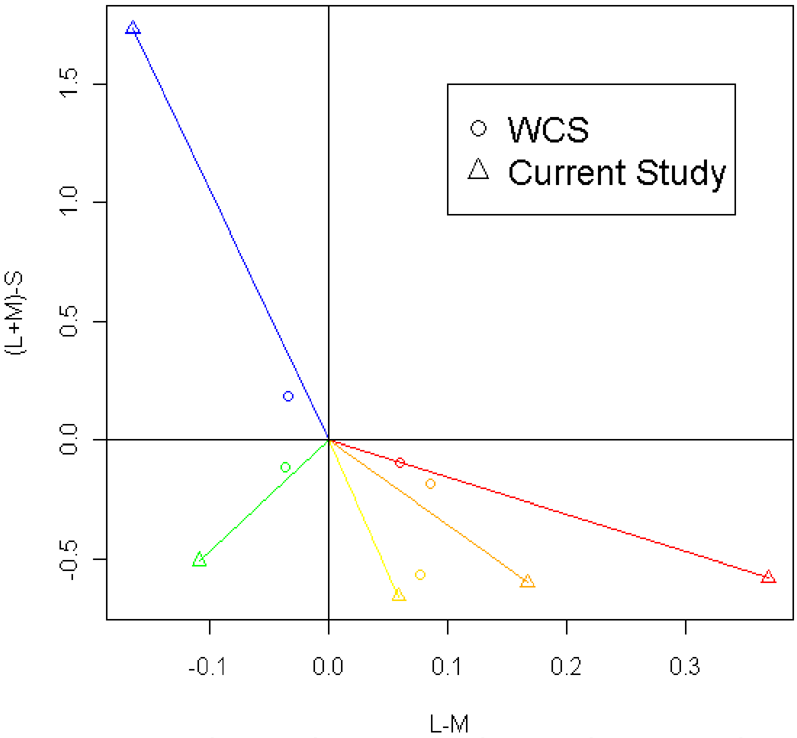

Figure 15: Comparison of hues for typical settings from the current study and those for English speakers from the WCS (Berlin & Kay, 1969, data from http://www.icsi.berkeley.edu/wcs/data.html).

these means passes through the adaptation point into the opposite colour space. That is, participants make the word ‘yellow’ look yellow in the typical condition, and adjust it to have a blue tint in the achromatic condition. The graphs on the right show the mean typical and achromatic settings for each individual experimental stimulus. A line is drawn from the typical setting (outside the bounds of the graph), through the mean subjective white point for all participants (calculated from the mean setting for uniform squares) and back out to the achromatic setting. The straightness and length of these lines is what contributes to the MCI.

The mean typical settings for each colour term in this study were compared with those chosen as the best examples of a colour term by English speakers in the WCS. The range of colour choices in the WCS differ in saturation and brightness, so the comparison was done according to the angle from the adaptation point in DKL space, equivalent to 'hue' (figure 15). The hues chosen in this study were not significantly different to those in the WCS (WCS mean = 216^{o}, sd = 1.4, Current Study mean = 228, sd = 1.6, t = -0.81, df = 4, p = .46, data from http://www.icsi.berkeley.edu/wcs/data.html). However, the mean achromatic setting for control stimuli is significantly different from the adaptation point (over all control stimulus trials, one-sample Hotelling’s T^2, Hotelling, 1931, T^2=129.2, df=2, p<.0001). This is not necessarily problematic, since subjective white points will vary, along with individuals’ idea of ‘grey’ (Webster et al., 2002). The MCI measurement takes this into account and returns a value based on each participant’s subjective colour settings.

Three post-hoc tests were run on the MCIs for colour terms. These included an ease-of-production measure, word frequency and word surface area. The MCI of colour terms were not significantly correlated with their mean ranking in the Battig-Montague norms (r=0.85, df=3, p=.07, Bonferroni-adjusted p with mutual correlation=.07, data from Van Overschelde, Rawson & Dunlosky, 2004). There was no significant correlation between colour term MCIs and colour term frequency (r= -0.70, df=3, p=.20, Bonferroni-adjusted p with mutual correlation =.21, frequencies from CELEX). There was no significant correlation between colour term MCIs and surface area (r=0.81, df=3, p=.09, Bonferroni-adjusted p with mutual correlation =.10). This shows that the effect in this study cannot be explained by ease of generation, typicality, frequency or stimulus surface area.

7.7 Discussion

This study found that participants choose achromatic colours for colour terms that extend into precisely the opposing colour space to the colour they describe. That is, when we read yellow, we see yellow. It is argued that this effect comes from a perceptual activation caused by the comprehension of the colour term. This supports an Embodied account of comprehension. However, the main effects were weaker in the current study than in Hansen et al: Colour words had a mean MCI of 1.3% in the current study - lower than Hansen et al. (2006) report for fruit (mean MCI of 8.23%). However, Olkkonen et al. (2008) found that more abstract stimuli elicited less of an MCI effect (mean MCI of Photographs=7.6%, Fruit painted white to remove surface texture=5.6%, Uniform outlines of fruit=2.3%). Colour terms are a further abstraction – they share no physical structure with their referent – so a smaller effect is expected. Furthermore, 'typical' colours for colour terms tended to be maximally saturated colours at the limits of the colour space, whereas more intermediate saturations would be likely for realistic photographs. Moving the typical setting further from the adaptation point increases the typical vector and decreases the MCI.

Although the current study found a significant effect using the MCI, the effect is not large or robust. Firstly, not all participants in the current study had a positive MCI. Secondly, the analysis of MCI by items shows a large effect for yellow, orange and green but a negative effect for red and blue. There are no blue or red stimuli in Hansen et al. (2006), but a red strawberry in Olkkonen et al. (2008) had a negative MCI value. There may be two explanations for this. Firstly, some inconsistency in the colour space or the calibration may attract all experimental stimuli towards the negative y-axis area. This would give a significant result for Hansen et al., because the typical y-axis values for all experimental stimuli are positive. Blue and red have lower or negative y-axis values, reducing their MCI value. However, it would not explain why there was a difference between control and experimental stimuli in both experiments. Alternatively, blue is not a usual colour for fruit. Recalling the co-evolution of fruit colour and colour vision, the colour term ‘blue’ may not work because the system is not adapted for processing it. However, it does not explain why ‘red’ should not have an effect, since red is a common colour for fruit.

Another explanation for the general effect is related to the Stroop Effect (Stroop, 1935). This is a delay in processing caused by conflicting stimuli. Initial experiments noted slower reaction times for naming the colour of the ink a word was printed in if the ink colour mismatched, for instance the word ‘red’ printed in green. This phenomenon is thought to involve parts of the brain that handle conflict resolution (e.g., Spreen, Strauss & Sherman 2006). However, it is unlikely that the Stroop effect has a large influence on the results of the current experiments because, unlike many experiments investigating categorical perception and Embodied Cognition, neither of the current experiments imposes a time limit and reaction times are not measured as a main effect.

The experimental effect also brings to mind Synaesthesia. Synaesthetes experience a mixing of their senses. For some individuals, linguistic structures, such as spoken or written words, evoke conscious perceptions of colour (Simner, 2007). There is a tendency for non-synaesthetes to associate certain graphemes with certain colours (Simner et al. 2005). However, these associations are phenomenologically different to synaesthetic experiences. The current study finds that colour words take on the perceptual features of their referents. However, synaesthetic effects usually involve feed-forward connections between perceptual areas, rather than by feedback connections from conceptual areas (Bargary & Mitchell, 2008, Barnett et al., 2008). The experimental effect is hypothesised to be a feedback effect, and so the results of this study will not be discussed in terms of synaesthesia.

Overall, the results support the Embodied implication (comprehension involves perception) and the Categorical Perception implication (concepts influence perception). However, these results are consistent with two basic explanations. Firstly, semantic information could be influencing the perception of the object itself. That is, the word 'yellow' appears to be yellow because the concept activates perceptual representations. Alternatively, the effect may be a part of the phenomenon of simultaneous colour contrast (e.g., Chevreul, 1868). That is, the perception of colour depends on the surrounding colours. In this experiment, semantic information may be used for colour constancy, and could be changing the perception of *all* colours. That is, the colour of the word 'yellow' is taken, in the absence of other cues, as a locus for the colour yellow, and the perception of the *background* changes to suit this. In this case, the background would look bluer than without the word 'yellow', and participants would try to match this colour. In order to improve the power of the results and to address the confound above, a second experiment was run, described in the next section.

8 Experiment 2

If people's perceptions of stimuli are altered by their prototypical colours, and if this extends into abstract stimuli such as colour terms, then a simple prediction is made: Two different colour terms printed side by side in the same colour will appear to be different colours. Furthermore, this will provide evidence to solve the possible confound mentioned at the end of the last section. The words will only appear to be different colours if semantic information causes the perception of the object itself to change. If semantic information is used to calibrate colour perceptions in general, then the two words will still appear to be different.

8.1 Apparatus

The same display apparatus was used as in experiment 1. Experiment 2 additionally used E-prime and a serial response box to display stimuli and record participant responses.

8.2 Methods

8.2.1 Participants. 9 male and 6 female, non-colourblind, native English speakers were recruited who had not participated in the first experiment.

8.2.2 Stimuli. Participants were shown pairs of opposing colour terms – 'yellow' and 'blue' as a pair and 'red' and 'green' as a pair. Four colour 'tints' were calculated that were equidistant (ΔE^{*}_{ab} of 1.0) from the adaptation point in the direction of the typical colours of these colour terms, as defined by the mean responses of participants in the first experiment ('red': l=32.14, x=0.322, y= 0.341; 'green': l=32.28, x=0.319, y =0.341; 'yellow': l=32.03, x=0.321, y=0.34; 'blue': l=31.98, x=0.319, y=0.339).

There were four colour conditions: The pair were shown both in one term's typical tint (biased), both in the other term's typical tint (biased), each in their own typical tint (typical) and each in the other term's typical tint (atypical). The colour terms were displayed in vertical alignment and each pair was shown in each condition in both spatial configurations. As a control measure, the same tint conditions were applied to a pair of shapes – a square and a cross. The difference in shapes mirrored the difference in colour terms. The surface area of each shape was the mean surface area for the colour terms. The stimuli had a luminance of 32 cd/m^2, as in the first experiment. All stimuli appeared on a uniform background with the same achromatic colour as in the first experiment (x=0.32, y=0.34, Luminance=29.0). All stimuli subtended a maximum of 7^{o} (words varied due to variation in length).

8.2.3 Procedure. A blank screen preceded each trial for 1 second. Participants were asked to categorise the colours of the two targets as either being the same or different. A training session was run first with random words and shapes. Feedback was provided to familiarise the participants with the degree of difference they were expected to detect. If the participants correctly identified the training stimuli, they moved on to the experimental stimuli. Participants saw each stimulus pair in both spatial configurations 12 times. The order of the trials was randomised. Participants had 2 optional breaks and the experiment took no longer than 20 minutes. At the end of the experiment, participants were asked whether shapes were easier or harder to classify than colour terms, or if there was no difference between the two. The prediction was that participants would have a higher error rate while classifying identically coloured colour terms while classifying shapes.

8.3 Results

All participants correctly completed the training session and stated that they were able to distinguish between the different tints. Participants were significantly more likely to categorise identically-coloured colour terms as different than identically-coloured shapes (t=13.32, df=2249, p<.0001). The error rates for identically coloured colour terms by participant ranged from 1% to 79% with a mean of 22.95% and the error rates for identically coloured shapes ranged from 0 % to 31% with a mean of 5.94%. There was no significant difference in the error rates for typical and atypical colour term stimuli (mean error rate for typical condition=5.6%, mean error rate for atypical condition=4.7%, t=0.80, df=1413, p=.42).

	Stimuli Colour		
	Different		**Same**
Stimuli structure	Typical	Atypical	
Shapes	3.94%		5.94%
Colour terms	5.59%	4.65%	22.95%

Table 1: Error rates for judgements of colour in experiment 2.

A linear mixed effects regression was used to analyse the results. The participants' responses were entered as the dependent variable. Colour contrast (typical, atypical or biased, entered as two dummy variables), stimulus type (words or shapes), reaction time, sex and trial number were entered as fixed effects with a by-participants random effect. Table 2 shows the statistics for the main fixed effects. Colour contrast, stimulus type and reaction times were significant predictors of responses. The sex of the participant, and the position of the trial in the experiment were not significant predictors.

Variable	**Log Likelihood Difference**	**χ2**	**df**	**p**
Colour contrast	3133.8	6267.69	2	<0.0001
Stimulus type	141.5	282.92	3	<0.0001
Reaction time	164.6	329.17	6	<0.0001
Sex	0.7	1.46	1	0.23
Trial num	1.7	3.52	1	0.06

Table 2: Main fixed effects statistics.

Reaction times were significantly longer for colour terms than squares (Mean reaction time for squares = 1765 ms, for colour terms =2276 ms, t =-7.76, MCMCp<.0001, calculated with Markov chain Monte Carlo method). All participants also reported that shapes were easier to classify than colour words. Reaction times for mismatching colour terms were significantly longer than matching colour terms (Mean reaction time for matching=1678 ms, mismatching=1739 ms, t=2.10, MCMCp=.04). Adding a by-participants random slope significantly improved the fit of the model (Log likelihood difference=340.2, χ2=680.3,df=20,p<.0001), suggesting that participants were susceptible to the categorisation effect to significantly different degrees.

8.4 Discussion

Experiment 2 found evidence that two different colour terms presented in the same colour appear to be different colours. Participants showed reduced discrimination accuracy between categories, fitting Pastore’s (1987) description of a categorical perception threshold effect. This supports the first experiment, is in line with other Embodied Cognition experiments, and is also freer from concerns of exact calibration, adaptation points and noise from the granularity of choices. It could be argued that the effect is a Stroop-type effect, rather than a perceptual one. However, there are three reasons to refute this: Firstly, there were significantly fewer errors for categorising colour terms presented in different colours. This suggests that the extra error rate for identically-coloured colour terms was caused by a separate effect to one of a Stroop nature. Secondly, the Stroop effect imposes a processing cost which is usually measured in response times. Participants in this experiment had no time constraint. Finally, since the effect on perception is hypothesised as threshold effect, one would expect the effect to come and go with the attention of the observer. That is, whether they were considering it as a word or as a shape. However, there is a possible confound in conditions where the two stimuli were different colours – although the difference between the colours was small, they were across category boundaries (e.g., yellow and blue), which might exaggerate the difference perceptually (e.g., Gilbert et al., 2006). This does not explain why there were fewer errors for shapes, but may interact with the comprehension of the word. Overall, the results support the first experiment, and confirm the hypothesis that the colour of the object itself changes because of its known referent.

9 Conclusion

This study considered three implications of the Embodied Cognition Hypothesis. The two experiments in this study found evidence to support the **Embodied implication** that comprehension involves activating perceptual symbols and the **Categorical Perception implication** that concepts can affect perception. Specifically, colour words are seen as grey only when they are tinted with the perceptually opposing colour to the one they describe. This suggests that people literally see yellow when they read the word ‘yellow’. Also, participants are more likely to classify two opposing colour words displayed in the same colour as different colours than abstract shapes. These findings fit into an Embodied theory of cognition whereby perceptual representations are activated by linguistic stimuli (colour terms). Furthermore, the first experiment showed that Embodied effects can be measured in ways other than delays in high-level processing, showing that perceptual symbols are persistently active during comprehension. Several questions remain unanswered, however, such as why certain colour terms have a larger effect on perception than others (‘yellow’ had more of an effect than ‘blue’) or whether less abstract colour terms (those more obviously grounded in real-world objects such as ‘violet’) show more or less of an effect than basic colour terms.

Past studies have shown that a wide range of factors constrain the categorisation of colour, including the physiology of perception, the environment and cultural transmission. This study shows that the categorisation acquired by individuals can feed back into perception and itself become a constraint both on the development of categorisation, the environment and genetic inheritance. In this sense, the feedback from categorisation allows Niche Construction dynamics to apply to linguistic categorisations. It was argued that this dynamic fits with the **Cultural implication** of an Embodied account of language comprehension. That is, this study has concluded, similarly to Kirby et al. (2007), that universal patterns across populations do not necessarily imply strong innate biases. This was done by arguing that Cultural, Embodied systems tend to drift towards better representations of the real world, which involves better coherence with perceptual and environmental constraints, creating cross-cultural patterns. Furthermore, an Embodied approach to cultural dynamics incorporating a mechanism for perceptual warping predicts that the perceptual spaces of individuals can be synchronised through language to achieve better communication.

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