Progress in Colour Studies

Volume II. Psychological aspects

Edited by N.J. Pitchford
and C.P. Biggam

John Benjamins Publishing Company

Progress in Colour Studies II

Progress in Colour Studies

Volume II. Psychological aspects

Edited by

N.J. Pitchford
University of Nottigham

C.P. Biggam
University of Glasgow

John Benjamins Publishing Company
Amsterdam / Philadelphia

Library of Congress Control Number 2006048782

ISBN 90 272 3240 7 (Hb; alk. paper)

John Benjamins Publishing Co. · P.O. Box 36224 · 1020 ME Amsterdam · The Netherlands
John Benjamins North America · P.O. Box 27519 · Philadelphia PA 19118-0519 · USA

CONTENTS

Section 1: Theoretical approaches

Section 2: Developmental and cultural aspects

Section 3: Cognitive and emotional aspects

PREFACE

When Prof. Christian Kay and Dr Carole Biggam decided to organize a conference on colour, one desideratum was foremost in their minds: they wanted to have representations from all those disciplines in the humanities and social sciences (broadly interpreted) which had already tackled this subject. Any colour researcher, whether linguist, psychologist, anthropologist, artist or other specialist, soon discovers that progress is limited without a multi-disciplinary approach, but how can any one researcher have a grasp of the ever-changing cutting-edge research of many other specialists? They felt that it would be immensely helpful to ask contributors to the conference to give a flavour of what was happening in their own disciplines, either by offering a general overview of the latest theories, or by presenting an example project illustrating their research methodology. They were delighted at the interest shown in the proposal, at the amazingly broad spread of subjects that was offered, at the number of nationalities represented at the conference, and at the quality of the papers presented. As a psychologist, Dr Pitchford embraced the opportunity to meet with colour researchers from a wide range of disciplines and suggested to Prof. Kay and Dr Biggam that she organize a session covering the psychological aspects of the development of colour vision and colour cognition. This proved to be highly successful, as experts in various fields gave papers reporting their latest research findings. Prof. Kay and Dr Biggam then invited Dr Pitchford to join them in editing this collection of papers.

The conference, entitled ‘Progress in Colour Studies 2004’ (PICS04), was held in the University of Glasgow from 30th June to the 2nd July 2004, and the event proved to be both academically stimulating and extremely convivial. The greatest sadness was that one of the speakers, Robert MacLaury, a towering and long-standing name in the linguistics and anthropology of colour studies, died not long before we gathered in Glasgow. It was immediately decided that the conference should be dedicated to his memory, as are the resulting volumes, and we would like to offer our grateful thanks and heartfelt sympathy to María MacLaury, who not only gave permission for these dedications, but attended the conference in person.

The study of colour semantics suffered another loss not long after our meeting, when the erudite and gentlemanly Robert Edgeworth, who gave a witty paper at the conference, sadly died soon after returning home to the U.S.A.

The publication of the majority of the conference papers has been a lengthy task, but we hope readers will agree that they make a valuable contribution to our understanding of this most intriguing of subjects. We are grateful to our publisher, John Benjamins, for agreeing to a two-volume work, roughly divided into linguistic and psychological aspects. The first volume is entitled *Progress in Colour Studies1: Language and Culture.*

In this second volume, Dr Pitchford and Dr Biggam are proud to present some fascinating papers that were offered at the conference. We invited three additional papers from researchers who could not attend the conference (those of Bornstein; Teller, Pereverzeva & Zemach; and Ling, Hurlbert & Robinson), as we were aware that they had exciting new theories and data that we wanted to include. All the papers in this volume review recent research findings, and, in addition, some new work is reported. The volume is divided into three sections. Section 1 considers different theoretical approaches to the scientific study of colour, with compelling reasoning being proffered by Dedrick; Jameson, Bimler & Wasserman; and Bornstein. Section 2 concentrates on developmental and cultural aspects of colour research, and includes papers that explore the early capabilities of young infants in the perceptual processing of colour (Teller, Pereverzeva & Zemach; Catherwood), as well as the manner in which infants categorize colour compared to adults with their highly specialized linguistic colour systems (Franklin & Davies; Bonnardel & Pitchford). Factors that influence the acquisition of colour terms by young children are then examined in two papers that investigate how children learn to name colours in English (Pitchford & Mullen) and in Himba (Roberson, Davidoff, Davies & Shapiro). A further paper explores how gender and culture influence colour preference by comparing adult males and females of English and Chinese origin (Ling, Hurlbert & Robinson). Section 3 examines cognitive and emotional aspects of colour processing, and includes papers that investigate the emotional connotations of colour words in Mexican adults (Prado-León, Avila-Chaurand & Rosales-Cinco), and certain neurological and linguistic aspects of the perplexing yet intriguing condition of synaesthesia (Kay & Mulvenna). Who could fail to find something of interest here?

Finally, the conference organizers would like to thank all those who contributed towards the smooth running of the event. Their work is much appreciated: Marc Alexander, Kathryn Allan, Jean Anderson, Andra Bean, Dave Beavan, William Biggam, Ellen Bramwell, Jane Duncan, Flora Edmonds, Ian Hamilton, Jim McGonigal and Catherine Mulvenna. We would also like to thank the reviewers of the papers for their helpful suggestions, and our editor at Benjamins, Anke de Looper. A more general, but no less heartfelt thank-you is also due to the Institute for the Historical Study of Language at the University of Glasgow. For financial help with the conference, the organizers would like to thank the University of Glasgow and the Linguistics Association of Great Britain.

N. J. Pitchford and C. P. Biggam
August 2006

DR ROBERT E. MACLAURY 1944-2004
AN APPRECIATION

TERRI MACKEIGAN & CHRIS SINHA
University of Edinburgh & University of Portsmouth

Dr Robert E. MacLaury died on February 18, 2004. Rob was a scientist and scholar of huge stature, enormous originality and breathtaking productivity. He began his academic life as an anthropologist, doing fieldwork in Oaxaca State, Mexico, where he carried out an exhaustive study of the phonology, grammar and semantics of Zapotec languages. Amongst the many publications resulting from this work was his seminal 1989 paper on the semantics of Zapotec body-part locative terms. He gained his Ph.D from the University of California, Berkeley in 1986. Rob became involved in the World Color Survey, based in Berkeley, and was himself responsible for the Meso-American Color Survey, culminating in his book *Color and Cognition in Mesoamerica: Constructing Categories as Vantages*, published in 1997. Rob's involvement in research in colour perception and language was not confined to Central America, but also encompassed work in Africa, Canada, New Zealand and the American North and Southwest. It was his colour research that provided the spur for the theoretical work that occupied the last few years of his life. Rob MacLaury's name will always be associated with Vantage Theory, an approach to categorization that significantly extended prototype theory by incorporating, as its name suggests, speaker vantage point, entrenched in the semantics of particular languages, into the process of human categorical perception.

It is for his kindness and humanity that we shall most remember Rob. We, and many others, benefited from the unstinting generosity with which he shared his time and his encyclopaedic knowledge with colleagues and students. Rob was not one of those who viewed scientific knowledge as primarily a vehicle for professional advancement, and we often felt that he did not receive the kind of recognition that his work deserved. During the last years of his life, Rob was immensely productive. Perhaps he sensed that he had only a little time in which to complete his life's work. Now Rob is no longer with us, but it is our profound hope that others, beside ourselves, will read his publications, be inspired, and develop the rich inheritance he has left behind him. Rob lives on, like all great intellectuals, in his work. In person, we shall miss him very much.

References

MacLaury, Robert E. 1989. “Zapotec Body-Part Locatives: Prototypes and Metaphoric Extensions”. *International Journal of American Linguistics* 55.119-154.

—. 1997. *Color and Cognition in Mesoamerica: Constructing Categories as Vantages*. Austin: University of Texas Press.

ABBREVIATIONS

AFC	Alternative Forced Choice
Ala	Alanine amino acid
ASL	Applied Science Laboratories
BCT	Basic Colour Term
CA	Chronological-Age
cd/m2	Candelas per meter squared
CHILDES	Child Language Data Exchange System
CIE	Commission Internationale de l'Éclairage
CRT	Cathode-Ray Tube
DAF	Dispersion Accounted For
DNA	Deoxyribonucleic acid
ERP	Event-Related Potential
F-M	Farnsworth-Munsell
fMRI	functional Magnetic Resonance Imaging
FPL	Forced-choice Preferential Looking
Gen.	Genesis (Bible)
H	Hue
jnd	just noticeable difference
L	Long wavelength; Lightness
LA	Language-Age
LH	Left Hemisphere
LHS	Lightness, Hue, Saturation
LR	Long Range
LVF	Left Visual Field
LWS	Long-Wavelength Sensitive
M	Medium wavelength
MDS	Multi-Dimensional Scaling
MWS	Medium-Wavelength Sensitive
msec or ms	millisecond
N or n or *n*	(total) Number
NIH	National Institutes of Health (U.S.A.)
nm	nanometre
NS	Neonatal Synaesthesia

OSA	Optical Society of America
P	Percent
p or p	probability
PC	Principal Component
PCA	Principal Component Analysis
PCR	Polymerase Chain Reaction
PET	Positron Emission Tomography
PIC	Pseudo-Iso-Chromatic
r or r	Correlation Coefficient
RH	Right Hemisphere
RVF	Right Visual Field
S	Short wavelength; Saturation
S, Ss	Subject, Subjects
SD or sd or s.d.	Standard Deviation
SE	Standard Error
SEM	Structural Equation Modelling
Ser	Serine amino acid
SOA	Stimulus Onset Asynchrony
SWS	Short Wavelength Sensitive
tCSF	Temporal Contrast Sensitivity Function
UCSD	University of California, San Diego
UV	Ultra-Violet
V1-4	(Areas of the visual cortex)
WCS	World Color Survey
wks	weeks

EXPLANATION(S) AND THE PATTERNING OF BASIC COLOUR WORDS ACROSS LANGUAGES AND SPEAKERS

DON DEDRICK
University of Guelph

> Different persons growing up in the same language are like different bushes trimmed and trained to take the shape of identical elephants. The anatomical details of the twigs and branches will fulfill the elephantine form differently from bush to bush, but the overall outward results are alike. (Quine 1960:8)

1. *Introduction: how many kinds of explanation?*

When one provides *an explanation* for colour naming regularities, what exactly is one providing? Here are five possibilities:

a. An explanation for the patterning in human languages across cultures.

b. An explanation for some cross-cultural subset of human languages.

c. An explanation for naming behaviour in a specific culture / language.

d. An explanation for a subset of the speakers of a specific language.

e. An explanation for an individual speaker.

This is not a multiple-choice test with a single right answer. All of these options, from a-e, have been proposed in the literature on colour naming. Since I want to write about these explanatory strategies and their interaction, it will be useful to have some exemplars to hand.

a. An explanation for the patterning in human languages across cultures

When one thinks of the colour naming literature, especially if one is not a specialist, this will be the sort of explanation that comes to mind. Paul Kay and his colleagues have argued for this type of explanation for years, a version of which we find in a recent paper: “The Kay and Maffi model takes universal constraints on color naming to be based on presumed universals of color experience” (Kay 2005:fn 4). Another well-known version of this explanation – which claims that the look of the colours is sufficient to generate the colour naming regularities – has been advanced by the philosopher Larry Hardin (1988; 2005). The target for this explanation: cross-cultural universals of color naming.

b. An explanation for some cross-cultural subset of human languages

In a recent paper, the ophthalmologists Lindsey and Brown argue that the reason why many peoples from the tropics have languages which lack separate terms for green and blue is an over-abundance of UV-B radiation:

> …languages spoken in the tropics, where the annual dose of UV-B radiation from sunlight is high, tend to lack a distinct word for “blue” [sic]. Instead, they use a single basic colour term (BCT) that means green-blue or green-or-blue-or-black… We suggest that this tendency to lack a distinct word for “blue” may be partly due to environmental damage to the eyesight. (Lindsey & Brown 2002).

The target for this explanatory strategy is a *subset* of the set of human languages (those that are sub-tropical, and lack distinct terms for green and blue.

c. An explanation for naming behaviour in a specific culture / language

Explanations like this are fairly common and may grow out of fieldwork (for examples, see Dedrick 1998a:140-143). One recent example is found in an influential paper arguing for a relativist explanation for colour names. Debi Roberson and her colleagues argue that

> Berinmo categories have not formed around prototypes, as for the most part there is little agreement about best examples… In any case, focal colors appear to play no part in facilitating recognition or encouraging new learning. (Roberson, Davies & Davidoff 2000:386).

This is partly a negative account. It denies an influential perceptual ‘prototypical’ explanation for colour names, similar to that of Kay (2005; see also Kay and Regier 2003), but identified explicitly with the work of Eleanor Rosch / Heider (Heider 1972; Heider & Olivier 1972). It is based on work with a specific linguistic group, the Berinmo (though Roberson generalizes; see Dedrick 2005 for some comments on this).

d. An explanation for a subset of the speakers of a specific language

The quotation from the late, great American philosopher, W.V. Quine, which begins this paper, is along these lines. Quine was talking about how very similar 'phenotypes' could be produced by distinct causal structures. In her interesting work on female tetrachromacy (Jameson, Highnote & Wasserman 2001), Kimberly Jameson argues that similar colour naming behaviour among the speakers of a single language (English) may have different causal antecedents. Jameson is arguing against perceptual accounts, such as that proposed by Kay (2005), described in a. above. To get the feel of Jameson's argument, consider her comments on tetrachromatic and trichromatic speakers of English (two groups she has studied experimentally). Given that there are human subjects with richer (for example, tetrachromatic) colour vision, then their colour experience will be different from the experience of more typical trichromatic subjects. Thus, if tetrachromats and trichromats posses a similar stock of basic colour words, there must be (for at least some of these speakers) a way of fixing their use that is not just determined by the nature of visual experience:

> If the potential for individual variation in color perception is so common, and the perceptual consequences are, in some cases, substantial, then why is so little intra-cultural disagreement observed in everyday color naming and categorization? (Jameson 2005:313).

Jameson's idea is that *different subsets* of a population may require different sorts of explanations for a common naming behaviour.

e. An explanation for an individual speaker

Explanations at the level of individual speakers are not common, and yet there is a clear rationale for them: it is individuals that actually use colour words, so there must, for each individual, be an account of how such use is accomplished. The late Robert MacLaury was, more than any other researcher, interested in the individual data:

> Modeling categories as points of view incorporates a commitment to what categorization is and to what it is not. It is a process that a person undertakes, maintains, and changes in order to comprehend the world… it has no existence apart from the person who produces it on the basis of an edited selection of external reality. (MacLaury 1997:393).

MacLaury's concern was with individual categorical processing, which he modeled in terms of his 'vantage theory' (MacLaury 1997). One purpose of this theory is to account for individual differences in colour naming practice. While there is some concern as to whether we need a theory at this level of resolution (see Dedrick 2005 for a discussion of this issue), there is no doubt that MacLaury is concerned with the colour naming practices of *single speakers*, at least some of the time (e.g. 1997:450, 453).

These five kinds of explanation are not the only possible kinds. Nor are the examples I have given, within a kind of explanation, the only explanations compatible with their type (Type c., for example, will encompass many different ethnographic claims, and styles of reasoning). There are, in other words, a lot of very different kinds of claims passing for explanations in the domain of colour naming research.

2. *Are different kinds of explanation for the patterning of basic colour terms compatible?*

Let me begin this section by noting the obvious: not all explanations and explanation types are compatible with one another. Nonetheless, incompatibility may be more difficult to find than one might initially imagine. We have already noted the perceptual basis appealed to by Kay (2005, also Hardin 1988; 2005) for the distribution of basic colour terms. In contrast to this perceptual view, Saunders and van Brakel have claimed that cultural imperialism may account for the spread of basic colour terms (Saunders & van Brakel 1997). Are these two views incompatible? It would seem so, in that Saunders and van Brakel are concerned to argue that there are no important constraints on human colour naming, while Kay is committed to the view that such constraints are based in whatever grounds human colour perception (presumably primate neurophysiology). But the incompatibility is not certain. While it is true that the different authors interpret their explanatory strategies as incompatible, it is possible that, for example, cultural imperialism spreads colour names that have a basis in colour appearance, or that this is true in at least some cases, if not all. The same may be true of Jameson’s claim that it cannot be perceptual facts that ground colour naming for some subjects, given they are perceptually quite different from normal trichromatic colour perceivers (Jameson 2005). Let us grant that such subjects are perceptually different. It may still be the case that, as they are a minority, their colour language is shaped by the trichromatic majority who do have their colour words grounded in perceptual trichromacy. Other potential conflicts may not be such either. The fact every language has a particular history concerning the origins of its colour words cannot, a priori, establish that universalist claims are irrelevant (McNeill 1972; Dedrick 1998a for discussion). There may, for example, be different routes to a cognitively optimal set of colour words, where cognitive optimality interacts with other variables, such as cultural or ecological (Dedrick 1998a; Jameson 2005). More generally, many of the explanatory strategies and specific explanations proposed in colour naming research capture regularities at different 'levels' and are thus compatible. Here is an interesting, perhaps non-obvious case where this occurs.

I have already mentioned the phototoxicity hypothesis of Lindsey and Brown (2002). According to this view, many languages spoken in the tropics lack separate terms for green and blue because there is an over-abundance of UV-B radiation which damages the eye. A critic of Lindsey and Brown, Heidi Lazar-Meyn (2004), has responded to this claim as follows:

> Celtic language data from the British Isles establish not only the existence of grue in non-equatorial color systems, but also the persistence of this color term… despite nearly 200 years of exposure to other Indo-European languages and the consequent pressure to distinguish "blue" from "green". (Lazar-Meyn 2004:288).

Lazar-Meyn's point is this: people that are not exposed to an abundance of UV-B radiation nonetheless have a grue term. So the explanation for grue cannot be damage to the eye from UV-B radiation. Here is the way Lindsey and Brown counter this claim:

> We are always interested in learning more about the color lexicons of the world's languages… but the presence of grue in the Celtic languages does not undermine our argument. Our result was based on an analysis of 203 languages, not chosen by us. It cannot be refuted by a modest number of counterexamples. (Lindsey & Brown 2004:291).

Many would find this attitude cavalier. I view it and Lazar-Meyn's claims in a different light. Both of these authors treat the Celtic languages as potential counter-examples to the phototoxicity hypothesis. Yet this is only so if there is a strict determination of colour language by perception. If the only way you could have a grue term is in virtue of having an appropriately damaged eye, and the only way you can have an appropriately damaged eye is through exposure to UV-B radiation, then the Celtic languages refute the hypothesis. If, on the other hand, there are different ways of getting a grue term – some physiological, some cultural (we say, for the sake of argument) then there is no counter-example here at all. Which is not, note, technically the Lindsey and Brown position, according to which, (a) there is a counter-example, and (b) it does not count.

Here is another example, also, perhaps, of a non-obvious 'compatibility'. According to Roberson, Davies and Davidoff, color categories are not universal. Indeed, "Color Categories Are Not Universal" is the title of a recent paper by those authors in the *Journal of Experimental Psychology* (Roberson, Davies & Davidoff 2000). Paul Kay and Terry Regier (2003) appear to disagree, for, while they are cognizant of the Roberson paper, they state their own recent conclusions as follows:

> (1) There are clear cross-linguistic statistical tendencies for named color categories to cluster at certain privileged points in perceptual color space; (2) these privileged points are similar for the unwritten languages of non-industrialized communities and the written languages of industrialized societies; and (3) these privileged points tend to lie near, although not always at, those colors named "red", "yellow", "green", "blue", "purple", "brown", "orange", "pink", "black", "white", and "gray", in English. (Kay & Regier 2003:9089).

These claims recapitulate the original universalist findings of Berlin and Kay (1969), and we have to wonder as to the bases for the radically different claims of Roberson and her colleagues, and those of Kay and his. It would seem that at least one of them must be mistaken.

Yet these authors are talking about different things. Kay and Regier employ a statistical analysis that has the effect of concealing a great deal of variation in the population in order to determine central tendencies in color naming. Roberson is concerned to replicate the results of Eleanor Rosch (Heider) on color prototypicality (Heider 1972; Heider & Olivier 1972). The different claims can be put as follows. Kay and Regier offer a very robust, very abstract claim about the statistical tendency of named color categories to cluster in certain predictable areas of an abstractly specified colour space. Any claim that their results are 'abstracted from context' could hardly be news to Kay and Regier, for their result is very much a product of the methodology, which, in turn, reveals interesting regularities.

On the other hand, Roberson et al. make a language-specific claim about the cognition of color. Berinmo subjects do not conform to expectations, based on the work of Rosch, that color prototypes will be salient, independent of language. The authors are thus claiming that color prototypes are not psychologically salient in the ways that Rosch proposed. Further, Roberson et al. argue that it is boundary perception (that is, learned categorical perception at the boundaries of named colour categories) that provides the best psychological explanation for Berinmo colour categories. Roberson et al.'s explanatory strategy for Berinmo can hardly support a robust explanation to the effect that color categories are not universal, whatever it shows about Berinmo. Indeed, in a second article, Kay (2005) argues that, when the naming data collected by Roberson et al. is subjected to the same statistical analysis as their own World Color Survey data, Berinmo actually conforms to and supports the universalist claim! While debate about the methodological assumptions of Kay and Regier have been a regular feature of the debate over colour naming from the beginning (for example, Hickerson 1971), the universalist claim could hardly be thought to stand or fall on one set of experiments, for one language. So what was Roberson et al. thinking when they claimed that color categories “are not universal”? In order to answer this question we need to look more closely at Roberson’s et al.’s study.

The work in question was quite explicitly an attempt to replicate Rosch’s work on color prototypicality. Rosch argued that linguistic salience of certain color words was influenced by the psychological salience of certain prototypical colors, a salience which expressed itself in a variety of tasks (memory, recognition / recall, categorization). Rosch’s work has long been thought to provide one of the best explanations for the universality observed by Berlin and Kay (see Dedrick 1998a for a discussion): the basic color terms are linguistically salient, because there are prototypical colors that are psychologically salient, and these provide a perceptual-cognitive basis for basic color term development. Rosch’s work was, crucially, explicitly cross-cultural, comparing the performance of a non-Western, aboriginal people (the Dani of Indonesian New Guinea) with that of North American English speakers. Dani colour words were significantly different from those of Rosch’s American subjects.

Roberson et al. did not study the same language / speakers as Rosch. Nonetheless, the color vocabulary of their non-Western informants, the Berinmo, is significantly different from English. Roberson et al. found that virtually none of Rosch’s results could be replicated and, of special interest, discovered that there was no cognitive advantage that attached to focal / prototypical colors. Subjects were not, for example, better on a recall task if that task involved prototypical as opposed to non-prototypical colors. Categorical effects that Rosch uncovered and which implicated focal colors as psychologically fundamental were also absent – replaced, in fact, by results more conducive to the relativist view of color categorization that preceded Rosch’s ground-breaking work (see for example, Brown & Lenneberg 1954).

It turns out, then, that Roberson et al.’s claims do not challenge universality (despite the title of their paper!) so much as the *explanation* for universality. From the fact that there is a universal tendency for named color categories to cluster in certain regions of color space, it does not follow that any specific explanation for that clustering is correct. On the other hand, Roberson and her colleagues give us reason to think that at least one explanation will be problematical. For, even if it is the case that Berinmo actually conforms to the universalist statistical claims, as Kay and Regier assert, it cannot be the case that privileged focal colours explain Berinmo color nomenclature, in the absence of any significant differentiation in the cognitive salience of focal colors from non-focals. Kay and Regier do, in fact, suggest that “certain privileged points in color space appear to anchor the color naming systems of the world’s languages” (2003:9089). It is difficult to treat this claim as anything other than a metaphor when applied to Berinmo, in the absence of any psychological salience attaching to these points. Thus, while the claims of Kay and of Roberson turn out to be compatible, an interesting sense of incompatibility emerges about the nature of the explanation for color name universals. Berinmo (and almost certainly other languages) will need an explanation of how color terms are established – and it will not be in terms of the “privileged points” mentioned by Kay and Regier.

3. *Consequences of compatibility*

In the last section, I discussed a number of cases where claims about the explanation for the patterning of basic colour terms might seem incompatible but are not – or are not in any obvious sense. This is a position that can be overstated in that, with enough ingenuity, perhaps *any* two positions can be made non-contradictory or non-contrary.[1] I am sympathetic to this criticism and it is not my intention to argue that colour naming researchers should, really, be one big happy family, engaged in compatible, ultimately mutually supporting research into the multiple splendours of colour naming around the world. What then is the point, if there is one, to the explanatory pluralism this paper does advocate? There are two points. The first really is descriptive, and I have emphasized it throughout: there is less conflict and contradiction between different explanatory strategies, than some colour naming researchers imagine. The second point is, I hope, of greater interest. The dialectic I have tried to explore in this paper has the following structure: (1) some explanatory claim *a* appears to be, or is claimed to be incompatible with some explanatory claim *b*; (2) a proper analysis reveals *a* and *b* are not incompatible, in some specifiable sense (that is, we can articulate a sense in which *a* and *b* are both true). What is revealed in this process, is not just the ingenuity of the analysis, or the claimed compatibility of seeming incompatible claims, though that is revealed. What is also uncovered, if we are lucky, is the *basis* for the seeming incompatibility as

---

[1] In logic, two claims are contradictory if they have exactly the opposite truth values, on all occasions. I am, then, denying that many supposed conflicts between views involve contradictories.

well as the basis for possible agreement. By *basis* I mean something like the assumptions, perhaps fundamental, that guide the research in question. Consider the case of phototoxicity once again. In the dispute between Lindsey and Brown, and Lazar-Meyn over whether Celtic languages stand as counter-examples to the UV-B phototoxicity hypothesis, I pointed out that, to get that disagreement off the ground, one would need to believe that the guiding explanatory strategy for colour naming is something like this: *physiology determines named colour categories*. If this is not the case, then the presence or absence of a grue term neither confirms nor falsifies the principle, for the simple reason that there is no such principle. Explanation will then proceed on a case by case basis, with a possible outcome along the following lines: sometimes, grue is based in ‘blue weakness’ caused by the deterioration of the lens of the eye as a result of exposure to (relatively) high levels of UV-B radiation, sometimes there is another explanation for the presence of a grue term, as with, for instance, the Celtic languages. Of course, it is possible that the guiding assumption I have attributed to Lindsey and Brown is correct, and every difference in colour naming across cultures has a physiological explanation. This is, however, unlikely. There is, as Lazar-Meyn points out, the case of the Celtic languages. So they need a physiological explanation. But there are also other named ‘composite categories’ (see Dedrick 1998a for a discussion), often in the same languages that Lindsey and Brown identify as targets for the phototoxic explanation of grue. Consider attestations of a composite term for yellow-and-red (Kay, Berlin & Merrifield 1991). Are we to suppose this has a physiological explanation? What would that explanation be like? My point, in part, is this: the fact that the phototoxicity hypothesis is ‘empirical’ (a notion a number of vision scientists have pointed out to me as a virtue) is not in itself a great virtue. There are many ‘empirical’ hypotheses that no one wants to test because they are not worth it. I propose that the guiding principle: *physiology determines named colour categories* is just like that, for reasons that are obvious once we state such a hypothesis and compare it with other things we know about colour naming. But note: this is not to say that specific, case-by-case explanations are ruled out. Indeed, it is just such micro-explanations that are *ruled in*. It may seem that I am spending an inordinate amount of time on the Lindsey and Brown hypothesis. Yet the general strategy I advocate can be applied elsewhere. Saunders and van Brakel, in their critical work, seem guided by the following principle: *physiology plays no interesting role in the development of named colour categories*, a claim as implausible, given what we know about colour naming, as the principle I attributed to Lindsey and Brown. Indeed, Saunders and van Brakel seem *themselves* to be unsure of this principle, writing, as they do, that “Nobody disputes that the majority of languages contain a word that in some contexts can be translated as “red” and that this has something to do with what all ecological systems “humans-environment” have in common” (2001:543).

The first moral of this story – my story – is straightforward. Do not imagine conflicts and refutations when explanatory strategies target rather different phenomena. This is, in a way, nothing but a homily – a ‘caution’ as I have called it elsewhere (Dedrick 1998b). The second moral is both more and less profound. More profound, in that it proposes that empirical research operates in terms of fundamental assumptions that are often not stated. If a basic principle of your empirical research is that *physiology determines named color categories*, then you have set yourself a heroic empirical task, given the empirical facts about colour term distribution across cultures. Robert MacLaury, who knew more about the colour naming literature than anyone, came to see this quite clearly when he stopped worrying about physiological explanations for the grue category (compare MacLaury 1987 with MacLaury 1997). It is an important position to hold, for it closes off the grand reductive models of explanation – they are just too simplistic, it seems – and pushes us toward the explanatory pluralism this paper advocates. This is the sense in which my second moral is rather less than profound. For it asks, of colour naming researchers, that they answer a very basic question: What are the fundamental assumptions about your research? Do you think, when they are brought to the light of day, that they could realistically be true, for all the phenomena that matter to colour naming, given all you know about the rest of the literature? If your answer is ‘yes’” then, as I have put it, a heroic task is at hand. If your answer is ‘no’ then the hard, case by case analysis for your hypothesis begins.

Acknowledgements

With support from the Social Sciences and Humanities Research Council, Canada, Grant # 410-2005-0148.

References

Berlin, B. & P. Kay. 1969. *Basic Color Terms: their Universality and Evolution*. Berkeley: University of California Press.

Brown, R. & E. Lenneberg. 1954. “A Study in Language and Cognition”. *Cross-Cultural Research* 49.454-462.

Dedrick, D. 1998a *Naming the Rainbow: Colour Language, Colour Science, and Culture*. Dordrecht & London: Kluwer Academic.

—. 1998b “On the Foundations of the Universalist Tradition in Colour Naming (and their Supposed Refutation).” *Philosophy of the Social Sciences* 28:2.179-204.

—. 2005. “Explanation and Color Naming Research”. *Cross-Cultural Research* 39.111-133.

Hardin, C. L. 1988 *Color for Philosophers: Unweaving the Rainbow*. Indianapolis: Hackett.

—. 2005 “Explaining Basic Color Categories”. *Cross-Cultural Research* 39:1.72-87.

Heider, E. R. 1972. “Universals in Color Naming and Memory”. *Journal of Experimental Psychology* 93.10-20.

— & D. Olivier. 1972. “The Structure of the Color Space in Naming and Memory for Two Languages”. *Cognitive Psychology* 3:2.337-54, and *Philosophy* 8.1-21.

Hickerson, N. 1971. “Review of Berlin and Kay’s *Basic Color Terms*”. *International Journal of American Linguistics* 37:4.257-270.

Jameson, K. A. 2005. “Culture and Cognition: What is Universal about the Representation of Color Experience?” *Journal of Cognition and Culture* 5.293-348.

—, S. M. Highnote & L. M. Wasserman. 2001 “Richer Color Experience in Observers with Multiple Photopigment Opsin Genes”. *Psychonomic Bulletin and Review* 8:2.244-261.

Kay, P. 2005. “Color Categories are Not Arbitrary”. *Cross-Cultural Research* 39.39-55.

—, B. Berlin & W. R. Merrifield. 1991. “Biocultural Implications of Color Naming”. *Linguistic Anthropology* 1.12-25.

— and T. Regier. 2003. “Resolving the Question of Color Naming Universals”. *Proceedings of the National Academy of Science* 100.9085-9089.

Lazar-Meyn, H. A. 2004. “Color Naming: ‘Grue’ in the Celtic Languages of the British Isles”. *Psychological Science* 15.288.

Lindsey, D. T. & A. M. Brown. 2002. “Color Naming and the Phototoxic Effects of Sunlight on the Eye”. *Psychological Science* 13.506-512.

— & A. M. Brown. 2004. “Sunlight and ‘Blue’: the Prevalence of Poor Lexical Color Discrimination within the ‘Grue’ Range”. *Psychological Science* 15.291-294.

MacLaury, R. E. 1987. “Color Category Evolution and Shuswap Yellow-with-green”. *American Anthropologist* 89.107-124.

—. 1997. *Color and Cognition in Mesoamerica: Constructing Categories as Vantages*. Austin: University of Texas Press.

McNeill, N. B. 1972. "Color and Color Terminology". *Journal of Linguistics* 8.21-33.

Quine, W. V. 1960. *Word and Object*. Cambridge, Mass.: M.I.T. Press.

Roberson, D., I. Davies & J. Davidoff. 2000. "Color Categories Are Not Universal: Replications and New Evidence from a Stone-Age Culture". *Journal of Experimental Psychology: General* 126:3.369-398.

Saunders, B. A. C. & J. van Brakel. 1997 "Are there Non-trivial Constraints on Color Categorization?" *Behavioral and Brain Sciences* 20:2.167-179.

RE-ASSESSING PERCEPTUAL DIAGNOSTICS FOR OBSERVERS WITH DIVERSE RETINAL PHOTOPIGMENT GENOTYPES

KIMBERLY A. JAMESON, DAVID BIMLER &
LINDA M. WASSERMAN
University of California, Irvine & San Diego; Massey University, and University of California, San Diego

Introduction

For many years, reports have surfaced of atypical performance on standardized color-deficiency tests among female carriers of color-vision anomalies (presumed, on the basis of pedigree, to be heterozygous for the genetic alteration manifesting as the anomaly in their male relatives). As discussed by Cohn, Emmerich and Carlson (1989) heterozygous females fail to be detected by the use of an anomaloscope, although there are reported shifts in their anomaloscope color matches (Schmidt 1955; Crone 1959; Pickford 1959; Krill & Beutler 1964; Feig & Ropers 1978) as well as shifts using flicker photometry (Crone 1959; Yasuma, Tokuda & Ichikawa 1984). Heterozygous females were also found to exhibit higher absolute thresholds to small spots of red light (Krill & Beutler 1964, 1965). Unlike normal controls, these heterozygotes exhibit a failure of *additivity* of trichromatic color matches after exposure to a light bleaching of the rod system (Nagy, MacLeod, Heyneman & Eisner 1981). Thus, in some existing research, albeit much of it before 1984, subtle deviations from trichromacy were found using heterozygote participants. Still, these subtle deviations are generally considered to be examples of the large individual differences possible in color perception, and are not interpreted as deviations from functional trichromacy.

Some investigators have conjectured that such individuals, whose retinal cone-cell mosaics contain four photopigments, might experience a dimension of perceptual experience denied to trichromat individuals (Jordan & Mollon 1993; Mollon 1995; Deeb & Motulsky 1996). A model exists among some New World primates, where polymorphism of one of the two cone opsin genes they possess supports trichromatic vision among heterozygous females, although homozygous females and hemizygous females are dichromatic (Shyue, Boissinot, Schneider, Sampaio, Schneider, Abee, Williams, Hewett-Emmett, Sperling, Cowing, Dulai, Hunt & Li 1998). However, the above conjecture about human observers is not popular among most color vision researchers.

Over the last decade, this research direction was invigorated by progress in molecular genetics: in particular, the discovery that variant alleles exist for the L and M photo-opsins, even within the non-deficient population, associated with shifts in the spectral sensitivity functions. The shifts are smaller (~5 nm) than those causing color-vision deficiencies, but not negligible, given that the peak sensitivities of the L- and M-opsins differ by only ~35 nm. This creates a prospect of alternative phenomenal worlds (Mollon 1992), with divergent color processing according to these alleles. Moreover, two polymorphisms (substitution of alanine for serine at codon 180 of the L-opsin, or *vice versa* at codon 180 of the M-opsin) appear to be sufficiently common – at least, in Caucasian populations – for heterozygosity in females to approach the norm rather than the exception. At the level of distinct photoreceptor classes, four and even five classes are possible in some groups; this adds salience to the suggestion that human color vision is capable of extension beyond trichromacy at a *functional* level.

The standard instruments for assessing color vision in applied settings – pseudoisochromatic plates (PICs) and hue sorting tests – are primarily tests of color consensus. Does the subject use color terminology in a manner sufficiently similar to population norms for effective communication, in situations where color is critical? Historically, occupational and vocational concerns have been paramount (for example, resistor coding, train signals, printing, hue-matching in industry and decoration). Such tests serve as valuable screening procedures for detecting and classifying dichromat and anomalous-trichromat observers, whose color perception is deficient in certain ways (a pattern of confusions characteristic of reduced discrimination along particular axes in color space). Such individuals also exhibit impoverished color-naming behavior, recognizing fewer color bands within the spectral hues. However, such tests were not designed with the possibility in mind of observers whose color discrimination is good, but operates in a non-standard way. They are not necessarily appropriate for detecting deviations that might occur if the neural trivariant property of human color vision were extended to include more than the usual three color processing channels – a deviation perhaps made possible in individuals possessing more than three classes of retinal cones. As discussed at the end of this paper, there may be methodological reasons why color perception differences apparently experienced by some female heterozygotes are not widely demonstrated using standard psychophysical methods of color vision assessment.

Based on the controversy described above, this article investigates four issues concerning widely-used standardized tools for color vision assessment:

1. Do existing color vision assessment methods permit the detection of non-deficient deviations, or extensions, of trichromacy (if such extensions exist)?
2. Do existing methods sometimes mis-diagnose observers as deficient who otherwise have superior color vision abilities?
3. Are the patterns of confusions found in the Farnsworth-Munsell 100 Hue test (hereafter: F-M 100) predictable from individual observer's photopigment opsin genotype?
4. Do the F-M 100 results for genotypes capable of expressing four or more retinal cone classes clarify the nature of the color perception difference experience (if any), and do such F-M 100 results provide insights into the debate raised by others (namely, Mollon, 1992; Jordan & Mollon 1993; Deeb & Motulsky 1996) concerning the potential for extended dimensionality in human color perception?

In the Discussion we suggest directions for updating existing color vision assessment methods to identify and classify color perception differences found correlated with photopigment opsin genotypes.

The genes for retinal photopigments

Recent research into the molecular genetics of retinal photopigments enables an understanding of photopigment sensitivity as well as the genetic basis for individual differences in color perception. Studies show that variation at the level of the genotype corresponds to shifts in the absorption spectra of expressed retinal pigments (Asenjo, Rim & Oprian 1994, Merbs & Nathans 1992a, 1992b, 1993) that produce concomitant shifts in spectral sensitivity (Neitz, Neitz & Jacobs 1991, 1995; Winderickx, Lindsey, Sanocki, Teller, Motulsky & Deeb 1992).

The genes for medium-wavelength sensitive (M) and long-wavelength sensitive (L) retinal photopigments are located on the X chromosome, in a head-to-tail array, with the L gene first. The genetic sequences for these two photopigments are almost identical (Asenjo et al. 1994; Sharpe, Stockman, Jaegle, Knau, Klausen, Reitner & Nathans 1998; Neitz & Neitz 1998). The DNA sequence homology or identity for the two genes is 98%. Although the amino acid sequences of the M- and L-pigments are thus almost identical, studies have shown that photopigment sensitivity to medium or long wave light is determined entirely by substitutions of seven amino acids occurring at codons 116, 180, 230, 233, 277, 285 and 309 of each gene (Asenjo et al. 1994).

Individual variability in color perception is associated with genetic variability at one of these critical amino acids, codon 180 in exon 3 of the L- and M-opsin gene. In both genes, the amino acid at codon 180 has been shown to be polymorphic. In the Caucasian population, approximately 60% and 40% of males will have the amino acids serine and alanine respectively at codon 180 in their single L-photopigment gene. The average λ_{max} for red light is 557 nm for the 60% majority, but, in the minority, it is 552 nm: their red-light spectral sensitivity is shifted closer to the λ_{max} for green light, which is 532 nm. Thus, this amino acid substitution, or polymorphism, gives rise to differences in spectral sensitivity to light, and thus, to individual variation in color vision. The corresponding substitution in the M gene – of serine for alanine at codon 180 – is present in about 9% of Caucasian males, but appears to have a smaller effect on spectral sensitivity to green light (Sharpe et al. 1998).

Complicating further the analysis of the relationship between genotype and perceptual behavior is the location of the M- and L-genes on the X chromosome. By virtue of two X chromosomes, females have two arrays of M- and L-genes, whereas males, with only one X chromosome, are limited to a single array. As a result, the genetic variability in the M- and L-photopigment gene combination is potentially greater for females than for males: the number of possible M-opsin and L-opsin genotype combinations at codon 180 is ten and four respectively. For this reason, one might expect to find greater variability in perceptual behavior in females.

Here we use modern molecular methods to determine an individual's M- and L-photopigment opsin genotype, especially codon 180 polymorphisms, and examine its relationship to color vision behavior. The genotyping method employed has been described elsewhere, and will only be reviewed here as necessary for explanation of subjects' genotype classifications (Wasserman, Szeszel & Jameson 2001). Briefly, the method makes use of a long-range polymerase chain reaction technique (LR PCR) to generate gene-specific PCR products, DNA sequencing to confirm this gene specificity and then PCR and restriction digest to determine M and L codon 180 genotypes. Results from the use of this method demonstrate a correlation with perceptual behavior and give significant insight into mechanisms contributing to the variability in perceptual behavior (Wasserman et al. 2001).

Note, first, that a female who is putatively homozygous for the codon-180 polymorphism may, in fact, be heterozygous for protanopy or deuteranopy (if the L- or M-opsin gene respectively is missing from one X chromosome).

Conversely, more than one copy of either of these genes may occur in a single X-chromosome array. However, PCR analyses can detect the presence of both alleles of the L- or M-opsin in a female, without guaranteeing that they lie on separate arrays. The possibility must also be considered that both lie on the same X chromosome. So, if in a given female, the PCR detects the presence of both L-180 alleles and a normal M-180 gene, then one possible configuration is that both X chromosomes possess multiple L-opsin variants in the first two positions of the array. According to one theory, however, only the first two genes in the array are expressed, regardless of the opsins they encode; the M-opsin genes would not be expressed (being third or further downstream on the array). The individual would be thus heterozygous for deuteranopy. Another version of this theory states that, in the case of two L-opsin genes present on one X chromosome, only the first will be expressed, that is, the individual is *effectively* homozygous for the L-opsin, despite the PCR result indicating two L-180 variants. Similar complications exist for interpreting PCR detection of M-180 polymorphisms. However, the notion that L-gene variants are expressed with a greater probability than M-gene variants seems to be a popular idea. Until the mechanisms underlying these issues are resolved (see Carrel & Willard 2005), these alternatives to expression of heterozygosity must be borne in mind.

A final possibility is that, when the PCR detects (for instance) the alanine allele of the L-opsin, it is actually responding to a chimeric M-opsin gene (into which exon 3 of the L-opsin has been grafted by meiotic mishaps). The parallel possibility applies to the serine allele of the M-opsin. Thus, an individual who is putatively heterozygous for the polymorphism may, in fact, be heterozygous for protanomaly or deuteranomaly. Though rare in the population overall, these conditions may be encountered in a portion of the subjects' data discussed here, since some were recruited by an advert emphasizing a family history of color deficiency.

For these reasons, not all females genetically identified as heterozygotes possessing M- and L-opsin gene polymorphisms necessarily express more than three retinal cone classes in their phenotype. In a few cases, such heterozygous females could be phenotypically anomalous trichromat or deficient, some might be normal trichromat, whereas others, through the right combination of genes and expression events, might phenotypically express four or five classes of cones in their retinae. This issue is worth noting in the discussion of color vision assessment methods because it implies that, even under the assumption that neural trichromacy is a fixed feature of the system, color perception diagnoses might be expected to be more variable, or to be differently distributed for a group of female heterozygotes compared to a group of females with non-heterozygous genotypes. Thus, issues of functional tetrachromacy aside, the question of whether standard tests are capable of differentiating two such groups on purely perceptual grounds is a question of interest for evaluating the utility of such tests in genotype / phenotype investigations.

Color-vision assessment and photopigment genotyping

Subjects

With permission of the University of California, San Diego (UCSD) Human Subjects Committee, informed consent was obtained from 39 female and 26 male UCSD undergraduates for participation in this study. (Data for five of the male subjects sampled are not included in the present study because insufficient DNA was available for genotyping at the time of the implementation of the LR PCR method). Three milliliters of venous blood from each student was collected into EDTA vacutainer tubes by a trained phlebotomist. Subjects were solicited through either the Psychology Department Human Subjects pool, or by posted solicitations for experimental participation for either cash payment or for course extra-credit. To address specific empirical hypotheses, some female subjects were obtained through solicitations designed to maximize the yield of participants that were carriers or expressors of color vision deficiencies or anomalies. Following DNA extraction, a long-range polymerase chain reaction method was used to specify the presence of codon 180 polymorphisms on Exon 3 of the L- and M-opsin genes. The method used is described in Wasserman et al. (2001). Results of the genotype classification for 60 subjects are presented in Tables 1 and 2.

Stimuli and procedure

All subjects were assessed using (1) a chromatic banding task (Jameson, Highnote & Wasserman 2001), (2) standardized color vision assessment, and (3) photopigment opsin genotyping. In task (1) all subjects indicated where they saw distinct bands of color within a chromatic spectrum produced with a diffraction grating (Task 1 data from one subject was discarded due to non-compliance with the established protocol). Details of this chromatic banding task are provided elsewhere (Jameson et al. 2001). Next, all subjects were tested with the Ishihara PIC plates. In addition, the F-M 100 Hue test was administered to the subjects, using standard illumination and instructions. Finally, opsin genotyping was conducted, as described above, and in Wasserman et al. (2001). Experimenters and subjects were uninformed regarding retinal genotyping of the subjects assessed.

The F-M 100 belongs to a family of sorting and matching tests in which small pigment-coated stimuli (‘caps’) are arranged in linear sequence, so that most-similar caps are adjacent, together forming a color gradient (Farnsworth 1943). It uses eighty-five caps, of moderate lightness and saturation (Munsell Value 5, Chroma 5). They form a complete hue circle but, for convenience, are presented in four quadrants, to be sorted separately. Analysis consists of considering each cap’s immediate neighbors in the sequence: departures from their *numerical* sequence (the ‘correct’ arrangement) are converted to an error score. For instance, a simple transposition of two caps (for example, 1, 2, 4, 3, 5, 6…) means that four caps (2, 3, 4 and 5) are each adjacent to one cap that is two steps away in the sequence numbering, rather than a single step, and each accrues a score of one. Scores are generally plotted in polar coordinates (Figure 4).

The F-M 100 rationale is that the possibility of sequencing errors increases with any reduction in color discrimination. Reduced blue / yellow discrimination, for instance, as in tritanopia, makes confusions likely among red caps (which are distinguished only by tinges of blue or yellow) and among green caps. Since the difference between adjacent caps is small – near the threshold of perception – even a normal observer will commonly make a few minor errors such as transpositions. The total error score to be expected from a normal observer is dependent on age (Verriest, Van Laethem & Uvijls 1982, provide norms and standard deviations), but, according to one rough guideline, a total of less than twenty indicates superior color discrimination, while more than one hundred warrants further testing of the subject (on its own, the F-M 100 is not sufficient for diagnostic purposes). Because of floor effects, superior discrimination over *part* of the spectral range will not be localized in the same way as decreased discrimination, if it is detected at all.

Data analysis method

Results from the chromatic-banding task (Jameson et al. 2001) are summarized here by a simple descriptive measure of individual perceptual behavior: ‘median number of perceived colors’. This is tantamount to the median number of different chromatic percepts a given observer detects in a series of judgments for diffracted spectrum stimulus. Here, when group measures of individual data are reported, they are given as group means of median numbers of individually perceived colors. In essence, Jameson and colleagues found that subjects possessing polymorphous photopigment opsin genotypes significantly identified more chromatic appearances in diffracted spectra compared to subjects with non-polymorphous genotypes (see Jameson et al. 2001). Comparisons are made here between subjects' F-M 100 performance and the chromatic banding results reported in the Jameson et al. (2001) study. Total F-M 100 error scores were computed for each subject, as described above.

Underlying the development of the F-M 100 is a geometrical model: that the dissimilarities among colors perceived by a congenitally color-deficient individual correspond to a personal color space that is a compressed version of the color space perceived by normal trichromats (Farnsworth 1943). The direction and extent of compression indicate, respectively, the class and severity of the deficiency. Combined with the mathematical techniques of individual-differences MDS, this insight can be used to extract parameters of color-space compression from individuals' ratings of color dissimilarity (Paramei, Bimler & Cavonius 2000). However, MDS is not restricted to explicit *values* of dissimilarity. The algorithms can also handle *comparisons* between dissimilarities. Since F-M 100 sequences can be reduced to comparisons (to arrange two caps as neighbors is to assert that they are more similar to each other than to the other caps with which they were not arranged), they are amenable to this form of analysis. In this case, the emphasis is on the parameters for each subject, rather than on the 'map' of the stimuli also produced by MDS. Indeed, a *constrained* form of MDS was used: the coordinates of the F-M 100 points in CIELUV color space were provided (for details see Bimler, Kirkland & Jacobs 2000).

There followed another, more exploratory, application of MDS, involving comparisons between subjects rather than stimuli. A displacement was found for each cap (the absolute value of the difference between its positions in the correct F-M 100 and in an actual sequence). These were treated as the coordinates of a single point in an 85-dimensional space, and Euclidean distances among points were calculated, resulting in a 39-by-39 matrix of distances among female subjects, and a 21-by-21 matrix among males. The task of MDS in this case was to arrange subject points in a lower-dimensional space so that inter-point distances reconstructed these matrices as accurately as possible.

Results

Though results for males will be used to illustrate particular points, the emphasis on this report is on the female subjects. Their data (grouped by genotype) are summarized in Table 1. Here *Z* values are the square root of the F-M 100 total error, converted into the number of standard deviations away from age-specific norms (Verriest et al. 1982). Table 2 presents only opsin genotype information for male subjects, without going into detail about their test scores. Note, two males were found with both serine (Ser) and alanine (Ala) amino acid residues on the L-opsin gene at codon 180 in exon 3 (Table 2, row 4). Two additional males showed both Ser and Ala at M-180 in exon 3 (Table 2, row 5). And one additional male showed both Ser and Ala responses to both L-

Heterozygous females

L-180-Ser/Ala M-180-Ser/Ala 14 cases

ID	FM100	Z	Ishihara	Bands
27	84	1.68	2	13.5
28	20	-1.13	0	8
34	112	.96	0	9
36	20	-1.13	0	16.5
37	32	-.02	0	14.5
43	20	-.59	0	8
44	28	-.19	0	9
52	52	.73	1	9
58	64	.72	0	7
61	56	.87	1	8.5
67	32	-.51	0	7
70	16	-.93	0	14.5
85	132	2.54	0	12
91	84	.38	1	—

L-180-Ser/Ala M-180-Ser 1 case

ID	FM100	Z	Ishihara	Bands
51	16	-.82	0	6

L-180-Ser M-180-Ser/Ala 7 cases

ID	FM100	Z	Ishihara	Bands
08	32	-.36	0	13
10	80	1.57	0	11
16	56	.45	0	14
49	92	1.55	0	6
63	32	-.02	0	7
75	32	-.51	0	8
87*	20	-.59	0	11

Homozygous females

L-180-Ser/Ser M-180-Ser/Ser 10 cases

ID	FM100	Z	Ishihara	Bands
14	192	3.78	2	6
23	44	.00	0	10.5
38	24	-.38	2	6
46	108	2.27	1	8
68	28	-.19	1	12.5
73	12	-1.66	0	7
76	56	.87	2	7
77	60	.58	0	8.5
86	72	.97	2	8
89	40	.31	—	6

L-180-Ala/Ala M-180-Ala/Ala 7 cases

ID	FM100	Z	Ishihara	Bands
22	120	1.46	3	6
25	60	.99	1	6
32	36	-.33	0	10
54	20	-.59	0	7
62	36	.15	1	6
69	32	-.36	0	12
71	52	.73	2	6.5

* ‘L-180-Ser / Ala’ indicates Codon 180 amino acid residues present for both serine (Ser) and alanine (Ala) of the L-cone photopigment opsin gene. ‘M-180’ denotes M-cone opsins detected. The frequencies in Table 1 do not arise from a random sample and should not be taken to reflect population genotype frequencies.

Table 1: *Frequencies of genotypes from 39 female participants evaluated using the new LR PCR method.*

L-180-Ala	M-180-Ala	9 cases
L-180-Ser	M-180-Ser	6
L-180-Ser	M-180-Ala	1
L-180-Ser+Ala	M-180-Ala	2
L-180-Ser	M-180-Ser+Ala	2
L-180-Ser+Ala	M-180-Ser+Ala	1

* ‘L-180-Ser+Ala’ indicates Codon 180 amino acid residues present for both serine (Ser) and alanine (Ala) of the L-cone photopigment opsin gene. ‘M-180’ denotes M-cone opsins detected. The frequencies in Table 2 do not arise from a random sample and should not be taken to reflect population genotype frequencies.

Table 2: *Frequencies of genotypes from 21 male participants evaluated using the new LR PCR method.*

180 and M-180 in exon 3 (Table 2, row 6). Of these five, only the two males with both residues at M-180 made few F-M 100 errors: 20 and 28. These genotype cases reflect complexities produced by hybrid opsin genes that encode chimerical photopigments.

Ethical reasons made it necessary to test subject 87 (heterozygous at M-180) twice on the F-M 100. The first test result showed signs of tritanomaly, raising concerns about the state of her visual health. Fortunately, her retest results were normal and locate her within the central normative clusters of Figures 1 and 3. Retaining her initial results would locate her as an outlier, without affecting the conclusions.

Next, the subjects’ F-M 100 sequences were quantified with the individual-differences MDS method described by Bimler et al. (2000). Involving a Maximum-Likelihood algorithm, this yields a pair of color-space compression parameters that best account for a subject’s sorting decisions: an axis and an extent of compression, θ and r. A third parameter, the ‘discriminance’ β, is not used here. Here $-90° \leq \theta \leq 90°$ (where 0° corresponds to the Red-Green axis of the CIELUV color plane), and $0 \leq r \leq 1$ (where 1 corresponds to a dichromat’s color plane, collapsed to a line). The results for thirty-eight female subjects are plotted in polar coordinates as Figure 1, using 2θ as the angular coordinate, and r as the radial coordinate. Subject 14 (a double homozygote) is omitted as an outlier. As well as erring on two Ishihara plates and discerning only six bands in the spectrum (below the median), her parameters pointed to a protanomalous color deficiency. Also included in Figure 1 are parameters for two males (Subjects 80 and 90) who failed the Ishihara test: one (genotype Ser / Ser)

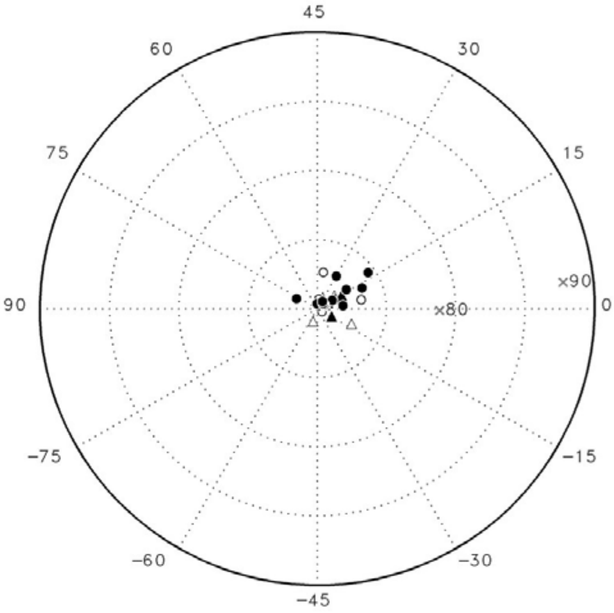


Figure 1: *Color-space compression parameters, plotted in polar coordinates, for female subjects. Results for two color-deficient male subjects (Ss 80 and 90) are also presented for comparison. Female genotype classes are represented by different symbols in the central cluster of the compression parameter plot.*

seems to be severely deuteranomalous, and the other (Ala / Ala) extremely so.

For clarity, the females' compression parameters are grouped by genotype and plotted on an enlarged scale in Figure 2. An interesting feature in panel (a) is the trend for cases to be displaced from the center in a specific direction, corresponding to an axis of compression of about 15° (causing confusions among green-yellow caps in the range 25-30, and among purple caps around 70). The compressions are subtle, but five out of fifteen cases exceed an arbitrary cut-off value of $r > 0.1$ (a sixth, S 34, also shows compression but in a different direction). These are subjects heterozygous for the L-180 polymorphism – all but one are also heterozygous for the M-180 polymorphism (giving the latter group five different classes of opsin gene variants). Similar but smaller compressions can be seen among the seven subjects heterozygous for the M-180 polymorphism only. The 16 homozygotes are spread with more symmetry; though three exceed the same cut-off, their axes of compression are different (S 22 performs below average in terms of Ishihara errors and color bands).

The impression of a systematic difference is necessarily only suggestive: statistical certainty would require considerably more data. Results of these analyses that show systematic differences in F-M 100 responses suggest improvements in F-M 100 scoring which could extend the diagnostic capabilities of the F-M 100 to identification of S-180-A heterozygotes.

The result of applying non-metric MDS to the matrix of inter-subject dissimilarities is shown as Figure 3. A two-dimensional MDS solution provided a good representation of the matrix, with $\text{Stress}_1 = 0.060$. Most of the F-M 100

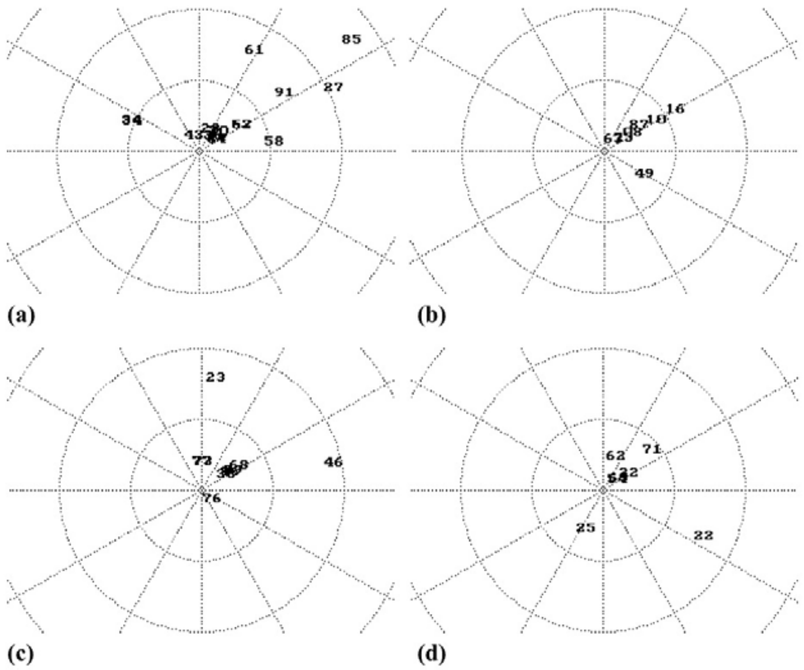


Figure 2: *Color-compression parameter plots for subgroups of genotyped females. Starting at upper-left, panels a, b, c and d depict: (a) 15 females heterozygous for L-180 polymorphism; (b) 7 females heterozygous for M-180 polymorphism; (c) 9 homozygous females (L-180-Ser, M-180-Ser genotype); (d) 7 homozygous females (L-180-Ala, M-180-Ala genotype).*

responses are close to the correct sequence, and consequently close to one another, forming a tight central cluster. The outlier 14 is not visible in the solution and lies some distance over to the left.

The index of inter-subject dissimilarity is crude and global. This way of approaching the data is less constrained than the individual-differences algorithm used above, and makes fewer assumptions about any pattern underlying the errors. Even so, some heterozygotes are again separated from the bulk of the individuals. A straight line can be drawn that discriminates six of fifteen double heterozygotes (Ss 85, 27, 61, 58, 91, and 34, whose point falls off

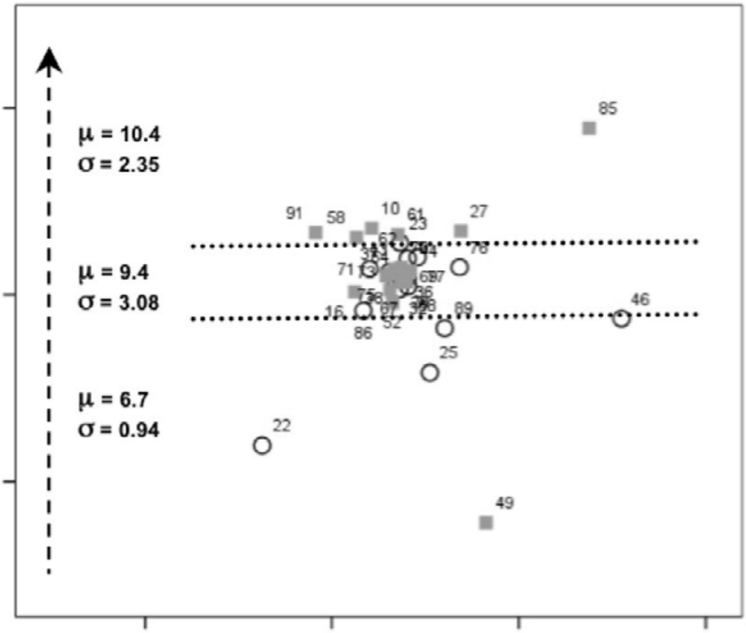


Figure 3: *Two-dimensional dissimilarity scaling of F-M 100 sorting performance for 37 female subjects. The two horizontal lines were drawn* ad hoc *to illustrate the association between F-M 100 performance, genotype, and perceived colors delineated in the Jameson et al. (2001) task. Gray square symbols denote heterozygote females, and unfilled circles denote homozygous females. Plotted numerals correspond to ID numbers in Table 1. The vertical dashed arrow represents increases and decreases in measured banding behaviour. Mean (μ) and standard deviation (σ) banding values for subgroup partitions are also shown.*

the top of the Figure 3 plot) and one M-180 heterozygote (S 10) from all the homozygotes.

Figure 3’s ‘top partition’ above the top-most horizontal line contains only heterozygotes; the ‘middle partition’ contains both heterozygotes and homozygotes; and the ‘bottom partition’, beneath the bottom-most horizontal line, contains homozygotes and one aberrant heterozygote. Gray square symbols indicate subjects who possess at least one codon-180 opsin gene polymorphism (n=21, excluding aberrant heterozygote 34 who is off the top of the plot). Unfilled circle symbols indicate subjects who are codon-180 homozygous (n=16, excluding the aberrant homozygote 14 who is off the left side of the plot). Summary data (means, μ and s.d., σ) for the median-banding measures are presented for each partition. The structure has been rotated to bring a regression-line for the chromatic banding data close to the vertical axis (in fact 5° counter-clockwise off vertical) which is shown as Figure 3’s vertical dashed arrow.

Interestingly, the seven heterozygotes departing from the normative grouping of homozygotes and heterozygotes in Figure 3 are not perceptually color-abnormal, as the F-M 100 scaling might appear to suggest. Indeed, these same subjects are also differentiated by their banding behavior in the Jameson et al. (2001) task as *above average*, not deficient, color perceivers. In the top partition of heterozygotes, the average number of median chromatic delineations was 10.4 bands (s.d.=2.35) (banding data was not available for S 91), compared to 7.9 bands (s.d.= 2.12) for homozygotes represented by open circle symbols across the 3 partitions. Five participants plotted below the bottom horizontal partition are homozygous and one is heterozygous for the M-180 opsin. This bottom partition averages a 6.67 (s.d.=0.94) chromatic banding measure. Although Figure 3’s horizontal lines form *ad hoc* partitions, they serve to illustrate a monotonic relationship between the number of chromatic bands observed and subject similarity based purely on dissimilarity scaling of F-M 100 data.

The important point conveyed by Figure 3 is that the results from two different and independent tasks converge in showing a difference between the color perception of female subjects with heterozygous and homozygous genotypes. Subject groupings derived by scaling F-M 100 inter-subject dissimilarities are related systematically to chromatic banding behavior (Jameson et al. 2001). While confirming the difference, this raises the question why observers who are excellent color discriminators – the top partition in Figure 3 – should emerge from the F-M 100 as non-normative ‘outliers’. While the F-M 100 appears to detect the variation in these observers’ color perception, in some cases, the scoring procedure does not distinguish between *non-normative* deficient and *non-normative* good color perception. The explanation that these aberrant heterozygotes are truly anomalous in the sense of deficiency is further undermined by the absence of color confusions in their everyday color experience, and the fact that the M-180 heterozygote (S 10) was the only one to report familial color deficiency (she reported paternal anomalous trichomacy).

These findings are further supported by comparing Table 1 data with the Jameson et al. (2001) banding results just described. Table 1 includes seven heterozygous females and six homozygous females with Z-values differing from normative F-M 100 performance by one standard deviation or greater (heterozygotes 27, 28, 34, 36, 85, 10, 49, and homozygotes 14, 46, 73, 86, 22, 25). Comparing the banding behavior of these seven heterozygotes and six homozygotes shows the heterozygotes average 10.9 median chromatic bands (s.d.=3.54), compared to the homozygotes' 6.9 (s.d.=1.11) average. A t-test shows this difference to be significant at p=.025 (two-tailed).

However, if outlier heterozygote S 49 is excluded from the heterozygote group, then the difference in banding behavior between the two groups obtains significance at p=.005 (two-tailed) based on the recomputed mean=11.7, s.d.=3.09 for heterozygotes. Also, the perceptual banding behavior of these six heterozygotes is not significantly different from the other heterozygotes who received Z-values indicating normal F-M 100 performance (p=.215, two-tailed).

At a minimum, these results suggest that, with the exception of S 49, the female heterozygotes who 'failed' the F-M 100 have good color perception on a spectral delineation task, their banding behavior does not differ from other heterozygotes whose Z-values indicate they passed the F-M 100 ($-1 < Z < 1$), and their banding behavior significantly differs from homozygotes who similarly 'failed' the F-M 100. A less conservative interpretation of these results is that the F-M 100 can diagnose heterozygotes as false-positive deficient when their color perception is otherwise unimpaired, and their color sense is generally regarded as excellent.

To illustrate how the subjects' F-M 100 responses are interpreted by Farnsworth's (1943) recommended scoring procedure, the error scores per cap are plotted in Figure 4 for two heterozygous observers, polymorphic at S-180-A for both the L and M genes (c. and d.), juxtaposed with the results for a 'classic' protanope (a.) and a normal trichromat (b.). Clearly, compared to normal (b.), the F-M 100 polar coordinate plots for (c.) and (d.) suggest impaired color perception, and resemble more closely the plot for dichromat (a.). Such a magnitude of difference would almost certainly affect everyday color processing: in dichromats, it is already known to dramatically affect the processing of color in applied circumstances such as color-coded data in information displays.

Despite the patterns in Figure 4 suggesting a ‘deficiency’ in color discrimination capabilities, individuals (c.) and (d.) were reported by Jameson et al. (2001) as exhibiting above-average color perception performance (they perceived 12 and 9 chromatic spectral bands, respectively). Compare this with the protanope (a), who perceived only 4 chromatic bands in the spectrum, and the ‘normal’ trichromat (b) who perceived 7 bands. Such discrepancies indirectly support the Jameson et al. (2001) results discussed earlier, in that the F-M 100 standardized method characterizes the color perception of some heterozygous females as *non-normative* compared to homozygous females who are generally characterized as color-vision ‘normal’.

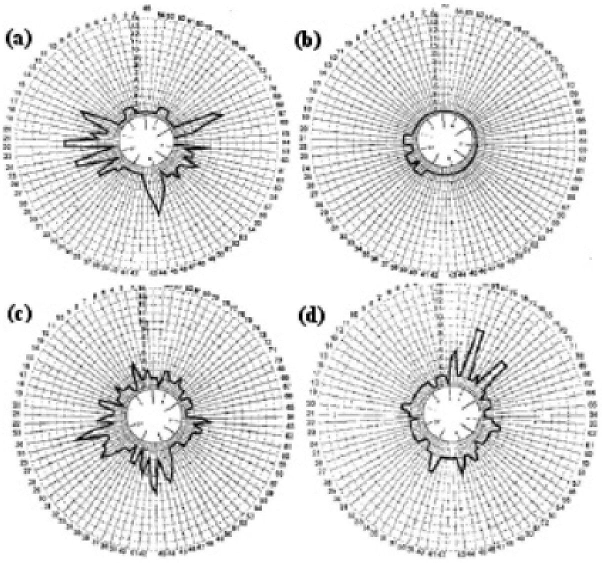


Figure 4: *Examples of Farnsworth-Munsell 100-Hue test results for: (a) a dichromat; (b) a trichromat; and two potential retinal tetrachromats ((c) and (d)).*

Such anomalies arising from color-vision assessment are perhaps not surprising. Standard color-vision tests like the F-M 100 were not designed to assess individuals expressing four photopigment classes, and, for this reason, they are difficult to evaluate as appropriate measures of the color perception abilities of such individuals. With their vocational focus, such tests were generally calibrated for males, for a combination of reasons – including the lower incidence of overt color deficiency among women, and the effective exclusion of women from many occupations at the time of the tests' design. These details further support the idea that some color vision screening tests may erroneously identify four-pigment females as color-deficient or anomalous.

To sum up, some of the heterozygotes depart from what is considered the trichromatic norm in a systematic way: in some circumstances, they experience color more richly than normal (for example, color bands delineated in spectra), while making color confusions in particular zones of the hue circle. Using standard interpretations, the latter phenomenon could be construed as reduced color discrimination in those zones; or, more directly, as evidence that a different sorting sequence for the stimuli is more natural for some heterozygotes. In the former case, there is a possibility that the reduced discrimination is compensated for by heightened discrimination in other zones (not picked up by the F-M 100, because of floor effects). Such heightened discrimination might dictate a subjective ordering of the F-M 100 samples that is at odds with the 'correct' ordering recommended by the scoring manual. In any case, this kind of discrimination difference does not necessarily translate into perceived dissimilarities when the color differences are larger.

Interestingly, although the present heterozygote subjects never reported experiencing color confusions, their F-M 100 errors were more than one standard deviation above average (age-adjusted Z-scores) for four out of twenty-two cases. Similarly, many errors were made by three out of eighteen homozygous subjects (including the deuteranomalous S 14). The more structured analysis of constrained MDS suggested some degree of polar anomaly ($r > 0.1$) for 32% of heterozygotes and 22% of homozygotes. These data warrant further analyses of the F-M 100 as a diagnostic tool for groups of potential retinal tetrachromats.

Also important, and not unexpected given the additional factors determining opsin gene expression, is that this departure is not *universal* among heterozygotes. That is, among the twenty-two female heterozygotes (on one or both genes), only seven of these were differentiated as perceptually non-normative in the F-M 100 dissimilarity scaling (despite superior color judgment in other tasks). Physiological tests may soon be able to determine if such individuals are expressing more than three photopigment classes (e.g. Roorda & Williams, 1999).

To consider a more mainstream position, it is also conceivable that retinal tetrachromacy from the codon-180 polymorphism has no effect on color processing, and that the aberrant minority observed in the present sample are actually heterozygous for color-vision deficiency, with chimeric or hybridized opsin genes, and thus, more likely to phenotypically express anomalous trichromacy or deficiency. Going on the F-M 100 scoring alone, this possibility is hard to exclude, although the aberrant minority of heterozygotes have little in common by dissimilarity measures with S 14, interpreted earlier as heterozygous and deficient by virtue of her F-M 100 sorting data. The problem with this explanation, however, is that it does not agree with patterns of results found in Figure 3 which illustrate how the F-M 100 dissimilarity scaling systematically tracks variation in chromatic banding results found using the Jameson et al. (2001) task, nor does it accord with the systematic tendencies in the angular and radial compression parameters shown in Figure 2. Finally, recent independent results by Sayim, Jameson, Alvarado and Szeszel (2005) suggest that female heterozygotes show significant differences in cognitive color processing in ways that accord with the results presented here.

Summary

The assessment of color perception in observers with the potential for four or more classes of retinal photopigments has often been undertaken with diagnostic tools designed to assess color vision under an assumption of trichromatic retinas and neural trichromacy. But what if neural trichromacy was not a constraint present in observers with four or more retinal photopigment classes? Non-human primate evolution provides precedents which serve as illustrative examples of how the human species could be polymorphous for color processing; and some existing research, albeit much of it before 1984, hints at this possibility through findings of subtle deviations from trichromacy in heterozygote participants. Jameson et al. (2001) found that color perception differences are associated with photopigment opsin genotype, and they suggest that some standard color vision assessment methods may not be appropriate for assessing the perception of retinal tetrachromats (that is, female heterozygotes). These new findings are consonant with some results in the existing literature.

As mentioned earlier, the standard instruments for assessing color vision in applied settings – pseudoisochromatic plates (PICs) and hue-sorting tests like the F-M 100 – are tests of color consensus, where consensus has been defined largely by a trichromatic norm. Previous research by Cohn et al. (1989) reports that heterozygotes are not generally detected by PICs. However, when such plates are used under conditions that make the task more difficult (modification of the spectral profile of the illuminant), the performance of the heterozygote is impaired to a greater degree than that of normal trichromat controls. Although such differences are typically interpreted to suggest perceptual deficiencies in heterozygote observers, such differences need not give rise to functional deficiencies under naturalistic viewing circumstances, and, indeed, retinal tetrachromacy could give rise to above-average capabilities under some circumstances. Such possibilities, and the suggestions inherent in existing findings, raise important questions about the nature of color differences experienced by persons with four or more cone classes and the optimal ways to assess such differences (if they do exist).

The results presented here suggest the somewhat surprising finding that the F-M 100, and its comparatively straightforward procedure, has some utility as a tool for differentiating the perceptions of putative retinal tetrachromats from those presumably with trichromat retinas. The results suggest that, through further investigation, the F-M 100 test and scoring methods could be refined and extended to serve as a useful diagnostic tool for retinal tetrachromat observers who tend toward the pole of normal to above-average color perception. Development of such advances requires further testing and confirmation of phenotypes through physiological assessment in order to develop proper scoring and descriptive interpretations.

Such advances are suggested for the first time by two findings presented here. First, it was found that the F-M 100 stimuli and task are capable of systematically differentiating some heterozygotes (presumably those expressing at least four cone classes) from persons possessing normal trichromat genotypes. The fact that this differentiation was achieved, opens the possibility of refining the test, as appropriate, for classifying such observers. Second, the manner with which the heterozygotes varied in their color sorting and dissimilarity scaling is itself systematic and suggestive regarding which color regions of the test might be adapted to increase diagnostic specificity when classifying non-standard retinal phenotypes. Thus, the present results call for further investigation on this issue, and the modification of the F-M 100 for assessing the color perception of the retinal tetrachromat, as it possibly differs from that of the trichromat.

References

Asenjo, A. B., J. Rim & D. D. Oprian. 1994. “Molecular Determinants of Human Red/green Color Discrimination”. *Neuron* 12.1131-1138.

Bimler, D., J. Kirkland & R. Jacobs. 2000. “Colour-vision Tests Considered as a Special Case of Multidimensional Scaling”. *Color Research and Application* 25.160-169.

Carrel, L. & H. F. Willard. 2005. “X-inactivation Profile Reveals Extensive Variability in X-linked Gene Expression in Females”. *Nature* 434.400-404.

Cohn, S. A., D. S. Emmerich & E. A. Carlson. 1989. “Differences in the Responses of Heterozygous Carriers of Color Blindness and Normal Controls to Briefly Presented Stimuli”. *Vision Research* 29.255-262.

Crone, R. A. 1959. “Spectral Sensitivity in Color-defective Subjects and Heterozygous Carriers”. *American Journal of Ophthalmology* 48.231-238.

Deeb, S. S. & A. G. Motulsky. 1996. “Molecular Genetics of Human Color Vision”. *Behavioral Genetics* 26.195-206.

Farnsworth, D. 1943. “The Farnsworth-Munsell 100-Hue and Dichotomous Tests for Color Vision”. *Journal of the Optical Society of America* 33.568-578.

Feig, K. & H. Ropers. 1978. “On the Incidence of Unilateral and Bilateral Colour Blindness in Heterozygous Females”. *Journal of Human Genetics* 41.313-323.

Jameson, K. A., S. Highnote & L. M. Wasserman. 2001. “Richer Color Experience in Observers with Multiple Photopigment Opsin Genes”. *Psychonomic Bulletin and Review* 8:2.244-261.

Jordan, G. & J. D. Mollon. 1993. “A Study of Women Heterozygous for Color Deficiencies”. *Vision Research* 33.1495-1508.

Krill, A. E. & E. Beutler. 1964. “The Red-light Absolute Threshold in Heterozygote Protan Carriers”. *Investigative Ophthalmology* 3.107-118.

— & E. Beutler. 1965. “Red Light Thresholds in Heterozygote Carriers of Protanopia: Genetic Implications”. *Science* 149.186-188.

Merbs, S. L. & J. Nathans. 1992a. “Absorption Spectra of Human Cone Pigments”. *Nature* 356.433-435.

— & J. Nathans. 1992b. “Absorption Spectra of Hybrid Pigments Responsible for Anomalous Color Vision”. *Science* 258.464-466.

— & J. Nathans. 1993. “Role of Hydroxyl-bearing Amino Acids in Differentially Tuning the Absorption Spectra of the Human Red and Green Cone Pigments”. *Photochemical Photobiology* 58.706-710.

Mollon, J. D. 1992. “Worlds of Difference”. *Nature* 356.378-379.

—. 1995. “Seeing Color”. *Colour, Art and Science* ed. by T. Lamb and J. Bourriau, 127-150. Cambridge: Cambridge University Press.

Nagy, A. L., D. I. A. MacLeod, N. E. Heyneman & A. Eisner. 1981. “Four Cone Pigments in Women Heterozygous for Color Deficiency”. *Journal of the Optical Society of America* 71.719-722.

Neitz, M. & J. Neitz. 1998. “Molecular Genetics and the Biological Basis of Color Vision”. *Color Vision: Perspectives from Different Disciplines* ed. by W. G. K. Backhaus, R. Kliegl & J. S. Werner, 101-119. New York: Walter de Gruyter.

—, J. Neitz & G. H. Jacobs. 1991. “Spectral Tuning of Pigments Underlying Red-green Color Vision”. *Science* 252.971-974.

—, J. Neitz & G. H. Jacobs. 1995. “Genetic Basis of Photopigment Variations in Human Dichromats”. *Vision Research* 35.2095-2103.

Paramei, G. V., D. L. Bimler & C. R. Cavonius. 2000. “Color-vision Variations Represented in an Individual Difference Vector Chart”. *Color Research and Application, Supplement* 26.S230-S234.

Pickford, R. W. 1959. “Some Heterozygous Manifestations of Colourblindness”. *British Journal of Physiological Optics* 16.83-95.

Roorda, A. & D. Williams. 1999. “The Arrangement of the Three Cone Classes in the Living Human Eye”. *Nature* 397.520-522.

Sayim, B., K. A. Jameson, N. Alvarado & M. K. Szeszel. 2005. “Semantic and Perceptual Representations of Color: Evidence of a Shared Color-naming Function”. *Journal of Cognition and Culture* 5:3-4.427-486.

Schmidt, I. 1955. “A Sign of Manifest Heterozygosity in Carriers of Color Deficiency”. *American Journal of Optometry* 32.404-408.

Sharpe, L. T., A. Stockman, H. Jägle, H. Knau, G. Klausen, A. Reitner & J. Nathans. 1998. “Red, Green and Red-green Hybrid Pigments in the Human Retina: Correlations between Deduced Protein Sequences and Psychophysically Measured Spectral Sensitivities”. *Journal of Neuroscience* 18.10053-10069.

Shyue, S. K., S. Boissinot, H. Schneider, I. Sampaio, M. P. Schneider, C. R. Abee, L. Williams, D. Hewett-Emmett, H. G. Sperling, J. A. Cowing, K. S. Dulai, D. M. Hunt & W.-H. Li. 1998. “Molecular Genetics of Spectral Tuning in New World Monkey Color Vision”. *Journal of Molecular Evolution* 46.697-702.

Verriest, G., J. Van Laethem & A. Uvijls. 1982. “A New Assessment of the Normal Ranges of the 100 Hue Total Scores”. *Documenta Ophthalmologica, Proceedings Series* 33.199-208.

Wasserman, L. M., M. Szeszel & K. A. Jameson. 2001. “Long Range Polymerase Chain Reaction Method for Detection of Human Red and Green Opsin Gene Polymorphisms”. Ms.

Winderickx, J., D. T. Lindsey, E. Sanocki, D. Y. Teller, A. G. Motulsky & S. S. Deeb. 1992. “Polymorphism in Red Photopigment Underlies Variation in Color Matching”. *Nature* 356.431-433.

Yasuma, T., H. Tokuda & H. Ichikawa. 1984. “Abnormalities of Cone Photopigments in Genetic Carriers of Protanomaly”. *Archives of Ophthalmology* 102.897-900.

HUE CATEGORIZATION AND COLOR NAMING
PHYSICS TO SENSATION TO PERCEPTION

MARC H. BORNSTEIN
National Institute of Child Health and Human Development
National Institutes of Health
Department of Health and Human Services
Bethesda MD, U.S.A.

Chapter 1 of *Genesis* tells us that, immediately following the creation of the heavens, the earth and light, God

> …separated the light from the darkness…called the light Day, and the darkness…Night…, separated the waters which were under the firmament from the waters which were above the firmament…called the firmament Heaven…called the dry land Earth, and the waters that were gathered together he called Seas (Gen.1.4-10).

Categorization followed by naming. Ontogenesis follows the same pattern, first creating order out of chaos by categorization, and then naming ordered categories of experience.

Introduction

This survey and update about basic hue categorization and basic color naming proceeds to four principal goals. In this chapter, I first review practical and theoretical characteristics and functions of psychological categorization, including a brief discussion of infants' capacities to categorize. These considerations identify, assert and highlight the essentialness and adaptive significance of categorization to mental life. Second, I address the psychological, biological, developmental and ethological manifestations of basic hue categorization and its connections to color vision. In a companion paper to this one (Bornstein 2006), I discuss, third, cultural variation in basic color naming and its feasible biological and experiential substrates. Toward the fourth and final goal, I assess the development of categorization to naming, and possible mechanisms for how we get from the start – universal biologically grounded basic categorizations of hue – to the end – cultural variation in basic color naming.

The overarching aim of this survey and update is to bring rudimentary order to the literature on *basic* hue categorization and color naming. These companion papers are heuristic and selective, and are not intended to constitute a comprehensive review of every topic covered or associated with color phenomena. Hue categorization and color naming involve physical, sensory, perceptual, cognitive, linguistic and cultural considerations. Moreover, I do not take as my purpose here the final adjudication of the origins or the development of hue categorization and color naming. However, the contemporary study of *basic* hue categorization and color naming wants clarity and demystification.

Categorization

Categorization is a central adaptive aspect of perception, cognition and language, and even young infants categorize.

Importance, attributes and functions of categorization

The capacity to categorize properties, objects, events, or other entities of experience lies at the core of adaptive, intelligent thought and behavior. Categorization normally refers to the treatment of a set of physically different and psychologically indiscriminable or discriminable entities as equivalent in some way (for example, by giving a group of discriminable colors the same color name). Without this ability, every distinct experience or encounter with the environment would demand a unique response, an intolerable circumstance that would quickly exceed human capability. When treating entities as equivalent, functionally relevant information about each is stored in memory, instead of, or in addition to instance entities being stored individually. Furthermore, accessing representations that are associated with a given category of entities can furnish information about completely novel entities as soon as those entities are categorized. Thus, categorization not only subserves economy of organization of knowledge, but it also allows us to extend knowledge beyond the limits of immediate experience. Thus categorization has far-reaching adaptive significance.

This is a mouthful about categorization, and it merits both unpackaging and measured contemplation. Beyond appreciating the power and robustness of categorization, the important thing to keep in mind, and the reason for this introduction to categorization, is that *hues are categorized* and *basic categories of hue are named as colors*.

Categorization is a many-to-one psychological reduction of physical stimulation. Some sensory continua are perceived continuously (as in the continuous variation of wavelength of light across the visible spectrum) but recoded into a set of discrete perceptual responses (hue categories), after which time the original sensory distinctions along the continuum may even be no longer accessible (Bornstein 1987; Pastore 1987). Entities in a category may be co-classified because they are perceived as being similar, because they share a common attribute, element or relation, because their membership status is affirmed relative to an extant or idealized prototype of the category,[1] or because they constitute the logical, or have been defined to constitute a conventional set included in the category. Often categories have an intrinsic qualitative distinctiveness about them. Categorization therefore automatically entails a decision rule whereby the membership status of new entities in the category can be judged.

Several comprehensive treatments of categorization exist (e.g. Bornstein 1981, 1984; Harnad 1987; Quinn & Eimas 1996; Rakison & Oakes 2003; Smith & Medin 1981). Categorization is essential and pervasive in mental life (Bornstein 1984). First, categories structure and clarify *perception*. Not only do human beings experience the world out of a constant biological flux, but also physical attributes and properties of the environment into which they are born, and in which they develop, are complex and unstable. Both these major sources of variation must be reduced if perception is to proceed with any degree of organization, order or coherence. This problem of ‘equivalence’ is a long-standing one in perception (Hochberg 1978). Categorization promotes structured perception and perceived stability in the world by surmounting such natural sources of variation. Our perceptions are in some measure organized so that psychological discreteness, coherence and stability cope with physical continuity, variety and instability. Categorization offers further perceptual advantage in clarifying different properties or objects or events; that is, mutually exclusive categorizations help to distinguish among entities. Between-category discrimination is more accurate, rapid and reliable than is within-category discrimination (e.g. Bornstein & Korda 1984; Boynton, Fargo, Olson & Smallman 1989; Roberson & Davidoff 2000).

Second, categories serve *cognition*, that is, thinking and memory, in ways that supersede perceptual filtering. Categories help us recognize familiar information, and categories facilitate the assimilation of new information. Even

---

[1] Not all stimuli in a category hold the same psychological status; rather, some are exemplary in that they tend to be preferred, processed faster and remembered better. Often such prototypes represent the category, and some theoreticians believe that categories form around prototypes.

elementary kinds of categorization anticipate modes of advanced cognition: the categorization principle of equivalent treatment of discriminable entities is formally identical to concept formation. In categorization, knowledge of some entity implies knowledge of other entities; thus, categorization also entails a (rudimentary) kind of inference. As categories imply generalization over variation, they further serve to enhance mnemonic capacity, initially by providing ‘receptacles’ into which incoming information can be encoded, then by reducing variety so that fewer items need to be retained individually after encoding, and, finally, by supplying a principle of organization whereby more information can be stored more efficiently in memory.

For these several reasons it would be difficult to overstate the adaptive significance of categorization in mental life or its development. Putting the obverse case is telling: could we think without categorizing? The difficulties would be formidable. Experiences would not be organized or structured. Biological variation and environmental diversity would overwhelm us. Important distinctions among some properties, objects and events would fade, while other unnecessary distinctions would interfere. Information would need to be encoded on a piecemeal basis, thereby retarding cognitive processes and necessitating increases in mnemonic storage. Recognition would need to proceed on a stimulus-by-stimulus basis. Higher conceptual abilities would have to develop *de novo* without prior, simpler formats on which to build. Finally, if every entity required a different name, language would be much more complex than it is already, and communication rendered considerably more difficult.

The problem of categorizing exists from the beginning of our perception of the world, and functions at several different levels of abstraction. First, we must transform an undifferentiated flux of contours, luminance levels and wavelengths into a set of entities distinct from their backgrounds. Next, we must organize the products of the initial parse into categories or equivalence classes. Finally, we must structure the taxonomic, spatial, and dynamic relations that can exist among entities into categories at different levels, such as superordinate, basic or subordinate. It is commonly thought that properties, objects and events in the world are categorized minimally at these three different levels. For example, a desk chair (the subordinate level) is a type of chair (the basic level) which is a type of furniture (the superordinate level). Chairs, beds, desks and tables are all subsumed under the superordinate category of furniture because they serve common human activities in related ways and are found in certain common locations, but these pieces of furniture do not (necessarily) look alike and they differ from other superordinate categories, such as vehicles, in function, meaning and perceptual attributes. More formally, in superordinate categorization, entities are grouped functionally and in terms of their meaning, and they may share few (if any) attributes with other category members; within-category similarity in function and meaning is high, and perceptual similarity may be low, whereas between-category similarity in function and meaning is low, and perceptual similarity is also low. In basic categorization, entities share function and meaning and may or may not share the same perceptual attributes; thus, within-category similarity in function and meaning is high and perceptual similarity low or high, whereas between-category function, meaning and perceptual similarity are low. Chairs of different styles share function and meaning as well as a number of perceptual attributes, and chairs are easily distinguished from desks, a different basic category in the domain of furniture. In subordinate categorization, members of a category share function and meaning, and within-category perceptual similarity is high, however, between-category function, meaning and perceptual similarity are also high. Desk chairs, kitchen chairs and highchairs represent subordinate categories of chairs, and these exemplars are discriminable from one another, yet they are functionally, meaningfully and perceptually similar to one other.

This hierarchical taxonomy of superordinate-basic-subordinate categorization is well established in adult cognition (Mervis & Rosch 1981; Rosch 1978). Looking forward to the balance of this chapter (and its companion, Bornstein 2006), we can apply this tripartite taxonomy to color. Superordinate categorization consists of the set of attributes of entities: volume, linear dimensions, movement, color and the like. Basic categorization consists of different qualities of one of those superordinate categories; for color: RED, YELLOW, GREEN and BLUE. Finally, subordinate categorization consists of different shades or tones of a given basic color category, as denoted by the English words: *cherry, crimson, vermilion, scarlet, ruby* and *carmine*. This survey and update concerns itself specifically with basic-level hue categorization and color naming.

Clearly, categorization implies a fundamental, economical and sophisticated cognitive approach to the world: categorization simultaneously embraces unity *and* diversity, constancy *and* variation, stability *and* instability, and it is central to a host of significant mental functions.[2]

---

[2] The ledger ought to be balanced: categories do have liabilities. To wit: categorization entails a loss of detail and information, memories based on categorizations are inexact, and inference from categorization is bound sometimes to be incorrect.

Infant categorization

Given the manifest significance of categorization to mental life, categories would be especially valuable in early childhood. Insofar as categorization makes comprehensible the otherwise bewildering diversity encountered in the natural environment, categories allow children to discriminate in the world and respond to novel entities as if they were familiar. Without categorization, children would have to learn to respond anew to each novel entity they experienced.

An accumulation of evidence attests that human infants are capable of formulating and representing a great diversity of categories (see Hayne 1996; Quinn 1999, for reviews). Newborns categorize very basic perceptual dimensions, such as forms and spatial relations and selected sounds (e.g. Bomba 1984; Eimas, Siqueland, Jusczyk & Vigorito 1971; Mehler, Dupoux, Nazzi & Dehaene-Lambertz 1996; Quinn 1994). Between three and six months, infants categorize forms composed of dot patterns (Bomba & Siqueland 1983; Younger & Gotlieb 1988), orientations of lines (Bomba 1984; Quinn, Siqueland & Bomba 1985), relations between lines and elements (Quinn 1994; Cohen & Younger 1984), emotional expressions (Bornstein & Arterberry 2003: Kestenbaum & Nelson 1990), different types of animals (Quinn & Eimas 1996) and animals and other nonliving objects such as vehicles or furniture (Behl-Chadha 1996). Before one year, infants categorize the gender of faces (Leinbach & Fagot 1993), and they categorize faces and schematic animals based on correlations among features such as legs, ears and tail length in animals, and nose size, eye separation and hairline in faces (Sherman 1985; Younger 1985, 1990, 1992; Younger & Cohen 1983).

Through this diversity of categorization, babies give evidence that they naturally perceive equivalences – that is, constancy and invariance – amidst the fluxes of their biology and ambient energy. Presumably, this accomplishment helps pave the way for the more difficult developmental challenges in perception, cognition, memory and language learning that loom on their developmental horizon.

Color vision and hue categorization

Color is a significant dimension of vision, and hue is a cardinal dimension of color vision. Hue is also perceived categorically by species that see color, and basic hue categories have a foundation in the biological functioning of the visual system.

Color

Color is one basic building block with which perceptions are constructed and around which memories are organized (Davidoff 1991). A narrow band of the continuous radiant spectrum of electromagnetic energy – between 400 and 700 nanometers (nm) is visible: we call it ‘light.’ For normal observers, an impressive quality of visible light is, as Sir Isaac Newton observed long ago, its color or *hue*.

> To establish the first principle, let us repeat the experiment with the prism set out at the beginning, namely the sun’s rays were permitted to enter the dark room through an aperture F…, and were refracted through a prism ABC arranged near that aperture within, and then were spread out on the opposite wall HI in a painted image PT, & that image, as could be commonly observed, was tinted with colors, *red* to one extreme T least bent in a vertical direction, & *purple* falling to the other inclined extreme P; in addition *blue* and *green & yellow* are distinguishable at intermediate locations Q, R & S [translation mine; emphasis added] (Newton 1730:153-154).[3]

Hue is the psychological correlate of the physical dimension of wavelength. In actuality, colors vary in three dimensions: hue, brightness and saturation. For most practical purposes (e.g. color printing, color television), these three dimensions suffice to describe color. Nickerson and Newhall (1943) estimated that 7,295,000 discriminable colors compose the 3-D psychological color solid. Although the psychological construct of the color solid is tridimensional, only one dimension of the three (hue) denotes relevant qualitative differences, and, clearly, no language discriminates semantically more than a fraction of visually discriminable colors. Further to this point, an organism is said to possess color vision if (and only if) it can discriminate between two stimuli solely on the basis of a difference in their wavelength composition, independently of brightness and saturation (Byrne & Hilbert 2003; Teller 1998). Thus, the plethora of potential color stimuli reduces to 120-150 discriminations of hue, of which only twelve are independently identifiable (Halsey & Chapanis 1951). We partition the color space into relatively few distinct qualitative sensations (a bright red is red, a saturated blue is blue). These companion papers concern themselves with hue (chromatic vision, perception, categorization and naming),

---

[3] Like modern scholars of color from Hering to Boynton, Newton (1730) himself was aware that ‘violet = purple’ is *not* a unique sensation: article 10 of his undergraduate notebook (1661-1665) on “combinations of colors” begins “Red and blue make purple”, and his sixty-ninth annotation on Robert Hooke’s *Micrographia* (1665), documents that he knew that “Purple is made of a deepe red and a deepe blew...” (see Hall & Hall 1962:405). Newton began with a smaller number of primaries, and only later, following Kepler, did he expand this number (to include orange and indigo) in order to harmonize the spectrum numerically with the number of notes in the musical scale (Houstoun 1917-1918).

and so will not (except where necessary) further discuss achromatics (brightness, terms for WHITE and BLACK, and the like) or saturation. It is remarkable that hue varies so little with changes in light intensity; that is, hue has almost perfect constancy. Similarly, differences in saturation are not a serious concern in the study of basic hues.

Color vision theory

Since the nineteenth century, two major theories of color vision have rivaled one another. One theory, deriving from Thomas Young and Hermann von Helmholtz, postulated trichromacy. Three retinal receptors, one sensitive in the short-wavelength or blue-appearing region of the spectrum (SWS), one in the middle-wavelength or green-appearing region (MWS), and one in the long-wavelength or red-appearing region (LWS), combine their mechanisms of action to give rise to the gamut of color sensations (see Wyszecki & Stiles 1982). In a competing / complementary theory, Ewald Hering proposed that an opponent-process system underlies color vision. Red-and-green and yellow-and-blue (in addition to black-and-white) sensitive processes, which are themselves mutually antagonistic, combine subtractively to give rise to the gamut of chromatic sensations (see Wyszecki & Stiles 1982).

Color neurophysiology

Two fundamental problems for color appearance are, first, the number and nature of basic color sensations and, second, their linkage to specific neural mechanisms (Abramov & Gordon 1997). Here I refer briefly to the second problem; the balance of these companion papers is really concerned with the first problem.

Information processing in color vision proceeds from cone photoreceptors in the retina through horizontal and bipolar cells in the inner retina then via the integrity of the parvocellular stream of the visual pathway through the lateral geniculate nucleus and on to area V4 of the prestriate visual cortex (see Burr, Morrone & Fiorentini 1996; Kaplan, Shapley & Purpura 1998; Knoblauch, Bieber & Werner 1998; Lennie & D’Zmura 1988; Shapley 1990; Zegura 1997). At the photoreceptor level, the spectral composition of light is analyzed by the three univariate cone photoreceptor classes with different absorption spectra as suggested by trichromatic theory (Knoblauch et al. 1998). However, at the next retinal stages, and at all subsequent sites, color information appears to be processed by cells organized into color-complementary receptive fields, as suggested by the opponent-process theory. Neurophysiological studies of the primate visual system have thus reconciled trichromacy and opponency in a cone-to-channel transformation ‘zone theory’ that suggests that the three retinal receptors filter their outputs so that cone signals recombine, by the level of the horizontal and bipolar cells of the retina, into three antagonistic opponent channels whose outputs are carried to the visual cortex on anatomically separate pathways (e.g. Gegenfurtner & Kiper 2003).

Discrimination and categorization

The physics of color, the psychophysics of color discrimination, and the psychology of color naming are not isomorphic. Physically, the wavelength spectrum varies continuously – one wavelength differs from another by simple quantitative change. Psychophysically, human observers can discriminate many wavelengths – our powers to discern are keen. Psychologically, hues vary in a more or less categorical fashion – our perceptions vary qualitatively and more or less discretely from one region of the wavelength continuum to another.

Certain features characterize hue categories. Most notably, viewing the spectrum today, we are impressed (as was Newton) that ranges of visible light are characteristically dominated by qualitatively different sensations of hue – let us call them *basic categories of hue*: operationally, adults co-classify select discriminable wavelengths under the same color name. Hues compare to each other in terms of similarity relations, and hue categorization reflects the perceived quality of similarity among discriminable wavelengths. Relative comparisons of similarity (X is more like X^1 than it is like Y) help to establish plateaus of hues and boundaries between hue categories (Dedrick 1996). Thus, numerous shades of red are qualitatively similar to each other and different from green. Hues are then *similarity categories*, groupings of non-identical wavelengths many of which may be perceptually discriminable or indiscriminable from one another but still treated as similar, in all probability because of their relative discriminability and qualitative similarity.

A related defining attribute of categorical perception is the relative indiscriminability of stimuli within categories, compared to the relative discriminability of stimuli at category boundaries, such that quantitative differences along a continuum are perceived as qualitative changes at category boundaries (Harnad 1987). Categorical perception of color has been evidenced using different methods. Besides color naming, discrimination of pairs of colors from adjacent categories is easier than discrimination of equivalently spaced colors within the same category. Using a same-different judgement task, Bornstein and Korda (1984) showed that adults were faster at responding when color stimuli were from different categories than from the same category. Using a triadic ‘odd-one-out’ judgement task, Kay and Kempton (1984) showed that adults more frequently chose the different category stimulus as the odd-one-out, despite the three stimuli being equidistant in color space. Using a two-alternative-forced choice task, Uchikawa and Shinoda (1996) showed that adults were faster and more accurate at identifying a colored target when asked to identify it from a pair of colored stimuli from different color categories than from the same color category. In adults, a visual search for a color target is facilitated if the target and distractors fall in different color categories (e.g. Daoutis, Pilling & Davies 2005). So, discrimination of stimuli is faster and more accurate across than within categories (Laws, Davies & Andrews 1995) with similar effects in memory when there is a delay between the presentations of the stimuli to be matched (Boynton, MacLaury & Uchikawa 1989; Uchikawa & Shinoda 1996). Categorical perception may even enhance between-category discrimination relative to within-category discrimination for physical differences of equal magnitude (Harnad 1987).

Last, categories contain both pure examples (in hue, spectral colors that are unique, for example, a green with no red, yellow, or blue in it) as well as mixtures of adjacent categories (in hue, the short-wave end of the green category is bluish, the long-wave end is yellowish). Color stimuli from the center of color categories are matched and classified faster than those at the boundary (Bornstein & Monroe 1980). Yendrikhovskij (2001) used cluster analysis to examine the distribution in color space of colors that can be observed in natural images, and showed that the resulting clusters – in effect, the regions of color space most often represented in natural images – fall near the foci for basic color terms that Kay and Regier (2003) identified as privileged points in color space, and that anchor the color naming systems of the world’s languages. Yélî Dnye is a language isolate spoken on Rossel Island in the Louisade Archipelago of Papua New Guinea. Levinson’s (2000) study of Yélî Dnye color naming produced the first experimentally documented example of a language lacking a set of basic color terms that still partitions the perceptual color space. On the basis of inspection of the World Color Survey data set, as well as the Mesoamerican Color Survey, MacLaury isolated four colors that represented the universal “elemental” hues of red, yellow, green and blue (1997:467). The Yélî Dnye hue naming centroids were compatible with them (Kay 2005).

The difference between sensory discrimination and perceptual categorization is crucial and warrants additional explication. *Discrimination* concerns how many different wavelengths (separate from brightness and saturation) observers can tell apart. To address the discrimination question, an experimenter might juxtapose two spectral fields (either monochromatic lights or reflectance colors that yield relatively homogeneous energy distributions of given wavelengths), and alter one relative to the other systematically across the spectrum to derive a wavelength discrimination ($\Delta\lambda$) function, the degree of wavelength change required to elicit a *jnd* (‘just noticeable difference’) in color as a function of the reference wavelength. With brightness and saturation controlled under the experimental conditions just described, adults with color-normal vision (trichromats) discriminate approximately 120 to 150 *jnd*s across the visible spectrum.

Categorization concerns how observers group wavelengths based (presumably) on perceived qualitative similarities of hue among them. To address this question, an experimenter might expose observers to spectral fields or reflectance colors that vary systematically in wavelength, asking them to name (or identify or group) the spectral fields to derive color-naming functions (say, the percentage of times different color names are applied to different wavelengths).

Boynton and Gordon (1965) asked trichromatic, native English-speaking adult observers to use four basic color terms – *blue*, *green*, *yellow* and *red* – singly or in pairs to describe wavelengths presented to them randomly from across the entire visible spectrum. The results of their color-naming experiment lend quantitative support to the foregoing central observations about the qualitative appearance of the chromatic spectrum. Boynton and Gordon’s observers were satisfied to name each of the wavelengths in the visible spectrum using one or, sometimes, a pair of the four basic color terms the experimenters permitted. Participants generated peaked color-naming functions with relatively shallow overlapping slopes; and they produced a high degree of inter-namer reliability in this judgment task. Moreover, only two color names ever competed in response to any one wavelength. Of course, the exact form that color-naming functions take depends on the way the category question is posed. For example, if observers are restricted to using the same four basic color terms (*blue*, *green*, *yellow* and *red*) monolexemically, they will generate discrete color-naming functions with broad plateaus of wavelength defining the range of each category, and a steep ascending portion of each color-name curve that is symmetrical with the descending portion of the preceding curve (see Beare 1963). The two types of color-naming functions are comparable, especially as regards their transition points, and both legitimately represent the relation between hue and wavelength; the type of function generated simply reflects the latitude of naming that observers are allowed.

As stated earlier, mapping from the physics of light to the physiological code to wavelength discrimination to hue categorization is complicated and inexact. Nonetheless, by the “inverse law” (Lashley & Wade 1946), organisms tend to generalize along a physical dimension where their discrimination is poor, and that generalization naturally contributes to grouping and categorization. Thus, two wavelengths that are poorly discriminated tend to be categorized together (Uchikawa & Shinoda 1996). Although a large number of wave-lengths is discriminated, many are still co-categorized: people with normal color vision regularly and satisfactorily partition the visible spectrum into four basic hue categories, labeled (as by Newton) in English: *blue*, *green*, *yellow* and *red*.

Basic hue categorization

An impressive, if incomplete, uniformity obtains in basic hue categorization, one that transcends English (e.g. Beare 1963; Boynton & Gordon 1965; Smith 1971) and even related Indo-European languages, for example, Swedish (Ekman 1963). First, a cross-cultural survey of color naming, undertaken by Berlin and Kay (1969), asked bilinguals from twenty different language communities to identify the best examples of a small set of basic color terms from an array of 320 colors (40 hues by 8 brightness levels). Their study confirmed that a limited number of basic hues exist within and across language and culture. (For a discussion of the definition of basic color terms, see Kay, Berlin & Merrifield 1991). Despite vast linguistic differences among them, observers identified relatively small and distinct areas of the two-dimensional color array as color exemplars. These areas match wavelength regions identified as predominantly one or another basic hue. Although Berlin and Kay's (1969) original study was criticized on a number of legitimate grounds, Kay and Regier (2003) used World Color Survey (WCS) data to overcome them and found similar results; but see Saunders and van Brakel (1995) for a critique of the WCS data. Second, similar results also obtain even when language labels are bypassed. A procedure that asked participants to scale similarity based on the assumption that the "degree of perceived similarity is a function of the degree of overlap between primary experiences (sensations, emotions) which are evoked by the stimuli" (Ekman 1954:467) resulted in a hue similarity matrix for Swedes similar to Beare's American-English color-naming functions. Third, grouping-by-similarity remains even when the ability to categorize colors by language is lost, as occurs in color anomia (Roberson, Davidoff & Braisby 1999). A male anomic patient had great difficulty color naming, but still showed categorical perception of hue in two-alternative forced-choice discrimination. Last, categorical color perception also survives verbal interference and occurs in visual search where decision rates are too fast for labels to influence performance (Pilling, Wiggett, Özgen & Davies 2003).

Consistent results such as these show clearly that, for English and perhaps other similar languages, only four hues and their corresponding color terms – *red, yellow, green* and *blue* – are necessary *and* sufficient to describe colors (Gordon, Abramov & Chan 1994; Werner & Bieber 1997), and that, for them, there is a consistent matching of percept of hue with basic color naming of the visible spectrum. Psychophysical study further confirms the basicness of these hues. The Commission Internationale de l'Éclairage (CIE) defined a unique hue to be a perceived hue that cannot be further described by the use of hue names other than its own (CIE 1987). Only the hues denoted in English by *red, yellow, green* and *blue* are unique (Byrne & Hilbert 2003). Jameson and Hurvich's (1955) cancellation experiments, supplemented by forced naming of color samples with a restricted vocabulary (Broackes 1997), further supports this assertion: color-normal observers looking at a stimulus produced by two monochromators are able to adjust one until they report seeing a red stimulus that is not all bluish or yellowish, and so forth for the yellow, green and blue unique hues. These unique hues are also stable across the life-course (Schefrin & Werner 1990; Werner & Schefrin 1993). Unique (elemental) hues are mutually exclusive in experience in that relations of hue similarity follow the predictions of opponency. Red and green are opposed so that no reddish shade is greenish, or vice versa; similarly for yellow and blue: red-green and blue-yellow are "forbidden colors" (Billock, Gleason & Tsou 2001). Binary hues that do exist are "perceptual mixtures" of unique hues (Hurvich, 1981). Color naming and unique hues provide powerful evidence of internal constraints on how the nervous system codes color – and human beings categorize hues – and they suggest that basic hue perception is (in part at least) physiologically determined (Simpson 1991).

Other psychological research reinforces the 'basicness' of basic hues and color terms from non-basic ones. Boynton and Olson (1990) found a complete dichotomy, based on converging criteria of consistency, consensus, and response time, between observers' use of basic and non-basic color terms to denote the three-dimensional subjective color space. They collapsed the three response measures by principal components analysis into a single measure of the ease of naming colors. In doing so, their data confirmed the uniqueness of basic color terms as compared with non-basic terms. Guest and Van Laar (2000, 2002) later provided additional evidence for the basicness of these categorical representations of color. They asked adults to name 1,044 unique foreground-background color combinations. Participants this time were allowed to use an unrestricted color vocabulary. Nonetheless, basic color terms predominated over non-basic terms and were applied to the majority of stimuli. They also found that peak nameability occurred in the vicinity of the elementary Hering colors and that nameability minima appeared where the opponent systems are changing polarity. Moreover, compared to non-basic, basic color names were used more consistently and confidently and were produced more quickly (but see Alvarado & Jameson 2005).

Together these data support the universal finding that basic color systems are grounded, with rare and partial exceptions, on the four primaries: red, yellow, green and blue (and black and white) (Kay & Berlin 1997). Boynton summarized modern scholarship on the issue:

> It is often productive to reduce a problem to the smallest number of variables that we can and still describe it adequately. In this spirit, many people have argued that only four color names are needed to describe the chromatic character of bright colors viewed in a dark surround.… The four basic color names are *red*, *yellow*, *green*, and *blue*. Each of these names is held to describe a unique sensation… There are other hues to which color names have been given, which do not meet the criterion of uniqueness… Orange does not qualify as a unique hue because - to most people at least - it can be appreciated as being made up subjectively of a mixture of red and yellow… The same can be said for the simultaneous red and blue component of a purple or violet sensation, and of blue-green and green-yellow blends (Boynton 1971:346) [emphasis added].

In contrast to the unique hues and their corresponding names, colors that fail as both sufficient and necessary are not elemental (Wooten & Miller 1997). Secondary chromatic sensations seem subjectively less basic because most people perceive them as blends of basic colors. Non-basic colors or other binary hues are reducible: orange to yellow-red and purple to red-blue, respectively. Namers use secondary color terms (*orange* or *purple*) less reliably, and all the wavelengths that namers describe using secondary terms can be analyzed into the four basic categories (Boynton, Schaefer & Nuen 1964; Sternheim & Boynton 1966).

Four unique hue sensations identified in English with the color names *red*, *yellow*, *green* and *blue* are called “basic hue categories” by Bornstein (1973; Bornstein, Kessen & Weiskopf 1976a, 1976b), “landmark” colors by Miller and Johnson-Laird (1976), and “primary basic” colors by Kay and McDaniel (1978). Thus, basic hue categorization subsumes groups of physically different wavelengths, some of which are discriminable and others of which are indiscriminable from one another. Wavelengths of light within one of these categories are grouped together because they appear perceptually similar in that they share a hue quality. In consonance with this perceptual stance, four color terms constitute a minimal, mutually contrastive set of color names that singly or jointly describe the color space exhaustively. All colors can be described as combinations of the four unique hues. Moreover, the English basic color names *red, yellow, green* and *blue* are etymologically distinct, most common in the language, and psychologically meaningful and inclusive.

For these reasons, these basic categories and names from the vast vocabulary and array of color confidently form a conceptual base for ethological comparison and a semantic base for cross-cultural comparison. To be sure, not all animals categorize hue similarly and not all languages make all four perceptuo-linguistic distinctions. As I discuss in the companion paper to this one (Bornstein 2006), even some basic hue categories / color names are sometimes grouped together.

Biological substrates of basic hue categorization

In the same way that color physics and color neurophysiology are not precisely congruent, there is no simple linkage between color vision neurophysiology and color appearance (Jameson 1997). Neurophysiologists and psychophysicists contend that possible ‘linking propositions’ are yet to be completely understood (Burns, Elsner, Pokorny & Smith 1984; Krantz 1975; Krauskopf, Williams & Heeley 1982; Lennie & D’Zmura 1988; all cited in Jameson & D’Andrade 1997). The chromatic opponent channels are not true hue mechanisms (Abramov 1997; Abramov & Gordon 1994) and do not, in themselves, determine color naming directly. As Mollon wryly observed, “There is no physiological evidence in the visual system for cells that secrete the sensations of yellowness and blueness or redness and greenness” (1995:144). As in all active areas of science, the field is still evolving, and psychological constructs like hue are understood as works-in-progress.

Nonetheless, the prevailing multi-stage model of color perception is based on a wide range of psychophysical and neurophysiological data (De Valois & De Valois 1993, 1996) that corroborate the thesis, advanced most explicitly by Bornstein (1973) and Ratliff (1976): there are specific activity states in the brain, perhaps common to everyone with normal color vision, that signal congenitally basic categories of hue sensation, and, during development, basic names become strongly and naturally associated with them.

Precisely controlled neurophysiological investigations in Macaque, a monkey species that possesses color vision essentially identical to that of *Homo sapiens*, have identified four classes of chromatic-sensitive cells at the level of the geniculate nuclei (DeValois 1973). The neurons that respond selectively to particular wavelengths or to combinations of wavelength appear to subserve wavelength discrimination. The envelope of maximal sensitivity of their individual sensitivity-functions across wavelength is non-monotonic, and, not fortuitously, it is congruent with behavioral wavelength discrimination in monkeys (DeValois 1973; A. A. Wright 1972; W. D. Wright 1947). Thus, the mechanism of action of color-coding cells helps to account for hue categorization. More specifically, the relative contribution of each of the four cell types to the total activity in the opponent system in monkeys matches Boynton and Gordon's (1965) color-categorization data for trichromatic human adults. Comparison shows that, for example, the hue quality 'red' is signaled by excitation of +R-G cells, the hue quality 'red-yellow' is signaled by the activity levels of +R-G and +Y-B cells, and so forth. Accordingly, DeValois, Abramov and Jacobs proposed the existence of an "isomorphic relationship between the relative activity rates of the various cell types and the hue of a given light" (1966:976). More recently, basic color zones derived by categorical color naming have been mapped with no overlap in an opponent-color response space: Okajima, Robertson and Fielder (2002) proposed a network model (with a threshold selector, maximum selectors and multiplication units with gain factors) to generate basic hue categories quantitatively from these elemental color responses.

Infrahuman color vision and hue categorization

Some degree of color vision appears to be the default condition for all the major groups of vertebrates, including most Old World primates, many birds and shallow water fish, and is also common among invertebrates, such as bees (Jacobs 1981, 1993; Menzel 1979). Color vision subserves a variety of vital adaptive functions in species that possess it – mate selection, food acquisition, recognition of predators or prey, communication and extraction of information about the environment (Zegura 1997) – just as it does for many 'colored' objects themselves. Perhaps chromatic vision in primates co-evolved with colored fruits (Mollon 1989): it is mutually advantageous for primates to acquire food, and for fruits to get their seeds dispersed. However, color vision systems also vary across species. Using just the most basic classification, some organisms are dichromats (possessing only two cone photoreceptors), others are trichromats, and still others tetra- or pentachromats (Bowmaker, Heath, Wilkie & Hunt 1997; Byrne & Hilbert 2003; Jacobs 1981, 1993).

If color vision evolved to highlight or signal properties of species-important objects, it would be most useful if the objects in question continued to fall in their same color categories despite normal variations in illumination, size, or position on the retina (Jacobs 1993; Mollon 1989). Across different viewing conditions (for example, under a light-bulb, versus the sun) and across the life span, light reaching the retina from any given object will differ greatly. Despite considerable differences in spectral composition, people generally refer to a given object with a particular color term. If this were not the case, color names would not have proved such useful linguistic tools. That is, *categorizing hue* and *color naming* serve color vision, language and information processing adaptively.

It comes as little surprise in this light that those infrahuman species which see color, likewise partition their visible spectral continua into species-specific basic categories of hue. At least one invertebrate and three vertebrate species (other than humans) which possess color vision provide evidence that they categorize basic hues. Data from the European honeybee (von Frisch 1964), from the pigeon (Wright 1972; Wright & Cumming 1971) and from the monkey (Sandell, Gross & Bornstein 1979) and chimpanzee (Matsuzawa 1985; Matsuno, Kawai & Matsuzawa 2004) indicate that categorization of hue is the common organization of color-vision processing in species that see color.[4]

Most notably, behavioral work indicates that color vision in monkeys and chimpanzees is quite similar to that of the human being (De Valois 1973; Grether 1940a, 1940b, 1942), based on common biological processes (Deeb, Jorgensen, Battisti, Iwasaki & Motulsky 1994; Dulai, Bowmaker, Mollon & Hunt 1994). We share our highly specialized photo-pigment and visual systems with other Catarrhine primates such as apes and Old World monkeys (Zegura 1997). Studying the monkey, *Macaca fascicularis* and *M. mulatta*, Sandell et al. (1979) found that the ranges of wavelengths monkeys categorized together, and points of transition between categories, matched those of trichromatic human adults. Likewise, Matsuzawa (1985) found that a four-year-old female chimpanzee, ‘Ai’, a *Pan troglodytes* which was born in Africa and received in the laboratory at about one year of age, classified colors like a human observer tested under the same conditions. A native speaker of Japanese was asked to name a set of color chips, with one trial per chip. Ai had been trained to recognize a focal chip for each of the eleven Berlin and Kay (1969) categories. Both human and animal observers divided the color space into eight clusters with broad areas within which single color names were applied consistently.

---

[4] Several differences in hue categorization across species are noteworthy too. First, the ranges of the radiant spectrum that are visible to different species differ: bees see ultraviolet, but not red like human beings. Second, different species partition the spectrum at different locations: the inter-hue boundary positions for the pigeon differ from those of the monkey. Third, the number of basic hue categories differs across species; the pigeon has three and the bee four. Last, in each of these species, wavelength-discrimination and color-‘naming’ functions are inversely related.

The human applied single color names to 74% of 215 chips; the chimp applied the same names to 79% of the chips. Areas of consistent color naming were separated by narrower areas in which the names applied to the two adjacent areas were used. Matsuno et al. (2004) later re-investigated color classification in a second chimpanzee, ‘Pendesa’, which had not acquired symbolic color names. This animal also showed a high level of accuracy in the performance of color matching at baseline trials. Thus, chimpanzees that were skilled and unskilled in the use of color names both perceived similar color groupings (despite some differences in the stability of their color classifications). In short, for multiple species studied in multiple laboratories in multiple ways spanning multiple years, *to see color is to categorize the spectrum into basic hues*.

The ethological approach to hue categorization clearly indicates that language, culture and experience are not prerequisites to basic categorizations of hues. Rather, physiological bases for color vision probably subserve basic hue categorization. The laws of trichromacy and opponency hold that there are nontrival neural constraints on color perception. That is, there exist objective transition points in the spectrum not dependent on language or experience. The fact that discontinuities in color space can be described using language does not mean that language causes these discontinuities (Ingling 1997). The neuropsychological and psychophysical evidence is consistent with color perception being hardwired and universal, even if the neurological bases of color categorization or qualitative sensations are not yet completely known (Stanlaw 1997; Valberg 2001; Van Laar 1997).

Human infant color vision and hue categorization

If various infrahuman species categorize hue, how about human beings? Human infants see color and also partition the spectrum into basic hue categories.

Infant color vision

The immaturity of the human newborn’s retina (Abramov, Gordon, Hendrickson, Hainline, Dobson & LaBossiere 1982), and the slow maturation of anatomical structures (Yuodelis & Hendrickson 1986; Hendrickson 1994), have consequences for color vision at birth (Abramov & Gordon 1997; Banks & Bennett 1988; Brown 1990, 1993; Banks & Crowell 1993). Evaluations of chromatic-achromatic discriminations in newborn and one-month-old human infants so far suggest that neonates are capable of some limited color vision. One study found that 74% of newborns discriminated red at a variety of luminances from an achromatic background, but only 25% yellow, 36% green, and 14% blue. By one month of age, however, infants’ performance with green and blue had improved (Adams 1995).

That said, anatomical and electrophysiological data show that all photoreceptor classes of the human retina are functioning approximately one month after birth (Adams & Courage 1995); one- to two-month-olds possess all the retinal components necessary for adult-like trichromatic vision (SWS, MWS and LWS cones and the corresponding post-receptoral circuitry (Knoblauch et al. 1998)); and the shapes and peaks of luminance tCSF in both three- and four-month-olds appear quite similar to those of adults. By three to four months of age, infants discriminate the basic four chromatic stimuli from white (Mercer, Courage & Adams 1991). Thus, human infants show a sharp development in chromatic sensitivity between birth and three to four months (Dobkins, Anderson & Kelly 2001); with the sensitivity to blue being the slowest to develop (Adams, Courage & Mercer 1994; Teller 1998). Indeed, by some measures, three-month-olds are more sensitive than adults to color (if chromatic thresholds are normalized to the luminance thresholds (Brown, Lindsey, McSweeney & Walters 1995)).

In short, chromatic discrimination emerges over the first postnatal months in human infants, and electrophysiological and behavioral evidence indicates that nearly all of the retinal components necessary for adult-like trichromatic vision are present as early as three months of age (Brown & Teller 1989; Bornstein 1976; Peeples & Teller 1975; Teller, Peeples & Sekel 1978; Thomasson & Teller 2000) so that infants only four months of age discriminate color (Hernandez-Reif & Bahrick 2001). These findings are consonant with the observation that monkey newborns (or even older monkeys reared in the dark!) are trichromats (Boothe, Teller & Sackett 1975). Offenbach (1980) showed that the basic perceptual color space is invariant in normally sighted individuals through the balance of development.

Color is important to early perception (Dobkins & Anderson 2002). For example, five-month-olds preferentially encode the color versus the shape of a stimulus (Catherwood 1994; Rose & Slater 1983). Color is also a prominent dimension in infants’ first categorization responses regarding stimuli of different shapes (Catherwood, Crassini & Freiberg 1989). Hue similarity constitutes one of the earliest bases children use to categorize objects (Melkman, Tversky & Baratz 1981), and, in early childhood, color can take precedence over shape or form as a critical factor in children’s learning and cognitive processing (Melkman et al. 1981; Zeaman & Hanley 1983). Of course, such outcomes depend on the particular colors or shapes involved. Nonetheless, infants and young children clearly find color salient and codable vis-à-vis shape. Moreover, cross-cultural studies of object sorting according to color, form, or function have repeatedly shown a clear developmental order with sorting by color first (Segall, Dasen, Berry & Poortinga 1990).

Infant hue categorization

As reviewed earlier, categories in several modalities have been identified and studied in infancy. Little surprise then that, soon after they see color, human infants also categorize hue. Bornstein et al. (1976a, 1976b) habituated four-month-olds to single radiant monochromatic lights and, afterwards, tested them with the same lights, new lights from the same hue category, and new lights from adjacent hue categories. In these contrasts, the new lights were equally spaced (in nm) from the habituation light. Infants treat physically and phenomenally discriminable hues from the same category as equivalent, whereas they discriminate between hue categories. A summary of the ranges of wavelengths that nonverbal infants treat as similar, and those they distinguish, shows that human infants, long before acquiring language, parse the spectral continuum into basic categories of hue and that infants' categories correspond to those of adults. Linguistic relativists have argued that the category effect in infants could be an artifact of the habituation / novelty preference methods (Özgen 2004). However, this finding showing infant categorical perception of hue has been replicated and extended several times by the same and different investigators (see Bornstein 1981). Similar hue category effects were found in a series of studies conducted by Catherwood and colleagues (Catherwood, Crassini & Freiberg 1987, 1989, 1990). In their studies, within- and between-category separation sizes were not equated in color space. Catherwood et al. (1989) familiarized five-month-old infants to a stimulus of one hue in either of two different shapes (face of a bear or a rabbit) and then presented infants with four test comparisons in which the familiar stimulus was paired with a novel stimulus in either the familiar or the alternate (novel) shape and in a novel hue from the same or a different category. Infants displayed a preference for the novel stimuli only in the new-category hue. Franklin and Davies (2004), using a novelty-preference technique and naturalistic reflective stimuli with stimulus separations equated in a perceptual (in addition to a physical) metric, showed that four-month-old infants respond categorically across hue boundaries. Finally, Franklin, Pilling, and Davies (2005, Experiment 2) found comparable categorical effects as four-month-olds were significantly faster at detecting a target when the background was from a different color cat-egory than when it was from the same color category. This result further suggests that the categorical responding in infants (as in adults) has a perceptual basis.

Control tasks in these several research lines eliminated alternative explanations in terms of differential brightness of the hues, hue preferences, or inability to discriminate shapes. In further control studies, Bornstein (1981) showed that babies can discriminate among (at least some) wavelengths they group into a hue category, and Franklin et al. (2005) also showed that infants can discriminate stimuli from the same color category although (just like adults) they are slower at discriminating within- than between-category colors.

The fact that the category findings extend to novel stimuli dissimilar in shape to the familiar stimulus (Catherwood et al. 1989) supports the adaptive value of hue categorization even in infancy. Further, there is evidence that, at brief exposure intervals (for example, ten or twenty seconds) infants even encode hue more readily than shape (Rose & Slater 1983).

Categorical responding to color has also been found in toddlers, using a forced-choice task (Franklin, Clifford, Williamson & Davies 2005) and in young children using a visual search task (Daoutis, Franklin, Riddett, Clifford & Davies in press). In the latter study, the category effect was observed in children who do not yet linguistically mark category boundaries, and the size of the category effect was unrelated to their color naming or the number of color terms they knew. The Himba are a people of Namibia, whose language segments the color space differently to English; Himba toddlers also learn color terms later than English toddlers (Androulaki 2003), so Himba toddlers know no color terms at all. Despite this, they show categorical responding. Franklin, Özgen, Drew and Davies (in prep) further tested categorical responding in toddlers with no color terms using a discrimination threshold task. Toddlers' discrimination thresholds were higher in the center of blue and green color categories than at the blue-green category boundary. As their threshold task has no memory component, it appears that the color category effect is perceptual.

Long before the acquisition of language or inculcation of the rudiments of culture, infants regularly partition the spectral continuum into basic categories of hue. This is a very substantial mental accomplishment so early in life because it implies the abilities to abstract what is common among physically different, even perceptually discriminable entities, and to generalize on the basis of that abstraction. Of course, categorization may change in development on account of maturation or experience or their interaction (Bornstein 2006). The demonstration of basic hue categories in human beings in no way implies that, between infancy and maturity, hue categorization is fixed or stable. Nonetheless, studies of human infancy reveal that the visible spectrum is organized into basic categories of hue well before experience, language acquisition, or formal tuition could operate extensively on cognition. Categorical responding in young infants strongly implicates anatomical, physiological, sensory and perceptual processes.

Conclusions

Physical attributes and properties of the world are complex and, like the physiology of the observer, constantly in flux. Through categorization, perception and cognition are organized so that psychological unity and coherence replace physical variety and biological instability. In this paper, I discussed one important domain of categorization. All physical stimuli in the color domain are not perceived as equally different from one another psychologically; rather, some are categorized together and treated as equivalent (but not necessarily as identical) probably based on their perceived similarity. Whether they are adults, or infants at the beginning of life, human beings perceive categories of hue. Psychophysical, developmental, and comparative findings support a universalist position on basic hue categories that articulates well with the biological substrates of these processes.

Four separate lines of argument meet to clarify, highlight, and embolden a universalist perspective on basic hue categorization of red, yellow, green and blue. The first draws on psychophysical and perceptual findings from studies with adults from diverse language and cultural communities that show that a high degree of uniformity and regularity obtains in basic color naming and in experimental studies that actually employ perceptual stimuli rather than rely on reports of language systems. The second and third derive from developmental and comparative studies, respectively: human infants, long before the acquisition of language or culture, and various infrahuman species that see color, but which are devoid of language and culture, also partition the spectral continuum into basic categories of hue. Last, the physiological responsiveness of neural pathways in the visual system shows patterns of wavelength discriminability that appear compatible with (and suggestively determinative of) basic hue categories. Psychology, physiology and anatomy contribute integrally to patterning basic hue categorizations of the color world and point to the existence of four natural divisions of the chromatic spectrum. This convergence of experimental, cultural, developmental, animal and neuroscientific comparisons is compelling, and lies at the heart of scientific inquiry (Bornstein 1980). There appear to be nontrivial biological constraints on color categorization and the phenomenology of color experience. The available evidence seems compatible with a position of moderate universality that leads to expectations of probabilistic rather than deterministic cross-cultural correspondence.

The psychological structures that characterize color perception have been revealed in modern psychophysical studies with adults, with infants and with various infrahuman species, and they show that basic categorization possesses an identifiable physiological substrate. As discussed in the companion paper to this one (Bornstein 2006), the data that these studies have yielded supplant an older psycholinguistic and anthropological literature that posited that language and culture alone govern perceptual processes and thought. Indeed, the modern studies invert the traditional view and point to the influence of perceptual and cognitive forces on shaping language. Thus, fresh data help to resolve an anthropological-linguistic question of direct and manifest importance to the study of neonate and infant cognition: does perception influence language, or does language influence perception? Hue is a model domain for how categorical perception, linguistic relativity, and perceptual learning interrelate. The existence in infancy of basic hue categories that appear to be firmly rooted in physiology strongly favors the primacy of perception. Unintentionally echoing *Genesis,* Lenneberg wrote “concept-formation [is] the primary cognitive process, and naming (as well as acquiring a name) the secondary cognitive process” (1967:332-333). A critical point of future research will be to disentangle purely linguistic influences on conceptual hue categories. In color, relativism appears to overlay a universalist foundation. Language exploits hardwired perceptual discontinuities in forming color categories, and other, presumably pragmatic, forces drive how many and (to some degree) which categories are formed.

All that said, an apparent paradox plagues the color literature: color categorization without the involvement of linguistics (perceptual categorization) supports universalism, whereas color categorization in which linguistics plays a role (color naming) points to relativism (see Bornstein 2006 for a proposed resolution).

Acknowledgments

This chapter summarizes selected aspects of my research, and portions of the text have appeared in previous scientific publications cited in the references. I thank C. Varron for assistance. Address correspondence to: Marc H. Bornstein, Child and Family Research, National Institute of Child Health and Human Development, National Institutes of Health, Suite 8030, 6705 Rockledge Drive, Bethesda MD 20892-7971, U.S.A.
Email: Marc_H_Bornstein@nih.gov.

References

Abramov, I. 1997. “Physiological Mechanisms of Colour Vision”. *Color Categories in Thought and Language* ed. by C. L. Hardin & L. Maffi, 89-117. Cambridge: Cambridge University Press.

— & J. Gordon. 1994. “Color Appearance: On Seeing Red or Yellow, or Green, or Blue”. *Annual Review of Psychology* 45.451-485.

— & J. Gordon. 1997. “Constraining Color Categories: The Problem of the Baby and the Bath Water”. *Behavioral and Brain Sciences* 20.179-180.

—, J. Gordon, A. Hendrickson, L. Hainline, V. Dobson & E. LaBossiere. 1982. “The Retina of the Newborn Human Infant”. *Science* 217.265-267.

Adams, R. J. 1995. “Further Exploration of Human Neonatal Chromatic-achromatic Discrimination”. *Journal of Experimental Child Psychology* 60.344-360.

— & M. L. Courage. 1995. “Development of Chromatic Discrimination in Early infancy”. *Behavioural Brain Research* 67.99-101.

—, M. L. Courage & M. E. Mercer. 1994. “Systematic Measurement of Human Neonatal Color Vision”. *Vision Research* 34.1691-1701.

Alvarado, N. & K. A. Jameson. 2005. ”Confidence Judgments on Color Category Best Exemplars”. *Cross-Cultural Research* 39.134-158.

Androulaki, A. 2003. *Color Term Acquisition and the Development of Working Memory in Children: a Cross-linguistic Investigation and a Test of the Linguistic Relativity Hypothesis*. Ph.D. dissertation, University of Surrey.

Banks, M. S. & P. J. Bennett. 1988. “Optical and Photoreceptor Immaturities Limit the Spatial and Chromatic Vision of Human Neonates”. *Journal of the Optical Society of America, A* 5.2059-2079.

— & J. A. Crowell. 1993. “Front-end Limitations to Infant Spatial Vision: Examination of Two Analyses”. *Early Visual Development Normal and Abnormal* ed. by K. Simons, 91-116. New York: Oxford University Press.

Beare, A. C. 1963. “Color-name as a Function of Wave-length. *American Journal of Psychology* 76.248-256.

Behl-Chadha, G. 1996. “Basic-level and Superordinate-like Categorical Representations in Early Infancy. *Cognition* 60.105-141.

Berlin, B. & P. Kay. 1969. *Basic Color Terms: their Universality and Evolution*. Berkeley: University of California Press.

Billock, V. A., G. A. Gleason & B. H. Tsou. 2001. “Perception of Forbidden Colors in Retinally Stabilized Equiluminant Images: an Indication of Softwired Cortical Color Opponency?” *Journal of the Optical Society of America* 18.2398-2403.

Bomba, P. C. 1984. “The Development of Orientation Categories between 2 and 4 Months of Age”. *Journal of Experimental Child Psychology* 37.609-636.

— & E. R. Siqueland. 1983. “The Nature and Structure of Infant Form Categories”. *Journal of Experimental Child Psychology* 35.294-328.

Boothe, R., D. Y. Teller & G. P. Sackett. 1975. “Trichromacy in Normally Reared and Light Deprived Infant Monkeys”. *Vision Research* 15.1187-1191.

Bornstein, M. H. 1973. “Color Vision and Color Naming: a Psychophysiological Hypothesis of Cultural Difference”. *Psychological Bulletin* 80.257-285.

—. 1976. “Infants are Trichromats”. *Journal of Experimental Child Psychology* 21.425-445.

—. 1980. *Comparative Methods in Psychology*. Hillsdale: Lawrence Erlbaum Associates.

—. 1981. “Psychological Studies of Color Perception in Human Infants: Habituation, Discrimination and Categorization, Recognition, and Conceptualization”. *Advances in Infancy Research* ed. by L. P. Lipsitt, vol. 1, 1-40. Norwood: Ablex.

—. 1984. “A Descriptive Taxonomy of Psychological Categories Used by Infants”. *Origins of Cognitive Skills* ed. by C. Sophian, 313-338. Hillsdale: Lawrence Erlbaum Associates.

—. 1987. “Perceptual Categories in Vision and Audition”. *Categorical Perception: the Groundwork of Cognition* ed. by S. Harnad, 287-300. Cambridge, Mass.: Cambridge University Press.

—. 2006. “Hue Categorization and Color Naming: Cognition to Language to Culture”. *Anthropology of Color: Interdisciplinary Multilevel Modeling* ed. by R. E. MacLaury, G. V. Paramei & D. Dedrick. Amsterdam & Philadelphia: John Benjamins.

— & M. E. Arterberry. 2003. ”Recognition, Discrimination and Categorization of Smiling by 5-month-old Infants”. *Developmental Science* 6.585-599.

—, W. Kessen & S. Weiskopf. 1976a. “The Categories of Hue in Infancy”. *Science* 191.201-202.

—, W. Kessen & S. Weiskopf. 1976b. “Color Vision and Hue Categorization in Young Human Infants”. *Journal of Experimental Psychology: Human Perception and Performance* 2.115-129.

— & N. O. Korda. 1984. ”Discrimination and Matching Within and Between Hues Measured by Reaction Times: Some Implications for Categorical Perception and Levels of Information Processing”. *Psychological Research* 46.207-222.

— & M. D. Monroe. 1980. ”Chromatic Information Processing: Rate Depends on Stimulus Location in the Category and Psychological Complexity”. *Psychological Research* 42.213-225.

Bowmaker, J. K., L. A. Heath, S. E. Wilkie & D. M. Hunt. 1997. “Visual Pigments and Oil Droplets from Six Classes of Photoreceptor in the Retinas of Birds”. *Vision Research* 37.2183-2194.

Boynton, R. M. 1971. “Color Vision”. *Woodworth and Schlosberg’s Experimental Psychology* ed. by L. A. Riggs & J. Kling, 315-368. New York: Holt, Rinehart and Winston.

—, L. Fargo, C. X. Olson & H. S. Smallman. 1989. “Category Effects in Color Memory”. *Color Research and Application* 14.229-234.

— & J. Gordon. 1965. “Bezold-Brücke Hue Shift Measured by Color-naming Technique”. *Journal of the Optical Society of America* 55.78-86.

—, R. E. MacLaury & K. Uchikawa. 1989. “Centroids of Color Categories Compared by Two Methods”. *Color Research and Application* 14.6-15.

— & C. X. Olson. 1990. “Salience of Chromatic Basic Color Terms Confirmed by Three Measures”. *Vision Research* 30.1311-1317.

—, W. Schaefer & M. E. Nuen. 1964. “Hue-wavelength Relation Measured by Color-naming Method for Three Retinal Locations”. *Science* 146.666-668.

Broackes, J. 1997. “Could We Take Lime, Purple, Orange, and Teal as Unique Hues?” *Behavioral and Brain Sciences* 20.183-184.

Brown, A. M. 1990. “Development of Visual Sensitivity to Light and Color Vision in Human Infants: a Critical Review”. *Vision Research* 30.1159-1188.

—. 1993. “Intrinsic Noise and Infant Visual Performance”. *Early Visual Development Normal and Abnormal* ed. by K. Simons, 178-196. New York: Oxford University Press.

—, D. T. Lindsey, E. M. McSweeney & M. M. Walters. 1995. “Infant Luminance and Chromatic Contrast Sensitivity: Optokinetic Nystagmus Data on 3-month-olds”. *Vision Research* 35.3145-3160.

— & D. Y. Teller. 1989. “Color Opponency in Human Infants”. *Vision Research* 29.37-45.

Burns, S. A., E. A. Elsner, J. Pokorny & V. C. Smith. 1984. “The Abney Effect: Chromaticity Coordinates of Unique and Other Constant Hues”. *Vision Research* 24.479-489.

Burr, D. C., C. M. Morrone & A. Fiorentini. 1996. “Spatial and Temporal Properties of Infant Colour Vision”. *Infant Vision* ed. by F. Vital-Durand, J. Atkinson & Oliver J. Braddick. (= *The European Brain and Behaviour Society Publication Series*, 2), 63-77. Oxford: Oxford University Press.

Byrne, A. & D. R. Hilbert. 2003. “Color Realism and Color Science”. *Behavioral and Brain Sciences* 26.3-63.

Catherwood, D. 1994. “Exploring the Seminal Phase in Infant Memory for Color and Shape”. *Infant Behavior and Development* 17.235-243.

—, B. Crassini & K. Freiberg. 1987. “The Nature of Infant Memory for Hue”. *British Journal of Developmental Psychology* 5.385-394.

—, B. Crassini & K. Freiberg. 1989. “Infant Response to Stimuli of Similar Hue and Dissimilar Shape: Tracing the Origins of the Categorization of Objects by Hue”. *Child Development* 60.752-762.

—, B. Crassini & K. Freiberg. 1990. “The Course of Infant Memory for Hue”. *Australian Journal of Psychology* 42.277-285.

CIE. Commission Internationale de l’Éclairage. 1987. *International Lighting Vocabulary*. (= CIE Publication 17.4.) Geneva: Bureau Central de la Commission Electrotechnique Internationale.

Cohen, L. B. & B. A. Younger. 1984. “Infant Perception of Angular Relations”. *Infant Behavior and Development* 7.37-47.

Daoutis, C. A., A. Franklin, A. Riddett, A. Clifford & I. R. L. Davies. (in press). “Categorical Effects in Children’s Color Search: a Cross-linguistic Comparison”. *British Journal of Developmental Psychology.*

—, M. Pilling & I. R. L. Davies. (manuscript submitted). “Categorical Effects in Visual Search for Color”.

Davidoff, J. B. 1991. *Cognition through Color*. Cambridge, Mass.: MIT Press.

Deeb, S. S., A. L. Jorgensen, L. Battisti, L. Iwasaki & A. G. Motulsky. 1994. ”Sequence Divergence of the Red and Green Visual Pigments in Great Apes and Humans”. *Proceedings of the National Academy of Sciences* 91.7262-7266.

Dedrick, D. 1996. “Color Language Universality and Evolution: On the Explanation for Basic Color Terms. *Philosophical Psychology* 9.497-524.

DeValois, R. L. 1973. “Central Mechanisms of Color Vision”. *Handbook of Sensory Physiology* ed. by R. Jung, vol. 7:3, 209-253. New York: Springer.

—, I. Abramov & G. H. Jacobs. 1966. “Analysis of Response Patterns to LGN Cells”. *Journal of the Optical Society of America* 56.966-977.

— & K. K. De Valois. 1993. “A Multi-stage Color Model”. *Vision Research* 33.1053-1065.

— & K. K. De Valois. 1996. “A Three-stage Color Model-comment”. *Vision Research* 36.833-836.

Dobkins, K. R. & C. M. Anderson. 2002. “Color-based Motion Processing is Stronger in Infants than in Adults”. *Psychological Science* 13.76-80.

—, C. M. Anderson & J. Kelly. 2001. “Development of Psychophysically-derived Detection Contours in L- and M-cone Contrast Space”. *Vision*

Research 41.1791-1807.

Dulai, K. S., J. K. Bowmaker, J. D. Mollon & D. M. Hunt. 1994. “Sequence Divergence, Polymorphism and Evolution of Middle-wave and Long-wave Visual Pigment Genes of Great Apes and Old World Monkeys”. *Vision Research* 34.2483-2491.

Eimas, P. D., E. R. Siqueland, P. Jusczyck & J. Vigorito. 1971. “Speech Perception in Infants”. *Science* 171.303-306.

Ekman, G. 1954. “Dimensions of Color Vision”. *Journal of Psychology* 38.467-474.

—. 1963. “Contributions to the Psychophysics of Color Vision”. *Studium Generale* 16.54-64.

Franklin, A., A. Clifford, E. Williamson & I. R. L. Davies. 2005. “Color Term Knowledge Does Not Affect Categorical Perception of Color in Toddlers”. *Journal of Experimental Child Psychology* 90.114-141.

— & I. R. L. Davies. 2004. “New Evidence for Infant Colour Categories”. *British Journal of Developmental Psychology* 22.349-377.

—, Emre Özgen, Rachel Drew & Ian R. L. Davies. In prep. “Toddlers’ Hue Discrimination Thresholds Show Category Effects even before Colour Term Acquisition”.

—, M. Pilling & I. Davies. 2005. “The Nature of Infant Color Categorization: Evidence from Eye Movements on a Target Detection Task”. *Journal of Experimental Child Psychology* 91.227-248.

Gegenfurtner, K. R. & D. C. Kiper. 2003. “Color Vision”. *Annual Review of Neuroscience* 26.181-206.

Gordon, J., I. Abramov & H. Chan. 1994. “Describing Color Appearance: Hue and Saturation Scaling”. *Perception and Psychophysics* 56.27-41.

Grether, W. F. 1940a. “Chimpanzee Color Vision, I: Hue Discrimination at Three Spectral Points”. *Journal of Comparative and Physiological Psychology* 29.167-177.

—. 1940b. “A Comparison of Human and Chimpanzee Spectral Hue Discrimination Curves”. *Journal of Experimental Psychology* 28.419-427.

—. 1942. “The Magnitude of Simultaneous Color Contrast and Simultaneous Brightness Contrast for Chimpanzee and Man”. *Journal of Experimental Psychology* 30.69-83.

Guest, S. & D. Van Laar. 2000. “The Structure of Colour Naming Space”. *Vision Research* 40.723-734.

— & D. Van Laar. 2002. “The Effect of Name Category and Discriminability on the Search Characteristics of Color Sets”. *Perception* 31.445-461.

Hall, A. R. & M. B. Hall, eds. and trans. 1962. *Unpublished Scientific Papers of Isaac Newton*. Cambridge: Cambridge University Press.

Halsey, R. M. & A. Chapanis. 1951. “On the Number of Absolutely Identifiable Spectral Hues”. *Journal of the Optical Society of America* 41.1057-1058.

Harnad, S. 1987. “Psychophysical and Cognitive Aspects of Categorical Perception: a Critical Overview”. *Categorical Perception: the Groundwork of Cognition* ed. by S. Harnard, 29-52. New York: Cambridge University Press.

Hayne, H. 1996. **“**Categorization in Infancy”. *Advances in Infancy Research* ed. by C. Rovee-Collier & L. P. Lipsitt, vol. 10, 79-120. Westport, Conn.: Ablex Publishing.

Hendrickson, A. E. 1994. “Primate Foveal Development: a Microcosm of Current Questions in Neurobiology”. *Investigative Ophthalmology and Visual Science* 35.3129-3133.

Hernandez-Reif, M. & L. E. Bahrick. 2001. “The Development of Visual-tactual Perception of Objects: a Modal Relations Provide the Basis for Learning Arbitrary Relations”. *Infancy* 2.51-72.

Hochberg, J. 1978. *Perception*. Englewood Cliffs, N.J.: Prentice-Hall.

Hooke, Robert. 1665. *Micrographia, Or, Some Physiological Descriptions of Minute Bodies Made by Magnifying Glasses with Observations and Inquiries Thereupon*. London: J. Martyn & J. Allestry.

Houstoun, R. A. 1917-1918. “Newton and the Colors of the Spectrum”. *Science Progress* 12.250-264.

Hurvich, L. M. 1981. *Color Vision*. Sunderland, Mass.: Sinauer Associates.

Ingling, C. R. 1997. “Constraints on the Definitions of ‘Unique Hues’ and ‘Opponent Channels’”. *Behavioral and Brain Sciences* 20.194-195.

Jacobs, G. H. 1981. *Comparative Color Vision*. New York: Academic Press.

—. 1993. “The Distribution and Nature of Colour Vision among the Mammals”. *Biological Review* 68.413-471.

Jameson, K. A. 1997. “What Saunders and van Brakel Chose to Ignore in Color and Cognition Research”. *Behavioral and Brain Sciences* 20.195-196.

— & R. G. D’Andrade. 1997. “It’s Not Really Red, Green, Yellow, Blue: an Inquiry into Perceptual Color Space”. *Color Categories in Thought and Language* ed. by C. L. Hardin & L. Maffi, 295-319. New York: Cambridge University Press.

— & L. M. Hurvich. 1955. “Some Quantitative Aspects of an Opponent-colors Theory, I: Chromatic Responses and Spectral Saturation”. *Journal of the Optical Society of America* 45.546-552.

Kaplan, E., R. M. Shapley & K. Purpura. 1998. “Color and Luminance Contrast as Tools for Probing the Primate Retina”. *Neuroscience Research* 8.S151-S165.

Kay, P. 2005. “Color Categories Are Not Arbitrary”. *Cross-cultural Research* 39.39-55.

— & B. Berlin. 1997. “Science and Imperialism: There are Nontrivial Constraints on Color Naming”. *Behavioral and Brain Sciences* 20.196-201.

—, B. Berlin & W. R. Merrifield. 1991. “Biocultural Implications of Systems of Color Naming”. *Journal of Linguistic Anthropology* 1.12-25.

— & W. Kempton. 1984. “What is the Sapir-Whorf Hypothesis?” *American Anthropologist* 86.65-79.

— & C. K. McDaniel. 1978. “The Linguistic Significance of the Meanings of Basic Color Terms”. *Language* 54.610-646.

— & T. Regier. 2003. “Resolving the Question of Color Naming Universals”. *Proceedings of the National Academy of Sciences* 100.9085-9089.

Kestenbaum, R. & C. A. Nelson. 1990. “The Recognition and Categorization of Upright and Inverted Emotional Expressions by 7-month-old Infants”. *Infant Behavior and Development* 13.497-511.

Knoblauch, K., M. L. Bieber & J. S. Werner. 1998. “M- and L-cones in Early Infancy, I: VEP Responses to Receptor-isolating Stimuli at 4- and 8-weeks of Age”. *Vision Research* 38.1753-1764.

Krantz, D. H. 1975. “Color Measurement and Color Theory, II: Opponent Color Theory”. *Journal of Mathematical Psychology* 12.304-312.

Krauskopf, J., D. R. Williams & D. W. Heeley. 1982. “Cardinal Directions in Color Space”. *Vision Research* 22.1123-1131.

Lashley, K. S. & M. Wade. 1946. “The Pavlovian Theory of Generalization”. *Psychological Review* 53.72-87.

Laws, G., I. Davies & C. Andrews. 1995. “Linguistic Structure and Non-linguistic Cognition: English and Russian Blues Compared”. *Language and Cognitive Processes* 10.59-94.

Leinbach, M. D. & B. I. Fagot. 1993. “Categorical Habituation to Male and Female Faces: Gender Schematic Processing in Infancy”. *Infant Behavior and Development* 16.317-332.

Lenneberg, E. H. 1967. *Biological Foundations of Language*. Oxford: Wiley.

Lennie, P. & M. D’Zmura. 1988. “Mechanisms of Colour Vision”. *CRC Critical Reviews in Neurobiology* 3.333-400.

Levinson, S. C. 2000. “Yélî Dnye and the Theory of Basic Color Terms”. *Journal of Linguistic Anthropology* 10.3-55.

MacLaury, R. E. 1997. *Color and Cognition in Mesoamerica*. Austin: University of Texas Press.

Matsuno, T., N. Kawai & T. Matsuzawa. 2004. “Color Classification by Chimpanzees (*Pan troglodytes*) in a Matching-to-sample Task”. *Behavioural Brain Research* 148.157-165.

Matsuzawa, T. 1985. “Colour Naming and Classification in a Chimpanzee (*Pan troglodytes*)”. *Journal of Human Evolution* 14.283-291.

Mehler, J., E. Dupoux, T. Nazzi & G. Dehaene-Lambertz. 1996. “Coping with Linguistic Diversity: the Infant’s Viewpoint”. *Signal to Syntax: Bootstrapping from Speech to Grammar in Early Acquisition* ed. by J. L. Morgan & K. Demuth, 101-116. Hillsdale, N.J.: Lawrence Erlbaum Associates.

Melkman, R., B. Tversky & D. Baratz. 1981. “Developmental Trends in the Use of Perceptual and Conceptual Attributes in Grouping, Clustering and Retrieval”. *Journal of Experimental Child Psychology* 31.470-486.

Menzel, R. 1979. “Spectral Sensitivity and Color Vision in Invertebrates”. *Handbook of Sensory Physiology* ed. by H. Autrum, vol. VII:6A, 503-580. Berlin: Springer-Verlag.

Mercer M. E., M. L. Courage & R. J. Adams. 1991. “Contrast/color Card Procedure: a New Test of Young Infants’ Color Vision”. *Optometry and Vision Science* 68.522-532.

Mervis, C. B. & E. Rosch. 1981. “Categorization of Natural Objects”. *Annual Review of Psychology* 32.89-115.

Miller, G. A. & P. N. Johnson-Laird. 1976. *Language and Perception*. Cambridge, Mass.: Harvard University Press.

Mollon, J. D. 1989. “‘Tho’ she Kneel’d in the Place Where they Grew...’: the Uses and Origins of Primate Colour Vision”. *Journal of Experimental Biology* 146.21-38.

—. 1995. “Seeing Colour”. *Colour: Art and Science* ed. by T. Lamb & J. Bourriau, 127-150. Cambridge: Cambridge University Press.

Newton, I. 1671-1672. “New Theory About Light and Colours”. *Philosophical Transactions of the Royal Society* 80.3075-3087.

—. [1730] 1952. *Opticks: Or a Treatise of the Reflections, Refractions, Inflections and Colours of Light*. New York: Dover Publications.

Nickerson, D. & S. M. Newhall. 1943. “A Psychological Color Solid”. *Journal of the Optical Society of America* 33.419-422.

Offenbach, S. I. 1980. “Children’s Perception of Munsell Colors”. *The Journal of Psychology* 104.43-51.

Okajima, K., A. R. Robertson & G. H. Fielder. 2002. “A Quantitative Network Model for Color Categorization”. *Color Research and Application* 27.225-232.

Özgen, E. 2004. “Language, Learning, and Color Perception”. *Current Directions in Psychological Science* 13.95-98.

Pastore, R. E. 1987. “Categorical Perception: Some Psychophysical Models”. *Categorical Perception: the Groundwork of Cognition* ed. by S. Harnad, 29-52. Cambridge: Cambridge University Press.

Peeples, D. R. & D. Y. Teller. 1975. “Color Vision and Brightness Discrimination in Two-month-old Human Infants”. *Science* 189.1102-1103.

Pilling, M., A. Wiggett, E. Özgen & I. R. L. Davies. 2003. “Is Color ‘Categorical Perception’ Really Perceptual?” *Memory and Cognition* 31.538-551.

Quinn, P. C. 1994. “The Categorization of Above and Below Spatial Relations by Young Infants”. *Child Development* 65.58-69.

—. 1999. “Development of Recognition and Categorization of Objects and their Spatial Relations in Young Infants”. *Child Psychology: a Handbook of Contemporary Issues* ed. by L. Balter & C. S. Tamis-LeMonda, 85-115. Philadelphia, Pa.: Psychology Press.

— & P. D. Eimas. 1996. “Perceptual Organization and Categorization in Young Infants”. *Advances in Infancy Research* ed. by C. Rovee-Collier & L. P. Lipsitt, vol. 10, 1-36. Norwood, N.J.: Ablex.

—, E. R. Siqueland & P. C. Bomba. 1985. “Delayed Recognition Memory for Orientation by Human Infants”. *Journal of Experimental Child Psychology* 40.293-303.

Rakison, D. H. & L. M. Oakes, eds. 2003. *Early Category and Concept Development: Making Sense of the Blooming, Buzzing Confusion*. London: Oxford University Press.

Ratliff, F. 1976. “On the Psychophysiological Bases of Universal Color Terms”. *Proceedings of the American Philosophical Society* 120.311-330.

Roberson, D. & Davidoff, J. 2000. “The Categorical Perception of Colors and Facial Expressions: the Effect of Verbal Interference”. *Memory and Cognition* 28.977-986.

—, J. Davidoff & N. Braisby. 1999. “Similarity and Categorization: Neuropsychological Evidence for Dissociation in Explicit Categorization Tasks”. *Cognition* 71.1-42.

Rosch, E. 1978. “Principles of Categorization”. *Cognition and Categorization* ed. by E. Rosch & B. Lloyd, 27-48. Hillsdale, N.J.: Erlbaum Associates.

Rose, D. H. & A. M. Slater. 1983. “Infant Recognition Memory Following Brief Stimulus Exposure”. *British Journal of Developmental Psychology* 1.221-230.

Sandell, J. H., C. G. Gross & M. H. Bornstein. 1979. “Color Categories in Macaques”. *Journal of Comparative and Physiological Psychology* 93.626-635.

Saunders, B. A. C. & J. van Brakel. 1995. “Translating the *World Color Survey*”. *Post-modernism and Anthropology: Theory and Practice* ed. by K. Geuijen, D. Raven & J. de Wolf, 161-178. Assen: van Gorcum.

Schefrin, B. E. & J. S. Werner. 1990. “Loci of Spectral Unique Hues Throughout the Lifespan”. *Journal of the Optical Society of America* 7.305-311.

Segall, M. H., P. R. Dasen, J. W. Berry & Y. H. Poortinga. 1990. *Human Behavior in Global Perspective: an Introduction to Cross-cultural Psychology*. Oxford: Pergamon Press.

Shapley, R. M. 1990. “Visual Sensitivity and Parallel Retinocortical Channels”. *Annual Review of Psychology* 41.635-658.

Sherman, T. 1985. “Categorization Skills in Infants”. *Child Development* 56.1561-1573.

Simpson, C. 1991. “Color Perception: Cross-cultural Linguistic Translation and Relativism”. *Journal for the Theory of Social Behavior* 21.409-430.

Smith, D. P. 1971. “Derivation of Wavelength Discrimination from Color-naming Data”. *Vision Research* 11.739-742.

Smith, E. E. & D. I. Medin. 1981. *Categories and Concepts*. Cambridge, Mass.: Harvard University Press.

Stanlaw, J. 1997. “Two Observations on Culture Contact and the Japanese Color Nomenclature System”. *Color Categories in Thought and Language* ed. by C. L. Hardin & L. Maffi, 240-260. New York: Cambridge University Press.

Sternheim, C. E. & R. M. Boynton. 1966. “Uniqueness of Perceived Hues Investigated with a Continuous Judgmental Technique”. *Journal of Experimental Psychology* 72.770-776.

Teller, D. Y. 1998. “Spatial and Temporal Aspects of Infant Color Vision”. *Vision Research* 38.3275-3282.

—, D. R. Peeples & M. Sekel. 1978. “Discrimination of Chromatic from White Light by Two-month-old Human Infants”. *Vision Research* 18.41-48.

Thomasson, M. A. & D. Y. Teller. 2000. “Infant Color Vision: Sharp Chromatic Edges Are Not Required for Chromatic Discrimination in 4-month-olds”. *Vision Research* 40.1051-1057.

Uchikawa, K. & H. Shinoda. 1996. “Influence of Basic Color Categories on Color Memory Discrimination”. *Color Research and Application* 21.430-439.

Valberg, A. 2001. “Unique Hues: an Old Problem for a New Generation”. *Vision Research* 41.1645-1657.

Van Laar, D. 1997. “Ekphrasis in Colour Categorisation: Time for Research, or Time for Revolution?” *Behavioral and Brain Sciences* 20.210.

von Frisch, K. 1964. *Bees: their Vision, Chemical Senses, and Language*. Ithaca, N.Y.: Cornell University Press.

Werner, J. S. & M. L. Bieber. 1997. ”Hue Opponency: a Constraint of Colour Categorization Known from Experience and Experiment”. *Behavioral and Brain Sciences* 20.210-211.

— & B. E. Schefrin. 1993. “Loci of Achromatic Points Throughout the Life Span”. *Journal of the Optical Society of America* 10.1509-1516.

Wooten, B. R. & D. L. Miller. 1997. “The Psychophysics of Color”. *Color Categories in Thought and Language* ed. by C. L. Hardin, 59-88. Cambridge: Cambridge University Press.

Wright, A. A. 1972. “Psychometric and Psychophysical Hue Discrimination Functions for the Pigeon”. *Vision Research* 12.1447-1464.

— & W. W. Cumming. 1971. “Color-naming Functions for the Pigeon”. *Journal of the Experimental Analysis of Behavior* 15.7-17.

Wright, W. D. 1947. *Researches on Normal and Defective Colour Vision*. St Louis: C. V. Mosby.

Wyszecki, G. & W. S. Stiles. 1982. *Color Science*. 2nd edn New York: Wiley.

Yendrikhovskij, S. N. 2001. “Computing Color Categories from Statistics of Natural Images”. *Journal of Imaging Science and Technology* 45.409-417.

Younger, B. A. 1985. “The Segregation of Items into Categories by Ten-month-old Infants”. *Child Development* 56.1574-1583.

—. 1990. “Infants’ Detection of Correlations among Feature Categories”. *Child Development* 61.614-620.

—. 1992. “Developmental Change in Infant Categorization: the Perception of Correlations among Facial Features”. *Child Development* 63.1526-1535.

— & L. B. Cohen. 1983. “Infant Perception of Correlations among Attributes”. *Child Development* 54.858-869.

— & S. Gotlieb. 1988. “Development of Categorization Skills: Changes in the Nature or Structure of Infant Form Categories?” *Developmental Psychology* 24.611-619.

Yuodelis, C. & A. Hendrickson. 1986. “A Qualitative and Quantitative Analysis of the Human Fovea during Development”. *Vision Research* 26.847-855.

Zeaman, D. & P. Hanley. 1983. “Stimulus Preferences as Structural Features”. *Perception, Cognition and Development: Interactional Analyses* ed. by T. J. Tighe & B. E. Shepp, 103-238. Hillsdale, N.J.: Erlbaum Associates.

Zegura, S. L. 1997. “Color Categories and Biology: Considerations from Molecular Genetics, Neurobiology, and Evolutionary Theory”. *Behavioral and Brain Sciences* 20.211-212.

INFANT COLOR PERCEPTION
AND DISCRETE TRIAL PREFERENTIAL LOOKING PARADIGMS

DAVIDA Y. TELLER, MARIA PEREVERZEVA & IRIS K. ZEMACH
University of Washington, Seattle

1. *Introduction*

As parents have known for millennia, infants often stare at things, and they stare more persistently at some things than at others. In the laboratory (Staples 1932; Fantz 1958), such *preferential looking* behavior has been used for testing many aspects of infant vision and infant perception. Over the years, a variety of formalized preferential looking-based techniques have been developed, including the techniques of *spontaneous preference* (Fantz 1958; Fantz, Fagan & Miranda 1975; Teller 1979), *familiarization / novelty* (Fantz 1964; Fagan 1970; Olson 1976; Hunter & Ames 1988) and *cross-familiarization* (compare Slater, Mattock & Brown 1990; Dannemiller & Hanko 1987; Stephens & Banks 1985).

A discrete trial, forced-choice version of the spontaneous preference technique, called *forced-choice preferential looking*, or *FPL*, was introduced by our laboratory in the late 1970s (Teller 1979), and has been used for many studies of visual detection and discrimination thresholds (for reviews, see Simons 1993; Teller 1997). More recently, we have turned our attention to supra-threshold aspects of infant color vision. To that end, we have undertaken the development of discrete trial variants of spontaneous preference, familiarization / novelty and cross-familiarization techniques (compare Orlian & Rose 1997). In the course of this project, we have gradually come to clearer understandings of these techniques and the interrelationships among them.

The results of experiments on infant color perception can be interpreted at two different levels. For example, suppose one carries out a systematic study of the effects of stimulus parameters such as dominant wavelength, purity, and luminance on infants' looking preferences. How should the results be described? The simpler option is to take a behavioral perspective, and describe the results in terms of the effects of stimulus parameters. We might find, for example, that, of the three parameters, stimulus purity is most closely correlated with infants' spontaneous preferences.

Alternatively, one can take a perceptual perspective, and attempt to draw inferences about the effects of the classical adult perceptual dimensions of hue, saturation, and / or brightness. We might find, for example, that infants' spontaneous preferences are more closely correlated with adult saturation judgments than with any physical dimension or any other perceptual dimension. In this case, it is tempting to assume that infants' perception of saturation is a lot like that of adults, and to conclude that perceived saturation is the biggest controlling factor in determining infant preferences. Of course, interpretations in terms of perceptual dimensions are always more speculative, but we accept this conceptual down-side because, at least for us, it is the perceptual question that drives the research in the first place.

The purpose of the present paper is twofold. First, we describe our discrete trial preferential looking techniques in such a way as to emphasize the formal interrelationships among them. And second, we describe some of our initial experiments, in which these techniques and various combinations of them have been used in attempts to study some of the supra-threshold aspects of infant color vision. For each experiment, both behavioral and perceptual interpretations will be discussed. As will become obvious, these early experiments have not always been perfect by our current standards, nor have they always yielded the desired outcomes; but it is our hope that these excursions will inspire others to explore this approach to studies of infant color vision.

2. *Three discrete-trial preferential looking techniques*

A schematic of a typical stimulus display used in measuring spontaneous preferences is shown in Figure 1. In this figure, two test stimuli, A and B, are embedded in a surround, X. The infant is held in front of the display. An adult observer who is blind to stimulus location views the infant's eye movements and staring behavior through a peephole or a video system. In the discrete trial variants of preferential looking with which we will be concerned in this chapter, trials last only a few seconds, and the observer's task is to judge, on each trial, at which side of the display the infant prefers to look. The dependent variable in a spontaneous preference experiment will be taken to be *P(A), the percent of trials on which the infant is judged to prefer test stimulus A.*

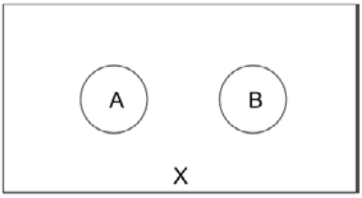


Figure 1: *The basic stimulus display used in preferential looking experiments. Two test stimuli, A and B, are embedded in a surround, X.*

Clearly, many different stimulus parameters of interest to color scientists will influence P(A). In particular, P(A) is likely to vary with the color of the second test stimulus (B, C, D, etc) and with the color of the surround (X, Y, Z, etc). It is also likely to vary with the prior history of familiarization (exposure) to A and / or B in surround X; and the prior history of exposure to other stimulus configurations, such as A and / or B in surround Y (or, in principle, any other stimulus configuration). The effects of the first two of these stimulus variations can be explored with spontaneous preference techniques; the third with familiarization / novelty techniques; and the fourth with cross-familiarization. These options potentially provide approaches for exploring, for example, the relative importance of hue, brightness and saturation to spontaneous preferences, and the phenomenon of simultaneous color contrast (see below).

Discrete trial variants of these three different techniques are shown schematically in Figure 2. The vertical columns show the three techniques: spontaneous preference at the left, familiarization / novelty in the two panels in the middle, and cross-familiarization at the right. The two horizontal rows show the two parts of each forced-choice trial: the *familiarization phase* in the upper row, and the *test phase* in the lower row. Importantly, in the test phase, both the stimulus display and the dependent variable are the same in all three techniques: a display of test stimuli A and B in the surround X, and a measurement of P(A).

The differences among the three techniques lie in the familiarization phase. In the spontaneous preference technique, the basic test display (A and B embedded in X) is used. Either there is no familiarization phase, or, as in the schematic, a blank field is used, in order to equate the timing across techniques (Civan, Teller & Palmer 2005). In the familiarization / novelty technique, the familiarization phase of each trial consists of duplicates of the same familiarization stimulus (either A,A or B,B) on the two sides of the display,

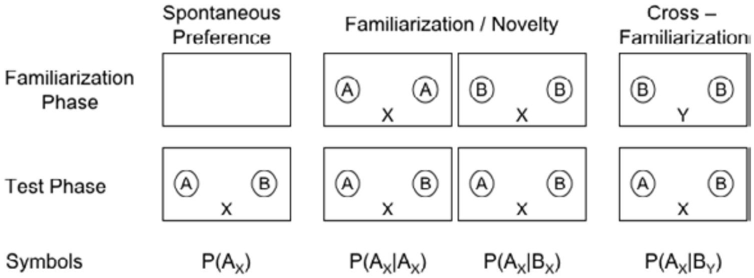


Figure 2: *Three discrete trial preferential looking techniques. The three columns show the three techniques: spontaneous preference on the left, familiarization / novelty in the double column in the middle, and cross-familiarization on the right. The two horizontal rows show the structure of each trial: the familiarization phase in the upper row, and the test phase in the lower row. Note that the stimulus display in the test phase is the same across all three techniques. The notation we use to refer to the results of each experiment is shown at the bottom of each column.*

embedded in X. And, in the cross-familiarization technique, some other aspect of the familiarizing stimulus is changed. In most of our experiments to date, the only change has been that the surround is changed from X to Y, in such a way as to pit specific pairs of perceptual hypotheses against each other (Chien, Palmer, & Teller 2003; 2005).

Both the familiarization / novelty and cross-familiarization techniques depend on the fact that infants show very reliable novelty effects (Fantz 1964; Fagan 1970; Welch 1974; Cohen & Gelber 1975; Hunter & Ames 1988). Classically, a novelty effect is defined as an increase in the preference for A after familiarization to B, and / or an increase in the preference for B after familiarization to A. In the terminology we have adopted, however, the second of these novelty effects would be described instead as a *decrease in the preference for A after familiarization to A*. This change will initially be confusing to readers accustomed to the opposite definition; but it has the advantage that, whether familiarization is to A or to B, the dependent variable is always P(A).

3. *Notation*

In order to distinguish between the different techniques and stimulus conditions used, we have found the following notational system useful (compare Civan et al. 2005). In each case, capital letters stand for test stimuli, and subscripts for surrounds. For simplicity, the identity of the second stimulus, B, is omitted from the notation; it is understood that the second stimulus is B unless specified otherwise.

For spontaneous preferences, let

(1) $P(A) \equiv$ percent of trials on which the infant prefers test stimulus A, and

(2) $P(A_x) \equiv P(A)$ for test stimulus A in surround X.

For familiarization / novelty, let

(3) $P(A_x|A_x) \equiv P(A_x)$ after familiarization to A in X, and

(4) $P(A_x|B_x) \equiv P(A_x)$ after familiarization to B in X.

For cross-familiarization, let

(5) $P(A_x|B_y) \equiv P(A_x)$ after cross-familiarization to B in surround Y.

4. ***Joint use of techniques***

Any one of these techniques can be used alone, but it can also be advantageous to use two (Civan et al. 2005) or all three together (Pereverzeva, in progress). Figure 3 shows the paradigm that results when all three techniques are used together. Four measurements are made, so there are four dependent variables in the experiment. The data shown are hypothetical.

The leftmost panel shows the results of a spontaneous preference experiment – a measure of the first dependent variable, the spontaneous preference $P(A_x)$. The two panels in the middle show the results of a pair of familiarization/novelty experiments, and the graphs show measures of the second and third dependent variables $P(A_x|A_x)$ and $P(A_x|B_x)$ respectively. It is assumed that there are reliable novelty effects, so that $P(A_x|A_x) < P(A_x)$, and $P(A_x|B_x) > P(A_x)$. The three rightmost panels show three possible results of a cross-familiarization experiment – a measure of the fourth dependent variable, $P(A_x|B_y)$. Of particular interest is the comparison of $P(A_x|B_y)$ – the cross-familiarized preference – to the other three variables.

The top right panel shows the case in which $P(A_x|B_y) = P(A_x|B_x)$. In this case, behaviorally, the change in the surround from Y to X had no effect. That is, familiarization to test stimulus B in surround Y, and familiarization to test stimulus B in surround X had the same effect on the preference for A. In perceptual terms, the most likely interpretation is that the change of surround from X to Y does not affect the infant’s perception of B, or that *B in Y looks the same as B in X*.

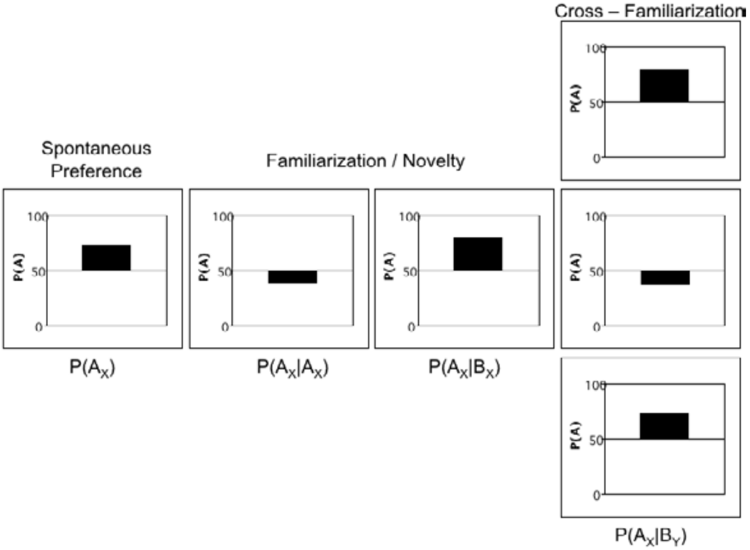


Figure 3: *A hypothetical example of the kinds of results that can be obtained from the three methods. In all cases P(A), the percent of trials on which stimulus A was preferred, is plotted on the ordinate. The leftmost panel represents a spontaneous preference experiment; the dependent variable is $P(A_x)$. The two middle panels represent the two conditions of a familiarization / novelty experiment; the dependent variables are $P(A_x|A_x)$ and $P(A_x|B_x)$ respectively. The three panels at the right represent three possible outcomes for a cross-familiarization experiment; the dependent variable is $P(A_x|B_y)$. Of interest is whether $P(A_x|B_y)$ most closely resembles $P(A_x|B_x)$, $P(A_x|A_x)$, or $P(A_x)$.*

The middle panel shows the case in which $P(A_x|B_y) = P(A_x|A_x)$. That is, behaviorally, familiarization to test stimulus B in surround Y and familiarization to test stimulus A in surround X had the same effect on the preference for A. The perceptual interpretation for this result would be that *B in Y looks the same as A in X*.

The bottom panel shows the case in which $P(A_x|B_y) = P(A_x)$. That is, behaviorally, familiarization to test stimulus B in surround Y has no effect on the infant's preference for test stimulus A: the familiarized preference equals the spontaneous preference. Perceptually, this result suggests that *B in Y has an intermediate appearance between B in X and A in X*. Moreover, various intermediate values could be taken to indicate the relative perceptual similarity between B in Y and B versus A in X.

Unfortunately, however, intermediate values of $P(A_x|B_y)$ are undesirable outcomes, because a variety of other interpretations are possible. For example, it could be that B in Y just looks too different from B in X, and there is little cross-familiarization because there is simply no perceptual or cognitive connection between B in Y and A in X for the infant.

We now turn to the use of spontaneous preference, familiarization / novelty, and cross-familiarization techniques, and combinations of them, in experiments in infant color perception.

5. *Experiments in infant color perception*

5.1 *General methods*

Unless stated otherwise, stimuli were displayed on black-and-white or color video display systems. The overall size of the stimulus displays was about 40 x 70 degrees. Test stimuli were disks about 10 degrees in diameter, located about 15 degrees to the left and right of the center of the display. The durations of familiarization and test phases of each trial were a few seconds each.

In describing the stimuli, the terms *CIE white* and *CIE white point* will be used interchangeably to refer to a stimulus with CIE 1931 (x,y) chromaticity coordinates of (0.33, 0.33). The color names *red, blue* and *green* will be used to refer to test stimuli composed of the red, green and blue video phosphors at 100% instrument purity. In describing perceived colors, color names such as *perceived white* or *perceived red* are used when necessary. It is hoped that the two different meanings of color terms will be clear in context.

All infants were either 3 or 4 months of age. In most experiments, an individual infant was tested in only a single condition, and groups of ten or more infants were tested in each condition. Adult subjects were always tested in the same apparatus used to test infants, under closely similar conditions. As will be seen below, data from adult subjects were used to select stimuli for use with infants, and / or to guide the interpretation of the infants' data.

5.2 *Simultaneous lightness contrast and lightness constancy*

The earliest uses of our discrete trial techniques concerned simultaneous lightness contrast and lightness constancy. In these experiments, familiarization-novelty and cross-familiarization techniques were used to show that, for stimuli embedded in higher luminance surrounds, infants' preferences are largely controlled by the ratio of test stimulus luminance to surround luminance (Wallach 1948; Chien et al. 2003), and that infants and adults demonstrate the same small departures from Wallach's ratio rule (Chien et al. 2005). Moreover, under the most favorable stimulus conditions, infants can demonstrate lightness constancy (Chien 2004; Chien, Bronson-Castain, Palmer & Teller 2006).

An example of the use of cross-familiarization to explore infant lightness contrast (Chien et al. 2003) is shown in Figure 4. Two versions of the experiment are shown. In the left panels (Experiment 1), infants were first familiarized to two 6 cd/m^2 test stimuli in a 36 cd/m^2 surround. They were then tested with 2 and 6 cd/m^2 test stimuli in a 12 cd/m^2 surround. The change of surround luminance from 36 to 12 cd/m^2 between familiarization and test phases makes this a cross-familiarization experiment, in which two hypotheses about infant lightness perception are tested against each other. If perceived lightness depends upon test stimulus luminance, without regard to the luminance of the surround, the infant should find the 6 cd/m^2 stimulus familiar and the 2 cd/m^2 stimulus novel, and should prefer to look at the 2 cd/m^2 test stimulus. On the other hand, if perceived lightness depends on the luminance ratio between surround and test stimuli, the infant should find the 2 cd/m^2 test stimulus familiar and the 6 cd/m^2 stimulus novel, and should prefer to look at the 6 cd/m^2 test stimulus. In fact, the latter result was found. The right panels show the complementary experiment, which yielded the same result. Behaviorally, we conclude that infants, like adults, obey an approximate ratio rule; perceptually, we infer that, for infants as for adults, the perceived lightnesses of decremental test stimuli depend on surround / test ratios rather than on absolute luminances.

As will be seen by examining the published papers, these experiments do not conform exactly to the more recently formalized test paradigms shown in Figure 3. Nonetheless, these experiments demonstrate the successful use of cross-familiarization to probe important properties of infant lightness perception. These studies encouraged us to continue the development of discrete trial paradigms, and to apply them more broadly to studies of infant color perception.

5.3 *Spontaneous color preferences*

Our first color study, using the spontaneous preference technique, was motivated by the earlier observations of Bornstein (1975). Bornstein used the classical spontaneous looking times approach to study looking preferences among chromatic stimuli in 4-month-old infants. He used a set of eight isoluminant, narrow-wavelength-band test stimuli, paired each wavelength with each other wavelength, and measured the infant's average looking time for each

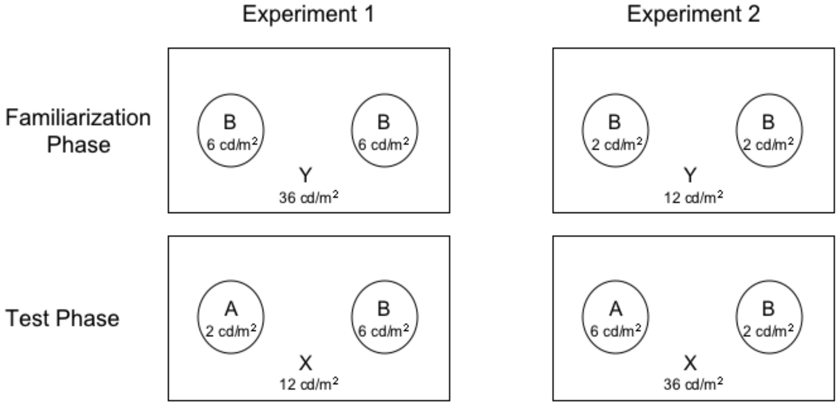


Figure 4: *Stimulus displays used in a study of infant lightness contrast using cross-familiarization. The luminances of the test stimuli and surrounds are shown on each panel. In this experiment, the surround luminance was changed between familiarization and test phases of each trial. In the two panels at the left, the surround luminance was decreased between familiarization and test phases; in the two panels at the right, it was increased. Note that the symbols A, B, X and Y are used with reference to the paradigms described in the section on notation, and do not correspond to the luminances of the stimuli.*

stimulus averaged across all pairs. In a second experiment, each stimulus was presented singly. In both cases, Bornstein found that isoluminant chromatic stimuli were not all equally preferred. Infants looked most at wavelengths from the spectral extremes – perceptually red and blue; and least at mid-spectral wavelengths – perceptually, blue-green, green and yellow-green.

In an attempt to replicate and extend this study using discrete trial techniques, we (Zemach, Chang & Teller, in preparation) investigated infants' spontaneous preferences between a standard white test stimulus, A, and each of 22 different chromatic stimuli, B, of varying dominant wavelength and colorimetric purity. The luminances of the test stimuli were fixed at 5 cd/m^2, and the test stimuli were embedded in a dim, 0.5 cd/m^2 white surround.

As shown in Figure 5, the test stimuli lay on ten different rays of constant dominant wavelength, emanating from the white point on the CIE 1931 chromaticity diagram. Three of these rays connected the white point to the red, green, and blue video phosphors. Three others were complimentary to the three video phosphors – nominally, yellow, blue-green and purple. Four additional stimuli – nominally reddish-yellow, greenish-yellow, green-blue-green and blue-blue-green – were added to improve the coverage of color space.

Figure 5 also shows the results of the experiment. For each chromatic stimulus, the size of the circle represents the infants' spontaneous preference for that stimulus over white, with increased circle sizes representing increased preference for the chromatic stimulus. Notice that, in this case, we plot the preference for the chromatic test stimulus, P(B) = 1 - P(A) rather than the preference for the fixed white stimulus, P(A).

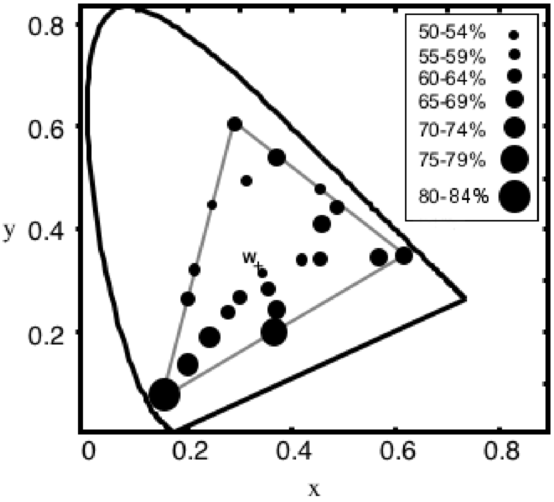


Figure 5: *Spontaneous preferences for 22 different chromatic stimuli. In each case, test stimulus A was at the CIE white point, with chromaticity coordinates of (0.33, 0.33), shown by the +. The locations of the filled circles represent the chromaticity coordinates of the 22 different chromatic stimuli, B. The size of each circle represents the infants' spontaneous preference, P(B) = 1 - P(A), for the chromatic stimulus B.*

At the behavioral level, there were two main findings. First, for each dominant wavelength, spontaneous preference for the chromatic stimulus generally increased with increasing purity (Adams 1987; Adams & Courage 1998), and the infant's least preferred stimulus lay at the CIE white point. Second, in general replication of Bornstein, at the maximum available purities, color preferences remained: blue and purple were preferred to all other stimuli.

At the perceptual level, how might these variations in infant chromatic preference be described? For adults, chromatic stimuli are classically described as varying along three perceptual dimensions: hue, brightness and saturation. Hue depends most closely on wavelength, brightness on luminance and saturation on purity. However, these variables interact; in particular, wavelength influences all three perceptual variables – brightness and saturation as well as hue (Wyszecki & Stiles 1982). The question then arises, can the variation of spontaneous preference seen in Figure 5 be taken to indicate preferences for stimuli of different *hues*; or might these variations come about solely because of the concomitant variations in brightness and / or saturation?

We carried out two supplementary experiments to address this question. First, we tested infants with stimuli matched in adult brightness rather than luminance, and showed that infants' preferences for reds, purples and blues persist even when brightnesses are matched (Teller, Civan & Bronson-Castain 2004). We conclude that brightness variations contribute little to infants' chromatic preferences. And second, we compared the infants' preferences with adult saturation judgments. Comparison with these data suggests that saturation contributes to infant preferences, but does not completely account for them. In particular, infants' preferences for high purity blues were greater than predicted from adult saturation judgments. In sum, although saturation probably has some effect, infants seem to have measurable residual preferences for stimuli of particular hues.

Notice that for white and chromatic stimuli selected along a ray of fixed dominant wavelength, infants behave as though they follow what one might call a Maximum Purity or Maximum Saturation looking rule. The behavioral version of this rule is: along each ray, look least at the CIE-defined white stimulus and most at the stimulus with the highest purity. The perceptual version is, look least at stimuli that look white, and most at stimuli that look most highly saturated. For simplicity, we will call these rules the Maximum Saturation rule below.

5.4 *Simultaneous chromatic contrast explored with spontaneous preferences*

Another classic phenomenon of adult color vision is simultaneous chromatic contrast – a change in the perceived color of a test field when the test field is embedded in a chromatic surround. To date, we have done three experiments aimed at the question of simultaneous color contrast in infants, with varying degrees of success.

In the first experiment, we asked whether and how infants' spontaneous preferences for test stimuli of different chromaticities change if the test stimuli are embedded in white versus chromatic surrounds (Pereverzeva & Teller 2004). For example, in one condition of the experiment, we explored the difference in the pattern of preferences for a set of three test stimuli of different purities, embedded in white versus red surrounds.

The stimuli are shown in Figure 6. The test stimuli were of slightly (0.1 log unit) lower luminance than their surrounds. The left panel of Figure 6 shows the chromaticities of the stimuli, with the surrounds being represented by rings and the test stimuli by solid circles. The test stimuli, T, lie along a ray connecting the chromaticities of the two surrounds. They include the two endpoints of the line – the white stimulus TW and the red stimulus TR. The third stimulus was TwR, a stimulus that, to adult observers tested *in situ, appears* white when embedded in the red surround. Since there are three test stimuli, there are three stimulus pairs, as shown schematically in the right panel of Figure 6. The same three stimulus pairs were tested in both white and red surrounds, making a total of six pairs overall.

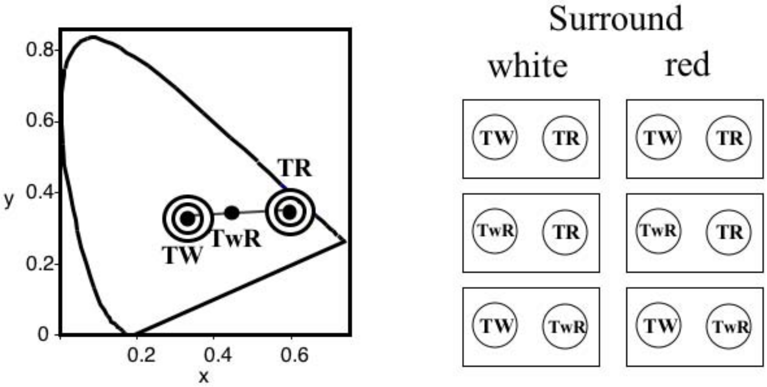


Figure 6: *Our first approach to simultaneous chromatic contrast, using spontaneous preferences. Preferences for three pairs of test stimuli were tested with white versus chromatic surrounds. The left panel shows the chromaticity coordinates of the stimuli. The rings represent the white and red surrounds, and the solid circles represent the test stimuli: TW, TwR and TR. The right panel shows the six pairs of test stimuli, three in the white surround and three in the red surround.*

The experiment with chromatic surrounds was initially motivated by two hypotheses that make different predictions. In developing both hypotheses we carried forward the perceptual Maximum Saturation looking rule: we assumed that infants prefer to look at the stimulus with the higher perceived saturation. Moreover, we assumed that this looking rule would hold with chromatic as well as white surrounds.

If these assumptions hold, we can use spontaneous preferences to ask whether or not infants have (adult-like) simultaneous color contrast. If they do not, then even with the red surround, the preference minimum should remain at the CIE white point. But if they do, then with the red surround, the preference minimum should shift to TwR, the stimulus originally selected precisely because it looks white to adults in the red surround. Note that neither of the two hypotheses predicts a preference minimum at TR, the highest purity test stimulus.

The resulting pattern of preferences is shown in Figure 7. The white bars show the data taken with the white surround, and the black bars with the red surround. Not surprisingly, with the white surround, the higher purity stimulus is preferred over the lower purity one in each pair. The preference minimum lies at the CIE white point, and the maximum lies at the stimulus with the highest purity. But, with the red surround, the pattern of preferences reverses completely: now the preference minimum lies at TR, and the maximum lies at the CIE white point. As stated earlier, neither of the two initial hypotheses is consistent with this result, and the logic that led to these two predictions must be abandoned. Moreover, the same pattern of results was replicated when green surrounds were used.

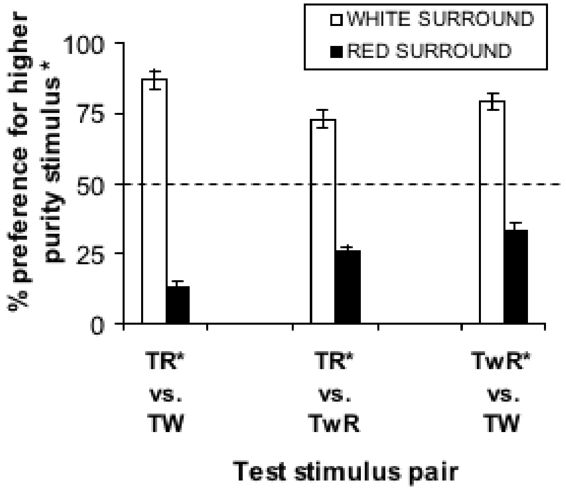


Figure 7: *Results of the spontaneous preference experiment with white versus chromatic surrounds. This plot shows the percent preference for the higher purity stimulus, for each of the six pairings of stimuli shown in Figure 6. White bars: white surround; dark bars: red surround.*

An alternative approach to explaining these data is to replace the Maximum Purity and Maximum Saturation looking rules with a Maximum Difference looking rule: perhaps infants prefer the stimulus that differs the most from the surround. The data are consistent with this rule in either behavioral or perceptual form. But, unfortunately, under this interpretation, the experiment is silent on the question of what infants perceive. If infants have no simultaneous color contrast, the three stimuli TW, TwR and TR should look white, pink, and red respectively, and, under the perceptual version of the Maximum Difference rule, infants should prefer TW. If infants do have adult-like color contrast, the three stimuli will look blue-green, white and pink respectively, and, under the same Maximum Difference rule, they should still prefer TW.

In sum, this experiment was successful in that it shows clearly that surround chromaticity has a strong influence on infants' spontaneous color preferences. But it is inconclusive about whether or not infants have simultaneous color contrast at the perceptual level.

5.5 *Simultaneous color contrast explored with a combination of all three techniques*

In a second experiment, we used a combination of all three techniques – spontaneous preferences, familiarization / novelty, and cross-familiarization – to address the question of simultaneous color contrast. The test stimuli were a white and a low purity red (0.38, 0.34) test disk, embedded in either a white or a blue-green (0.21, 0.33) surround (the blue-green surround is used only in the cross-familiarization phase of the experiment). The low purity red test stimulus was selected by adult observers *in situ*, since, embedded in the white surround, it matched the appearance of the white test stimulus embedded in the blue-green surround. The experimental design corresponds to that depicted in Figure 3, in that the low purity red test stimulus corresponds to A, the white stimulus to B, the white surround to X, and the blue-green surround to Y.

Experiments with all three techniques were carried out with closely similar stimuli and timing. The critical dependent variable is $P(A_x|B_y)$. We argued above that the outcome $P(A_x|B_y) = P(A_x|B_x)$ suggests the presence of adult-like color contrast. The outcome $P(A_x|B_y) = P(A_x|A_x)$ suggests the absence of adult-like color contrast. The intermediate outcome $P(A_x|B_y) = P(A_x)$ is less definitive. One inter-pretation is that infants have chromatic contrast effects that are smaller than those of adults. But an alternative interpretation is that there was a disconnect for the infant between familiarization and test phases, and that, for some reason, no effective familiarization took place. Since both of these interpretations are reasonable, the intermediate outcome would be inconclusive in regard to chromatic contrast.

The results are shown in Figure 8. The leftmost panel shows that $P(A_x)$ = 62% – a modest spontaneous preference for the desaturated red stimulus A in the white surround. The two middle panels show the expected familiarization / novelty effects from familiarization to A and to B – $P(A_x|A_x)$ = 43%, and $P(A_x|B_x)$ = 67%. The right panel shows the results of the cross-familiarization experiment; in this experiment, $P(A_x|B_y)$ = 59%. Unfortunately, the cross-familiarized preference is less than the familiarized preference $P(A_x|B_x)$, and more than the familiarized preference $P(A_x|A_x)$; and it does not differ reliably from the spontaneous preference. So, once again, this experiment does not allow an unambiguous conclusion about the presence or magnitude of simultaneous color contrast in infants.

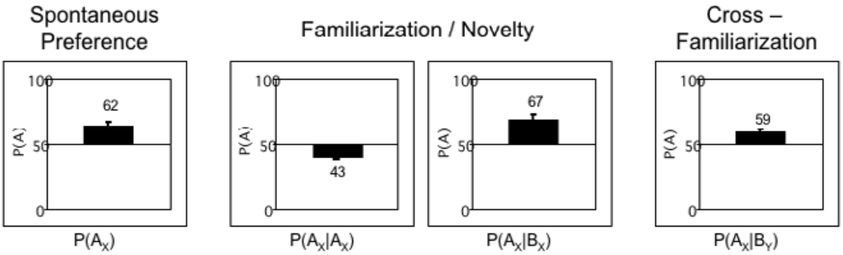


Figure 8: *A second simultaneous chromatic contrast experiment, using a combination of all three techniques. Test stimulus A was a low purity red, and test stimulus B was CIE white. Surround X was CIE white, and surround Y was blue-green. All ordinates show P(A). The left panel shows the spontaneous preference $P(A_x)$. The middle two panels show the two familiarized preferences, $P(A_x|A_x)$ and $P(A_x|B_x)$, after familiarization to the low purity red test stimulus and the white test stimulus respectively. The right panel shows the cross-familiarized preference $P(A_x|B_y)$, after cross-familiarization to the white test stimulus embedded in the blue-green surround. Note that $P(A_x|B_y)$ is approximately equal to $P(A_x)$.*

5.6 *Simultaneous color contrast explored with a temporal modulation paradigm*

In a third assault on the question of infant color contrast, we are now working with a spontaneous preference technique used in combination with stimuli that are temporally modulated in chromaticity (Pereverzeva, in preparation).

One of the paradigms for the temporal modulation experiments is shown in Figure 9. As shown in the top panels of the figure, the infants were presented with two test stimuli, A and B, embedded in either of two different surrounds, X and Y. The chromaticity of test stimulus A was temporally static, whereas the chromaticity of B was temporally modulated. Similarly, surround X was temporally static, whereas surround Y was temporally modulated. The modulation rate for both test stimulus A and surround Y was 1.2 Hz, and, when both were modulated, they were modulated in phase. The temporal characteristics of the stimuli are shown schematically in the bottom panels of Figure 9.

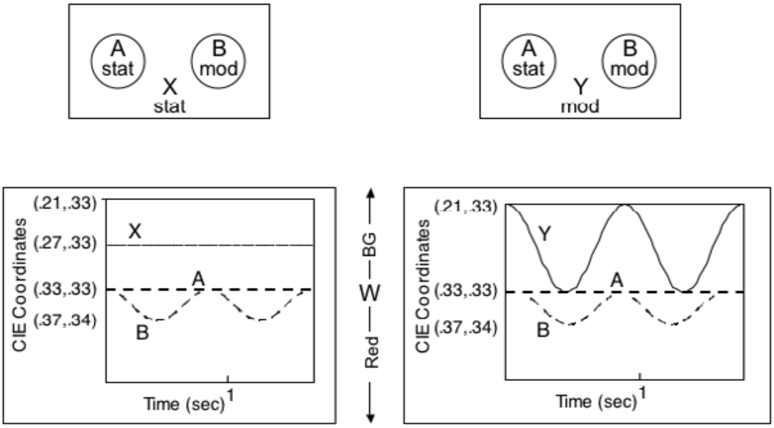


Figure 9: *A third approach to simultaneous chromatic contrast, using stimuli temporally modulated in purity. The two upper panels show the two conditions of the experiment. In each case, test stimulus A is unmodulated and test stimulus B is modulated in purity at 1.2 Hz. In the left panel the surround is unmodulated; in the right panel the surround is modulated in purity at 1.2 Hz. The two lower panels display the temporal characteristics of the stimuli in more detail. The color names in the center column are intended only to orient the reader; they indicate the approximate colors of the test stimuli when viewed by adults in an unmodulated white surround.*

The chromaticities and perceived colors of the stimuli (for adults) were as follows. The chromaticity of the static surround X was fixed at CIE coordinates (0.27, 0.33); perceptually it appeared as a desaturated blue-green. The chromaticity of the modulated surround Y was modulated between (0.21, 0.33) and the CIE white point; perceptually it varied from a relatively saturated blue-green to white. The time average chromaticities of X and Y were equal.

The chromaticity of the static test stimulus A was fixed at the CIE white point. Perceptually, it appeared a desaturated red in the static surround X, and it appeared to vary from a relatively saturated red to white in the modulated surround Y. The chromaticity of the modulated test stimulus B was modulated from the CIE white point to a low purity red with chromaticity coordinates (0.37, 0.34). This chromaticity was selected in pilot experiments on adults *in situ*, such that, when viewed in the modulated surround, the modulated test stimulus appeared as a nearly unchanging desaturated red. That is, as a result of simultaneous chromatic contrast, for adults the perceived modulation of the test stimulus was cancelled by the modulation of the surround. The basic question of the infant experiment was, will this same cancellation also occur for infants?

The predictions for the static surround condition (left panel) are as follows. In the static surround, B should be preferred to A for two reasons. First, it is being modulated, and many studies have shown that, other things being equal, infants prefer temporally modulated stimuli (Regal 1981; Dobkins, Lia & Teller 1997), and, second, the chromatic difference between B and X is always equal to or greater than the chromatic difference between A and X, so, if the Maximum Difference rule is still in force under these conditions, B will be preferred to A. This prediction should hold whether or not infants have simultaneous color contrast. Thus, the static surround condition by itself yields no information about its presence or absence.

However, for the modulated surround condition (right panel), the perceptual situation differs depending on whether or not infants have simultaneous chromatic contrast. If they do not, then A should appear static, and B should appear to vary in time. B should be preferred to A, for the reasons given above. But if infants do have simultaneous chromatic contrast, the static stimulus A would appear to vary, while by design the modulated stimulus B would appear static. Thus, if infants do have simultaneous chromatic contrast, and if they still prefer the perceptually varying stimulus, they should prefer A to B. Moreover, comparing between static and modulated surround conditions, the preference for B in Y should be reduced compared to the preference for B in X.

Notice that the design of this experiment pits the potential effects of simultaneous color contrast against the Maximum Difference rule. If the preference for B in Y is less than the preference for B in X, the result cannot be attributed to the operation of a Maximum Difference rule, and the inference that infants have simultaneous color contrast seems remarkably secure.

The results showed a significant reduction in preference for B when the stimuli were viewed in the modulated surround Y, compared to when they were viewed in the static surround X. In sum, these results are our strongest evidence to date that infants' color perceptions are influenced by simultaneous color contrast. These experiments are still in progress.

6. *Future directions*

In the present paper we hope to have convinced the reader of the potential value of discrete trial preferential looking techniques for studying supra-threshold aspects of infant color vision. But beyond the preliminary work described here, many methodological and conceptual issues remain to be explored. We here delineate three examples.

First, in the familiarization / novelty and cross-familiarization techniques as we have used them, in the familiarization phase of each trial the infant views two copies of the same stimulus (A,A or B,B). In the test phase, the two test stimuli A and B occupy the same physical locations as did the two copies of the familiarization stimulus, but one of the two test stimuli changes between familiarization and test phases, and the other does not. It could be that the infant codes the characteristics of the two stimuli, and looks for the *different* stimulus in the test phase; or it could be that the infant codes very little about the two stimuli, but just detects and stares at the location of stimulus *change* (Civan et al. 2005). Either option is interesting, as the first invites more perceptual, and the second more sensory interpretations. One way to sort out this question is to try familiarizing with a single, centrally placed stimulus rather than two copies of the same stimulus. We have not carried out systematic studies of this parameter, and it remains an interesting project for the future.

Second, in our attempts to study lightness and color, we have confined our use of cross-familiarization techniques to the case of changes in surround luminance or chromaticity. But, in principle, given a theoretical motivation, any other stimulus could be used as the cross-familiarizing stimulus. For example, color constancy could be studied by using real objects in real three-dimensional scenes, and changing the illumination spectrum between familiarization and test phases (cf. Chien 2004; Chien et al. 2006); or color categorization could be studied by changing the wavelength composition of the test stimuli themselves between familiarization and test phases (cf. Bornstein, Kessen & Weiskopf 1976).

Third, we return to the question of looking rules, which are always inextricably intertwined with interpretation in studies of infant preferences (Haith 1980; Banks & Ginsburg, 1985). In the present chapter, we have relied on two different looking rules to explain infants’ spontaneous looking preferences: the Maximum Saturation rule and the Maximum Difference rule. The Maximum Saturation rule – infants prefer chromatic stimuli to CIE white, and the greater the saturation the greater the preference – was formulated to describe the results of the spontaneous color preference experiment (Figure 5).

Notice that the rule is formulated solely in terms of the perceived saturations of the two test stimuli; the dim white surround is omitted from consideration.

In contrast, the Maximum Difference rules – infants prefer the stimulus with the maximal physical or perceptual difference from its surround – were formulated to describe the results of the first simultaneous chromatic contrast experiment (Figures 6 and 7). In this experiment, the chromaticity of the surround had a major effect on infants' looking preferences. With chromatic surrounds, infants abandoned their preference minimum at CIE white, and instead preferred the test stimulus that differed most from the surround, thus contradicting the Maximum Saturation rule.

In fact, these two rules are closely related. In the spontaneous color preference experiment the surround was a dim white, and in each instance the chromatic stimulus was more different than was the white stimulus from the white surround. If we include the surround in the spontaneous color preference experiment, we see that the Maximum Saturation rule is just a special case of the Maximum Difference rule with a fixed white surround. In the future it would be interesting to explore the generality of the Maximum Difference rule in the color domain, and perhaps even use infant color preferences to define a metric for the magnitudes of perceptual differences in infant color space.

In our experiments, the Maximum Difference rule is invoked in the color domain. However, chromaticity is just one attribute of the stimulus. Conceptually, we can think of all of the attributes of the stimulus – chromaticity, luminance, spatial frequency, temporal frequency, and so on – as variables in a multidimensional space. When more attributes differ between stimuli it will be interesting to find out how these variables are combined to influence infants' preferences.

Notice also, that in all of our experiments to date, the surround has been a homogeneous field surrounding the test stimuli. However, more diverse surrounds can also be used. For example, the surround can differ from the test stimuli in a variable other than chromaticity, such as spatial frequency, in order to study contrast adaptation; or the surround can be subdivided into smaller stimulus elements, to study the effects of surround articulation. In each case, in principle, a difference can be calculated between the surrounding elements and the target, and the Maximum Difference rule used to predict infants' preferences.

In summary, we have developed discrete trial versions of three classical preferential looking paradigms, and used them to probe several aspects of infant color perception. These techniques, like their many predecessors, should find broad use in future studies of infant perception, both within and beyond the perception of lightness and color.

Acknowledgements

Preparation of this manuscript was supported by NIH Training grant EY 07031 to MP and IZ, and research grant EY 04470 to DT. The experimental work was supported by EY 04470. We thank Sarina Chien and John Palmer for many conceptual and empirical contributions to the work described.

References

Adams, R. J. 1987. “An Evaluation of Color Preference in Early Infancy”. *Infant Behavior and Development* 10.143-150.

— & M. L. Courage. 1998. “Human Newborn Color Vision: Measurement with Chromatic Stimuli Varying in Excitation Purity”. *Journal of Experimental Child Psychology* 68.22-34.

Banks, M. S. & A. P. Ginsburg. 1985. “Infant Visual Preferences: a Review and a New Theoretical Treatment”. *Advances in Child Development and Behavior* ed. by H. W. Reese, 207-246. New York: Academic Press.

Bornstein, M. H. 1975. “Qualities of Color Vision in Infancy”. *Journal of Experimental Child Psychology* 19.401-409.

—, W. Kessen & S. Weiskopf. 1976. “The Categories of Hue in Infancy”. *Science* 191.201-202.

Chien, S. 2004. *Lightness Constancy in 4-month-old Infants: a Cue Elimination Approach*. Ph.D. dissertation, University of Washington, Seattle.

—, K. Bronson-Castain, J. Palmer & D. Y. Teller. 2006. “Lightness Constancy in 4-month-old Infants”. *Vision Research*, in press.

—, J. Palmer & D. Y. Teller. 2003. “Infant Lightness Perception: Do 4-month-olds Follow Wallach’s Ratio Rule?” *Psychological Science* 14.291-295.

—, J. Palmer & D. Y. Teller. 2005. “Achromatic Contrast Effects in Infants: Adults and 4-month-old Infants Show Similar Deviations from Wallach’s Ratio Rule”. *Vision Research* 45:22.2854-2861.

Civan, A. L., D. Y. Teller & J. Palmer. 2005. “Relations among Spontaneous Preferences, Familiarized Preferences, and Novelty Effects: Measurements with Forced-choice Techniques”. *Infancy* 7:2.111-142.

Cohen, L. B. & E. R. Gelber. 1975. “Infant Visual Memory”. *Infant Perception: from Sensation to Cognition* ed. by L. B. Cohen & P. Salapatek, 347-403. New York: Academic Press.

Dannemiller, J. L. & S. A. Hanko. 1987. “A Test of Color Constancy in 4-month-old Human Infants”. *Journal of Experimental Child Psychology* 44.255-267.

Dobkins, K. R., B. Lia & D. Y. Teller. 1997. “Infant Color Vision: Temporal Contrast Sensitivity Functions for Chromatically-defined Stimuli in 3-month-olds”. *Vision Research* 37.2699-2716.

Fagan, J. F. 1970. “Memory in the Infant”. *Journal of Experimental Child Psychology* 9.217-226.

Fantz, R. L. 1958. “Pattern Vision in Young Infants”. *Psychological Record* 8.43-47.

—. 1964. ”Visual Experience in Infants: Decreased Attention to Familiar Patterns Relative to Novel Ones”. *Science* 146.668-670.

—, J. F. Fagan & S. B. Miranda. 1975. “Early Visual Selectivity as a Function of Pattern Variables, Previous Exposure, Age from Birth and Conception, and Expected Cognitive Deficit”. *Infant Perception: from Sensation to Cognition* ed. by L. B. Cohen & P. Salapatek, vol. 1, 249-345. New York: Academic Press.

Haith, M. M. 1980. *Rules that Babies Look by: the Organization of Newborn Visual Activity*. Hillsdale, N.J.: L. Erlbaum Associates.

Hunter, M. A. & E. W. Ames. 1988. “A Multifactor Model of Infant Preferences for Novel and Familiar Stimuli”. *Advances in Infancy Research* ed. by C. Rovee-Collier & L. P. Lipsitt, vol. 5, 73-95. Hillsdale, N. J.: Ablex.

Olson G. M. 1976. “An Information-processing Analysis of Visual Memory and Habituation in Infants”. *Habituation: Perspectives from Child Development, Animal Behavior, and Neurophysiology* ed. by T. J. Tighe & R. N. Leaton, 239-277. Hillsdale, N.J.: L. Erlbaum Associates.

Orlian, E. K. & S. A. Rose. 1997. “Speed vs. Thoroughness in Infant Visual Information Processing”. *Infant Behavior and Development* 20.371-381.

Pereverzeva, M. (in preparation). “Simultaneous Color Contrast in 4-month-old Infants as Revealed by a Temporal Modulation Paradigm”.

— & D. Y. Teller. 2004. “Infant Color Vision: Influence of Surround Chromaticity on Spontaneous Looking Preferences”. *Visual Neuroscience* 21.389-395.

Regal, D. 1981. “Development of Critical Flicker Frequency in Human Infants”. *Vision Research* 21.549-555.

Simons, K., ed. 1993. *Early Visual Development, Normal and Abnormal: Symposium on Infant Vision Research: Papers*. New York: Oxford University Press.

Slater, A., A. Mattock & E. Brown. 1990. “Size Constancy at Birth: Newborn Infants’ Responses to Retinal and Real Size”. *Journal of Experimental Child Psychology* 49.314-322.

Staples, R. 1932. “The Responses of Infants to Color”. *Journal of Experimental Psychology* 15.119-141.

Stephens, B. R. & M. S. Banks. 1985. “The Development of Contrast Constancy”. *Journal of Experimental Child Psychology* 40.528-547.

Teller, D. Y. 1979. “The Forced-choice Preferential Looking Procedure: a Psychophysical Technique for Use with Human Infants”. *Infant Behavior and Development* 2.135-153.

—. 1997. “First Glances: the Vision of Infants: the Friedenwald Lecture”. *Investigative Ophthalmology and Visual Science* 38.2183-2203.

—, A. L. Civan & K. Bronson-Castain. 2004. “Infants’ Spontaneous Color Preferences are not Due to Adult-like Brightness Variations”. *Visual Neuroscience* 21.397-401.

Wallach, H. 1948. “Brightness Constancy and the Nature of Achromatic Colors”. *Journal of Experimental Psychology* 38.310-324.

Welch, M. J. 1974. “Infants’ Visual Attention to Varying Degrees of Novelty”. *Child Development* 45.344-350.

Wyszecki, G. & W. S. Stiles. 1982. *Color Science: Concepts and Methods, Quantitative Data and Formulae*. 2nd edn New York: Wiley.

Zemach, I., S. Chang & D. Y. Teller. (in preparation). “Infant Color Vision: are Infants’ Spontaneous Color Preferences Predictable from Adult Saturation Judgments?”

THE RIVALRY BETWEEN COLOUR AND SPATIAL ATTRIBUTES IN INFANT RESPONSE TO THE VISUAL FIELD

DI CATHERWOOD
University of Gloucestershire

Even for young infants, the perception of coloured objects involves the accurate co-location of colour (hue, brightness, saturation) and shape or form (contours and surfaces defined by variations in luminance, spatial frequency, texture and depth) (Slater, Mattock, Brown, Burnham & Young 1991; Taga, Ikejiri, Tachibana, Shimojo, Soeda, Takeuchi & Konishi 2002). Nonetheless, there are grounds for predicting that, at early processing intervals, this binding of colour and shape or form may not be in evidence, and either feature may dominate early perceptual and / or attentional response. Erroneous or 'illusory' conjunctions of colour and shape can arise even for adults (Treisman & Gormican 1988) and there is evidence of asynchrony in adult processing of chromatic and spatial features (e.g. Clifford, Arnold & Pearson 2003; Karayandis & Michie 1997; Moutoussis & Zeki 1997; Proverbio, Burco, del Zotto & Zani 2004). Such asynchrony may be more likely to occur in early infancy when the binding of object properties may be slower (Csibra, Davis, Spratling & Johnson 2000) and any infant response that draws on patterns of preliminary encoding may be likely to reveal inequity in rates or extent of processing for colour and spatial attributes.

On the one hand, correspondence between colour and spatial attributes might be expected on the basis of the high degree of commonality in the processing channels for these respective attributes. At cortical level in particular, there is extensive interaction for these processing streams. Many cortical neurons in V1 and V4 show selectivity both for colour and orientation (Gegenfurtner & Kiper 2003) and neuro-imaging evidence shows common areas of activation in the inferotemporal cortex for colour and form (for example, the collateral sulcus of the fusiform gyrus: Corbetta, Miezin, Dobmeyer, Shulman & Petersen 1991).

On the other hand, despite the overlap in chromatic and spatial encoding at cortical level (Gegenfurtner & Kiper 2003), there is still some degree of neuronal specialization for these attributes in the preliminary pathways from the retina to the cortex and, possibly, in V1 and V4 (Ts'o & Gilbert 1988). Even if the same cortical neurons code for both colour and spatial properties, there may be temporal separability in the response to these qualities, in accord with findings for macaque V1 (McClurkin & Optican 1996). Moreover, a region in the lateral occipital cortex (the *Lateral Occipital Complex*) appears to be specialized for the early processing of object shape on the basis of either contrast or texture cues (Kourtzi & Kanwisher 2000). There are also inferotemporal or ventral stream regions that code selectively for spatial qualities (especially the fusiform gyrus region for familiar patterns such as faces: Allison, McCarthy, Nobre, Puce & Belger 1994; Nakamura et al. 2000). Furthermore, attention to colour and shape may yield overlapping, but not necessarily identical patterns of activity in occipito-temporal and inferotemporal cortex, especially for three-dimensional objects (Chao & Martin 1999; Corbetta et al. 1991; McKeefry & Zeki 1997; Proverbio et al. 2004; Tanaka 1996). Finally, independence of chromatic and spatial channels is further confirmed by cases of achromatopsia (colour impairment without spatial deficits: Zeki 1990) and, conversely, of visual agnosia (spatial impairment without loss of colour response: Warrington & James 1988).

Thus despite the obvious interface between chromatic and spatial processing, there is also room for independence, especially during the primary phases of encoding. One sign of such early independence would be asynchrony in the rate of processing for colour and spatial properties. Such asynchrony is not apparent if colour-shape attributes for a particular object are typically or canonically bound in long-term memory (for example, 'yellow chicken' as opposed to 'yellow elephant': Proverbio et al. 2004), but, for novel objects, there is ample evidence of asynchronous encoding of colour and spatial attributes. For the most part, this evidence favours colour over spatial properties, with faster detection of, and reaction times for, coloured targets than spatial targets and earlier ERP attentional components for colour than for orientation or natural or abstract shapes (Clifford et al. 2003; Karayandis & Michie 1997; Moutoussis & Zeki 1997). Nonetheless, this bias towards colour would not seem to be immutable, since a contrary precedence of spatial features is evident if these aspects are more salient than colour for the required response (Delorme, Richard & Fabre-Thorpe 2000; Proverbio et al. 2004). These findings thus indicate the potential for a dynamic rivalry between colour and spatial attributes during the early intervals of perceptual-attentional response.

To some extent, there may seem little point in examining early intervals of processing to ascertain whether asynchrony is apparent since, as noted, even for infants, there is, typically, correspondence in the encoding of colour and spatial attributes, albeit after more prolonged exposure to stimuli (Slater et al. 1991; Taga et al. 2002). Nonetheless, exploration of asynchrony in early processing intervals may yet reveal valuable insights into the fundamental encoding trajectories that pre-empt the binding of these features. This issue has been examined by the author via a number of paradigms including backward visual masking (Catherwood 1994; Catherwood, Skoien, Green & Holt 1996) and 'visual search'-type approaches (Catherwood, Skoien & Holt 1996; Catherwood, Green, Freiberg & Holt 2003).

One of the backward visual masking experiments (Catherwood, Skoien, Green & Holt 1996) essentially involved familiarizing 5-month-old infants to a bi-chromatic facial pattern, but with the condition that, after each exposure of this stimulus, there was an interval followed by a further display intended to 'mask' or truncate processing of the target. The issue in question was whether the colours defining the target pattern were encoded (per se) and, if so, whether they were tagged to their correct spatial location – or, alternatively, were processed without reference to spatial location.

In other studies, infants have shown performance consistent with binding of colour and spatial properties (Slater et al. 1991; Taga et al. 2002). However, such studies typically involved extensive exposure to the target via habituation or familiarization without control over the post-exposure processing interval. Thus it is not clear from such evidence if there is parity of encoding for colour and spatial attributes during early phases of processing. In the sample masking experiment, the target exposure duration and also the stimulus-mask interval were varied in order to compare or probe progressive phases of encoding.

The precise mechanisms involved in backward visual masking effects have been debated for adults – especially as to whether such effects are localized in the periphery of the visual system or occur at cortical level (Turvey 1973). Masking could thus reveal information about sensory transduction / transmission time, rate of central processing or of information extraction during reponse to the target. The locus of masking effects for infants cannot be specified at this juncture, but prior experiments established that the processing of simple coloured shapes could be influenced by visual masking stimuli at 1000msec but not 2000msec (Catherwood 1994). Hence backward visual masking had been demonstrated for infants, and offered a tool for further exploration of the relative rates of processing for stimulus components.

In the sample experiment (Catherwood, Skoien, Green & Holt 1996), infants were presented with computer displays of eighteen repetitions of a three-trial sequence, showing, respectively, a target face comprised of equal areas of two colours followed by the stimulus-mask interval and then by the masking stimulus consisting of an achromatic (white) grating superimposed over the target face. The extent to which the colour and shape of the target had been ‘bound’ in their correct locations was then assessed by means of two 10-second paired-comparison tests in which the familiar target was presented along with either its chromatic reversal (that is, the same shape with the colours in their reversed locations) (reversal test) or the same shape in totally novel colours (new-colour test). The colours of the familiar and novel items were fully counterbalanced as was the order of the tests and location of the novel and familiar items on the tests.

In the terms of the familiarization paradigm, preferential fixation to the novel item in the new-colour test would provide evidence of recognition for the colours of the familiar target, but preferential fixation on the reversal test would also indicate that the colours had been encoded in their correct spatial location – that is, that colour and shape had been processed in a conjoined way. In contrast, if the reversal test did not reveal a bias to the novel stimulus (while the new-colour test did), then this would be consistent with asynchrony in the processing of colour and shape, in favour of colour. In other words, the colours of the target would have been encoded but not in their correct spatial locations.

There were four main conditions in the experiment, according to the duration of the target exposure and of the stimulus-mask interval (see Table 1 for details) (a further condition compared a full-field mask with the grating mask but revealed no significant difference).

Target & Mask Exposure Duration	Stimulus-Mask Interval (& Stimulus Onset Asynchrony)	Sample (n=12 in each case)
250msec	1000msec (1250msec)	22.8wks (3.0)
250msec	2000msec (2250msec)	23.9wks (4.9)
2500msec	1000msec (3500msec)	23.0wks (3.5)
2500msec	2000msec (4500msec)	22.5wks (3.6)

Table 1: *Main conditions for the masking experiment.*

The dependent variable was the overall duration of fixation to the novel item on each test trial (as timed by two independent naive observers from video records) and estimated as a percentage of the total fixation to the two items on each test trial. The extent to which infants showed an above-chance (> 50%) bias to the novel item was estimated. For all conditions, there was a clear novelty preference on the new-colour test, indicating that the colours of the target had been encoded (or at least one of them had), but there was only a significant novelty preference on the reversal test for the condition in which the target and the target-mask duration had been at the maximum intervals (2500 / 2000msec) ($p < .05$).

The results indicate that at least one of the colours of the target was processed into memory (SOA: 1250msec) in advance of the correct spatial distribution of the colours (SOA: 4500msec). This outcome is consistent with the operation of separable processing trajectories for these attributes, either during the initial encoding of the target properties, and / or during response on the recognition tests. It is also possible that the masking stimulus was more efficient at masking the location of the colours than masking the colours per se. However, any of these scenarios could only arise if there was independence at some juncture in the processing trajectories for colours, relative to the distribution of those colours in space.

Another masking experiment indicated that infants may also process colour ahead of simple shapes (Catherwood 1994), and this concurs with the adult evidence showing predominance of colour in early intervals of processing (Clifford et al. 2003; Karayandis & Michie 1997; Moutoussis & Zeki 1997). Nonetheless, the adult data also show that colour is not inevitably encoded ahead of spatial attributes and the outcome of any rivalry for these attributes may depend on the salience of the spatial characteristics. This possibility was explored for infants in another experiment (Catherwood, Freiberg, Green & Holt 2001, 2003) that assessed infant encoding of colour, relative to facial pattern in the left and right visual fields.

It is well established that facial configuration is a particularly compelling stimulus for young infants (Dannemiller & Stephens 1988) and the spatial attributes of facial pattern may thus be a worthy competitor to colour in infant processing of visual information. This rivalry may be especially vigorous in the right hemisphere (RH), since, for both infants (Deruelle & de Schonen 1998) and adults (Allison et al. 1994; Bradshaw & Sherlock 1982), there is evidence of a RH advantage in the encoding of the configurational or relational aspects of facial patterns – with a LH bias to more local facial attributes. It thus seemed possible that facial pattern may dominate colour encoding in the RH. However, there is also evidence for children (Bernasek & Haude 1993) and adults (Chao & Martin 1999; Rosler, Heil, & Henninghausen 1995) of a RH bias in post-V1 response to colour, provided colour naming is eliminated (McKeever & Jackson 1979). Despite the lack of comparable data regarding infant hemispheric asymmetry in response to colour, it seemed conceivable that colour and facial pattern may compete for processing resources within the infant RH. The sample experiment was designed to explore this possibility.

To this end, 32 infants (mean age 23.9 weeks, SD 3.6) were familiarized over 24 trials to a computer-generated ‘oddball’-type display comprised of an array of three coloured schematic faces in either the left or right visual field (between-subjects). One of the faces (target) was in an upright orientation while the others were inverted (distractors). For adults, upright faces are considered to be encoded in terms of configurational aspects (the spatial relationships amongst the features), while inverted faces are more likely to be processed in terms of the features per se (Yin 1970). Thus the upright face in the displays may have been more likely to be processed in terms of the configurational aspects known to be favoured by the infant RH.

The faces in each display had different internal features and expressions (happy, sad, angry or surprised) and colours (saturated blue, green, yellow or red), so that the only means for distinguishing the target from the others was in regard to orientation of the facial pattern. The colour-face combinations were constant for any one infant and were counterbalanced over the sample. The faces were arranged in a vertical array, with the inner edge being at about a 4° visual angle from the central focal point. On each trial, fixation was firstly centred with an achromatic bullseye or checkerboard stimulus, and then the lateral facial array was presented for 250msec. Since none of the infants diplayed saccadic orientation to the lateral displays, it can be assumed that these were projected to the contralateral hemisphere. Following familiarization, the infants were then presented with a series of four trials respectively involving either the target or one of the distractors paired with a face that was novel in either colour or in facial features and expression (with novel and familiar attributes and location counterbalanced over the sample, and test order randomized). In terms of the familiarization paradigm, above-chance levels of fixation to the novel item on the tests is taken as an index of recognition or encoding of the familiar test item – specifically regarding the target colour or pattern and distractor colour or pattern.

If facial configuration were to dominate, then it could be expected that the processing focus would be for the upright target stimulus in the familiarization displays, leading to better recognition of the characteristics of this item than for the others. Moreover, there might be a RH advantage in this respect with better target processing in the LVF than the RVF. However, of most interest in this experiment was the fate of colour, relative to encoding of facial pattern. If colour were to wholly dominate facial pattern, then there would be no basis for parsing the displays into target versus two distractor items (since these three items were all different in colour) and, hence, no selective encoding of the target properties. In contrast, if facial configuration were to dominate colour, then the target might be selected, and its pattern, but not its colour, encoded. Finally, if there were mutuality of encoding for colour and spatial attributes, then the target pattern might be preferentially processed along with its colour.

The video records of infant fixation were scored by a naive observer, and the time spent fixating the novel test item converted to a percentage of the total fixation time for each test trial (with correspondence with the scores of a second coder being $r = 0.98$). These scores were then compared to chance levels (50%). For the RVF (LH), there was evidence of recognition of the distractor colour and pattern ($p < .05$), but no evidence of recognition for the colour or pattern of the target item ($p > .05$). On the other hand, for the LVF (RH), there was significant recognition of the target colour ($p < .05$), but not of anything else.

This pattern of results is consistent with the interpretation that, for both the LH and RH, there was a parsing of the displays in regard to the spatial attributes of facial configuration – albeit with an ensuing focus on the inverted distractors for the LH and on the upright target for the RH. This bias to the upright face for the RH is expected on the basis of prior evidence regarding RH preference for facial configuration in adults and infants (as cited above). However, this RH focus on the upright face did not incorporate encoding of the facial pattern to the exclusion of target colour. On the contrary, the target colour would seem to have been encoded to the neglect of its spatial pattern, since there was recognition of the former but not the latter for the RH.

This outcome indicates a dynamic sharing of processing resources between spatial and chromatic attributes for the RH: with an initial dominance of spatial pattern (as reflected in the focus on the upright target item) followed by a shift to colour (as shown by the recognition of the target colour) without further concomitant encoding of the facial pattern (as indicated by the lack of recognition for this aspect on the test trials). Thus, for these particular stimulus conditions, spatial attributes seem to have had initial precedence over colour but then to have lost this ground while colour was encoded.

The overall indication from these masking and ‘pop-out’ studies is that spatial attributes and colour are not necessarily bound together in the early intervals of infant response to coloured stimuli. On some occasions, colour may dominate spatial attributes, but, if the latter are sufficiently salient for infants, colour may take a temporary secondary place. Given the reliance on memory in these paradigms, the locus of these processing patterns is not certain and they may involve either perceptual or memory mechanisms, or both. However, the important conclusion is that, when dealing with coloured objects, infant processing may involve a dynamic interplay between chromatic and spatial properties with a shifting focus for supremacy – until the point at which these qualities are encoded in a conjoined manner.

References

Allison, T., G. McCarthy, A. Nobre, A. Puce & A. Belger. 1984. "Human Extrastriate Visual Cortex and the Perception of Faces, Words, Numbers, and Colours". *Cerebral Cortex* 5.544-554.

Bernasek, J. L. & R. H. Haude. 1993. "Colour-naming and Colour-matching by Preschool Children as a Function of Visual Field and Sex". *Perceptual and Motor Skills* 77.739-747.

Bradshaw, J. L. & D. Sherlock. 1982. "Bugs and Faces in Two Visual Fields: the Analytic / Holistic Processing Dichotomy and Task Sequencing". *Cortex* 18.211-226.

Catherwood, D. 1994. "Exploring the Seminal Phase in Infant Memory for Colour and Shape". *Infant Behaviour and Development* 17.235-243.

—, K. Freiberg, V. Green & C. Holt. 2001 "Intra-hemispheric Dynamics in Infant Encoding of Coloured Facial Patterns". *Infant and Child Development* 10.47-57.

—, V. Green, K. Freiberg & C. Holt. 2003. "Hemispheric Dynamics in Infant Response to Colourful Faces". *The Development of Face Processing in Infancy and Early Childhood* ed. by O. Pascalis & A. Slater, 169-178. New York: Nova Science.

—, P. Skoien, V. Green & C. Holt. 1996. "Assessing the Primal Moments in Infant Encoding of Compound Stimuli". *Infant Behaviour and Development* 19.1-11.

—, P. Skoien & C. Holt. 1996. "Colour Pop-out in Infant Response to Visual Arrays". *British Journal of Developmental Psychology* 14.315-326.

Chao, L. L. & A. Martin. 1999. "Cortical Regions Associated with Perceiving, Naming, and Knowing about Colours". *Journal of Cognitive Neuroscience* 11.315-326.

Clifford, C. W. G., D. H. Arnold & J. Pearson. 2003. "A Paradox of Temporal Perception Revealed by a Stimulus Oscillating in Colour and Orientation". *Vision Research* 43.2245-2253.

Corbetta, M., F. M. Miezin, S. Dobmeyer, G. L. Shulman & S. E. Petersen. 1991. "Selective and Divided Attention During Visual Discriminations of Shape, Colour, and Speed: Functional Anatomy by Positron Emission Tomography". *Journal of Neuroscience* 11.2383-2402.

Csibra, G., G. Davis, M. W. Spratling & M. H. Johnson. 2000. "Gamma Oscillations and Object Processing in the Infant Brain". *Science* 290.1582-1584.

Dannemiller, J. & B. R. Stephens. 1988. "A Critical Test of Infant Pattern Preference Models". *Child Development* 59.210-216.

Delorme, A., G. Richard & M. Fabre-Thorpe. 2000. "Ultra-rapid Categorization of Natural Scenes Does Not Rely on Colour Cues: a Study in Monkeys and Humans". *Vision Research* 40.2187-2200.

Deruelle, C. & S. de Schonen. 1998. "Do the Left and Right Hemispheres Attend to the Same Visuo-spatial Information Within a Face in Infancy?" *Developmental Neuropsychology* 14.535-554.

Gegenfurtner, K. R. & D. C. Kiper. 2003. "Colour Vision". *Annual Review of Neuroscience* 26.181-206.

Karayandis, P. & P. T. Michie. 1997. "Evidence of Visual Processing Negativity with Attention to Orientation and Colour in Central Space". *Electro-encephalography and Clinical Neurophysiology* 103.282-297.

Kourtzi, Z. & N. Kanwisher. 2000. "Cortical Regions Involved in Perceiving Object Shape". *Journal of Neuroscience* 20.3310-3318.

McClurkin, J. W. & L. M. Optican. 1996. "Primate Striate and Prestriate Cortical Neurons During Discrimination, 1: Simultaneous Temporal Encoding of Information about Colour and Pattern". *Journal of Neurophysiology* 75.481-495.

McKeefry, D. J. & S. Zeki. 1997. "The Position and Topography of the Human Colour Centre as Revealed by Functional Magnetic Resonance Imaging". *Brain* 120.2229-2242.

McKeever, W. F. & T. L. Jackson. 1979. "Cerebral Dominance Assessed by Object Colour Naming Latencies". *Brain and Language* 7.175-190.

Moutoussis, K. & S. Zeki. 1997. "A Psychophysical Dissection of the Brain Sites Involved in Colour-generating Comparisons". *Proceedings of the National Academy of Sciences* 97.8069-8074.

Nakamura, K., R. Kawashima, N. Sato, A. Nakamura, M. Sugiura, T. Kato, K. Hatano, K. Ito, H. Fukuda, T. Schormann & K. Zilles. 2000. "Functional Delineation of the Human Occipito-temporal Areas Related to Face and Scene Processing". *Brain* 123.1903-1912.

Proverbio, A. M., F. Burco, M. del Zotto & A. Zani. 2004. “Blue Piglets?: Electrophysiological Evidence for the Primacy of Shape over Colour in Object Recognition”. *Cognitive Brain Research* 18.288-300.

Rosler, F., M. Heil & E. Henninghausen. 1995. “Distinct Cortical Activation Patterns During Long-term Memory Retrieval of Verbal, Spatial, and Colour Information”. *Journal of Cognitive Neuroscience* 7.51-65.

Slater, A., A. Mattock, E. Brown, D. Burnham & A. Young. 1991. “Visual Processing of Stimulus Compounds in Newborn Infants”. *Perception* 20.29-33.

Taga, G., T. Ikejiri, T. Tachibana, S. Shimojo, A. Soeda, K. Takeuchi & Y. Konishi. 2002. “Visual Feature Binding in Early Infancy”. *Perception* 31.273-286.

Tanaka, K. 1996. “Inferotemporal Cortex and Object Vision”. *Annual Review of Neuroscience* 19.109-139.

Treisman, A. & S. Gormican. 1988. “Feature Analysis in Early Vision: Evidence from Search Asymmetries”. *Psychological Review* 91.185-215.

Ts’o, D. Y. & C. D. Gilbert. 1988. “The Organization of Chromatic and Spatial Interactions in the Primate Striate Cortex”. *Journal of Neuroscience* 8.1712-1727.

Turvey, M. T. 1973. “On Peripheral and Central Processes in Vision: Inferences from an Information Processing Analysis of Masking with Patterned Stimuli”. *Psychological Review* 80.1-52.

Warrington, E. K. & M. James. 1988. “Visual Apperceptive Agnosia: a Clinico-anatomical Study of Three Cases”. *Cortex* 24.13-32.

Yin, R. K. 1970. “Face Recognition by Brain-injured Patients: a Dissociable Ability”. *Neuropsychologia* 8.395-402.

Zeki, S. 1990. “A Century of Cerebral Achromatopsia”. *Brain* 113.1721-1777.

CONVERGING EVIDENCE FOR PRE-LINGUISTIC COLOUR CATEGORIZATION

ANNA FRANKLIN [1] & IAN R. L. DAVIES
University of Surrey

1. *Introduction*

Adults respond categorically to colour. Adults are faster at discriminating two coloured stimuli from different colour categories (between-category) than two coloured stimuli from the same colour category (within-category). This facilitation for between-category discrimination compared to within-category holds even when between- and within-category stimulus chromatic separation sizes are equated (see Figure 1).

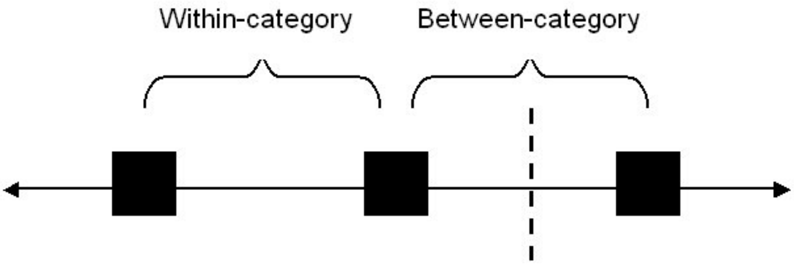


Figure 1: *Diagram to show the stimulus design for studies of colour categorization. Black boxes denote the stimulus, the dashed line denotes the category boundary. Separation sizes for between- and within-category stimuli are equated.*

---

[1] Gerhardstein, Renner and Rovee-Collier (1999) addressed this question and found no evidence of a category effect on a perceptual pop-out task in three-month-old infants. However, Davies and Franklin (2002) provide evidence that flaws in the design and flaws in the technical control

Category effects in adults have been found using a variety of tasks. For example, using a same-different judgements task, Bornstein and Korda (1984) showed that adults were faster at responding when the stimuli were from different categories than when they were from the same category. Using a triadic ‘odd-one-out’ judgements task, Kay and Kempton (1984) showed that adults more frequently chose the different category stimulus as the odd-one-out, despite the three stimuli being equidistant in colour space. Using a two-alternative-forced choice task (2-AFC), Uchikawa and Shinoda (1996) showed that adults were faster and more accurate at identifying a coloured target when asked to identify it from a pair of coloured stimuli from a different colour category than from the same category. Category effects have also been found across a variety of colour boundaries (for example, blue-green, blue-purple, pink-red) and when equating within- and between-category separations with a variety of colour spaces (for example, Munsell colour order system, OSA colour space).

The origin and nature of this categorical responding to colour is under debate. One theory is that colour categorization is linguistically constructed (eg. Roberson 2005). For example, it has been argued that adults respond categorically to colour because the language that we speak carves the colour space up into different categories. Evidence to support this theory comes in part from cross-cultural research that shows that categorical responding is only found when the speaker’s language marks the category boundary. For example, if a language does not mark the boundary between blue and green then categorical responding across this boundary is not seen on a triadic ‘odd-one-out’ task (e.g. Kay & Kempton 1984) or a 2-AFC task (e.g. Roberson, Davies & Davidoff 2000). Similar language effects are also found in children on a visual search task (Daoutis, Franklin, Riddett, Clifford & Davies 2005). The theory that colour categorization is linguistically constructed predicts that the category effect will not be found before colour terms are learnt. Therefore, pre-linguistic infants or toddlers who have not yet learnt their colour terms should not respond categorically to colour.

This paper outlines converging evidence that categorical responding to colour can be found pre-linguistically. Firstly, evidence from several studies for colour categorization in four-month-old infants is outlined. Secondly, the nature of infant colour categorization is discussed, and evidence is provided that categorical responding to colour in infants is perceptual. Thirdly, further

---

of stimuli can account for their pattern of results. Questions about whether the task was really measuring pop-out were also raised.

evidence for pre-linguistic colour categorization from studies of toddlers' colour perception is outlined. Finally, the implications for the debate about the origin and nature of colour categorization are discussed.

2. *Infant colour categorization*

2.1 *Bornstein, Kessen and Weiskopf 1976*

Bornstein, Kessen and Weiskopf (1976) investigated hue categorization in four-month-old infants using a habituation technique. Habituation is a technique commonly used for assessing infant perception. During the habituation phase, an infant is shown a stimulus repeatedly until the amount of time spent looking at the stimulus decreases. Then, during a test phase, a novel stimulus is shown. As infant looking is increased by novelty, if the infant can discriminate the novel from the original stimulus, then the novel stimulus should reinstate the infant's attention and infant looking should increase. The amount of looking at the novel stimulus after habituation to the original becomes a measure of how similar the novel and the original stimulus appear to the infant. Bornstein, Kessen and Weiskopf (1976) used this technique to assess whether two within-category stimuli would be perceived by four-month-old infants as more similar than two between-category stimuli. During the habituation phase, infants were shown one wavelength repeatedly for fifteen trials, each lasting fifteen seconds. Then, during a nine trial test phase, infants were shown the original habituated wavelength, a same-category wavelength (within-category), and a different-category wavelength (between-category), with order of presentation randomized across infants. The separation size in wavelength of the novel and original habituated stimulus was equated in wavelength for within- and between-category stimulus pairs (see Figure 2).

If infants respond categorically on this task, we would expect the between-category novel stimulus to reinstate looking, more than the within-category novel stimulus. Bornstein et al. found exactly this, for three category boundaries: blue-green, green-yellow and red-yellow. For example, when the infant was habituated to 480nm (blue), the mean looking time at the test phase stimulus was: 5.7 seconds for the habituated stimulus; 5.8 seconds for the within-category stimulus (450nm, blue); and 7.3 seconds for the between-category stimulus (510nm, green). Similar effects were found across the other boundaries. Interestingly, the within-category stimuli reinstated no more looking than the original habituated stimulus, possibly suggesting that infants could not discriminate the two within-category stimuli at all (this is returned to later). On the basis of these results, Bornstein et al. inferred that four-month-old infants categorize colour.

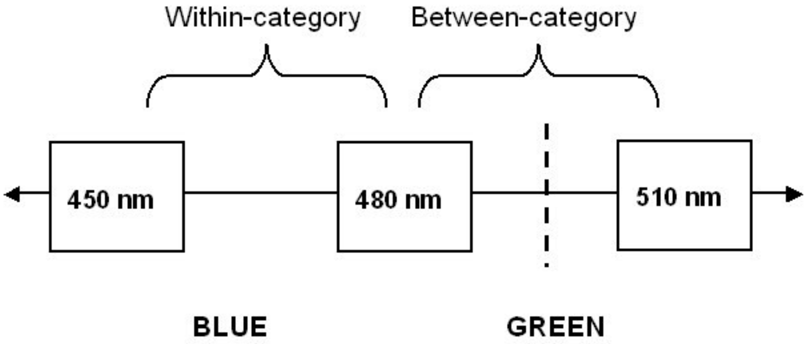


Figure 2: *An example of within- and between-category stimulus pairs in Bornstein et al.'s investigation of infant colour categorization. Stimulus pairs are separated by 30nm of wavelength. The dashed line indicates the blue-green category boundary. (Figure from Franklin, Pilling & Davies 2005).*

A second experiment also provided evidence that four-month-old infants categorize colour. Here, four-month-old infants were allocated to one of three groups (habituation to a single stimulus; habituation to two within-category stimuli; habituation to two between-category stimuli). Over twenty-four trials, each of fifteen seconds, infants were either habituated to a single stimulus of 480nm, or to a combination of two within-category stimuli, one of 480nm and the other of 450nm, or to a combination of two between-category stimuli, one of 480nm and the other of 510nm. If infants perceive the between-category stimuli as more perceptually dissimilar than the within-category stimuli, then the mean looking time across the twenty-four habituation trials should be greater when the infants are shown two between-category stimuli than for either two within-category stimuli or just one stimulus. This is exactly what Bornstein et al. found. The mean looking time for two between-category stimuli was 6.4 seconds while the mean looking time for two within-category stimuli was 3.7 seconds. When infants were shown only one stimulus (480 nm) the mean looking time was 3.8 seconds. Note that showing two within-category stimuli did not significantly increase looking time compared to showing just one stimulus, again possibly suggesting that infants could not discriminate between the two within-category stimuli. On the basis of these two studies, Bornstein et al. concluded that: "human infants, long before the acquisition of language or the experience of formal tuition, see hues and respond to the continuous photic spectrum in a categorical fashion" (1976:123). Similar category effects have also been found in a series of studies by Catherwood and colleagues (Catherwood, Crassini & Freiberg 1987, 1989, 1990), although, in these studies, within- and between-category separation sizes were not equated in colour space.

2.2 *Limitations of the study by Bornstein et al.*

Several limitations of Bornstein et al.'s investigation have been highlighted. These are mainly concerned with the technical control of the coloured stimuli. Firstly, Werner and Wooten (1985) argue that infants' responding may actually be due to residual differences between stimuli in luminance and saturation. Stimuli were at adult isoluminance, yet Werner and Wooten argue that stimuli may not have been isoluminant for infants, due to differences in infant and adult spectral sensitivity functions. Werner and Wooten also argue that, due to the use of monochromatic lights to produce the colours, there were residual differences in saturation between stimuli. Can residual differences in luminance and saturation explain Bornstein et al.'s pattern of results? Recent research on the spectral sensitivity functions of infants and adults suggest that mean adult isoluminance values can be used as a good estimate of infant isoluminance (Pereverzeva, Chien, Palmer & Teller 2002). This, therefore, suggests that Bornstein et al.'s stimuli were actually likely to be isoluminant for infants as well as adults. It is also unlikely that residual differences in saturation could explain Bornstein et al.'s results, as differences in saturation are likely to exist for both between- and within-category stimuli. Such differences, therefore, could not explain why infants only dishabituate for between- but not within-category novel stimuli.

A second limitation of Bornstein et al.'s investigation is that stimulus differences were equated in wavelength. Wavelength discrimination thresholds vary with position in the spectrum, and, therefore, equal wavelength separations are not necessarily equal perceptual separations (see Wyszecki & Stiles 2000:571). For this reason, studies of colour categorization in adults have equated within- and between-category stimulus separation sizes using standardized uniform colour metrics such as the Munsell system, or the CIE (L*u*v* 1976) colour space, rather than in wavelength. Is it possible that unequal between- and within-category separation sizes can account for Bornstein et al.'s pattern of results? Again, this is unlikely. When the wavelength separations are converted to the CIE metric (L*u*v*, ΔE), it appears that inequalities in between- and within-category separation sizes cannot explain the category effect. For unequal separation sizes to explain the category effect, the separation size would need to be larger for between-category stimuli than within. However, this is not always the case. For example, for the red-yellow set, the CIE separation for the between-category pair (94.7ΔE) was smaller than for the within-category pair (114.5ΔE), yet looking time was greater (between-category mean test phase looking time = 6.0 seconds, within-category mean test phase looking time = 4.1 seconds). So, although the between-category stimulus reinstated more attention than the within-category, the between-category separation size was actually smaller than the within. It is, therefore, unlikely that unequal between- and within-category separation sizes are the cause of the category effect in Bornstein et al.'s investigation.

A third limitation of Bornstein et al.'s investigation is that coloured stimuli were produced using extremely saturated monochromatic lights. This may be a problem, as this is not typical of the way in which we experience colour in our everyday environment – colours are typically at lower saturation levels and are reflective not radiant. It is possible, although, again, unlikely, that the categorical responding in Bornstein et al.'s study is due to this.

2.3 *Further evidence for infant colour categories*

Franklin and Davies (2004) replicated and extended Bornstein et al.'s investigation, testing for category effects in four-month-old infants across various adult category boundaries. To overcome the limitations of Bornstein et al.'s investigation, a standardized, perceptually uniform colour space (the Munsell system) was used to equate within- and between-category separations: stimuli were reflective and were at natural saturation levels. A variant of the habituation technique – a paired comparison novelty preference task, was used. During a familiarization phase, one colour was presented to left and right visual fields for fifteen trials, each lasting eight seconds. Then, during the test phase, a novel colour was presented, either on the left or the right, alongside the familiar colour, in the alternate visual field for five trials, each lasting eight seconds. On this task, the amount of time spent looking at the novel colour, relative to the familiar colour, during the test phase (expressed as a percentage) is used as an index of perceptual similarity. A novelty preference score significantly greater than 50% indicates discrimination of the novel stimulus. Novelty preference was compared for between- and within-category stimulus pairs.

In one experiment, categorical responding across the blue-green and blue-purple hue boundaries was investigated. Between- and within-category stimulus pairs were equated in Munsell hue steps and did not vary in Munsell lightness (value) or saturation (chroma). Significant novelty preference (around 70%) was shown when the novel stimulus was from a different category but not when the novel stimulus was from the same category (around 50% – equal looking at familiar and novel stimuli). This category effect was found for both the blue-green and the blue-purple boundaries, and for two separation sizes (near and far) (see Figures 3 and 4).

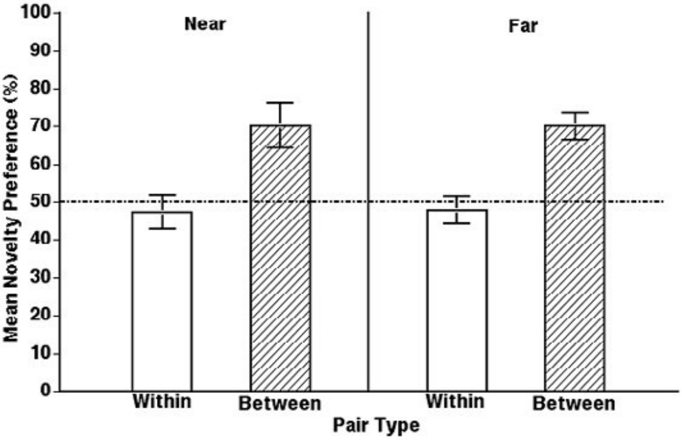


Figure 3: *Mean novelty preference (+/-1 SE) for the within- and between-category blue-green stimulus pairs, for two separation sizes (near and far). (Figure from Franklin & Davies 2004).*

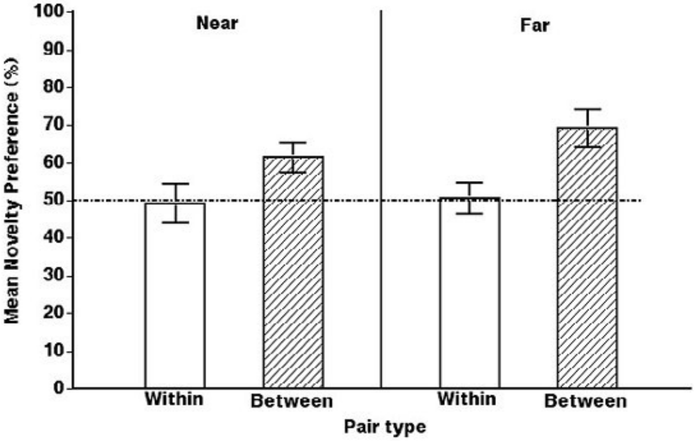


Figure 4: *Mean novelty preference (+/-1 SE) for the within- and between-category blue-purple stimulus pairs, for two separation sizes (near and far). (Figure from Franklin & Davies 2004).*

This experiment, therefore, replicated Bornstein et al.'s finding of categorical responding in infants across the blue-green hue boundary, and also extended it to the blue-purple hue boundary.

As category boundaries are not only defined by hue, another experiment tested categorical responding across a pink-red boundary defined by differences in lightness and saturation. Between- and within-category stimulus differences in lightness (Munsell value) and saturation (Munsell chroma) and stimuli were equated, and stimuli were constant in hue. As for the blue-green and blue-purple boundaries, significant novelty preference was only shown for the between-category stimulus pairs (around 70%), but not for the within-category stimulus pairs (around 50%).

Therefore, Franklin and Davies (2004) showed that, even when stimulus separations were equated with a perceptually uniform metric, even when stimuli are at natural saturation levels and are reflective not radiant, and even when the three dimensions of colour are controlled, four-month-old infants still respond categorically to colour. Furthermore, it was shown that four-month-old infants not only have primary categories such as blue and green, but also have secondary categories such as purple and pink.

2.4 *The nature of infant colour categorization*

Bornstein et al.'s, Catherwood et al.'s and Franklin & Davies' investigations clearly show that pre-linguistic infants categorize colour. However, there has been some scepticism about the category effect. Most of this scepticism has come from the fact that it is unclear what the nature of the category effect is in infants. In adult studies of colour categorization, categorical responding to colour is often referred to as 'categorical perception' implying that adults perceive and discriminate colour categorically. However, is categorical responding to colour in infants really perceptual? Are infant and adult colour categories really equivalent?

Some have argued that infant colour categorization may not be perceptual. For example, Özgen has argued that the techniques used in the infant studies, do not necessarily measure perceptual discrimination, stating that "it is difficult to know exactly what perceptual ability [the techniques] tap into … [infants may] 'prefer' to look at certain stimuli rather than others for a reason that is not related to perceptual sensitivity" (2004:97-98). Novelty preference and habituation techniques rather than the measurement of infants' ability to discriminate colour, could be measuring recognition memory. If this is the case, category effects on such tasks may actually be 'categorical memory' rather than 'categorical perception'. For example, the category effect could be due to memory effects such as the 'shift towards prototype' (Huttenlocher, Hedges &

Vevea 2000). Here, stimuli are remembered as their prototype, making it harder to recognize a stimulus when presented with another stimulus of the same prototype than when presented with another stimulus of a different prototype. Of course, category effects in adults, found using memory tasks such as the 2-AFC task, could also be due to a 'shift towards prototype', so these category effects in adults also need not necessarily be perceptual. However, category effects in adults have also been found using tasks which have no memory component. For example, adults respond categorically on visual search tasks – targets are found faster when distractors are between- rather than within-category (Kawai, Uchikawa & Ujike 1995; Daoutis, Pilling & Davies 2006; Franklin, Pilling & Davies 2004). In order to establish whether category effects in infants are really perceptual, category effects need to be tested for in infants, using tasks which have no memory component.

Other aspects of infants' colour categorization also need exploration. In Bornstein et al.'s investigation, the amount of dishabituation when the novel stimulus was from the same colour category as the original stimulus, was no greater than the amount of dishabituation when the original stimulus was presented. In Franklin and Davies' investigation, for all boundaries tested, no significant novelty preference was shown when the novel stimulus was from the same colour category. As mentioned earlier, this may suggest that infants are unable to discriminate within-category stimuli. Therefore, as adults *are* able to discriminate within-category stimuli, this could suggest that the category effect in infants is more absolute than the category effect in adults. However, the lack of dishabituation or novelty preference by infants to within-category stimuli does not necessarily imply that infants are unable to discriminate two colours from the same colour category. One of the problems with the novelty preference and habituation technique is that interpretation of no significant novelty preference is not clear-cut. If novelty preference is found, then infants must be able to discriminate. However, a lack of significant novelty preference implies nothing about discriminability. For example, in an investigation by Snyder, Blank, Cheek, Kuefner and Marsolek (2004) infants who showed novelty preference and infants who didn't show novelty preference to a novel visual stimulus, both showed evidence of discriminating the novel stimulus in their pattern of ERPs (a physiological measure) on an oddball task. Even though infants were discriminating the novel stimulus, no novelty preference was shown for some infants. Therefore, it is possible that infants are actually capable of discriminating two stimuli from the same colour category, but that the novelty preference and habituation measures are not sensitive enough to detect this. In order to establish whether infants can discriminate within-category stimuli, category effects in infants need to be tested for using a technique that is more sensitive to discrimination than novelty preference or habituation.

To investigate whether the category effect in infants is a truly perceptual effect, and whether infants can actually discriminate within-category stimuli, Franklin, Pilling and Davies (2005) tested for categorical responding in four-month-old infants on a target detection task. Adults were also tested for categorical responding on this task so that comparisons of the category effect in infants and adults could be made. The target detection task was designed to measure how well a coloured target could be discriminated when presented on a coloured background. If category effects are shown on the task then discrimination should be faster when the chromatic difference of the target and the background is between- rather than within-category. Participants were centrally fixated with the presentation of a flashing bullseye, then a grey screen was presented for 250ms, and then the target and background were simultaneously presented. The target was a coloured circle (2cm diameter, visual angle = 3.22˚), and this was presented in one of eight locations on a coloured background that filled the entire display (40 x 30cm). The eight possible target locations were positioned in a ring around the central fixation point – this 'ring design' has been used in studies of visual search to standardize the distance of the target to the central fixation point (e.g., Adler & Orprecio 2006).

Participants' eye-movements while completing the task were recorded with an ASL eye-tracker. The eye-tracker provides an accurate record of the participants' eye-movements so that scan paths, speed of fixation, and duration of fixation can all be monitored. The usual measure of perceptual similarity in adult studies of categorical perception is reaction time. However, eye-movements are also considered to be a reliable index of perceptual similarity. For example, studies that have recorded both reaction time and eye-movements when adults are completing a visual search task, have highlighted the correspondence between reaction time and eye-movement measures such as the number of fixations and eye-movement latencies (Mailoli, Bengalio, Siri, Sosta & Cappa 2001; Shen, Reingold & Pomplun 2000; Zelinsky & Sheinberg 1997) and it has been claimed that "saccades and perception share a similar visual processing mechanism" (Beutter, Eckstein & Stone 2003:1532). Eye-tracking has also previously been used to investigate perceptual and cognitive abilities in infancy (Adler & Orprecio 2006; Gredebäck & von Hofsten 2004; Hunnius & Geuze 2004; Johnson, Slemmer & Amso 2004; Lécuyer, Berthereau, Taïb & Tardiff 2004; McMurray & Aslin 2004). Therefore, for both infants and adults, eye-tracking data was used to assess the time taken for the participant's fixation to move from the central fixation point to the target. Target fixation time was compared for between- and within-category targets. If participants show category effects on this task, we would expect them to be faster at fixating the target when the chromatic difference of the target and the background was between- rather than within-category.

Category effects across the blue-green boundary were tested. The colour of the target (green) was fixed, and the colour of the background was either from the same colour category (green) or from a different colour category (blue). The target and background colours differed only in hue (lightness and saturation were kept constant), and the chromatic difference of the target and the background was equated for between- and within-category pairs in CIE (L*u*v* 1976) space. For the adults, there were two target-background chromatic separation sizes: 23ΔE and 40ΔE (see Figure 5).

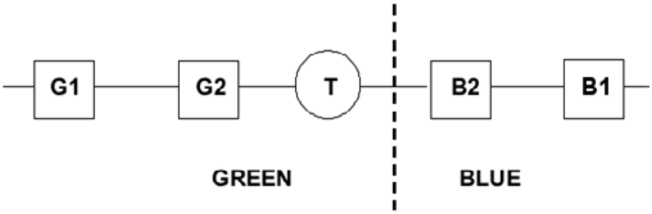


Figure 5: *Diagrammatic representation of the five stimuli: the target (T) and the four background stimuli (G1/G2/B1/B2). The dashed line represents the category boundary. The four conditions are: between/far (T-B1); between/near (T-B2), within/far (T-G1), within/near (T-G2). (Figure from Franklin, Pilling & Davies 2005).*

Therefore, for the adults, there were four conditions: target and background between-category, separation size 23ΔE; target and background within-category, separation size 23ΔE; target and background between-category, separation size 40ΔE; target and background between-category, separation size 40ΔE. For the adults, there were three trials for each condition. Infants were only tested with the 40ΔE between- and within-category stimulus pairs. For the infants, there were six trials for each condition.

How can adults’ and infants’ performance on this task tell us anything about the nature of infant colour categories? First, unlike the habituation and novelty preference tasks, the target detection task has no memory component. Therefore, if category effects are shown by infants on this task, then it is unlikely that the category effect could be ‘categorical memory’, and more likely that the category effect would be a truly perceptual effect. Second, compared to habituation and novelty preference tasks, inferences about discrimination are more easily made. Eye-movements can be monitored to assess whether infants actually do discriminate the target and the background colour. If infants cannot discriminate within-category stimuli (as the lack of dishabituation and novelty preference in Bornstein et al. and Franklin and Davies' investigations may suggest), then infants would not fixate the target when it is presented on a coloured background from the same colour category. This would suggest that the category effect in infants is more absolute than the category effect in adults. However, if infants do fixate the target on the within-category conditions, then this would suggest that the category effect is not more absolute in infants, and that the lack of within-category dishabituation or novelty preference is actually an artifact of habituation and novelty preference techniques. Finally, as the target detection task is a task that can be used for both infants and adults, and as the task demands (both are just required to look) and the way of measuring target fixation (recording eye-movements) are the same for both infants and adults, direct comparisons of the category effect in infants and adults can be made.

Adults fixated the target on 100% of the trials. Figure 6 shows the target fixation times for adults on these trials, for the two chromatic separation sizes. As can be seen in Figure 6, adults show a category effect for both separation sizes. Adults were faster at fixating the target (around 40ms faster) when on a between-category background than a within-category background.

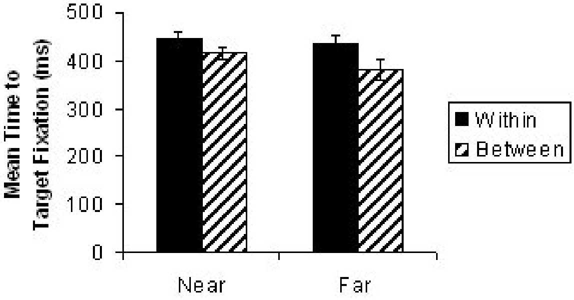


Figure 6: *Mean target fixation times (ms) (+/-1 SE) of adults for between- and within-category stimulus pairs for two separation sizes. (Figure from Franklin, Pilling & Davies 2005).*

For the infants, a good eye-track was obtained for 75% of the trials. When eye-tracking infants, it is usual not to obtain a good eye-track for a proportion of the trials as, if infants move their heads excessively, or if they 'scrunch up' their eyes, then the eye-tracker cannot record the eye-movement successfully (see Haith 2004). Of the trials for which a good eye-track was obtained, infants fixated the target on 85% of the within-category trials, and 88% of the between-category trials. This difference was not significant. However, of the trials on which the target was fixated, there was a significant difference in speed of target fixation for between- and within-category conditions. The average fixation time for the between-category condition was (1101ms, sd = 539) and the average fixation time of the within-category condition was (1529ms, sd = 660). Therefore, infants were around three times slower than adults at fixating the target, yet they were still faster at fixating the target (around 500ms faster) when on a between- than within-category background.

First, these results suggest that the category effect in infants is not based on a memory process, and suggest that the categorical responding in infants, as in adults, is likely to be perceptual. Second, these results show that four-month-old infants can discriminate two within-category stimuli, they are merely slower at discriminating within- than between-category colours (just like adults). Therefore, this suggests that categorical responding in infants is not more absolute than in adults. Why do infants discriminate within-category stimuli on the target detection task in Franklin, Pilling and Davies' investigation, yet show no evidence of discriminating within-category stimuli on habituation or novelty preference tasks? The within-category stimulus separation sizes were much larger in Bornstein et al.'s investigation (up to 252ΔE) than in Franklin, Pilling & Davies' investigation (40ΔE), so the lack of within-category novelty preference or dishabituation is not due to smaller separation sizes. It may be that the lack of within-category dishabituation or novelty preference is an artifact of habituation and novelty preference tasks – either these tasks encourage prototypical responding, or they are not sensitive to perceptual discrimination (see Franklin, Pilling & Davies 2005, for further discussion). Either way, the important thing to note is that, even though infants could discriminate within-category stimuli on the target detection task, they were still slower at doing this than discriminating between-category stimuli. Infants still show a category effect.

3. *Further evidence for pre-linguistic colour categorization*

To summarize, categorical responding to colour by four-month-old infants has been shown using habituation, novelty preference and target detection tasks. Four-month-old infants categorize a range of colours – blue, yellow, green, red, purple and pink have been tested so far. It is likely that this categorization is perceptual. Therefore, there is evidence that perceptual colour categorization is found pre-linguistically. Converging evidence for pre-linguistic colour categorization has also been provided from investigations of toddlers' colour perception. For example, Franklin, Clifford, Williamson and Davies (2005), using a 2-AFC task, investigated categorical responding to colour in 2- and 3-year-olds. Category effects were tested across the same boundaries and using the same stimuli as in Franklin and Davies' investigation of infant colour categories. The 2-AFC task was made into a game about finding the right-coloured jumper for a bear (see Franklin et al. 2005, for details of the method). After being shown a target colour, children were significantly more accurate at identifying the target when it was presented alongside a between-category stimulus than a within-category stimulus. This facilitation of recognition memory for between-category stimuli compared to within-category was found across all three boundaries (blue-green, blue-purple, pink-red). Toddlers also completed naming and comprehension tasks. The category effect was found even in toddlers who did not yet linguistically mark the category boundaries, and the size of the category effect was not related to naming or to the number of colour terms known. In addition, the category effect was tested for in Himba toddlers (a people of Namibia, whose language segments the colour space differently to the English language). Himba toddlers learn their colour terms later than English toddlers (Androulaki 2003), so the groups of toddlers tested knew no colour terms at all. Despite this, the Himba toddlers also showed categorical responding in a similar manner to that of English-speaking toddlers. These findings suggest that categorical responding is found in toddlers irrespective of colour term acquisition.

As a 2-AFC task is a memory task, the category effect need not necessarily be perceptual. Franklin et al. (2005) investigated this by manipulating the length of the delay between the presentation and identification of the target. If the category effect is based on a memory process, then the category effect should weaken as the delay is reduced. The category effect was even found when there was no delay between the presentation and identification of the target, and there was no effect on length of delay on the strength of the category effect, suggesting that the effect is likely to be perceptual. Recent research has also found categorical responding in toddlers with no colour terms, using a discrimination threshold task (Franklin, Özgen, Drew & Davies in prep). Toddlers' discrimination thresholds are shown to be higher in the centre of the blue and green colour categories than at the blue-green category boundary. As the threshold task has no memory component, it appears that the category effect is perceptual.

4. *Implications for the debate*

The evidence outlined in this chapter shows that perceptual colour categorization can be found before colour terms are learnt. What are the implications of this for the debate about the origin of colour categorization? The evidence is problematic for the theory that colour categories are linguistically constructed. However, if colour categories are not linguistically constructed, how do we explain the evidence from cross-cultural studies of colour categorization in adults (e.g. Kay & Kempton 1984; Roberson, Davies & Davidoff 2000), and in children (Daoutis, Franklin, Riddett, Clifford & Davies 2005) which suggest that categorical responding is only shown when the category boundary is marked by the speaker's language. One possibility is that colour categorization is not linguistically constructed, yet is linguistically modified. This 'perceptual re-organization' theory suggests that perceptual colour categorization is innate – we automatically carve up the colour space into different categories, yet language modifies the location and strength of category boundaries when colour terms are learnt and when colour terms become 'cognitively engrained'. There is evidence that perceptual discrimination is flexible (see Fahle & Poggio 2002), and can be influenced by learning language (e.g. Özgen & Davies 2002). There is also evidence that similar mechanisms are at play in other domains of perceptual development such as speech perception (e.g. Werker & Tees 1984), and spatial perception (e.g. Hespos & Spelke 2004). However, the 'perceptual re-organization' model as an account of the origin and development of colour categorization remains highly speculative. Cross-cultural developmental studies, using perceptual tasks to test for category effects in infants and throughout development, are needed to test the theory.

The finding that perceptual colour categorization is shown before the acquisition of colour terms, in some ways, raises more questions than it answers. For example, if there is an innate set of perceptual colour categories, why do different languages segment the colour space differently from each other? Why does language not follow on from perception? If colour categorization is hardwired, what are the perceptual mechanisms for this – is it retinal or cortical? These questions are hard ones to answer, but they need to be answered before we can fully understand the origins of perceptual and linguistic colour categories.

5. *Conclusions*

This paper has outlined and discussed the evidence that perceptual colour categorization can be found pre-linguistically. It has been shown that four-month-old infants respond categorically across a range of colour boundaries, and that this categorical responding is likely to be perceptual. It has been shown that toddlers who have not yet learnt their colour terms, or who do not yet linguistically mark category boundaries, still respond categorically to a range of colour boundaries, and that this categorical responding is also likely to be perceptual. So the evidence outlined here overwhelmingly suggests that perceptual colour categorization can be found in the absence of language. This suggests that colour categorization is not linguistically constructed. The evidence presented in this chapter is not incompatible with cross-cultural research that shows a parallel between language and the category effect, as the location of category boundaries may be 'perceptually reorganized' by language when colour terms are learnt. Further research is needed to investigate the origins and interactions of perceptual and linguistic colour categorization.

References

Adler, Scott K. & Jazmine Orprecio. 2006. "The Eyes Have It: Visual Pop-out in Infants and Adults". *Developmental Science*.

Androulaki, Anna. 2003. *Colour Term Acquisition and the Development of Working Memory in Children: a Cross-linguistic Investigation and a Test of the Linguistic Relativity Hypothesis*. Ph.D. dissertation, University of Surrey.

Aslin, Richard N. & Bob McMurray. 2004. "Automated Corneal-reflection Eye-tracking in Infancy: Methodological Developments and Applications to Cognition". *Infancy* 6.155-163.

Beutter, Brent R., Miguel P. Eckstein & Leland S. Stone. 2003. "Saccadic and Perceptual Performance in Visual Search Tasks, I: Contrast Detection and Discrimination". *Journal of the Optical Society of America* A20.1341-1355.

Bornstein, Marc H., William Kessen & Sally Weiskopf. 1976. "Color Vision and Hue Categorization in Young Infants". *Journal of Experimental Psychology: Human Perception and Performance* 1.115-129.

— & Nancy O. Korda. 1984. "Discrimination and Matching Within and Between Hues Measured by Reaction Times: Some Implications for Categorical Perception and Levels of Information Processing". *Psychological Research* 46.207-222.

Catherwood, Di, Boris Crassini & Kate Freiberg. 1987. "The Nature of Infant Memory for Hue". *British Journal of Developmental Psychology* 5.385-394.

—, Boris Crassini & Kate Freiberg. 1989. "Infant Response to Stimuli of Similar Hue and Dissimilar Shape: Tracing the Origins of the Categorization of Objects by Hue". *Child Development* 60.752-762.

—, Boris Crassini & Kate Freiberg. 1990. "The Course of Infant Memory for Hue". *Australian Journal of Psychology* 42.277-285.

Daoutis, Christine, Anna Franklin, Amy Riddett, Ally Clifford & Ian R. L. Davies. 2005. “Categorical Effects in Children’s Color Search: a Cross-linguistic Comparison”. *British Journal of Developmental Psychology* (in press).

—, Michael Pilling & Ian R. L. Davies. 2006. “Categorical Effects in Visual Search for Color”. *Visual Cognition* (forthcoming).

Davies, Ian R.L. & Anna Franklin. 2002. “Categorical Similarity May Affect Colour Pop-out in Infants After All”. *British Journal of Developmental Psychology* 20.185-203.

Fahle, Manfred & Tomaso Poggio. 2002. *Perceptual Learning*. Cambridge, Mass.: MIT Press.

Franklin, Anna, Ally Clifford, Emma Williamson & Ian R. L. Davies. 2005. “Color Term Knowledge Does not Affect Categorical Perception of Color in Toddlers”. *Journal of Experimental Child Psychology* 90.114-141.

— & Ian R. L. Davies. 2004. “New Evidence for Infant Color Categories”. *British Journal of Developmental Psychology* 22.349-377.

—, Emre Özgen, Rachel Drew & Ian R. L. Davies. In prep. “Toddlers’ Hue Discrimination Thresholds Show Category Effects even before Colour Term Acquisition”.

—, Michael Pilling & Ian R. L. Davies. 2004. “Category Effects in Visual Search: Evidence from Eye Movement Latencies”. *Perception* 32.147.

—, Michael Pilling & Ian Davies. 2005. “The Nature of Infant Color Categorization: Evidence from Eye Movements on a Target Detection Task”. *Journal of Experimental Child Psychology* 91.227-248.

Gerhardstein, Peter, P. Renner & Carolyn Rovee-Collier. 1999. “The Roles of Perceptual and Categorical Similarity in Colour Pop-out in Infants”. *British Journal of Developmental Psychology* 17.403-420.

— & Carolyn Rovee-Collier. 2002. “The Development of Visual Search in Infants and Very Young Children”. *Journal of Experimental Child Psychology* 81.194-215.

Gredebäck, Gustaf & Claes von Hofsten. 2004. “Infants’ Evolving Representations of Object Motion during Occlusion: a Longitudinal Study of 6- to 12-month-old Infants”. *Infancy* 6.165-184.

Haith, Marshall M. 2004. “Progress and Standardization in Eye Movement Work with Human Infants”. *Infancy* 6.257-265.

Hespos, Susan J. & Elizabeth S. Spelke. 2004. “Precursors to Spatial Language”. *Nature* 430.453-456.

Hunnius, Sabine & Reint H. Geuze. 2004. “Developmental Changes in Visual Scanning of Dynamic Faces and Abstract Stimuli in Infants: a Longitudinal Study”. *Infancy* 6.231-255.

Huttenlocher, Janellen, Larry V. Hedges & Jack L. Vevea. 2000. “Why Do Categories Affect Stimulus Judgment?” *Journal of Experimental Psychology: General* 129.220-241.

Johnson, Scott P., Jonathan A. Slemmer & Dima Amso. 2004. “Where Infants Look Determines How They See: Eye Movements and Object Perception in 3-month-olds”. *Infancy* 6.185-201.

Kawai, M., K. Uchikawa & H. Ujike. 1995. “Influence of Color Category on Visual Search”. *Investigative Opthalmology* 36.654.

Kay, Paul & Willett Kempton. 1984. “What is the Sapir-Whorf Hypothesis?” *American Anthropologist* 86.65-79.

Lécuyer, Roger, Sophie Berthereau, Amel B. Taïb & Nadia Tardiff. 2004. “Location of a Missing Object and Detection of its Absence by Infants: Contribution of an Eye-tracking System to the Understanding of Infants’ Strategies”. *Infant and Child Development* 13.287-300.

McMurray, Bob & Richard N. Aslin. 2004. “Anticipatory Eye Movements Reveal Infants’ Auditory and Visual Categories”. *Infancy* 6.203-229.

Maioli, Claudio, Irene Bengalio, Simona Siri, Katiuscia Sosta & Stefano Cappa. 2001. “The Integration of Parallel and Serial Processing Mechanisms in Visual Search: Evidence from Eye Movement Recording”. *European Journal of Neuroscience* 13.364-372.

Özgen, Emre. 2004. “Language, Learning, and Color Perception”. *Current Directions in Psychological Science* 13.95-98.

— & Ian R. L. Davies. 2002. “Acquisition of Categorical Color Perception: a Perceptual Learning Approach to the Linguistic Relativity Hypothesis”. *Journal of Experimental Psychology: General* 131.477-493.

Pereverzeva, Maria, Sarina H-L. Chien, John Palmer & Davida Y. Teller. 2002. “Infant Photometry: Are Mean Adult Isoluminance Values a Sufficient Approximation to Individual Infant Values?” *Vision Research* 42.1639-1649.

Roberson, Debi. 2005. “Color Categories are Culturally Diverse in Cognition as Well as in Language”. *Cross-Cultural Research* 39.56-71.

—, Ian R. L. Davies & Jules Davidoff. 2000. “Color Categories Are Not Universal: Replications and New Evidence from a Stone-Age Culture”. *Journal of Experimental Psychology: General* 129.369-398.

Shen, Jiye, Eyal M. Reingold & Marc Pomplun. 2000. “Distractor Ratio Influences Patterns of Eye Movements During Visual Search”. *Perception* 29.241-250.

Snyder, Kelly A., Michael P. Blank, Danielle M. Cheek, Dana M. Kuefner & Chad J. Marsolek. 2004. “Converging Evidence for a Dissociation Between Preferential-looking in the Visual-paired Comparison Task and

Recognition Memory”. Poster presented at the Annual Meeting of the Cognitive Neuroscience Society, San Francisco.

Uchikawa, Keiji & Hiroyuki Shinoda. 1996. “Influence of Basic Color Categories on Color Memory Discrimination”. *Color Research and Application* 21.430-439.

Werker, Janet F. & Richard C. Tees. 1984. “Cross-language Speech Perception: Evidence for Perceptual Reorganization During the First Year of Life”. *Infant Behavior and Development* 7.49-63.

Werner, John S. & Billy R. Wooten. 1985. “Unsettled Issues in Infant Color Development”. *Infant Behavior and Development* 8.99-107.

Whorf, Benjamin L. 1956. *Language, Thought and Reality: Essays by B.L. Whorf* ed. by John B. Caroll. Cambridge, Mass.: MIT Press.

Wyszecki, Gunter & W. S. Stiles. 2000. *Color Science: Concepts and Methods, Quantitative Data and Formulae.* New York: John Wiley.

Zelinsky, Gregory J. & Sheinberg, David L. 1997. “Eye Movements During Parallel-serial Visual Search”. *Journal of Experimental Psychology: Human Perception and Performance* 23.244-262.

COLOUR CATEGORIZATION IN PRESCHOOLERS

VALERIE BONNARDEL & NICOLA J. PITCHFORD
University of Sunderland & University of Nottingham

1. *Introduction*

Human observers effortlessly divide the physical continuum of wavelength, or sort a set of coloured samples, into a finite number of categories. Moreover, these perceptual colour categories are indexed with linguistic labels that enable successful communication between individuals sharing the same language, although the number of basic colour terms differs across languages. The origin of the mechanisms underpinning colour categorization remains hypothetical. A traditional controversy opposes the view of 'universalists', who consider colour categories to be constrained by the physiology of the visual system, to that of 'relativists', who recognize the fundamental role of culture and language in the way people perceive and name colours.

Berlin and Kay's (1969) landmark cross-cultural study that was conducted with speakers from over twenty different languages suggested colour categories were universal in nature. In particular, the best exemplars of a particular colour category that was marked across languages tended to cluster in a relatively small portion of the colour space. This area of colour space is typically referred to as the focal area for a particular colour. However, results from other cross-cultural studies have demonstrated the influence of linguistic colour categories in facilitating colour recognition and influencing perceptual colour judgments (e.g. Davidoff, Davies & Roberson 1999; Roberson 2005). At present, this contentious debate remains unresolved (see Schirillo 2001 and Jameson 2005 for critical reviews).

A possible reason for the contradictory results, and their subsequent interpretation, from cross-cultural studies of colour categorization is that different tasks are typically employed across studies, and these, in turn, may tap different levels of colour representation, which may have a different underlying organization. Many studies, including those cited above, have used colour-naming tasks to assess colour categorization. However, as Sayim, Jameson and

Alvarado (2003) point out, the underlying assumption in these studies is that colour terms can be considered as proxies for colour percepts, yet the results from their study that compared similarity judgments of colour words (lexical) and colour samples (perceptual) suggested otherwise. The authors proposed that their results were best accounted for by positing two levels of colour representations: linguistic representations that have a normative organization based on the use of colour terms within a culture, and perceptual representations that may vary uniquely across individuals (Jameson 2005). Franklin, Clifford, Williamson and Davies (2005) have also noted that colour categorization behaviour could arise at the level of perception, memory, and / or labelling, and that each of these factors may have a differential influence, depending on the task used. In order to address this issue experimentally, studies need to use tasks designed to isolate particular levels of representation, although this is difficult to achieve with adult participants that have fully established systems of colour processing, as any colour sample will automatically activate representations at the perceptual and linguistic level.

This issue can, however, be addressed by adopting a developmental approach and contrasting the performance of children that have established perceptual representations of colour but only emerging linguistic representations, with that of adults with a fully established perceptual-linguistic colour processing system. Infant studies suggest that, well before the onset of colour term acquisition, colour percepts are categorically organized in a similar manner to that shown by adults. Children as young as four months of age show novelty preference for colours from a different, rather than from the same, category to which they have previously been exposed (Bornstein, Kessen & Weiskopf 1976; Catherwood, Crassini & Freilberg 1989; Franklin & Davies 2004, this volume). Furthermore, categorical responding appears to be consistent across childhood, as children aged two to four years, more accurately identify colours belonging to different categories than colours from the same category, and this has been shown to be independent of the degree of colour term knowledge acquired (Franklin et al. 2005; see also Franklin & Davies, this volume).

These studies suggest that infants possess a categorical organization of colour percepts prior to the onset of colour term acquisition. Moreover, Pitchford and Mullen (2003) showed that, during the period in which children acquire a basic colour vocabulary, their erroneous colour naming appears to be influenced by perceptual similarity, as children progress from applying colour terms in a haphazard and inconsistent manner (for example, naming red as *blue*, *black*, *pink*, and so on) to perceptually-bound adjacent colour categories (for example, naming red as *pink* or *purple* only). The influence of perceptual similarity on the misapplication of colour terms during colour term acquisition suggests that a categorical system of colour percepts exists prior to the complete acquisition of colour terms, and that the task of colour term acquisition involves mapping linguistic labels onto this perceptual system of colour categories (see Pitchford & Mullen, this volume).

How uniform the perceptual organization of colour in early childhood is, however, remains to be determined. Whilst infant studies show evidence of category boundaries marked at the same point in colour space as in adults, these studies test for category effects over a limited number of colour samples, typically four per boundary. Although this methodology shows the existence of categorical perception at a particular point of a category boundary, it does not allow the partitioning of colour space over entire boundaries to be revealed. Studies with adults using tasks that sample across a larger range of colour space show variations in the extent of uniformity to which adults represent colour perceptually (e.g. Jameson 2005). As a result, Jameson argues that lexical representations of colour serve to normalize perceptual colour space by providing a consensus that is adaptable across languages.

In this study, we examined the possibility that language serves to sharpen the categorical organization of colour percepts by comparing the performance exhibited on a standard experimental colour-sorting paradigm across groups of children and adults that vary in their ability to name colours accurately. We gave young children aged between two and four years (that is, the developmental period in which children acquire basic colour terms, see Pitchford & Mullen 2002) and young adults, the same colour-sorting task, thus allowing direct comparison across participant groups. We used a constrained sorting-task that required participants to allocate each of one hundred different Munsell chips into one of eight perceptual colour categories (identified by a focal colour chip). As such, the task does not require the explicit use of colour names and can be performed on a purely perceptual dimension only. However, the eight perceptual colour categories were chosen to correspond to the eight basic chromatic colour terms used in English, hence the task could also be performed using a colour naming strategy.

By comparing children with emerging colour term knowledge to those with accurate colour naming skills, and adults with fully automated colour naming, we examined the influence of lexical representations of colour on the division of colour samples across eight perceptual colour categories. In addition, the one hundred Munsell samples used in our task were a subset of the 160 samples used by Davidoff et al., (1999) in a colour-naming task with adults, thus this also enabled us to compare directly the colour categories set up by our participants in the colour-sorting task to those obtained by adults in a colour-naming task.

2. *Question of terminology*

The term *colour* is traditionally ambiguous, designating both the stimulus (wavelength or surface reflectance) and the percept (colour sensation). In the present study, ambiguity lies between the colour percepts elicited by a given set of Munsell samples varying in hue, saturation, and luminance, and the category name ascribed to this set. For practical reasons, we assigned a colour name to a given set of colour samples, and the name we used was the consensus name provided in an explicit colour-naming task to those particular colour samples. In such instances we use the following notation: for example, [Red].

3. *Method*

3.1 *Participants*

A group of fifty preschool children (28 boys and 22 girls, aged 26-57 months, SD = 9 months), and a group of thirty adults (15 men and 15 women, mean age 29 years old, SD = 9 years) participated in the experiment, all of whom were screened for colour vision deficits using standardized colour plates (Matsubara 1957). Children were recruited to the study via two local daycares in Nottinghamshire, and the volunteers' register at the Nottingham Toddler Lab. Adult participants were members of the School of Psychology at the University of Nottingham.

3.2 *Colour-sorting task*

All participants (both children and adults) were given the same task of colour categorization under daylight illumination conditions. Categorical perception was assessed using a constrained colour-sorting task, in which participants were required to sort one hundred Munsell chips into eight colour categories. The set of Munsell chips was systematically selected from the most saturated chip available at each of two hue values (5 and 10) for the ten Munsell hues, at each of five lightness values (from 8 to 4).

Children were sat facing a semi-circular arrangement of eight boxes placed on a neutral-coloured table. On the front of each box was a picture of a teddy-bear and an anchor colour chip. The anchor chip corresponded to the most representative sample of the [Red] (7.5R 4/16), [Pink] (5RP 7/8), [Orange] (2.5YR 6/16), [Brown] (7.5R 4/8), [Yellow] (2.5Y 8/16), [Green] (7.5GY 6/12) [Blue] (2.5PB 5/12) and [Purple] (2.5P 4/12) categories, as judged by the authors. Children were told that each of the teddy-bears collected colours but only colours like the one on the box (that is, the anchor colour chip). The one hundred chips were then presented individually, in a random order, and the child was required to place the chip in the box belonging to the teddy-bear that collected that particular colour. The order of box and chip presentation was randomized across participants.

To ensure that children understood the task demands, a pre-test (employing four basic shapes and four basic colours) was given, in which children were required to sort sixteen stimuli (two for each of the four shapes and four colours) into the corresponding boxes. Only children that successfully completed all of the control stimuli participated in the colour categorization experiment.

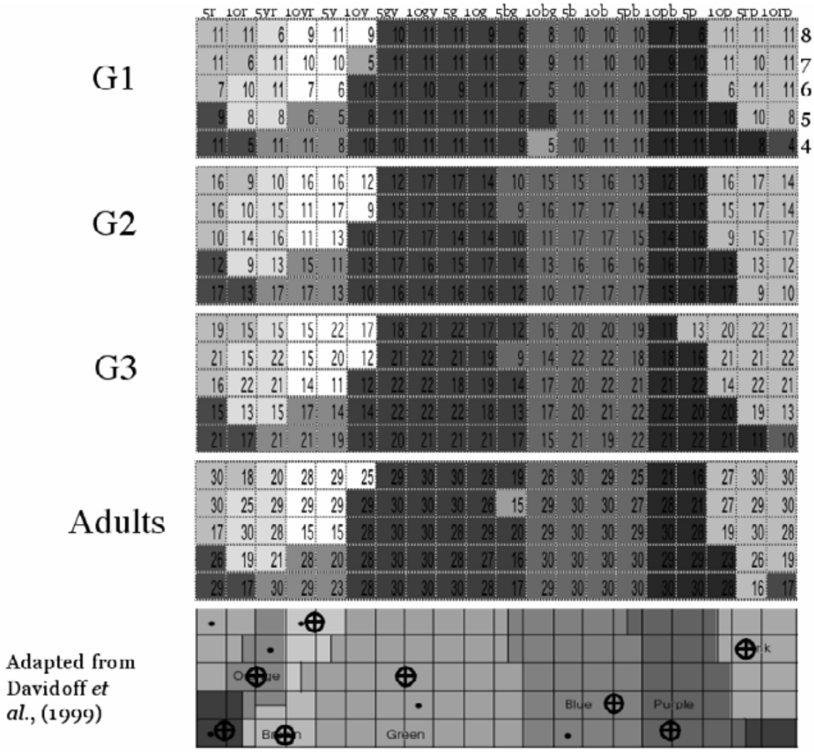
Upon completion of the colour-sorting task, children were asked to name each of the eight anchor chips on the teddy-bear boxes on three separate occasions. This was to establish an index of colour naming for each of the eight basic colours used in the experiment. Children were then grouped on the basis of their colour-naming ability into one of three naming groups: group 1 (G1) were starting to learn colour terms and consisted of children that named 75% or less of colour chips accurately (N = 11, 6 boys and 5 girls, mean age 33.6 months, SD = 6 months); group 2 (G2) were developing colour term knowledge and consisted of children that named more than 80% of the colours accurately but were not 100% accurate (N = 17, 9 boys and 8 girls, mean age 38.7 months, SD = 7.8 months); and group 3 (G3) had acquired basic colour terms and consisted of children that achieved 100 % accuracy in colour naming (N = 22, 14 boys and 8 girls, mean age 46.4 months, SD = 7.6 months). The three colour-naming groups differed significantly in chronological age, reflecting a typical developmental progression (G1 & G2, t (26) = 1.67, p = .038; G2 & G3, t (37) = 3.14, p = .0018, all one-tailed). The adult version of the colour-sorting task was to sort the one hundred colour chips in the eight colour categories as identified by the anchor colour chips on the front of each box.

4. *Results*

Data generated by each of the participants on the colour-sorting task was subjected to three separate analyses. The first analysis consisted of the derivation of a modal map and was performed to compare our sorting data directly to the naming data obtained by Davidoff et al. (1999). Secondly, for each participant group, hierarchical cluster analysis was performed to obtain a prototypical partitioning of the Munsell samples. Thirdly, multidimensional scaling analysis was conducted to obtain a representation of the cognitive structure from which partitioning of colour space is derived.

4.1 *Modal maps*

Following Davidoff et al. (1999), for each of the four participant groups, and for each of the one hundred colour chips, we determined the modal category response which referred to the colour of the anchor chip (on the box) to which the largest number of participants within a given group associated a given colour sample. Figure 1 shows the modal maps for the four groups of participants on the colour-sorting task together with the adult colour naming data obtained by Davidoff et al. (1999).



G1

5r	10r	5yr	10yr	5y	10y	5gy	10gy	5g	10g	5bg	10bg	5b	10b	5pb	10pb	5p	10p	5rp	10rp	
11	11	6	9	11	9	10	11	11	9	6	8	10	10	10	7	6	11	11	11	8
11	6	11	10	10	5	11	11	11	11	9	9	11	10	10	9	10	11	10	11	7
7	10	11	7	6	10	11	10	9	11	7	5	10	11	10	11	11	6	11	11	6
9	8	8	6	5	8	11	11	11	11	8	6	11	11	11	11	11	10	10	8	5
11	5	11	11	8	10	10	11	11	11	9	5	10	11	11	11	11	11	8	4	4

G2

16	9	10	16	16	12	12	17	17	14	10	15	15	16	13	12	10	16	17	14
16	10	15	11	17	9	15	17	16	12	9	16	17	17	14	13	15	15	17	14
10	14	16	11	13	10	17	17	14	14	10	11	17	17	15	14	16	9	15	17
12	9	13	15	11	13	17	16	15	17	14	13	16	16	16	16	17	13	13	12
17	13	17	17	13	10	16	14	16	16	12	10	17	17	17	15	16	17	9	10

G3

19	15	15	15	22	17	18	21	22	17	12	16	20	20	19	11	13	20	22	21
21	15	22	15	20	12	21	22	21	19	9	14	22	22	18	18	16	21	21	22
16	22	21	14	11	12	22	22	18	19	14	17	20	22	21	21	22	14	22	21
15	13	15	17	14	14	22	22	22	18	13	17	20	21	22	22	20	20	19	13
21	17	21	21	19	13	20	21	21	21	17	15	21	19	22	21	22	21	11	10

Adults

30	18	20	28	29	25	29	30	30	28	19	26	30	29	25	21	16	27	30	30
30	25	29	29	29	29	30	30	30	26	15	29	30	30	27	28	21	27	29	30
17	30	28	15	15	28	30	30	28	29	20	29	30	30	29	30	28	19	30	28
26	19	21	28	20	28	30	30	28	27	16	30	30	30	30	29	29	23	26	19
29	17	30	29	23	28	30	30	30	28	17	29	30	30	30	30	30	28	16	17

Adapted from Davidoff *et al.*, (1999)

Figure 1: *Partitioning of the one hundred Munsell samples obtained from the four participant groups on the colour-sorting task (G1, beginning colour namers (N = 11); G2, developing colour namers (N = 17); G3, accurate colour namers (N = 22); adults).*

As is clearly shown, the modal maps first reveal remarkably similar patterns of performance on the colour-sorting task across the four groups of participants, as they differ, in total, by only eight colour samples.[1] This result would suggest a consistent and robust partitioning of colour samples across colour space that is unaffected either by age or the level of colour term acquisition. Secondly, the modal maps generated by our participants on the colour-sorting task are almost identical to that obtained by adults who performed a colour-naming task reported by Davidoff et al. (1999), the main difference being in the extension of the green category to the 5Y sample row in the naming task. Thus, despite a difference in task and in participants (children and young adults compared to twenty-two mostly older women in Davidoff et al.'s study), little variation is observed in the colour categories. This result suggests an almost perfect isomorphism between sorting and naming of colour samples into basic categories.

4.2 *Hierarchical cluster analysis*

The modal maps reported above provide one method for representing the categorical structure embedded in the sorting data but, essentially, this method lacks information pertaining to the degree of consensus with which samples have been placed in a given box. As a result, inter-group differences concerning the degree of agreement between participants in sorting the colour samples might have been missed by the modal analysis.

Cluster analysis offers a method of grouping colour samples based on their degree of association, such that those within each cluster are more closely related to one another than samples assigned to different clusters. In the present study, the degree of association reflects the consensus between participants so that the more participants who place two colour samples in the same box, the closer these two samples will be associated. Moreover, it has been suggested that this is the heuristic used in the cognitive process of categorization (Garner 1974, cited by Jameson 2005). Thus, for each participant group, the cluster analysis provides a prototypical partitioning of colour space based directly on the degree of association between colour samples. In addition, the cluster analysis will reflect the emergence of categories within a particular participant group with each successive increase in the number of clusters derived (ranging from two to eight clusters).

For each group of participants, similarity matrices were derived, in which

---

[1] In the case of bimodality, the box colour chosen was that attributed by the other three groups to a particular sample.

cell entries corresponded to the number of participants who placed a given pair of colour samples together (that is, in the same box) for each of the possible colour pairings ([100X99]/2). Prototypical colour mappings for each group were obtained using a hierarchical cluster analysis (using the between-groups linkage method for count data) for two to eight clusters.

Results are shown in Figure 2. Despite local differences in category boundaries, for up to five clusters the resulting categories are very similar across the four participant groups and correspond to [Blue], [Green-turquoise], [Purple], [Pink-red], [Yellow-orange-brown-red].[2] These five primitive clusters are also in good agreement with those derived from the modal maps as reported in Figure 1. At six clusters, the four groups operate a division within [Yellow-orange-brown-red] and, at seven clusters, this category is further divided by the adults and the children with developing or accurate colour term knowledge (G2 and G3) so that, at this stage, the three groups share the same seven categories. However, at this level, the youngest children, who were beginning to learn colour terms, split the [Green] category vertically to form a [Turquoise] category. By eight clusters, the adults' mapping diverges from that of the older child groups (G2 and G3) by setting a [Turquoise] category (5BG column), whereas these children single out three dark samples from the [Pink] and [Orange] categories to form a [Red] category. For the youngest children in G1, this stage is characterized by a vertical boundary that splits the [Orange] category (see Figure 2).

Quantitative consideration shows the partitioning of colour samples is identical for 69% of the colour samples across the four participant groups. Children in G2 and G3 (developing and accurate colour namers) provide the most similar clusters, differing only by five colour samples. In addition, their clusters are almost identical to those derived from their modal maps, differing by only three colour samples. The partitioning of colour space by these two groups of children (G2 and G3) is identical to that of adults for 87% and 88% of the colour samples respectively. Furthermore, the adult clusters are 90% similar to the categories derived from their modal map. The main difference lies between these three participant groups and the group of younger children (G1) who are acquiring a colour vocabulary: G1 shares 78%, 79% and 82% of the samples with G2, G3, and adults respectively. In addition, the overlap of the categories derived from the cluster analysis with those derived from the modal map is reduced to 83%.

---

[2] These primitive categories further divide into the categories whose names follow the hyphen.

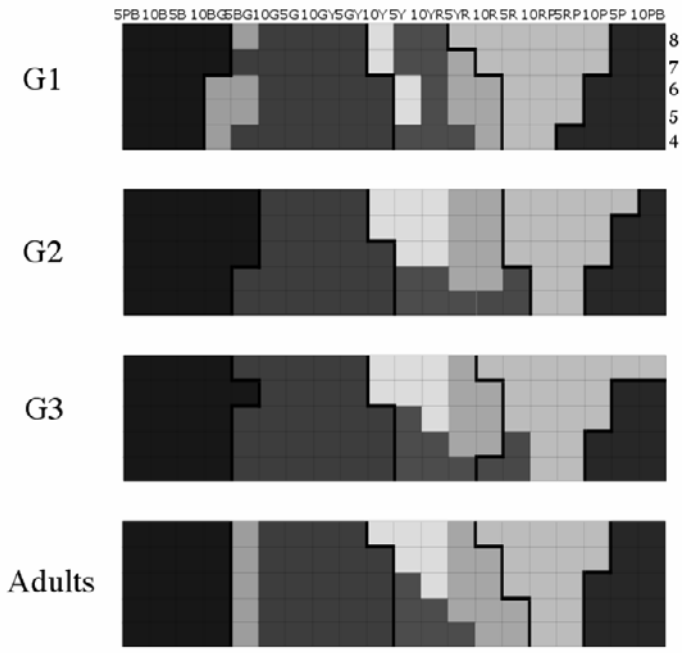


Figure 2: *Partitioning obtained from hierarchical cluster analysis. Note that the Mercator projection is organized according to the most robust cluster boundary, and starts on the left side by 5PB samples.*

In summary, as shown by the modal maps, the way in which the four participant groups partitioned the colour samples was remarkably similar, being identical for 69% of the colour samples. However, subtle differences were observed between groups in the later stages of division. The main difference in the clustering of adults compared to children with either developing or accurate colour term knowledge (G2 and G3) was the trading of the [Red] category for a [Turquoise] category, a pattern that was also observed in the youngest children (G1). However, the youngest children also make a division of the 10YR-10Y block, which is unconventional, at an inner vertical boundary, and do not follow the luminance partitioning observed in the other three groups.

4.3 *Multidimensional scaling*

To obtain a representation of the cognitive structure from which the colour categories are derived, and to compare these across the different groups of participants, we subjected our data to multidimensional scaling analysis (MDS). This technique enabled us to derive a low dimensional geometrical space in which points represent colour samples, and inter-point distances, their perceived proximity. If this type of representation is considered to be isomorphic to the structure of inner colour space, from which colour categories are derived (Romney, Boyd, Moore, Batchelder & Brazill 1996), then we may expect large inter-point distances to be indicative of category boundaries, as revealed by the cluster analysis. We applied a non-metric multidimensional scaling to our data, where if two colour samples (i, j) share the same category the cell entry is ‘1’ and if not the cell entry is ‘0’. In the resulting configuration, the distances preserved only the rank order of the proximities.

A unique solution for partitioning the colour samples was derived for each participant group using stacked individual similarity matrices. Results are shown in Figure 3a-d. A two dimensional solution provided a satisfying overall fit to the data, as a natural raw stress was found of 0.11 (Dispersion Accounted

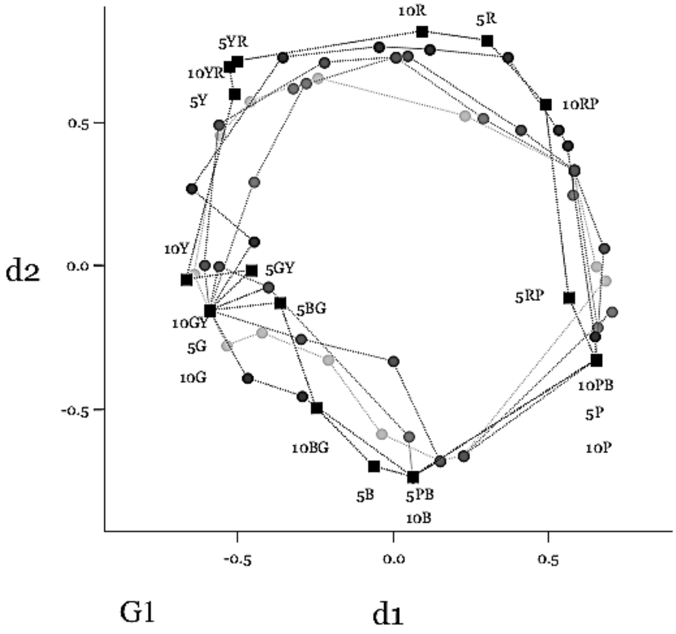


Figure 3a: *MDS solutions for beginning colour namers (G1). Samples plotted according to Munsell value: increasing value represented by increasing lightness of symbols.*

For of 89.4%) for children beginning to learn colour terms (G1); 0.12 (DAF = 88.5%) both for children with developing colour naming skills (G2) and children with accurate colour naming (G3); and 0.10 (DAF = 89.8%) for adults. Interestingly, these two dimensions, which were not pre-determined and resulted from the best fitting MDS solution to our data, correspond roughly to a red-green (d1) and blue-yellow (d2) colour opponency (see Figure 3).

As is clearly shown in Figure 3, when colour samples are plotted for each Munsell value, a complete Munsell hue circle is formed, which, apart from the inversion of samples 10B and 5B at Munsell value 8, is a flawless arrangement, with rather regular contours, especially in the case of the adult participants. For the three groups of children, hue circles show slightly less regular contours, and some Munsell hue inversions are observed, together with slightly larger variations in the data points across Munsell values. These variations can be

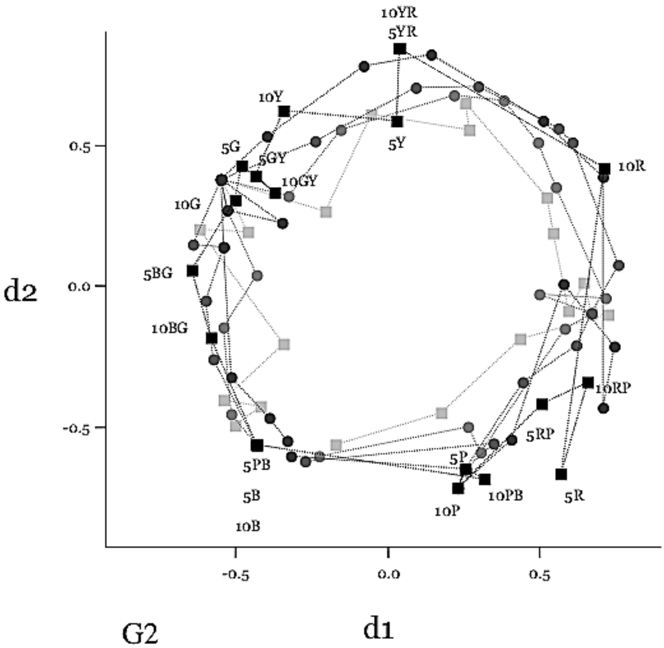


Figure 3b: *MDS solutions for developing colour namers (G2). Samples plotted according to Munsell value: increasing value represented by increasing lightness of symbols.*

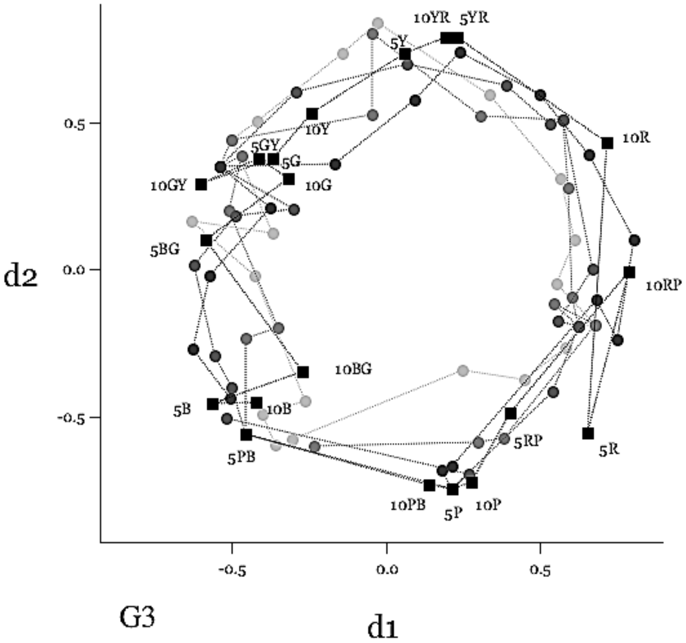


Figure 3c: *MDS solutions for accurate colour namers. Samples plotted according to Munsell value: increasing value represented by increasing lightness of symbols.*

attributed to a larger degree of statistical noise due to the smaller sample sizes of each of the child groups.

5. *Discussion*

This study aimed to investigate the influence of language on colour categorization by studying how preschool children, with varying degrees of colour naming, categorize perceptual colour space. We used one hundred different Munsell chips varying in hue, saturation and luminance, in a constrained sorting task that required participants to place individual colour samples into eight perceptually similar groupings (as identified by a focal anchor colour chip). This enabled us to investigate how colour space is partitioned across many category boundaries. The sorting behaviour of three groups of preschool children with different levels of colour naming (G1 = beginning colour namers; G2 = developing colour namers; G3 = accurate colour

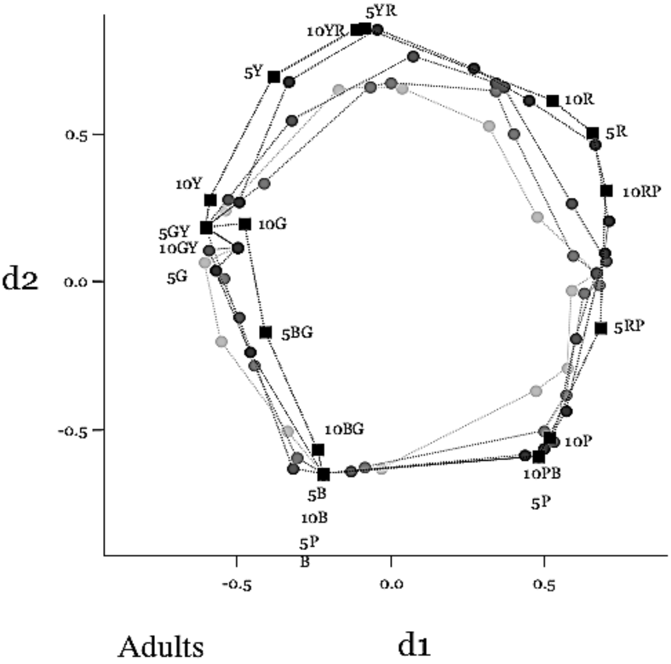


Figure 3d: *MDS solutions for adults. Samples plotted according to Munsell value: increasing value represented by increasing lightness of symbols.*

namers) was compared to that of adults, using exactly the same stimuli and task. In addition, the sorting behaviour of the colour samples for each group was compared with the naming of the colour samples by a group of adults reported by Davidoff et al. (1999).

Overall, results showed remarkable similarity between groups on the sorting task, with 69% of the chips being placed in the same colour categories by all participants, irrespective of their colour-naming abilities. In addition, the sorting behaviour of our participants corresponded closely with the naming of the colour samples by the group of adults reported by Davidoff et al. (1999), illustrating a similar categorical organization of perceptual colour space across different tasks and stages of development.

The performance of the two older groups of children (G2 and G3) was almost identical, as the two groups sorted 95% of the chips into the same colour categories, despite differing in age (G2 mean age = 38.5 months; G3 mean age = 46.5 months) and stage of colour term acquisition (developing versus accurate colour namers). Children in G2 (developing colour namers) had a mean age of 38.5 months, which corresponds with the age that Pitchford and Mullen (2002) identified as marking the end of the first stage of colour term acquisition in their dichotomous developmental order. In a large-scale study on the developmental acquisition of basic colour terms in English-speaking children living in Canada, Pitchford and Mullen (2002) showed that most children acquire knowledge of the eleven basic colour terms over two distinct time periods: first, between the ages of 36-39 months, knowledge of nine of the eleven basic colour terms is acquired (*black, white, red, green, yellow, blue, red, pink, orange* and *purple*); second, knowledge of the remaining two basic colour terms, *brown* and *grey*, is acquired, at around 46 months. Of the seventeen children in this group (G2), six failed to name BROWN accurately, two failed to name ORANGE, two failed to name PINK, and two failed to name RED. In contrast, the children in G3 had a mean age of 46.5 months, which corresponds with the age at which Pitchford and Mullen (2002) showed that complete knowledge of the eleven basic colour terms had been established. Furthermore, both of these groups showed very similar sorting behaviour to that of adults. Thus, despite differences in the stage of colour term development across groups, and the lack of accurate knowledge for specific terms exhibited by children in G2, the sorting behaviour of children in G2 and G3 was almost identical, which suggests that complete knowledge of colour terms is not essential for adult-like partitioning of the colour space.

In addition, considerable overlap was also shown between the youngest children in G1 and the other participant groups. Children in G1 had a mean age of 33.6 months and were in the first stage of acquiring a basic colour vocabulary, as evidenced by their colour-naming abilities. Within this group, the number of colour terms named correctly on each of three occasions varied from zero to six. Brown was the colour most often misnamed as nine of the eleven children in this group failed to supply the term *brown* when the category anchor sample was presented, and only one child gave this term accurately on three occasions. In contrast, red was named by eight of the eleven children on each occasion, and all children named it at least once. Between these two extremes, the other six terms were applied with varying degrees of frequency. Despite being in the process of acquiring a colour vocabulary, the children in G1 still placed approximately 80% of the colour chips in the same categories as the older children and adults, again illustrating that, in general, accurate knowledge of colour terms is not a prerequisite for an adult-like organization of perceptual colour space.

However, the performance of the youngest group of children (G1) differed from that of the older children in G2 and G3 and adults for one particular area of colour space, namely the area defined by the 5Y-10R block, where [Yellow], [Orange], [Brown] and [Red] are normally established. Within this area, the younger children set an improper hue boundary, instead of a luminance boundary shown by the older children and adults, to delineate a [Brown] category. Interestingly, *brown* was the colour term that was least likely to be applied accurately by children in G1 and denoted the only area of colour space to be partitioned in a different manner from that of the older children and adults, which suggests that, for this particular category, some degree of conceptualization may be needed for the category to be established. This appears to be specific to the colour brown however, as children in G1 also failed to name the other basic colours (although their knowledge of brown was the least accurate), yet their partitioning of all other areas of colour space was similar to that of the other participant groups with more accurate knowledge of colour terms.

The finding that children in G1 partition brown in an atypical manner to that of older children and adults is particularly interesting because Pitchford and Mullen (2002) observed that, of the eleven basic colour terms, all of the terms that refer to colour categories that lie to the outside of the colour space (BLACK, WHITE, RED, GREEN, BLUE, YELLOW, ORANGE, PINK and PURPLE) are conceptualized at an earlier stage than the terms for the categories BROWN and GREY, that fall to the inside of the colour space. It is plausible then that colour categories that lie to the outside of perceptual colour space require little, if any, mediation from language in their establishment (as evidenced by our study and that of others, for example, Franklin & Davies 2004), whereas categories forming the interior may require linguistic input to fully emerge. This speculation would be best tested by infant studies.

Another difference that emerged between groups concerns the temporal appearance of the [Red] category that was prompted by an anchor sample, and the novel generation of a [Turquoise] category, for which there was no anchor chip. Hierarchical cluster analysis showed that, for both the youngest group of children (G1) that were in the early stages of colour term acquisition and the group of adults, cluster solutions differed essentially from those of the children with either developing (G2) or accurate (G3) colour term knowledge by trading-off the [Red] category shown by the two groups of older children (G2 and G3) for a novel [Turquoise] category. This exchange could be attributed to the equally low consensus of responding in these two regions of the colour space. For the [Red] category, which was prompted by an anchor chip, the number of colour samples typically used to represent this category was very small, with an average of three chips being consistently used to mark this category by the children in G2 and G3. In the case of the novel TURQUOISE category, shown by children in G1 and adults, which was not prompted by an anchor chip, it is likely that, either the GREEN / BLUE boundary varied across these participants, thus weakening both the GREEN and BLUE borders, or that this border may not be clearly defined because of the existence of an additional [Turquoise] category between the [Green] and [Blue] borders. A [Turquoise] category has been shown to exist in Russian speakers, who were requested to sort sixty-five samples into a given number of categories (Davies 1998; Davies & Corbett 1998), so may well be perceptually isolated. As both the youngest children (G1) and the adults show emergence of a [Turquoise] category rather than a [Red] category this suggests a limited role for language in generating this category as, unlike adults, the youngest children would be unlikely to be able to identify this area of colour space with a unique colour term.

Interestingly, the five primitive clusters identified by the hierarchical cluster analysis, which were shared largely across the four groups of participants, and are broadly defined as [10P -5R: Pink-Red], [10R-5Y: Yellow-Orange-Brown], [10Y-5BG: Green], [10BG-5PB: Blue] and [10P-5P: Purple], correspond to the four elementary colour sensations to which the [Purple] category is added. This observation is consistent with infant studies that have shown categorical responding in four-month-olds using novelty preference across [Purple/Blue] (Franklin & Davies 2004) and its perceptual saliency in both English and Himba children who have not yet acquired the corresponding colour terms (Franklin et al. 2005).

Furthermore, MDS analysis revealed that the categorical organization of colour space was essentially the same for the four groups of participants, and could best be accounted for within a bi-dimensional model, in which the classical hue circle is organized along two roughly colour–opponent dimensions, red-green and blue-yellow. Although the colour circles for the three groups of children presented some hue inversions and greater variability in data point locations across luminance compared to the adults, the origin of these differences is unlikely to be attributable to the degree of colour term acquisition, as the hue circle of the youngest children (G1) showed no more inversions and no more variability across Munsell values than those generated by the groups of older children (G2 and G3). It is more likely that the increased variability shown in the hue circles of the three groups of children compared to the adults reflects greater statistical noise generated from smaller numbers of participants in the groups of children relative to the group of adults.

To summarize, this study has shown that, in general, the categorical organization of perceptual colour space is similar across the developmental period during which children acquire basic colour terms and that this organization typifies the end-state observed in adults. As such, we found little influence of language in the categorization of colour percepts, except for [Brown] which lies to the inside of perceptual colour space and is typically conceptualized later than the other basic colours.

6. *Acknowledgements*

A University of Sunderland Research Development Fellowship awarded to Valerie Bonnardel supported preparation of this paper.

References

Berlin, B. & P. Kay. 1969. *Basic Color Terms: their Universality and Evolution.* Berkeley: University of California Press.

Bornstein, M. H., W. Kessen & S. Weiskopf. 1976. “Color Vision and Hue Categorisation in Young Infants”. *Journal of Experimental Psychology: Human Perception and Performance* 1.115-129.

Catherwood, D., B. Crassini & K. Freilberg. 1989. “Infant Response to Stimuli of Similar Hue and Dissimilar Shape: Tracing the Origins of the Categorization of Objects by Hue”. *Child Development* 60.752-762.

Davidoff, J. B., I. R. L. Davies & D. Roberson. 1999. “Colour Categories in a Stone-Age Tribe”. *Nature* 398.203-204.

Davies, I. R. L. 1998. “A Study of Colour Grouping in Three Languages: a Test of the Relativity Hypothesis”. *British Journal of Psychology* 89.433-452.

— & G. Corbett. 1998. “A Cross-cultural Study of Color-grouping: Tests of the Perceptual-physiology Account of Color Universals”. *Ethos* 26.338-360.

Franklin, A. & I. R. L. Davies. 2004. “New Evidence for Infant Colour Categories”. *British Journal of Developmental Psychology* 22.349-377.

—, A. Clifford, E. Williamson & I. R. L. Davies. 2005. “Color Term Knowledge Does Not Affect Categorical Perception of Color in Toddlers”. *Journal of Experimental Child Psychology* 90.114 –141.

Garner, W. R. 1974. *The Processing of Information and Structure*. Potomac: Erlbaum Associates.

Jameson, K. A. 2005. “Culture and Cognition: What is Universal About the Representation of Color Experience?” *Journal of Cognition and Culture* 5.293-347.

Matsubara, H. 1957. *Colour Vision Test Plates for the Infants*. Tokyo: Handaya.

Pitchford, N. J. & Mullen, K. T. 2002. “Is the Acquisition of Basic Colour Terms in Young Children Constrained?” *Perception* 31.1349-1370.

— & Mullen, K. T. 2003. “The Development of Conceptual Colour Categories in Pre-school Children: Influence of Perceptual Categorisation”. *Visual Cognition* 10.51-77.

Roberson, D. 2005. “Color Categories are Culturally Diverse in Cognition as Well as in Language”. *Cross Cultural Research* 39.56 – 71.

Romney, A. K., J. P. Boyd, C. C. Moore, W. H. Batchelder & T. J. Brazill. 1996. “Culture as Shared Cognitive Representations”. *Proceedings of the National Academy of Sciences* 93.4699-4705.

Sayim, B., K. A. Jameson, N. Alvarado. 2003. “Color Naming Relations in Perceptual Color Space”. *Investigative Ophthalmology and Visual Science* suppl. 44.1912.

Schirillo, J. A. 2001. “Tutorial on the Importance of Colour in Language and Culture. *Color Research and Application* 26.179-192.

THE DEVELOPMENTAL ACQUISITION OF BASIC COLOUR TERMS

NICOLA J. PITCHFORD & KATHY T. MULLEN
University of Nottingham and McGill University

1. *Introduction*

The difficulties young children experience in acquiring basic colour vocabulary have intrigued scientists for well over a hundred years. One of the earliest observations was reported by Charles Darwin (1877) who was struck by the relative ease with which his children acquired the names for everyday objects compared to the tardy and erratic nature by which they learnt colour terms, as the following extract illustrates:

> I carefully followed the mental development of my small children, and I was astonished to observe in two or, as I rather think, three of these children, soon after they had reached the age in which they knew the names of all the ordinary things, that they appeared to be entirely incapable of giving the right names to the colours of a colour etching. They could not name the colours, although I tried repeatedly to teach them the names of colours. I remember quite clearly to have stated that they are colour blind. But afterwards this turned out to be an ungrounded apprehension. (Translated from the German by, and cited in Bornstein 1985:74)

Based on the naturalistic observations and empirical studies of early investigators (e.g. Baldwin 1893; Nagel 1906; Binet & Simon 1916; Vernon 1962; Istomina 1963; Modreski & Goss 1969; Miller & Johnson-Laird 1976; Bartlett 1978; Cruse 1977), Bornstein (1985) identified six features that characterize colour term acquisition: (1) children can perceive (discriminate, match and categorize) colour from early infancy, well before they learn colour names; (2) children answer questions about colour with colour words prior to accurate collour term acquisition; (3) children acquire different colour terms before they have referential meaning; (4) colour terms are applied erroneously in a haphazard manner; (5) colour terms are acquired relatively late, at around four years of age; and (6) girls tend to acquire colour terms at an earlier age than boys.

Another feature of colour term acquisition concerns the order in which children acquire colour vocabulary. Berlin and Kay (1969) proposed that colour terms are added to languages across the world in a fixed order, and this order was believed to be universal in nature as it was thought to arise from the neurophysiology of the human visual system. In their seminal study, Berlin and Kay identified a maximum of eleven basic colour categories that they proposed are mapped systematically to the corresponding colour terms of a given language, these being black, white, red, yellow, green, blue, brown, orange, purple, pink and grey. Miller and Johnson-Laird speculated as to whether "ontogeny recapitulates phylogeny", such that young children may be expected to acquire knowledge of the terms identified by Berlin and Kay as being universal by progression through seven stages, as illustrated in Figure 1a (Miller & Johnson-Laird 1976:354). However, a simplified version (Figure 1b) predicts children should acquire the terms referring to the first six categories (acquired in Stages 1-5) before the remaining five (acquired in stages 6-7), as the first six terms denote the 'primary' categories (black, white, red, yellow, green and blue) that are considered to be perceptually unitary or unique and cannot be described in terms of any other colour combination, whereas the remaining five terms denote the 'non-primary' categories that can be described by using a combination of the six primary terms. Even in the most recent reformulations of Berlin and Kay's original theory (e.g., Kay, Berlin & Merrifield 1991; Kay, Berlin, Maffi & Merrifield 1997), a temporal advantage for the acquisition of primary over non-primary colour terms is predicted.

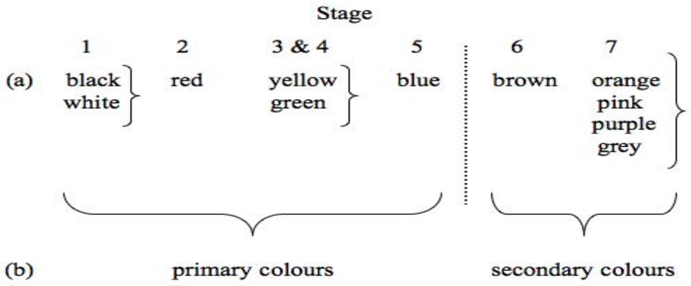


Figure 1: *Fixed developmental order of colour term acquisition proposed by Berlin and Kay (1969). (a) Original seven-stage order that is analogous to the evolutionary order thought to reflect colour term acquisition across languages. (b) Simplified version in which a temporal advantage for primary colours is predicted.*

In this paper we review evidence from our own studies and others that addresses three fundamental features of colour term acquisition. First, we investigate the tardy acquisition of colour terms. Second, we examine if there is a developmental order of colour term acquisition. And third, we consider different factors that may shape any differential acquisition process.[1]

2. *Are colour terms acquired late?*

One of the most striking features concerning the difficulties young children experience with learning colour terms is that, during the early stages of infancy, the ability to perceive colour develops well before the onset of colour term acquisition. By four months of age, psychophysical studies have shown that infants can distinguish between colours (e.g., Maurer & Adams 1987; Teller 1998; Teller & Bornstein 1985); sensitivity to colour contrasts develops alongside sensitivity to differences in luminance (Allen, Banks & Norcia 1993; Teller 1998); and basic colour categories are perceived (Bornstein, Kessen & Weiskopf 1976; Catherwood, Crassini & Freilberg 1989; Franklin & Davies 2004). Although refinements in chromatic discrimination continue throughout childhood into adolescence (Knoblauch, Vital-Durand & Barbur 2001), these studies show that, when a child starts to learn colour terms, they have been experiencing the world in colour since infancy and possess a categorical organization of colour percepts onto which linguistic labels can be mapped (see also Bornstein; Franklin & Davies; and Bonnardel & Pitchford, in this volume).

As such, the task of acquiring colour nomenclature requires the referential mapping of colour terms to colour percepts (Soja 1994; Braisby & Dockrell 1999), yet this appears to be particularly problematic for young children. An established literature suggests there is a lower age limit by which children develop accurate colour naming, which is surprisingly late, at around four years (e.g., Heider 1971; Mervis, Catlin & Rosch 1975; Johnson 1977; Bornstein 1985). Furthermore, children have been shown to require sometimes hundreds of presentations of a colour term paired with a colour sample before the appropriate term is learned (Rice 1980). The effortful and tardy nature by which children acquire colour terms contrasts sharply with the relative ease and speed by which they learn the names of everyday objects, which can occur within a single occurrence of hearing a novel noun spoken in context (e.g. Carey 1978). As a consequence, colour terms have been regarded as having a special status in

---

[1] All the children in these studies had English as a first language; some were British and some Canadian.

lexical development, requiring the implementation of a unique system of multiple mappings for successful acquisition (Sandhofer & Smith 1999).

We questioned, however, whether it is really appropriate to compare the lexical acquisition of colour terms to that of familiar objects, given that these two types of words differ greatly in functional significance (Pitchford & Mullen 2001). Unlike nouns that are used to label everyday objects, colour terms are adjectives and refer to a perceptual object property that can be used to distinguish between objects of similar shape. In contrast, nouns are used to distinguish objects that typically differ in shape. It has been suggested that children may initially conceptualize object shape, as it is relatively more informative about the function of an object than is colour (Au & Markman 1987; Macario 1991; Soja 1994). Knowing the colour of an object may provide no information as to its function. For example, different-coloured objects may share the same function (for example, a dress may be red, black, orange, or any other colour), and similarly-coloured objects may have different functions (for example, a yellow object may be a daffodil, canary, banana and so on). Consequently, during the early stages of vocabulary acquisition, children may expect novel linguistic labels to refer to an object's shape rather than its colour (Baldwin 1989), and this may impair the lexical acquisition of colour terms relative to common nouns. Given the differences in the functional significance of colour compared to familiar objects, we argued that it might be more appropriate to compare the lexical acquisition of colour terms to that of other perceptual object attributes, such as size and motion, that, like colour, are used to make within-category distinctions. Very few studies have yet taken this approach (Sandhofer & Smith 1999).

To investigate whether colour terms are selectively delayed relative to other comparable visual attributes, we compared the ability of young children with language skills ranging from two to five years, to comprehend and name two colours (red and green), two sizes (big and small), two speeds (fast and slow side-to-side motion), and two shapes (T and O) that were functionally meaningless to preliterate children (Pitchford & Mullen 2001). The tasks were all computerized and stimuli are illustrated in Figure 2. The comprehension task required children to point to one of two simultaneously presented stimuli, each of which comprised one of the four visual attributes, and differed only in the attribute being tested (see Figure 2a). For example, when testing comprehension of colour, a stimulus pair comprising a big, red T moving slowly and a big, green T moving slowly was presented and the child was asked "Which is green?" The naming task also presented pairs of stimuli differing only in the attribute to be named, and computer voice-over named each attribute twice as attention was drawn to the appropriate stimulus by means of a large arrow. The child was then shown only one of the stimuli and was asked “What’s this one?” (see Figure 2b). We were surprised to find no difference in children’s ability to

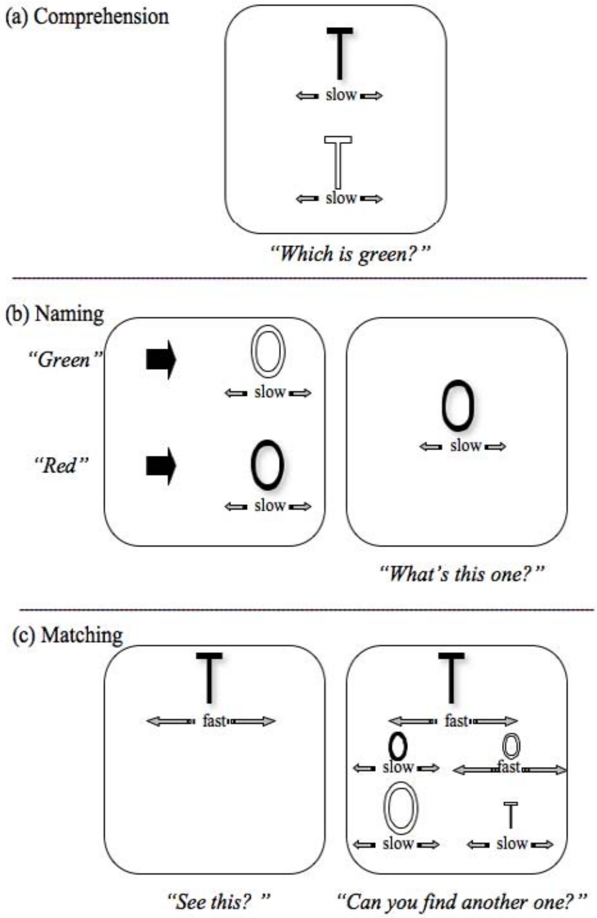
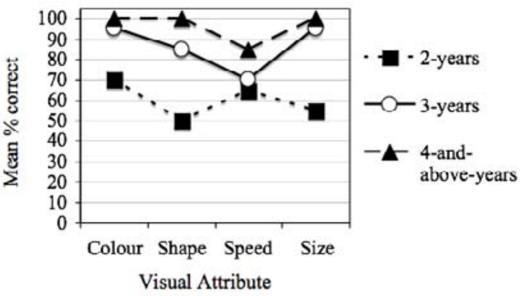


Figure 2: *Schematic illustration of experimental stimuli used in Pitchford and Mullen (2001) where filled-black indicates red stimuli and open-white indicates green stimuli.*

either comprehend or name colour compared to the other visual attributes, by children of any age (see Figure 3). This result is intriguing because it challenges the historical contention that colour terms are selectively delayed.

In an additional experiment, we assessed the relative perceptual saliency of these four attributes using a match-to-sample task that required children to match to a target stimulus with each of the four attributes (for example, a big, red T moving fast), to one of four alternative stimuli, each of which matched the target in only one attribute (for example, a stimulus matching the above target in colour would be a small, red O moving slowly) (see Figure 2c).

(a) Comprehension



(b) Naming

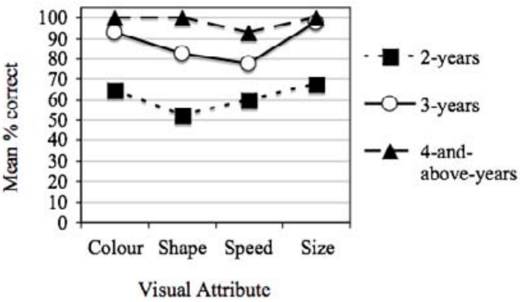


Figure 3: *Mean percentage of correct responses on the (a) comprehension and (b) naming test used in Pitchford and Mullen (2001). As comprehension was measured using a two-alternative-forced-choice task, there was a 50% chance of answering correctly by guessing.*

Children’s responses on this task indicated their preference for matching objects on a particular visual attribute.

Results revealed that colour was a salient object property, particularly for children with a language-age of three years, as they made significantly more matches on the basis of colour (55%) than any other visual attribute (shape 26%, speed 9%, size 10%). By comparison, for children of four years and above, shape became the most salient attribute on which to make perceptual groupings, with these children making significantly more shape-based matches (90%) than matches based on colour (7%), speed (1%), or size (2%). The shift in perceptual saliency from colour to shape at this age is consistent with previous studies (e.g. Brian & Goodenough 1929; Kagan & Lemkin 1961; Suchman & Trabasso 1966; Miller 1977; Baldwin 1989), and has been regarded by some to reflect an awareness of object shape as more indicative of category membership than object colour (e.g. Baldwin 1989; Landau, Smith & Jones 1988). The predominant perceptual saliency of colour compared to other visual attributes at three years contrasts with the fact that there is no selective advantage in the ability to either comprehend or name colour compared to the other visual attributes by children at three years, or any other age (see Figure 3). This result is intriguing because it shows that differences in perceptual saliency do not appear to facilitate lexical acquisition.

Thus, in summary, when colour is compared to that of other visual attributes, using identical experimental procedures, we find no selective delay in the developmental acquisition of colour terms. We suggest that colour terms do not constitute a special class of words in lexical acquisition, but rather develop alongside the acquisition of other adjectives that describe the visual properties of objects.

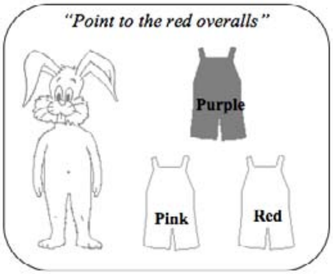
3. *Are basic colour terms acquired in a fixed developmental order?*

As outlined above, Miller and Johnson-Laird (1976:354-355) proposed that children would acquire a vocabulary of the eleven basic colour terms in the same sequential order in which Berlin and Kay (1969) had claimed colour terms were added to the different languages of the world. This order, illustrated in Figure 1 in its simplest form, predicts that children will learn the six primary colour terms at an earlier developmental stage than the five non-primary colour terms. Support for this developmental order, however, has been mixed. For example, an advantage for naming primary over non-primary colour terms has been found in studies of English-speaking children (e.g. Heider 1971; Johnson 1977; Cruse 1977) and in cross-cultural studies of other languages (e.g. Davies, Corbett, McGurk & Jarrett 1994; Davies & Corbett 1998; Dougherty 1978; Istomina 1963). However, an advantage for primary over non-primary colour terms is typically not found when using non-production (for example, comprehension or matching) tasks to assess colour term knowledge (Heider 1971; Andrick & Tager-Flusberg 1986). Furthermore, several studies have failed to find any support for the earlier appearance of primary compared to non-primary colour terms in preschool children (e.g. Bartlett 1978; Mervis et al. 1975; Mervis, Bertrand & Pani 1995; Shatz, Behrend, Gelman & Ebeling 1996).

It is difficult to draw conclusions from such contradictory findings, and the matter is further complicated by methodological differences between studies. Most studies measure colour term knowledge using only one task (for example, comprehension or naming) and this varies across studies (e.g. Cruse 1977; Heider 1971; Johnson 1977). Colour term knowledge is typically measured in only one age group, which varies across studies (e.g. Heider 1971; Shatz et al. 1996). Many studies test knowledge of less than the full complement of eleven basic colours, which makes comparisons between primary and non-primary colours difficult (e.g. Andrick & Tager-Flusberg 1986; Davidoff & Mitchell 1993; Heider 1971; Johnson 1977; Shatz et al. 1996). In addition, all previous studies have taken mean number or percent correct as the dependent variable (e.g. Andrick & Tager-Flusberg 1986; Bartlett 1978; Heider 1971), which is likely to give a misleading impression of colour term knowledge, especially when there is a response bias. Typically, when a child has very few colour terms in their lexicon, they will tend to use one colour term repeatedly. For example, a child that has only acquired the term *blue* will answer ‘blue’ to all colour stimuli (e.g. Cruse 1977; Modreski & Goss 1969), generating a score of 100% correct for naming blue, although this clearly does not reflect the accurate referential application of this term.

In an attempt to overcome these methodological issues, we conducted an extensive study with preschool children to determine whether the developmental acquisition of basic colour terms is constrained by a fixed order that is analogous to the evolutionary order proposed by Berlin and Kay (1969). We measured the acquisition of knowledge of the full complement of eleven basic colour terms across four groups of preschool children aged between two and five years (Pitchford & Mullen 2002). Children were grouped according to their general language abilities, as assessed using a standardized measure of language functioning (including measures of both receptive and expressive language skills), as our previous research (Pitchford & Mullen 2001) showed that grouping on the basis of language-age (LA) reduces the variance found when grouping on the basis of chronological-age (CA), although it does not qualitatively alter the pattern of results. Furthermore, we used the statistical measure of d′ (see Macmillan & Creelman 1991) as the dependent variable on which to compare results, as it takes into account the number of occasions a colour term is applied correctly in relation to the number of times a colour term is misapplied, thus accounting for biases in responding with particular colour terms. Two tasks of colour term knowledge were given to each child and the same stimuli were used in both tasks. The stimuli, shown in Figure 4, were focal examples of each of the eleven basic colour categories. The first task measured children's comprehension of the eleven basic colour terms using a spoken-word-to-colour-matching task and did not require a verbal response. Children were required to match a spoken colour word to one of three different

(a) colour comprehension



(b) colour naming

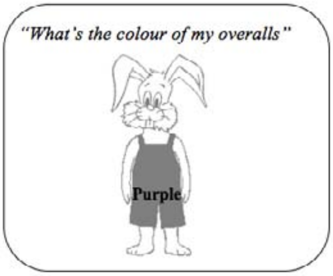
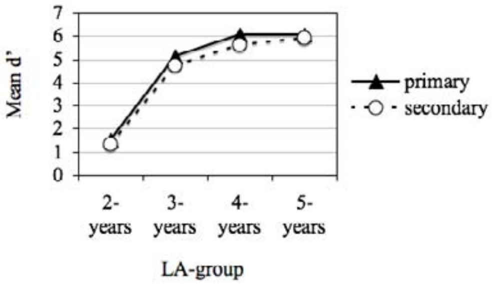


Figure 4: *Schematic illustration of the experimental stimuli used in Pitchford and Mullen (2002).*

colour samples, one of which was the target colour and the other two acted as distracter colours (see Figure 4a). The second task assessed children’s production of the eleven basic colour terms and required children to orally name individually presented colour stimuli (see Figure 4b).

Our data showed only minimal support for a developmental order of colour term acquisition based on the evolutionary order proposed by Berlin and Kay (1969). We found no advantage for the primary colours on the comprehension task in any of the four LA-groups, as is clearly shown in Figure 5a. In contrast, we found a significant advantage for primary over non-primary colour terms on the colour naming task, but only for children with a language-age of three years (see Figure 5b). For the other age groups (two years and four and five years),


(a) Colour Comprehension

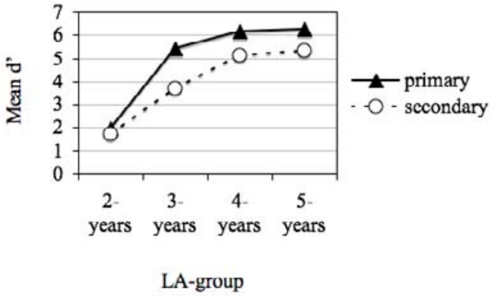

(b) Colour Naming

Figure 5: *Mean d’ achieved on the tasks of (a) colour comprehension and (b) colour naming for preschool children with a language-age of 2 years, 3 years, 4 years and 5 years, from Pitchford and Mullen (2002). Maximum d’ is 6.39.*

there was no significant advantage of naming primary colours compared to non-primaries. These results are consistent with previous studies that have found the advantage for primary colours to be task-specific, being only elicited in production tasks (e.g. Heider 1971; Andrick & Tager-Flusberg 1986). In addition, our data suggest the superior naming of primary over non-primary colours is also age-specific, being shown only by children with a language-age of three years.

More importantly, our data revealed a different developmental order of colour term acquisition. For each child, we combined their performance on the tasks of colour comprehension and colour naming to produce an overall measure of their receptive and expressive knowledge of each of the eleven basic categories. We then determined the mean language-age at which knowledge of a particular colour term became statistically reliable (that is, the point at which children correctly identified a particular colour term without applying it erroneously). Results revealed that children acquired an accurate knowledge of the basic colour terms in two distinct temporal periods; firstly, children acquired knowledge of nine of the eleven basic terms (*yellow, blue, black, green, white, pink, orange, red,* and *purple*), in any order, between 36 to 40 months. Secondly, children gained accurate knowledge of the remaining two basic colour terms, *brown* and *grey*, in either order, but only after a substantial

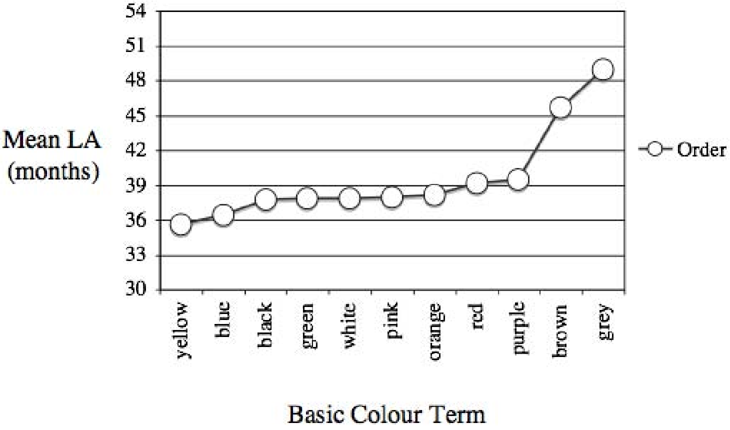


Figure 6: *Dichotomous developmental order of colour term acquisition found by Pitchford and Mullen (2002).*

gap of 6-9 months, at 46 to 49 months, as illustrated in Figure 6.

This dichotomous developmental order of colour term acquisition was replicated in a subsequent study (Pitchford & Mullen 2005) using separate tests of colour naming and colour comprehension, on two different groups of children. Consistent with our earlier study (Pitchford & Mullen 2002), we found that the acquisition of only the two non-primary colour terms, *brown* and *grey*, was delayed compared to the others, with the three non-primary colour terms (*purple, pink* and *orange*) and the six primary colour terms (*black, white, red, yellow, green* and *blue*) being acquired at a similar rate.

Thus, rather than a delayed acquisition of all five non-primary colour terms relative to the six primary colour terms, as suggested by Miller and Johnson-Laird (1976), we found evidence for a dichotomous developmental order marked only by a selective delay in the acquisition of *brown* and *grey***.** Aside from these two non-primary colour terms (*brown* and *grey*), the order by which the other nine basic colour terms are acquired appears to be unconstrained. This finding is consistent with recent cross-cultural studies suggesting that adult colour naming is unconstrained (Davidoff, Davies & Roberson 1999; Roberson, Davies & Davidoff 2000), and questions the assertion of Berlin and Kay (1969) that the developmental order of colour term acquisition is constrained by visual neurophysiology (see Roberson, Davidoff, Davies & Shapiro, in this volume). Instead, it raises the possibility that other factors may be important in shaping the acquisition process.

4. *What factors help shape the developmental acquisition of basic colour terms?*

In a series of experiments with two- to five-year-olds, we investigated what might constrain the acquisition of *brown* and *grey* relative to the other nine basic colour terms, by investigating the role of perception, language, and preference on the acquisition process (Pitchford & Mullen 2005).

4.1 *Does perception limit the acquisition of* brown *and* grey*?*

First, we investigated two possible ways in which a perceptual constraint may inhibit the developmental acquisition of *brown* and *grey*. In the first experiment, we investigated whether children could visually discriminate brown and grey because, in a previous study, we found that children often mistook brown for grey and vice versa on colour comprehension and naming tasks (Pitchford & Mullen 2003). Although infants develop colour vision within the first few months of life (e.g. Maurer & Adams 1987; Teller 1998; Teller &

Bornstein 1985), systematic comparisons across the range of basic colour categories have not been made. Thus it is possible that differences in the timing of the perceptual development of different categories may influence the rate at which they are conceptualized. We argued that, if the delayed linguistic acquisition of *brown* and *grey* arises from an underlying perceptual deficit, preschool children that cannot comprehend or name *brown* and *grey* should also confuse these two colours perceptually.

To test this hypothesis, we gave tasks of colour discrimination and colour comprehension to a group of preschool children aged two to three years. Colour discrimination was measured in a match-to-sample task that required one of two colour stimuli to be selected that was identical to a target colour. For example, a triangular display of three circles, two of which were brown and one grey, was shown to the child, and the experimenter pointed to one of the brown circles and said “See this. Can you show me the other one?”, and the child responded by pointing to one of the other two circles. A similar stimulus display was used in the colour comprehension task, except three different colours were presented and the child was required to point to one in response to a colour name spoken by the experimenter (“Can you show me the brown one?”). Results showed that, consistent with our previous studies, children’s comprehension of *brown* and *grey* was significantly poorer than their comprehension of the other nine basic colour terms, however, their ability to discriminate all of the basic colours was flawless. These results clearly illustrate that the relative delay in the linguistic acquisition of *brown* and *grey* does not reflect a perceptual deficit in discriminating these two colours.

In a second experiment, we investigated whether children found brown and grey to be less salient perceptually than the other basic colours. Children were given a preferential-matching task, similar to that used by Pitchford and Mullen (2001), in which they were shown a target stimulus, for example, a brown square, and were told, “See this, can you find another one?”, after which two stimuli were revealed, one was consistent with the target in its colour (for example, a brown circle) and the other in its shape (for example, a grey square). The child was required to point to the stimulus that matched the target. We tested three different colour pairs across three separate conditions: (1) two primary colours (blue and green); (2) two non-primary colours (pink and purple) that are acquired at the same time as primary colours; and (3) the two non-primary colours (brown and grey) that are acquired late. As children’s responses on this task indicate whether they match on the basis of colour or shape, we compared the number of colour matches made across the three experimental conditions. Interestingly, we found that children made a similar number of colour-based matches across all three conditions (blue & green = 47%, pink & purple = 47%, brown & grey = 51%), indicating that the nature of the colour stimuli did not influence children's decisions to use colour as the basis for perceptual grouping. This suggests that, at a time when children have difficulty comprehending and naming brown and grey they will match objects on the basis of these two colours. Thus, brown and grey do not appear to be any less salient as colours to preschool children than the nine basic categories that are conceptualized earlier.

4.2 *Does linguistic input shape colour term acquisition?*

We next considered the role of language in the delayed acquisition of *brown* and *grey*, as previous studies have found that maternal input correlates significantly with colour naming ability in preschool children (Andrick & Tager-Flusberg 1988). We investigated whether *brown* and *grey* are significantly less frequent colour terms used by mothers when communicating with their young children compared to the other nine basic colour terms. We generated two objective counts of linguistic frequency for each of the eleven basic colour terms using: (1) books aimed at the preschool years, and (2) mothers' spoken interactions with their children. Mean written word frequency counts were generated by counting the number of occasions each of the eleven basic colour terms appeared in 374 different books designed to be read to preschool children. For the spoken frequency counts we used the Manchester corpus (Theakston, Lieven, Pine & Rowland 2001) from the CHILDES database (MacWhinney 2000) that includes thirty-four hours of continuous speech from each of twelve mothers recorded whilst interacting playfully with their children. All the children were aged between two and three years and were thus likely to be learning colour terms. For each of the mother-child interactions, we extracted the number of occasions each of the eleven basic colour terms were used by the twelve mothers, from which we generated a mean frequency count.

The two objective measures of colour term frequency generated from child-directed language correlated significantly ($r = .69$ ($n = 11$), $p = .02$), indicating a strong degree of concordance between these two measures. Interestingly, both measures of basic colour term usage in child-directed language consistently supported an advantage for primary over non-primary colour terms, which is consistent with the prediction made by Miller and Johnson-Laird (1976), although our data shows that children acquire primary colour terms at the same time as the non-primaries, *orange*, *pink* and *purple* (Pitchford & Mullen 2002; 2005). Linguistic frequency may, however, contribute to the late acquisition of the colour terms *brown* and *grey* by preschool children, as these two colour terms were consistently found to be the least frequent across both measures of linguistic frequency (written and spoken counts).

In addition to linguistic input, other environmental or cultural factors have been shown to influence colour term acquisition. For example, Shatz et al. (1996) found attendance at preschool significantly improved colour term knowledge in two-year-olds. Furthermore, Zollinger (1988) showed that Japanese children were influenced by Western culture when learning to name non-primary colours, although this did not affect their naming of primary colours. Together, these results and our own data suggest that the linguistic environment to which the preschool child is exposed helps shape the order by which they acquire basic colour vocabulary.

4.3 *Does colour preference influence colour term acquisition?*

Finally, we explored whether colour preference may be related to the order in which children acquire basic colour terms. In particular, we sought to investigate whether children like brown and grey less than the other basic colours. Differences in preference for the eleven basic colours may influence their linguistic acquisition in several ways. For example, Zentner (2001) suggested children might focus their attention towards colours they prefer in their environment, which may, in turn, make these colours more memorable. Bornstein (1975) suggested that differences in colour preference might reflect underlying differences in the biological meaningfulness of particular colours, which may, in turn, facilitate colour term learning.

To investigate whether children's preferences for the eleven basic categories were associated with their linguistic development we gave a group of preschool children a task of colour preference and a task of colour naming. To test colour preference, we showed children a random display of the eleven basic categories and asked them to indicate which colour they liked the best. This colour was then removed from the display and the procedure was repeated until only one colour remained. The resultant order indicated the ranked colour preference order for each child. Results showed, as in our previous studies, that children named brown and grey significantly less than the other nine colours, and they also preferred brown and grey significantly less than the other colours. A significant, negative correlation was found between colour preference and colour naming ($r = -.77$ ($N = 11$), $p = .004$). These results suggest that colour preference and colour naming are developmentally linked. Furthermore, children disliked brown and grey irrespective of whether or not they could name brown and grey accurately, illustrating that differences in colour preference are established before accurate knowledge of colour terms is acquired. This raises the possibility that colour preference may exert a direct influence on the process by which children acquire colour terms.

5. *Summary of research findings and conclusions*

Our investigations into the anomalies of colour term acquisition have revealed three key findings. First, we have questioned the claim that colour terms appear unusually late in lexical acquisition. Although colour terms may appear later than object names, we argued this might well be expected, given the differences in functional significance between colour terms and common nouns. However, when the lexical acquisition of colour terms is compared with that of other terms used to describe visual attributes, no selective delays are found (Pitchford & Mullen 2001). Second, we investigated whether colour term acquisition progresses through a fixed developmental order that is analogous to the evolutionary order proposed by Berlin and Kay (1969), as suggested by Miller and Johnson-Laird (1976). We found little support for a temporal advantage in the acquisition of primary compared to non-primary colour terms. Instead, our data revealed a dichotomous developmental order marked only by the late acquisition of *brown* and *grey* (Pitchford & Mullen 2002). Finally, we sought to investigate factors that may influence the acquisition of basic colour terms. Whilst perception did not appear to limit colour conceptualization, we found that linguistic input, colour preference, and colour naming are developmentally linked (Pitchford & Mullen 2005), although the nature of this association remains to be elucidated.

References

Allen, D., M. S. Banks & A. M. Norcia. 1993. “Does Chromatic Sensitivity Develop More Slowly than Luminance Sensitivity?” *Vision Research* 33.2553-2562.

Andrick, G. & H. Tager-Flusberg. 1986. “The Acquisition of Color Terms”. *Journal of Child Language* 13.119-134.

Au, T. K. & E. M. Markman. 1987. “Acquiring Word Meanings via Linguistic Contrast”. *Cognitive Development* 2.217-236.

Baldwin, D. 1989. “Priorities in Children’s Expectations about Object Label Reference: Form over Color”. *Child Development* 60.1291-1306.

Baldwin, J. M. 1893. “A New Method of Child Study”. *Science* 21.213-214.

Bartlett, E. J. 1978. “The Acquisition of the Meaning of Color Terms: a Study of Lexical Development”. *Recent Advances in the Psychology of Language* ed. by R. Campbell & P. Smith, 89-108. New York: Plenum.

Berlin, B. & P. Kay. 1969. *Basic Colour Terms: their Universality and Evolution*. Berkeley: University of California Press.

Binet, A. & T. Simon. 1916. *The Development of Intelligence in Children*. Baltimore: Williams & Wilkins.

Bornstein, M. H. 1975. “Qualities of Color Vision in Infancy”. *Journal of Experimental Child Psychology* 19.401-419.

—. 1985. “On the Development of Color Naming in Young Children: Data and Theory”. *Brain and Language* 26.72-93.

—, W. Kessen & S. Weiskopf. 1976. “Color Vision and Hue Categorization in Young Human Infants”. *Journal of Experimental Psychology: Human Perception and Performance* 2.115-129.

Braisby, N. & J. Dockrell. 1999. “Why is Colour Naming Difficult?” *Journal of Child Language* 26.23-47.

Brian, C. R. & F. L. Goodenough. 1929. “The Relative Potency of Color and Form Perception at Various Ages”. *Journal of Experimental Psychology* 12.197-213.

Carey, S. 1978. “The Child as a Word Learner”. *Linguistic Theory and Psychological Reality* ed. by M. Halle, J. Bresnan & G. Miller, 264-293. Cambridge, Mass.: MIT Press.

Catherwood, D., B. Crassini & K. Freilberg. 1989. “Infant Response to Stimuli of Similar Hue and Dissimilar Shape: Tracing the Origins of the Categorization of Objects by Hue”. *Child Development* 60.752-762.

Cruse, D. A. 1977. “A Note on the Learning of Color Names”. *Journal of Child Language* 4.305-311.

Davidoff, J. B., I. Davies & D. Roberson. 1999. “Colour Categories in a Stone-Age Tribe. *Nature* 398.203-204.

— & P. Mitchell. 1993. “The Colour Cognition of Children”. *Cognition* 48.121-137.

Davies, I. & G. Corbett. 1998. “A Cross-cultural Study of Color-grouping: Tests of the Perceptual-physiology Account of Color Universals”. *Ethos* 26.338-360.

—, G. Corbett, H. McGurk & D. Jarrett. 1994. “A Developmental Study of the Acquisition of Colour Terms in Setswana”. *Journal of Child Language* 21.693-712.

Dougherty, J. W. D. 1978. “On the Significance of a Sequence in the

Acquisition of Basic Colour Terms". *Recent Advances in the Psychology of Language* ed. by R. N. Campbell & P. T. Smith, 133-148. New York: Plenum Press.

Franklin, A. & I. R. L. Davies. 2004. "New Evidence for Infant Colour Categories". *British Journal of Developmental Psychology* 22.349-377.

Heider, E. R. 1971. "'Focal' Color Areas and the Development of Color Names". *Developmental Psychology* 4.447-455.

Istomina, Z. M. 1963. "Perception and Naming of Colour in Early Childhood". *Soviet Psychology and Psychiatry* 1.37-46.

Johnson, E. G. 1977. "The Development of Color Knowledge in Preschool Children". *Child Development* 48.308-311.

Kagan, J. & J. Lemkin. 1961. "Form, Color and Size in Children's Conceptual Behavior". *Child Development* 32.25-28.

Kay, P., B. Berlin, L. Maffi & W. Merrifield. 1997. "Color Naming Across Languages". *Color Categories in Thought and Language* ed. by C. L. Hardin & L. Maffi, 21-56. Cambridge: Cambridge University Press.

—, B. Berlin & W. R. Merrifield. 1991. "Biocultural Implications of Systems of Color Naming". *Journal of Linguistic Anthropology* 1.12-25.

Knoblauch, K., F. Vital-Durand & J. L. Barbur. 2001. "Variation of Chromatic Sensitivity Across the Life Span". *Vision Research* 41.23-36.

Landau, B., L. B. Smith & S. S. Jones. 1988. "The Importance of Shape in Early Lexical Learning". *Cognitive Development* 3.299-321.

Macario, J. F. 1991. "Young Children's Use of Color in Classification: Foods and Canonically Colored Objects". *Cognitive Development* 6.17-46.

Macmillan, N. A. & C. D. Creelman. 1991. *Detection Theory: a User's Guide*. Cambridge: Cambridge University Press.

MacWhinney, B. 2000. *The CHILDES Project: Tools for Analyzing Talk*. 3rd edn., vol. 2. Mahwah, N.J.: Lawrence Erlbaum Associates.

Maurer, D. & R. J. Adams. 1987. "Emergence of the Ability to Discriminate Blue from Gray at One Month of Age". *Journal of Experimental Child Psychology* 44.147-156.

Mervis, C. B., J. Bertrand & J. R. Pani. 1995. "Transaction of Cognitive-linguistic Abilities and Adult Input: a Case-study of the Acquisition of Color Terms and Color-based Subordinate Object Categories". *British Journal of Developmental Psychology* 13.285-302.

—, J. Catlin & E. Rosch. 1975. "Development of the Structure of Color Categories". *Developmental Psychology* 11.54-60.

Miller, D. 1977. "Color / Form Matching as Indicator of Cognitive Reorganization in Kindergarten Children". *The Journal of Genetic*

Psychology 130.271-278.

Miller, G. A. & P. N. Johnson-Laird. 1976. *Language and Perception*. Cambridge, Mass.: Harvard University Press.

Modreski, R. A. & A. E. Goss. 1969. “Young Children’s Initial and Changed Names for Form-color Stimuli”. *Journal of Experimental Child Psychology* 8.402-409.

Nagel, W. A. 1906. “Observations on the Color-sense of a Child”. *Journal of Comparative Neurology and Psychology* 16.217-230.

Pitchford, N. J. & K. T. Mullen. 2001. “Conceptualisation of Perceptual Attributes: a Special Case for Colour?” *Journal of Experimental Child Psychology* 80.289-314.

— & K. T. Mullen. 2002. “Is the Development of Basic Colour Terms in Young Children Constrained?” *Perception* 31.1349-1370.

— & K. T. Mullen. 2003. “The Development of Conceptual Colour Categories in Pre-school Children: Influence of Perceptual Categorisation”. *Visual Cognition* 10.51-77.

— & K. T. Mullen. 2005. “The Role of Perception, Language and Preference in the Developmental Acquisition of Basic Colours”. *Journal of Experimental Child Psychology* 90.275-302.

Rice, M. 1980. *Cognition to Language: Categories, Word Meanings, and Training*. Baltimore: University Park Press.

Roberson, D., I. Davies & J. B. Davidoff. 2000. “Colour Categories are not Universal: Replications and New Evidence from a Stone-Age Culture”. *Journal of Experimental Psychology: General* 129.369-398.

Sandhofer, C. M. & L. B. Smith. 1999. “Learning Color Words Involves Learning a System of Mappings”. *Developmental Psychology* 35.668-679.

Shatz, M., D. Behrend, S. A. Gelman & K. S. Ebeling. 1996. “Color Term Knowledge in Two-year-olds: Evidence for Early Competence”. *Journal of Child Language* 23.177-199.

Soja, N. N. 1994. “Young Children’s Concept of Color and its Relation to the Acquisition of Color Words”. *Child Development* 65.918-937.

Suchman, R. G. & T. Trabasso. 1966. “Color and Form Preference in Young Children”. *Journal of Experimental Child Psychology* 3.177-187.

Teller, D. Y. 1998. “Spatial and Temporal Aspects of Color Vision”. *Vision Research* 38.3275-3282.

— & M. H. Bornstein. 1985. “Color Vision and Color Perception in Infancy”. *Handbook of Infant Perception* ed. by L. B. Cohen & P. Salapatek, 185-236. New York: Academic Press.

Theakston, A. L., E. V. M. Lieven, J. M. Pine & C. F. Rowland. 2001. “The

Role of Performance Limitations in the Acquisition of Verb-argument Structure: an Alternative Account". *Journal of Child Language* 28.127-152.

Vernon, M. D. 1962. *The Psychology of Perception*. Harmondsworth: Penguin.

Zentner, M. R. 2001. "Preferences for Colours and Colour-emotion Combinations in Early Childhood". *Developmental Science* 4.389-398.

Zollinger, H. 1988. "Categorical Colour Perception: Influence of Cultural Factors on the Differentiation of Primary and Derived Basic Colour Terms in Colour Naming by Japanese Children". *Vision Research* 28.1379-1382.

COLOUR CATEGORIES AND CATEGORY ACQUISITION IN HIMBA AND ENGLISH

DEBI ROBERSON, JULES DAVIDOFF, IAN R. L. DAVIES
& LAURA R. SHAPIRO
*University of Essex, Goldsmiths College, University of Surrey
and University of Warwick*

For over fifty years, the domain of colour categorization has been used as a testing ground to investigate the degree to which culture (through language) might influence thought. While it has been known for many years that different cultures use different sets of linguistic categories to describe the visible range of colours, many researchers retain the view, first put forward by Berlin and Kay (1969) that there is a particular set of basic colour categories, shared between all humans, named in English by basic colour terms (BCTs) and deriving from the structure of the visual system (e.g. Guest & Van Laar 2002; Munnich & Landau 2003). These basic categories (named in English as: *red, green, blue, yellow, black, white, grey, pink, orange, purple* and *brown*) are considered distinct from other terms (for example, *turquoise* or *maroon*) because they are known to all members of a community, not subsumed within another category and generally named with mono-lexemic words (Kay, Berlin & Merrifield 1991). This view proposes that the organization of cognitive representations of colour (the set of possible categories) is tightly constrained by perception, even though the organization of linguistic categories for colour varies widely.

At the same time, there is a growing body of evidence, from a variety of other cognitive domains, that interactions between culture, language and thought are widespread and complex. Gumperz and Levinson (1997) found that variations in number systems were mirrored by differences in numerical reasoning, and both Levinson (1996), Levinson, Kita, Haun and Rasch (2002) and Choi, McDonough, Bowerman and Mandler (1999) found similar results for cultures whose categories for spatial relations differed. Malt and Johnson (1998) found that category judgments for artefact categories were made in line with semantic categories; a result also found for classification by material or shape by Lucy (1992), for time by Boroditsky (2001), and for modes of motion by Gennari, Sloman, Malt and Fitch (2000). Roberson, Davidoff and Shapiro (2002) found that speakers of a language that does not distinguish basic shape categories (square, circle, and triangle) were unable to sort stimuli into these categories, whereas Sera and colleagues (Sera, Berge & Pintado 1994; Sera, Elieff, Forbes, Burch, Rodriguez & Dubois 2002) have reported differing effects of grammatical gender on classification across languages. Thus the weight of evidence in favour of tight links between culture, language, and thought would make colour a unique field of classification, if cognitive colour categories can truly be independent of the terms used to describe them.

A series of cross-cultural studies of adult colour categorization have found consistent differences in a range of perceptual and memory tasks, systematically linked to the colour categories in each culture (Davidoff, Davies & Roberson 1999; Roberson, Davies & Davidoff 2000). Most recently, Roberson, Davidoff, Davies & Shapiro (2005) have shown that, even though two coding systems may appear to be superficially very similar, speakers of the two languages encode, remember and discriminate colour stimuli in different ways. Himba, a language spoken by a semi-nomadic, cattle-herding people in South West Africa, shows similarity in its number of linguistic categories for colour to Berinmo, the Papua New Guinean language previously studied by Roberson et al. (2000). Both languages have five basic colour categories, according to the criteria of Kay et al. (1991). However, Himba participants showed categorical perception only for their own linguistic categories and not for either the supposed universal categories, as occurring in English, or to those of the Berinmo language.

These findings might be accounted for in several different ways. Firstly, it might be the case that all adults have a universal set of cognitive categories that may be innately determined and independent of the terms used to describe them. Despite this, they might always recruit a culture-specific naming system, even when making perceptual matching judgements for colour, so that two items that are called by the same name would always be judged more similar than two items that are given different names, as suggested by Munnich and Landau (2003). This seems unlikely, however, for three reasons. Firstly, there is no correspondence between BCTs and any processes yet found in the visual system (Boynton 1997; Webster, Miyahara, Malkoc & Raker 2000; Valberg, 2001) that would support such a universal categorization system. Secondly, nameability has been shown to be an important feature of colour sets, independent of any perceptual qualities of focality (Guest & Van Laar 2002), and thirdly, a number of recent cross-cultural studies have found no increased salience for the proposed universal ‘focal’ colours (Davidoff, Davies &

Roberson 1999; Jameson & Alvarado 2003; Özgen & Davies 1998; Roberson, Davidoff, Davies & Shapiro 2004; Roberson et al. 2005) around which it has been suggested such universal categories develop (Rosch Heider 1972).

Alternatively, all humans might be born with a universal set of cognitive categories, that are later distorted by learning the appropriate set of categories for their language (Bornstein, Kessen & Weiskopf 1976; Franklin & Davies 2004). Such distortions might arise if learned colour categories were mentally represented by prototypes and these stored representations acted as perceptual magnets, distorting the perceived colour space. Some recent studies of languages having eleven basic categories (Sturges & Whitfield 1997; Guest & Van Laar 2000; Lin, Luo, MacDonald & Tarrant 2001) have provided some support for the pre-eminence of category centres, or ‘foci’. Moreover, recent training studies have shown that new categories can be induced for brightness (Goldstone 1994) and for hue (Özgen & Davies 2002). However, many recent studies have suggested that cognitive organization changes in these cases, because there is a shift in attention to differences at category boundaries that causes enhanced discrimination of boundary items, relative to category centres (Özgen & Davies 2002; Roberson & Davidoff 2000; Pilling, Wiggett, Özgen & Davies 2003; Goldstone 1998). Such a mechanism for category acquisition would imply less, rather than more attention to category centres, over time.

Finally, it might be the case that there is no single set of categories that is universal and independent of culture and language, and that all divisions of the perceived continuum of colour must be learned. In that case, individuals who have yet to learn the set of categories appropriate to their own culture and language might still group colours in a principled way, such as by similarity, but fail to categorize along the lines of the proposed universal set. The tendency to group by similarity is pervasive, both across cultures and across cognitive domains. Colour cognition is no exception to this and no culture / language has yet been reported that violates this principle by grouping together two areas of colour space (for example, yellow and blue) in a category that excludes the intermediate area (for example, green).[1] Roberson, Davidoff and Braisby (1999)

---

[1] However, McNeill (1972) documents a number of instances of languages in which a term comes, over time, to be used for either one of opposing colours (red / green or blue / yellow) in different derivative languages. In the case of Slavonic languages, the same term, *plav*, at different times has meant ‘pale yellow / blonde’ in some East Slavonic languages, but ‘pale blue’ in some South and West Slavonic languages. Fasske, Jentsch and Michalk (1972) suggest that the original meaning of the term in Proto-Indo-European was ‘pale’ or ‘grey’ and that the ‘yellow / blonde’ meaning came from the ‘pale’ sense, while the ‘pale blue’ meaning came from the ‘grey’ sense.

found that an adult patient with colour anomia, who had lost the ability to categorize colours, explicitly grouped colours on the basis of perceptual similarity. If categories are initially formed based on the relative similarity of stimuli, as Dedrick (1996) and Roberson et al. (2000) have argued, then both the range of available stimuli in the environment and variability in the need to communicate about colour should affect the eventual set that a community arrives at.

A further set of studies examined this question by turning to a new source of evidence: the acquisition of colour terms by children. Estimates of the age at which children acquire a minimum colour vocabulary (four basic terms) have dropped from the 7-8 years of age estimated by Binet and Simon (1916) to 2-3 years (Shatz, Behrend, Gelman & Ebeling 1996; Andrick & Tager-Flusberg 1986), but competent use of a full set of BCTs is acquired relatively late, compared to other dimensional terms (Bornstein 1985; Mervis, Bertrand & Pani 1995; Soja 1994; Sandhoffer & Smith 1999) even by English-speaking children for whom the set of basic terms to be acquired would be just those that are presumed to be universally present before the correct terminology is acquired. With constant intensive training, children as young as 1.5 years can produce and use some colour terms accurately (Cruse 1977; Mervis, Catlin & Rosch 1975), but hundreds of training trials are required to reach such early competence (Rice 1980), compared to the single presentation learning demonstrated for object terms (Carey 1978). With choices restricted to only two widely separated colours (for example, red and green), young children may show the same degree of success as for dimensions such as size or form (Pitchford & Mullen 2001) but, without intensive input, estimates of the age at which children acquire a full set of colour terms fall between two and six years, depending on the number of terms examined and the measures of knowledge taken. Our studies examined naming and comprehension systematically over a three-year period in order to establish a reliable measure of children’s colour term acquisition.

The study also examined whether colour term acquisition might differ in speakers of different languages. In the framework of a presumed innate, universal fixed set of colour categories, Bornstein (1985) predicted that acquiring colour terms would be even more difficult for children learning a language in which the innate universal set must be over-written by a new set, even if there were fewer terms to be learnt. They might have to assimilate their existing hue-based universal categories into a new and orthogonal set of semantic categories based on another dimension, such as lightness in the case of the Dani reported by Rosch Heider (1972). Similarly, Bowerman and Choi

(2003) suggest that, the more robust and pre-potent the pre-linguistic organization of the perceived world is, the greater the resistance that language acquisition would have to overcome, in order to re-structure mental life. Thus, the acquisition of a set of named categories that are different to the presumed set of innate, universal categories might show a different developmental pattern to that of English-speaking children.

Roberson et al. (2004) addressed these questions in a study that included a group of young English children, who were tested initially before they entered pre-school and, subsequently, through three years of formal education, and a group of Himba children from northern Namibia, few of whom received any formal education during the period of the study. Himba has five BCTs according to the criteria of Kay et al. (1991). Children's colour term knowledge and memory for colours were tested at six-month intervals over three years. At the first test, 32 English three-year-olds and 36 four-year-olds were tested, along with 42 Himba three-year-olds and 27 Himba four-year-olds. In the longitudinal sample, 28 of the English three-year-olds and 63 of the Himba children completed all six tests. All had normal colour vision. Color Aid matte stimuli were used (best examples of black, white, grey, red, orange, yellow, green, blue, pink, purple and brown, and eleven intermediate colours). The children completed a colour term listing task ("tell me all the colours that you know"), colour naming ("what colour is this?"), colour term comprehension ("can you find a red one?") and a recognition memory task in each of the six testing sessions. Details of the methodology can be found in Roberson et al. (2004).

Despite the considerable environmental, linguistic and educational differences between the two groups, there were some noticeable similarities in our data. Considering the order in which colour terms were learned, the order of acquisition observed over time differed according to the measure used and showed great individual variation. However, no measure showed the pattern, predicted by universalist theory, in which primary colour terms (in English: *red, blue, green* and *yellow*) are learned before non-primary terms, a finding consistent with other recent studies. Over the course of the longitudinal study, neither population showed a predictable order of acquisition, and there were considerable individual differences in term acquisition, such that terms for brown and grey were acquired very early by some children, although the English group, as a whole, acquired the terms *brown* and *grey* later than other terms (consistent with Pitchford & Mullen 2002). The present study supported previous findings of the lack of a predictable order of term acquisition in both languages (e.g. Macario 1991; Mervis et al. 1975; Pitchford & Mullen 2002; Shatz et al. 1996).

Considering the trajectory of colour term acquisition in the two cultures, the longitudinal results suggested that children continue to refine their conceptual colour categories for some years after they first show evidence of term knowledge for ‘focal’ colours. Previous cross-sectional studies have found conflicting evidence about the age at which children reliably produce and use colour terms appropriately. This could be due to the wide range of methodologies used, the number of colour terms assessed, or to increased developmental variability introduced by the use of chronological, rather than language age as a measure, as suggested by Pitchford and Mullen (2003). A further possibility, uncovered by repeated testing in the present study, is the tendency of children to subsequently fail either to name or to comprehend a BCT that they had previously used correctly (the mean subsequent failure rate was 8% for both groups). Such error-prone performance may help to explain the inconsistency of previous estimates based on a single test of knowledge.

Children know that a set of terms refer to ‘colour’ and can select colour as a property on which to match objects as early as two years of age (Soja 1994). In the present study, three-year-olds in both cultures listed only colour terms when asked, demonstrating their understanding of colour as a dimension. However, even at the end of the study, some children from both language groups could not correctly apply all their BCTs (even though the English children had had three years of specific instruction). Despite the similarities in learning trajectory across the two populations, English children acquired their first colour words earlier than the Himba. Greater exposure to coloured objects and the increased cultural salience of colour in Western society may contribute to an earlier conceptual understanding of colour as a separable dimension. However, from then on, the differences between the groups are less marked than the similarities, which are clearly seen in their performance on the recognition memory tasks.

At the first time of testing, for both Himba and English children who knew no colour terms, the pattern of memory errors was very similar, and, crucially, neither pattern resembled that derived from the eleven basic categories of English. Both appeared to be based on perceptual distance rather than a particular set of predetermined categories. Additionally, for this group of children, there was no advantage in memory for the stimuli that were central (focal) to the BCTs in either language. This finding supports the hypothesis that the eleven basic categories that exist in English are not cognitive universals, and conflicts with the findings of some studies of infant colour categories (Bornstein, Kessen & Weiskopf 1976; Franklin & Davies 2004). We return to this issue later in the discussion.

In our longitudinal study, from an initial reliance on perceptual similarity, an advantage for the (language appropriate) set of focal colours became evident as soon as children acquired colour terms. Of those children knowing one or more colour terms at the first time of testing, English children showed superior memory performance for the items that are focal to English, but not to Himba categories, while Himba children showed the reverse pattern. Such rapid divergence in the cognitive organization of colour for the two groups, from the time that the first terms are learnt, suggests that cognitive colour categories are learned rather than innate. Thus, these data, like those for adult Himba and Berinmo speakers, argue against an innate origin for the eleven basic colour terms in English.

For both populations, once colour terms were acquired, memory performance was determined by the number of terms known. Children made more correct identifications of focal items for terms that they knew than for terms that they did not, regardless of the absolute number of terms known. Thus, the effect of term knowledge on memory cannot be an artefact of superior memory, and language skills of children with higher general intelligence; children who knew more terms got the same proportion of the items they knew correct as those who knew few. Knowledge of even one colour term appears to change the cognitive organization of colour, and from this point on there are language-dependent differences between the two groups. Once knowledge is acquired, it appears to restructure the cognitive organization of colour in a reliable way, and this restructuring relates to term acquisition per se, not to maturation or educational input. Additionally, the type of recognition errors made changed over time. The perceptual distance of memory errors decreased as children learned more BCTs and, in most cases, more within-category than across-category errors were made at later tests.

Acquisition of term knowledge caused a reduction of memory errors, and these changed in nature over time. The effects of naming were particularly evident in the case of two items that were called by the same name in one language and by different names in another, such as navy blue, or dark orange. By the time children were six years old, the few errors that were made to these tiles were to within- rather than cross-category items, regardless of perceptual distance. It was not simply the case that improving memory allowed children to make fewer and less distant errors. There were two cases, however, in which perceptual and categorical errors could be directly contrasted. One was the navy blue tile, which lies perceptually between English focal blue and black. For English speakers, this tile is in the same category as the focal blue tile. For Himba speakers, however, it is in the same category as the black tile (and both are equally focal). Within the test set, there was also a closer perceptual alternative than either of these; the English focal purple tile. If choices were only influenced by perceptual similarity, the purple tile should have been a more frequent erroneous choice than either the lighter blue or the black tile for both populations. A similar comparison was carried out for children's performance on the dark orange tile, which lies perceptually between English focal red and focal orange. For English speakers, this tile is in the orange category. For Himba speakers, however, it is in the same category as the red tile (and also focal). The red tile is also the closest perceptual alternative within the set. If choices were only influenced by perceptual similarity the most frequent erroneous choice for both populations would be the red tile. In both cases, errors in early tests were very varied, for both groups of children. In later tests, although there were fewer errors, these diverged and, within each language group, were significantly more likely to be made in connection with the best example of the category into which the tile fell. For example, by the sixth test, the only errors made by English children for the navy blue tile were to the focal blue tile. Over the same period, Himba children's errors narrowed until the only errors made were to the (within-category) black tile

The advantage for items central (focal) to children's native language categories also increased throughout the longitudinal study. Thus, the importance that Rosch gave to focality in establishing categories seems justified from the present data; nevertheless, it is important to stress that the focality is not universal but, as shown both at first testing and longitudinally, it is language dependent. For English children, this effect may be unsurprising since these are just the colours that are taught from the earliest age, and most readily available in their playthings. For Himba children, focality was determined on the basis of adult naming agreement. Those targets deemed focal were those for which over 90% of adults agreed on the name. Other targets received little adult naming agreement. Himba children do not encounter constant presentation, through printing, dyeing and screen images of best example, highly saturated colours. In their environment only muted, natural colours are encountered, for which adult naming might often disagree. Children should then learn more quickly those colours that adults reliably call by the same name, hence the more accurate results for 'focal' colours.

Himba, like many other traditional cultures, has fewer than eleven basic categories, each containing a wide range of exemplars, each extending to very desaturated colours, and with little inter-individual agreement among adults on where the best examples of categories are located (Roberson et al. 2000; MacLaury 1987; Rosch Heider & Olivier 1972). Without the full range of saturated stimuli that can be artificially produced, traditional communities may have no need of the finer categorical distinctions required when a wider variety is available, and thus lack the motivation to refine their colour lexicon further.

However, a large proportion of the world's major languages have the same number of colour categories, and one may ask why. It is possible that the eleven-colour organization yields the optimal combination of discriminability and cognitive economy for recognition and representation of large numbers of colours. If so, languages with fewer terms would gain by introducing / borrowing new terms, when increasing technological advances or contact with other cultures introduced a greater need to communicate more precisely about colour. Nevertheless, even if the eleven-term organization were found to be optimal, and eventually adopted by all cultures, it need not be innate.

Early studies by Bornstein and colleagues (Bornstein, Kessen & Weiskopf 1976; Sandell, Gross & Bornstein 1979) suggested that categorical divisions between red, green, blue and yellow might be innate and perceived categorically by both infants and other primates. However, there were methodological issues with these studies (Banks & Salapatek 1981; Werner & Wooten 1985) and, under controlled conditions, Davidoff, Goldstein and Fagot (2004) found qualitatively different colour categorization in humans and primates. Franklin and Davies (2004), using a preferential looking technique, found that 4-month-old infants showed categorical novelty preferences for a wide range of colour categories, both across hue boundaries (such as that between blue and green) and across brightness boundaries (such as that between pink and red), but there are reasons to be cautious of interpreting infant 'categorization' as resembling that acquired later in life.

Infants show remarkable abilities to form short-term dynamic 'on line' categories, within a preferential looking paradigm, for a wide range of stimuli such as cats and lions (Quinn & Eimas 1997), but these categorizations are labile and can change when the perceptual features of the input are changed (Rakison & Butterworth 1998a, 1998b). Moreover, recent work by Bremner and others (Bremner & Bryant 2001; Bremner & Mareschal 2004) suggests that colour and location information are processed separately in infants, and that dorsal and ventral streams of visual processing are not integrated until much later in development. This has been proposed as an explanation as to why children of 2-3 years of age often fail on other categorization tasks that infants appear to have passed, since it is around this age that children begin to try to integrate information about colour, shape, texture and location of stimuli. Xu and Carey (1996; Xu, Carey & Quint 2004) have also shown that, even at 12 months of age, infants fail to represent perceptual features of objects such as colour, size or pattern and they suggested that infants' representational systems only begin to distinguish kinds and properties of objects towards the end of the first year of life.

Given the difficulty in interpreting infant performance on preferential looking tasks, Roberson et al.'s (2004) study set out to examine when and how children acquire a set of colour categories appropriate to their own language and culture. The results suggest that children gradually acquire the organization of such categories, and progress gradually from an uncategorized organization of colour based on perceptual similarity (where dimensions are viewed as continua) to a structured organization of categories that varies across languages and cultures. The increase in the influence of linguistic categorization on memory for colours is progressive and cumulative in both groups. Moreover, without intensive adult input, colour category acquisition is universally slow and effortful.

References

Andrick, G. R. & H. Tager-Flusberg. 1986. "The Acquisition of Colour Terms". *Journal of Child Language* 13.119-134.

Banks, M. S. & P. Salapatek. 1981. "Infant Pattern Vision – a New Approach Based on the Contrast Sensitivity Function". *Journal of Experimental Child Psychology* 31.1-45.

Berlin, B. & P. Kay. 1969. *Basic Color Terms: their Universality and Evolution*. Berkeley: University of California Press.

Binet, A. & T. Simon. 1916. *The Development of Intelligence in Children*. Baltimore: Williams & Wilkins.

Bornstein, M. H. 1985. "On the Development of Color Naming in Young Children: Data and Theory". *Brain and Language* 26.72-93.

—, W. Kessen & S. Weiskopf. 1976. "Color Vision and Hue Categorization in Young Human Infants". *Journal of Experimental Psychology: Human Perception and Performance* 2.115-129.

Boroditsky, L. 2001. "Does Language Shape Thought?: Mandarin and English Speakers' Conceptions of Time". *Cognitive Psychology* 43.1-22.

Bowerman, M. & S. Choi. 2003. "Space under Construction: Language-specific Spatial Categorization in First Language Acquisition". *Language in Mind: Advances in the Study of Language and Thought* ed. by D. Gentner & S. Goldin-Meadow, 387-429. Cambridge, Mass.: MIT Press.

Boynton, R. M. 1997. "Insights Gained from Naming the OSA Colors". *Color Categories in Thought and Language* ed. by C. L. Hardin & L. Maffi, 135-150. Cambridge: Cambridge University Press.

Bremner, A. & P. Bryant. 2001. "The Effect of Spatial Cues on Infants'

Responses in the AB Task, With and Without a Hidden Object". *Developmental Science* 4.408-415.

— & D. Mareschal. 2004. "Reasoning … What Reasoning?" *Developmental Science* 7.419-421.

Carey, S. 1978. "The Child as Word Learner". *Linguistic Theory and Psychological Reality* ed. by J. Bresnan, G. Miller & M. Halle, 264-293. Cambridge, Mass.: MIT Press.

Choi, S., L. McDonough, M. Bowerman & J. Mandler. 1999. "Early Sensitivity to Language-specific Spatial Categories in English and Korean". *Cognitive Development* 14.241-268.

Cruse, D. A. 1977. "A Note on the Learning of Colour Names". *Journal of Child Language* 4.305-311.

Davidoff, J., I. Davies & D. Roberson. 1999. "Colour Categories of a Stone-Age Tribe". *Nature* 398.203-204, 402, 604.

—, J. Goldstein & J. Fagot. 2004. "Monkeys Categorise Colours Differently to Humans". Poster presented at PICS 04: Progress in Colour Studies.

Dedrick, D. 1996. "Color Language Universality and Evolution: on the Explanation of Basic Color Terms". *Philosophical Psychology* 9.497-524.

Fasske, H., H. Jentsch & S. Michalk, eds. 1972. *Sorbischer Sprachatlas,* vol. 4. Bautzen: Domowina.

Franklin, A. & I. R. L. Davies. 2004. "New Evidence for Infant Color Categories". *British Journal of Developmental Psychology* 22.349-377.

Gennari, S. P., S. Sloman, B. Malt & W. T. Fitch. 2000. "Motion Events in Language and Cognition". *Cognition* 83.49-79.

Goldstone, R. 1994. "Influences of Categorization on Perceptual Discrimination". *Journal of Experimental Psychology: General* 123.178-200.

—. 1998. "Perceptual Learning". *Annual Review of Psychology* 49.585-612.

Guest, S. & D. L. Van Laar. 2000. "The Structure of Colour Naming Space". *Vision Research* 40.723-734.

— & D. L. Van Laar. 2002. "The Effect of Name Category and Discriminability on the Search Characteristics of Colour Sets". *Perception* 31.445-461.

Gumperz, J. J. & S. C. Levinson. 1997. "Rethinking Linguistic Relativity". *Current Anthropology* 32.613-623.

Jameson, K. A. & N. Alvarado. 2003. "Differences in Color Naming and Color Salience in Vietnamese and English". *Color Research and Application* 28.113-138.

Kay, P., B. Berlin & W. Merrifield. 1991. "Biocultural Implications of Systems of Color Naming". *Journal of Linguistic Anthropology* 1.12-25.

Levinson, S. C. 1996. “Language and Space”. *Annual Review of Anthropology* 25.353-382.

—, S. Kita, D. B. M. Haun & B. H. Rasch. 2002. “Returning the Tables: Language Affects Spatial Reasoning”. *Cognition* 84.155-188.

Lin, H., M. R. Luo, L. W. MacDonald & A. W. S. Tarrant. 2001. “A Cross-cultural Colour-naming Study, Part I: Using an Unconstrained Method”. *Color Research and Application* 26.40-60.

Lucy, J. A. 1992. *Language and Diversity of Thought: a Reformulation of the Linguistic Relativity Hypothesis*. Cambridge: Cambridge University Press.

Macario, J. F. 1991. “Young Children’s Use of Colour in Classification: Foods and Canonically Coloured Objects”. *Cognitive Development* 6.17-46.

MacLaury, R. E. 1987. *Color and Cognition in Mesoamerica: Constructing Categories as Vantages*. Austin: University of Texas Press.

Malt, B. C. & E. C. Johnson. 1998. “Artifact Category Membership and the Intentional-historical Theory”. *Cognition* 66.79-85

McNeill, N. B. 1972. “Colour and Colour Terminology”. *Journal of Linguistics* 8.21-33.

Mervis, C. B., J. Bertrand & J. R. Pani. 1995. “Transaction of cognitive-linguistic Abilities and Adult Input: a Case-study of the Acquisition of Color Terms and Color-based Subordinate Object Categories”. *British Journal of Developmental Psychology* 13.285-302.

—, J. Catlin & E. Rosch. 1975. “Development of the Structure of Color Categories”. *Developmental Psychology* 11.54-60.

Munnich, E. & B. Landau. 2003. “The Effects of Spatial Language on Spatial Representation: Setting Some Boundaries”. *Language in Mind: Advances in the Study of Language and Thought* ed. by D. Gentner and S. Goldin-Meadow, 113-156. Cambridge, Mass.: MIT Press.

Özgen, E. & I. R. L. Davies. 1998. “Turkish Color Terms: Tests of Berlin and Kay’s Theory of Color Universals and Linguistic Relativity”. *Linguistics* 36.919-956.

— & I. R. L. Davies. 2002. “Acquisition of Categorical Color Perception: a Perceptual Learning Approach to the Linguistic Relativity Hypothesis”. *Journal of Experimental Psychology: General* 131.477-493.

Pilling, M., A. Wiggett, E. Özgen & I. R. L. Davies. 2003. “Is Color Categorical Perception Really Perceptual?” *Memory and Cognition* 31.538-551.

Pitchford, N. J. & K. T. Mullen. 2001. “Conceptualization of Perceptual Attributes: a Special Case for Color?” *Journal of Experimental Child Psychology* 80.289-314.

— & K. T Mullen. 2002. “Is the Acquisition of Basic-colour Terms in Young Children Constrained?” *Perception* 31.1349-1370.

— & K. T. Mullen. 2003. “The Development of Conceptual Colour Categories in Pre-school Children: Influence of Perceptual Categorization”. *Visual Cognition* 10.51-77.

Quinn, P. C. & P. D. Eimas. 1997. “A Re-examination of the Perceptual-to-conceptual Shift in Mental Representations”. *Review of General Psychology* 1.271-287.

Rakison, D. H. & G. E. Butterworth. 1998a. “Infants’ Use of Object Parts in Early Categorization”. *Developmental Psychology* 34.49-62.

— & G. E. Butterworth. 1998b. “Infants’ Attention to Object Structure in Early Categorization”. *Developmental Psychology* 34.1310-1325.

Rice, M. 1980. *Cognition to Language: Categories, Word Meanings, and Training*. Baltimore: University Park Press.

Roberson, D. & J. Davidoff. 2000. “The Categorical Perception of Colours and Facial Expressions: the Effect of Verbal Interference”. *Memory and Cognition* 28.977-986.

—, J. Davidoff & N. Braisby. 1999. “Similarity and Categorization: Neuropsychological Evidence for a Dissociation in Explicit Categorization Tasks”. *Cognition* 71.1-42.

—, J. Davidoff, I. R. L Davies & L. R. Shapiro. 2004. “The Development of Color Categories in Two Languages: a Longitudinal Study”. *Journal of Experimental Psychology: General* 133.554-571.

—, J. Davidoff, I. R. L Davies & L. R. Shapiro. 2005. “Color Categories: Evidence for the Cultural Relativity Hypothesis”. *Cognitive Psychology* 50.378-411.

—, J. Davidoff & L. Shapiro. 2002. “Squaring the Circle: the Cultural Relativity of Good Shape”. *Journal of Cognition and Culture* 2.29-53.

—, I. Davies & J. Davidoff. 2000. “Colour Categories Are Not Universal: Replications and New Evidence from a Stone-Age Culture”. *Journal of Experimental Psychology: General* 129.369-398.

Rosch Heider, E. 1972. “Universals in Color Naming and Memory”. *Journal of Experimental Psychology* 93.10-20.

— & D. C. Olivier. 1972. “The Structure of the Color Space in Naming and Memory for Two Languages”. *Cognitive Psychology* 3.337-354.

Sandell, J. H., C. G. Gross & M. H. Bornstein. 1979. “Color Categories in Macaques”. *Journal of Comparative and Physiological Psychology* 93.626-635.

Sandhoffer, C. M. & L. B. Smith. 1999. “Learning Color Words Involves a System of Mappings”. *Developmental Psychology* 35.568-679.

Sera, M. D., C. Berge & J. del Castillo Pintado. 1994. “Grammatical and Conceptual Forces in the Attribution of Gender by English and Spanish Speakers”. *Cognitive Development* 9.261-292.

—, C. Elieff, J. Forbes, M. C. Burch, W. Rodriguez & D. P. Dubois. 2002. “When Language Affects Cognition and When it Does Not: an Analysis of Grammatical Gender and Classification”. *Journal of Experimental Psychology: General* 131.377-397.

Shatz, M., D. Behrend, S. A. Gelman & K. S. Ebeling. 1996. “Colour Term Knowledge in Two-year-olds: Evidence for Early Competence”. *Journal of Child Language* 23.177-199.

Soja, N. N. 1994. “Young Children’s Concept of Color and its Relation to the Acquisition of Color Words”. *Child Development* 65.918-937.

Sturges, J. & T. W. A. Whitfield. 1997. “Salient Features of Munsell Colour Space as a Function of Monolexemic Naming and Response Latencies”. *Vision Research* 37.307-313.

Valberg, A. 2001. “Unique Hues: an Old Problem for a New Generation”. *Vision Research* 41.1645-1657.

Webster, M. A., E. Miyahara, G. Malkoc & V. E. Raker. 2000. “Variations in Normal Color Vision, II: Unique Hues”. *Journal of the Optical Society of America, A: Optics, Image Science and Vision* 17.1545-1555.

Werner, J. S. & Wooten, B. R. 1985. “Unsettled Issues in Infant Color Development”. *Infant Behavior and Development* 8.99-107.

Xu, F. & S. Carey. 1996. “Infants’ Metaphysics: the Case of Numerical Identity”. *Cognitive Psychology* 30.111-153.

—, S. Carey & N. Quint. 2004. “The Emergence of Kind-based Object Individuation in Infancy”. *Cognitive Psychology* 49.155-190.

SEX DIFFERENCES IN COLOUR PREFERENCE

YAZHU LING, ANYA HURLBERT & LUCY ROBINSON
University of Newcastle upon Tyne

Introduction

The history of quantitative colour preference studies dates back to at least the late 1800s (Chandler 1934). In the early 1900s, colour preference studies abounded, and typically adopted one of these paradigms: forced rank-ordering of simultaneously presented samples, fixed-scale subjective ratings of successively presented samples, verbal reports of emotional associations with colour names, or paired comparisons (Dorcus 1926; Chandler 1934). Samples were typically taken from standardized coloured paper sets (for example, Prang or Milton Bradley) with a limited range of colours; illumination was not explicitly controlled; and the methods of quantifying preference were often unreliable. General patterns within the individual results were, therefore, difficult to discern, and, given the chaotic character of the results, Chandler (1934) refuted the notion of a universal mechanism underlying colour preference. Nonetheless, a consistent top ranking of blue emerged amongst the varied observers across studies (for example: college men and women; ‘negro’ children; 4,556 visitors to the Chicago World Exposition in 1897). More recent studies have demonstrated that certain individual factors do influence colour preference and, therefore, must be controlled explicitly: not least, age (Adams 1987; Pereverzeva & Teller 2004) and culture, or at least, geographical origin (Saito 1981).

Since the mid-1900s, as more and better-controlled experimental studies have been performed, the evidence for a universal pattern in colour preference has steadily accrued. As suggested by the early data, preferences are highest in the region of green to blue and lowest in the region of yellow and yellow-green (Guilford & Smith 1959). Eysenck’s (1941) early discovery of a general order of preference (blue, red, green, purple, orange and yellow) has been largely supported by subsequent studies (Granger 1955; Guilford & Smith 1959; Helson & Lansford 1970; Gelineau 1981; McManus, Jones & Cottrell 1981; Camgoz, Yener & Guvenc 2002; Ou, Luo, Woodcock & Wright 2004).

Some studies have attempted to quantify the relative contributions of distinct colour attributes to preference (Guilford & Smith 1959), and to determine whether the general order of either hue, saturation or brightness preference remains independent of changes in level of the other two (Granger 1955); more recently, others have developed mathematical models which predict the preference value of a given colour based on its coordinate location in perceptually uniform colour space (Ou, Luo, Woodcock & Wright 2003; Ou et al. 2004). Yet, except for studies of animal colour preference (Humphrey 1972; Sahgal & Inverson 1975), few have addressed the question of the underlying biological or evolutionary drivers of colour preference. We suggest that we must not discount the possibility that our extant colour preferences may, at least in part, have been determined by the fitness needs of our evolutionary ancestors.

The evolution of colour vision

Most mammals have only two types of photoreceptors, the short-wavelength-sensitive (S) and long-wavelength-sensitive (L) cones. Comparing signals between these cone types endows mammals with a basic dichromatic colour vision (Bowmaker 1998). Among all mammals, only certain primate species (including humans) have developed routine trichromatic colour vision, via the evolution of an additional middle-wavelength-sensitive (M) cone, derived originally from mutation of the L cone-pigment-encoding gene (Nathans 1999). In these primates, chromatic sensations are obtained through two cone-opponent channels, the ‘modern’ L-M channel, in which the L cone signal is compared with the ‘new’ M cone signal, enabling spectral discriminations within the red-green range; and the ‘ancient’ S channel, where the S cone signal is compared with the combined L and M cone signals (Mollon 1989).

It is generally accepted that primates who evolved the modern ‘red-green’ subsystem must have gained selective advantages from trichromacy (Mollon 1989). The question of which particular advantages were gained is still under investigation, but the most prevalent hypothesis is that trichromacy boosted the ability to find edible food. This edible food could either be ripe, yellow fruit against a background of green foliage, as Regan, Julliot, Simmen, Vienot, Charles-Dominique & Mollon (2001) suggest, or red leaves rich in protein, as Dominy and Lucas (2001) suggest. It is unclear yet whether frugivory or folivory is more important (Sumner & Mollon 2003), but both proposals imply that the detection and consumption of food distinguished in its colour appearance by higher L-cone and lower M-cone responses against the background, are crucial to the evolution of trichromatic colour vision. The correlation between parvocellular cell numbers and volume in the lateral geniculate nucleus, and neocortical expansion with frugivory in diurnal species also supports the notion that colour vision evolved to support food-finding (Barton 1998).

As food-seeking has likely influenced the evolution of trichromatic colour vision, it is natural to speculate that it may also have affected colour preference. The colours of more desirable foods may naturally be more preferred, and variations in preference may be closely linked to variations in colour coding by the cone-opponent channels.

Sex differences

Previous studies of sex differences in colour preference have proved inconclusive. Eysenck (1941) found minor sex differences involving orange and yellow, while Granger (1955) concluded from his controlled rankings study, with fifty subjects, of more than 400 Munsell colours covering the entire colour solid, that there was no evidence of any marked difference between the preference rankings of men and women. In contrast, McManus et al. (1981), using a controlled paired comparison task, found that females have greater preference for red, and more pronounced dislike for yellow, compared to males, while Gelineau (1981), using a 77-item sorting test, found that females show greater stability of preference rankings over time. Yet more recent preference studies have found no significant sex differences (Camgoz et al. 2002; Ou et al. 2004).

On the other hand, robust sex differences have been reported for other tasks of colour vision. For example, Greene and Gynther (1995) confirm that females use a richer and more extensive vocabulary in colour identification tasks than males, and conclude that much of the sex difference may be attributed to differential socialization. Bonnardel and Miller (2002) find that females use more qualifiers than males in naming hues, particularly for reddish hues. In a colour similarity study, Bimler, Kirkland and Jameson (2002) report that males attend more to lightness, and less to red and green, but are less reliable than females. Likewise, Griffin (2003) concludes that males are individually more ‘noisy’ than females in reporting colour similarities.

Sex differences have also been reported repeatedly for visual spatial tasks (Silverman & Eals 1992; Eals & Silverman 1994; McBurney, Gaulin, Devineni & Adams 1997; McGivern, Huston, Byrd, King, Siegle & Reilly 1997; Dabbs, Chang, Strong & Milun 1998). Males outperform females in mental rotation and route navigation tasks, and are also more accurate in tests of target-directed motor skills. Females tend to outperform males in identifying matching items, or recalling landmarks from a route (Kimura 1992). This general pattern of sex differences in visual behaviour has been attributed to the evolutionary division of labour between the sexes – the hunter-gatherer distinction (Silverman & Eals 1992). Males, as hunters, would be expected to develop visual skills that better enabled them to track and kill animals, for example, to orient themselves with respect to objects or places, assess distances and perform mental rotations to maintain accurate orientations. Females, as gatherers, would be expected to develop skills useful in foraging for edible plants, such as the ability to learn rapidly and remember objects, and to recognize objects in various spatial configurations (Silverman & Eals 1992).

While the hunter-gatherer theory has been explicitly proposed to explain sex differences in visual spatial tasks, it may also account for sex differences in other visual tasks, a possibility which we explore here.

Aims of this study

One difficulty in correlating colour preferences with biological factors is the complexity and non-physiological nature of most standard colour systems. While delivering the preference order of basic colours may be straightforward, further analysis is difficult without simplification of the factors involved.

Our aim in the experiments reported here was to employ a simple, forced-choice ‘colour-picking’ task which, by its nature, enforces immediate, un-premeditated responses, and in which the stimuli are colorimetrically controlled so that the relative contributions to preference of hue, saturation and luminance – as well as their physiological encoding – may be separated and compared. We also controlled for the individual factors of age, sex, and cultural background of the observers.

Method

Participants

94 subjects (48 females; 46 males), aged 20-26, participated in the main preference experiment (see below). All tested normal on the Farnsworth-Munsell colour vision test. Of these, 53 subjects were British Caucasian (25 males; 28 females), and 37 Chinese (19 males; 18 females). All Chinese subjects were ethnic Han Chinese, raised in mainland China, the majority of whom had arrived in Britain within the year prior to the experiment; none had lived in Britain for more than three years. Subjects also completed a set of questionnaires and all females reported on each visit the date of their last menstrual period and whether they were oral contraceptive pill-users. The role

of other factors determined from these additional measurements are not considered in this paper.

Stimuli

We generated 24 distinct colours from 8 distinct hues with 3 combinations of 2 lightness and 2 saturation values (as listed in table 1, with coordinates specified in CIE Yxy and LUV space, the latter as LHS derivations). We divided the stimuli into three groups, each group varying only in hue. We deliberately selected hues that are not typical of basic colour categories, and which, therefore, cannot easily be named with the basic colour terms such as *red, green, yellow* or *blue*. The stimuli were slightly darker than the neutral background (luminance contrast either –28% or –7%).

Experimental procedure

The colour stimuli were presented on a calibrated CRT monitor as pairs of rectangular patches (2x3 degrees), 2 degrees above and below the central fixation point on a uniform background. Subjects viewed the monitor from a distance of 57cm, their heads comfortably placed in a chin rest, in an otherwise dark room. Subjects initially adapted to the neutral colour of the uniform background for one minute. Immediately after the adaptation phase, the paired comparison trials began. On each trial, the subject’s task was to move the mouse pointer to select which of the two colour patches s/he preferred, after which the next pair would appear almost immediately. There was no time limit on responses, but subjects were explicitly instructed to choose as quickly as possible, without cogitation and, particularly, without reference to any possible use of the colours (for example, clothes, wall colours, and so on). On average, over all subjects, each trial lasted 1.5 seconds. Each experiment was split into two sessions, each with 240 trials. In the first session, the constant-saturation session, each pair-wise comparison between the sixteen colours in groups 1 and 2 was tested twice. In the second, constant-lightness session, each pair-wise comparison between the sixteen colours in groups 1 and 3 was tested twice. Each subject performed the two sessions in a single initial visit, and again, in a return visit approximately two weeks after the first.

Results

For the basic result, we first look at pair-wise comparisons within each group of colours, that is, hue preferences for iso-saturation iso-lightness pairs. Within each session, each colour in a group appears an equal number of times. We therefore obtain a hue preference curve for that group by plotting the

Group 1 (L=80, S=0.5)

Stimulus No.	CIEY	CIEx	CIEy	L	H	S
Background	50	0.32	0.34	100	0	0
1	28.34	0.38	0.34	80	1.29	0.5
2	28.34	0.36	0.32	80	1.69	0.5
3	28.34	0.35	0.30	80	2.03	0.5
4	28.34	0.30	0.28	80	3.01	0.5
5	28.34	0.26	0.33	80	4.42	0.5
6	28.34	0.27	0.36	80	4.84	0.5
7	28.34	0.29	0.38	80	5.17	0.5
8	28.34	0.35	0.41	80	6.15	0.5

Group 2 (L=95, S=0.5)

Stimulus No.	CIEY	CIEx	CIEy	L	H	S
9	43.81	0.38	0.34	95	1.29	0.5
10	43.81	0.36	0.32	95	1.69	0.5
11	43.81	0.35	0.30	95	2.03	0.5
12	43.81	0.30	0.28	95	3.01	0.5
13	43.81	0.26	0.33	95	4.42	0.5
14	43.81	0.27	0.36	95	4.84	0.5
15	43.81	0.29	0.38	95	5.17	0.5
16	43.81	0.35	0.41	95	6.15	0.5

Group 3 (L=80, S=0.8)

Stimulus No.	CIEY	CIEx	CIEy	L	H	S
17	28.34	0.41	0.34	80	1.29	0.8
18	28.34	0.39	0.31	80	1.69	0.8
19	28.34	0.36	0.28	80	2.03	0.8
20	28.34	0.28	0.25	80	3.01	0.8
21	28.34	0.23	0.33	80	4.42	0.8
22	28.34	0.24	0.37	80	4.84	0.8
23	28.34	0.27	0.41	80	5.17	0.8
24	28.34	0.38	0.47	80	6.15	0.8

Table 1: *Specifications for experimental stimuli. Lightness, hue and saturation values derived from CIELUV colour space.*

proportion of trials each colour was chosen as the preferred colour, as a function of its hue. Figure 1 shows the Group 1 (L=80, S=0.5) hue preference curve for the initial visit, averaged over both sessions and all subjects.

Both male and female preference curves peak around a hue value of 3 (corresponding to a purplish-blue colour against the neutral background) and fall gradually towards the end of the range, reaching their lowest point at a hue of 6.15 (corresponding to a greenish-yellow colour). Compared with the average male curve, the average female curve is shifted toward red, and more pronounced in both its peaks and troughs. Thus, the average female strongly prefers pinks and lilacs, while the average male has less marked preferences; both 'dislike' yellow-greens. The overall flattened shape of the average male curve suggests, either less consistency amongst males as a population, or generally weaker preferences within individuals – in fact, as further analysis shows (not described here), both of these factors contribute.

Although Figure 1 shows results only for Group 1 colours, similar hue preference curves were obtained for other lightness / saturation levels, confirming the invariance of hue preference under changes in other attributes (Granger, 1955).

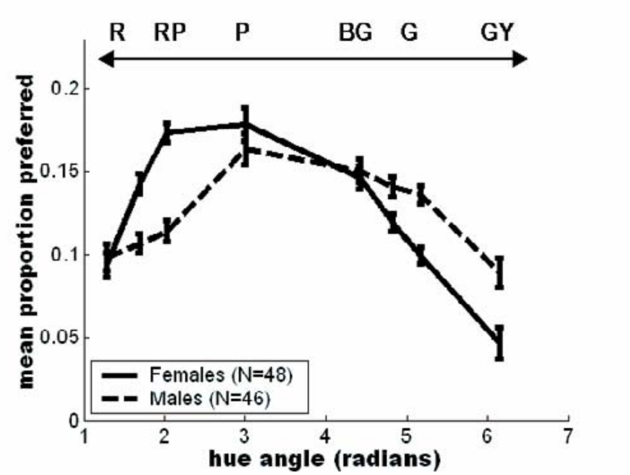


Figure 1: *Group 1 mean hue preference curves for all subjects, both sessions, initial visit. Error bars indicate SEM. Upper labels: the hue labels of the nearest-matching Munsell colour, for illustrative purposes only.*

Cultural differences in hue preference

Our subjects can be divided into four main sub-populations: Chinese males, Chinese females, British males and British females. Figure 2 illustrates the average Group 1 (L=80, S=0.5) hue preference curves for each of these sub-populations.

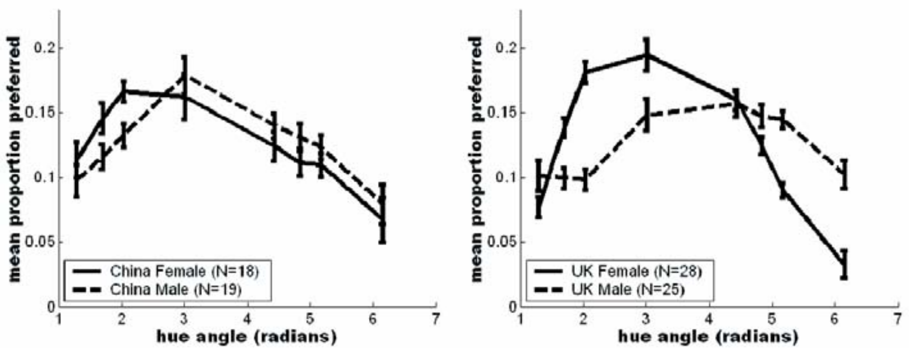


Figure 2: *Group 1 hue preference curves for Chinese (left) and British (right) subjects. Error bars indicate SEM.*

Figure 2 illustrates that, although sex differences exist in both Chinese and British sub-populations, the difference is less pronounced in the Chinese. The larger sex difference in the British sub-population is now unmasked, relative to the global results in Figure 1. Note, however, that, for both sub-populations, the pattern of sex differences is the same, with the average female preference for reddish hues significantly higher than the male, and a steeper decline in female preference for greenish-yellow hues, compared to the male. Thus, the results suggest an underlying universal hue preference system, which is influenced by cultural factors.

Lightness and saturation preference

To assess lightness and saturation preferences as a function of hue, we transform the proportion preferred for each of the sixteen colours from both groups within a session into z scores, according to Case V of Thurstone’s Law of Comparative Judgement (Thurstone 1927). Larger z scores indicate higher preferences within the session, and may then be directly compared across groups to determine whether there are consistent preferences for higher or lower lightness or saturation. For example, if the z scores for Group 2 stimuli are larger than those for Group 1 in the first session, we would conclude that observers consistently prefer colours of higher lightness.

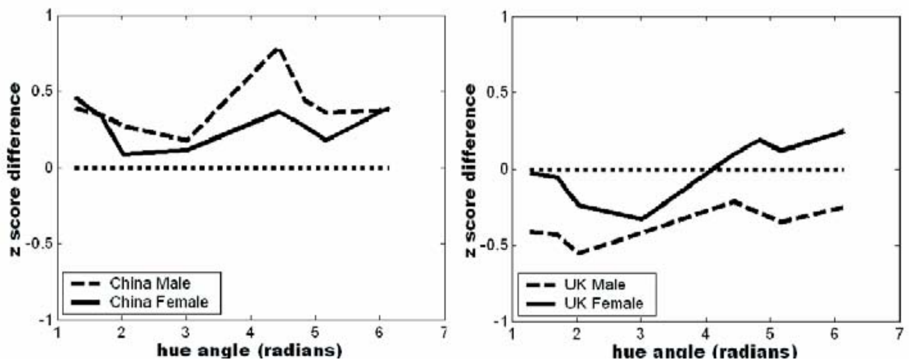


Figure 3: *Lightness preference curves for Chinese and British subjects, obtained from pooled data in the first session, initial visit. Dotted black lines indicate the zero-level z score. Chinese subjects, left; British subjects, right.*

Figure 3 illustrates the differences in z scores between Group 1 and Group 2 colours as a function of hue angle. Positive values indicate larger z scores for Group 2 colours, that is, preference for higher lightness; negative values indicate larger z scores for Group 1 stimuli, that is, preference for lower lightness. Thus, it is clear that both Chinese males and females prefer lighter colours and British males prefer darker colours, at all hues. Although British females tend to prefer lighter colours relative to British males, they show no consistent lightness preference across hues.

Saturation preference curves, obtained in the same way for Session 2, are shown in Figure 4. Again, positive z score differences indicate higher preferences for higher saturations. Thus, Chinese males consistently prefer more saturated colours, while Chinese females show no preference for saturation, except at hue angle 1.29 (red). British subjects show the opposite pattern, with females preferring more saturated colours, and males exhibiting no saturation preference.

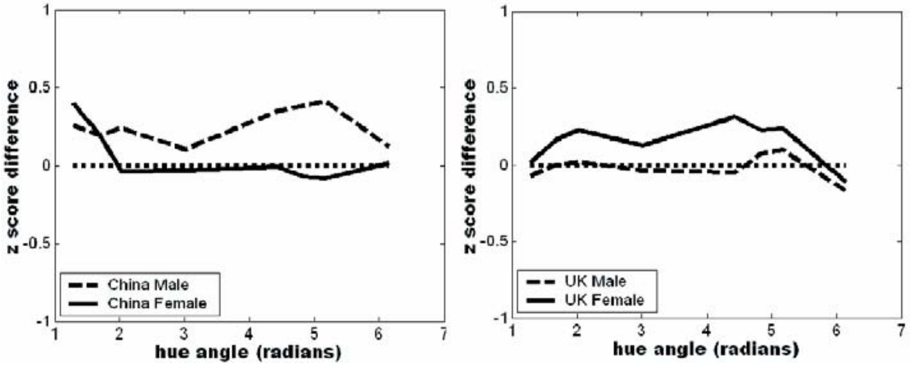


Figure 4: *Saturation preference curves for Chinese and British subjects, obtained from pooled data, second session, initial visit. Dotted lines indicate the zero-level z score. Chinese subjects, left; British subjects, right.*

The factors underlying hue preference

Our results support previous indications of an underlying universal system for hue preference. Although hue preference curves vary between individuals, the variations appear to cluster in only a few distinct patterns (see McManus et al. 1981 for a similar finding). To quantify this evident universality, and to reduce the number of variables with which to characterize the underlying preference system, we employed Principal Component Analysis (PCA) to determine whether a small set of basis functions would explain the inter-individual variability.

Accordingly, we extracted principal components from the matrix of all ninety-four hue preference curves for Group 1 colours, obtained from all subjects in both sessions for the initial visit. The first three PCs account for 85% of the variance across this set, while the first two PCs account for 69% of the variance. We may, therefore, simplify the description of each subject’s individual hue preference curve into the set of three PC weights necessary to reconstruct the curve.

Because the colours within each group lie within an isoluminant plane, they may be fully characterized by the two cardinal colour-coding dimensions of the primate visual system: the cone-opponent channels S-(L+M) and (L-M). In order to determine the physiological significance of the PCs, we calculate the contrast values of the hues against the background within the two cone-opponent channels and compare these with the preference basis functions (see appendix for contrast calculations). Although the PCs are by definition orthogonal, and the cone-contrast components are not, nonetheless the first PC closely matches the S-(L+M) contrast component, and the second, the (L-M) contrast component. This resemblance is consistent – and, in some cases, particularly striking (Figure 5, bottom left) – across all three lightness / saturation groups, as well as across observer sub-groups, as shown in Figure 5.

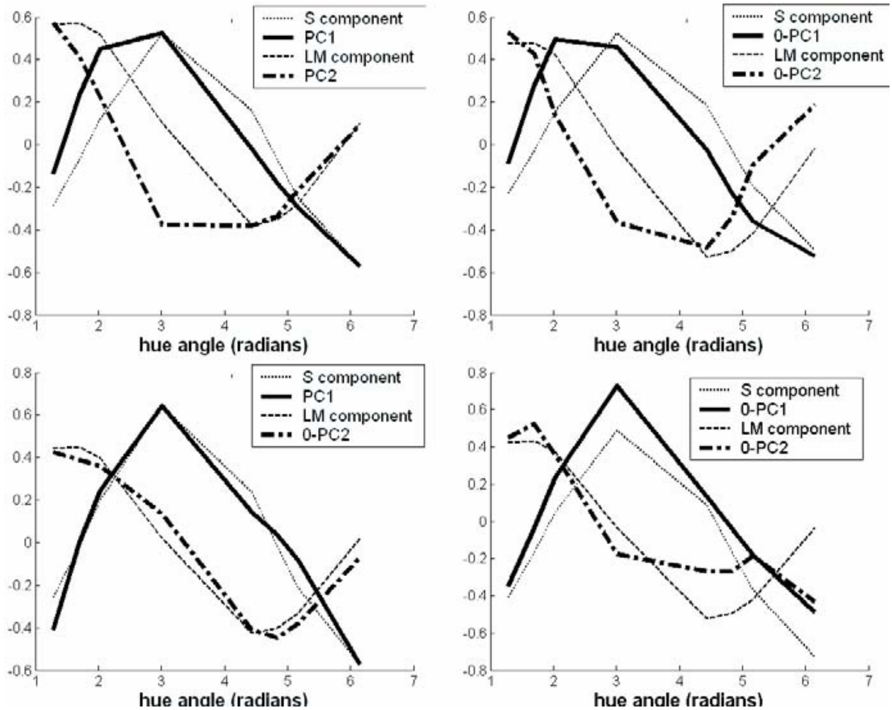


Figure 5: *The first two PCs as a function of hue, compared with the cone contrast values from the two cone-opponent channels. Top left: Group 1, all; top right: Group 2, all; bottom left: Group 1, males; bottom right: Group 1, females.*

We therefore perform an alternative decomposition of the individual preference curves using a least-squares regression to determine the best-fitting weights on the S-(L+M) and (L-M) cone-contrast components. The interpretation of the weights is, therefore, entirely straightforward: a positive weight on the first component indicates that the subject tends to prefer hues with positive S-(L+M) contrast, that is, a bias for blue over yellow, while a negative weight indicates a preference for yellow over blue. Likewise, a positive weight on the second component indicates that the subject prefers hues with positive L-M cone contrast, that is, a bias for red over green.

Figure 6 illustrates the weights given to the two cone-contrast components for all subjects from all sub-groups, for the Group 1 hue preference curves. For both nationalities combined, both males and females give positive weights to the S-(L+M) component, with the average female weight significantly higher, while the average female gives a positive weight to the L-M contrast component and the average male a negative weight. This result is also true for British observers alone, with an even more pronounced sex difference. The Chinese show no significant sex difference in the weights on the S-(L+M) component, but a robust sex difference for the L-M component. Notably, both Chinese males and females give larger weights to the L-M component than the British, suggesting that the Chinese have a stronger preference for red.

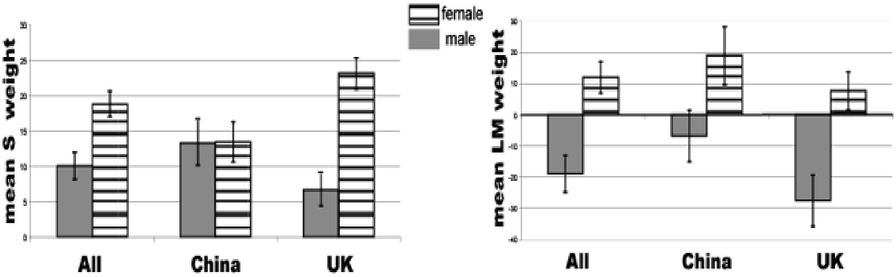


Figure 6: *Mean weights on the first cone-opponent contrast components of the individual hue preference curves for Group 1, both sessions, initial visit. S-(L+M) component weights, left. L-M component weights, right. Error bars indicate SEM.*

Discussion

We find that hue preference at constant saturation and lightness can largely be explained by two factors: the S-(L+M) cone and L-M cone-contrast components of the stimulus against the background. On one hand, this result is unsurprising, since the cone-opponent channels are the two fundamental mechanisms along which colours are encoded by neurons, and, therefore, they characterize the basic dimensions along which the colours differ from each other. On the other hand, the result argues against previously held views that preference is unsystematic, highly individual, or largely determined by contextual or cognitive factors. Instead, our results suggest that preference is systematically governed by sensory encoding, and, to a significant extent, predictable. The simplification of the hue preference curves into a set of weights on these components also allows us to characterize and quantify other influences on preference.

The main effect revealed by analysis of the PC weights is the significant difference between male and female weights on the L-M cone-contrast component across both Chinese and U.K. cultures, with female weights significantly more positive. Thus, females tend to have stronger preference for positive L-M cone-contrast or red. We are not the first to report a female bias towards red: in his study of 4,500 observers, Jastrow (1897) found that women were roughly 1.66 times as likely as men to choose red as their single most preferred colour. McManus et al. (1981) also found that, although both sexes were more likely to prefer blue and to dislike red and yellow, of those who preferred red or yellow, significantly more were female. The solidity of our results suggest, though, that there is underlying biological origin to this bias.

We speculate that the female preference for red may be influenced by evolutionary factors. Males have ‘ruddier’ complexions than females, and this sex difference arises at puberty and is universal across races (Frost 1994). Females may, therefore, naturally prefer redder faces, and this preference may be ingrained in the tendency to give positive weighting to the L-M contrast component that we see here. Nevertheless, considering the robust and consistent sex difference in hue preference that we find across cultures, it is unlikely that sexual selection plays the only or largest role. We propose instead that the division of labour in human evolution accounts for most of the effect.

The hunter-gatherer theory (Silverman & Eals 1992) proposes that female brains should be specialized for foraging-related tasks and is well supported by studies of visual spatial abilities (Kimura 1992; Eals & Silverman 1994; McBurney et al. 1997; McGivern et al. 1997; Dabbs et al. 1998). Given the importance of colour vision and especially ‘modern’ trichromacy for food-finding (Barton 1998; Regan et al. 2001), it is logical to speculate that sex-specific differences in colour preference may also arise from this evolutionary division of labour.

Our results support this speculation. Females give higher weight to positive L-M cone contrast against the background. This preference for red against green may have evolved to facilitate the gatherer’s identification of ripe, yellow fruit embedded in green foliage (Nathans 1999; Regan et al. 2001), or of edible red leaves amidst unripe green foliage (Dominy & Lucas 2001). As a gatherer, the female would also need to be more aware of colour information than the hunter. This requirement would emerge as greater certainty and more stability in female colour preference, which we find to be the case.

Sex differences in colour preference may, therefore, be largely hard-wired, but, as our results clearly show, other factors play a role. The fact that Chinese observers overall have a stronger preference for red than U.K. observers demonstrates the influence of cultural background. Red is the colour of good luck in Chinese culture. The strong Chinese preference for lighter colours also suggests cultural determinants, and is supported by other findings (Ou et al. 2003; Ou et al. 2004).

The design of our simple paired-comparison task, which requires subjects to pick their preferred colour rapidly and manually, in a situation almost entirely devoid of context, naturally discourages the intrusion of other higher-level factors. Nonetheless, we conclude that there are robust, inherent sex differences in colour preference, which are largely biologically determined. We speculate that these are the result of sex-specific functional specializations of vision that arose in the evolutionary division of labour.

Appendix

The cone-opponent colour contrasts are derived from the L, M and S cone excitations of the stimulus and background, calculated using the Smith-Pokorny cone fundamentals (Smith & Pokorny 1975). The S-cone contrast, dS, is defined as $(s_p - s_b)/s_b$, where $s_p = S_p/(L_p + M_p)$, $s_b = S_b/(L_b + M_b)$, the subscript p denotes the stimulus, and b the background. Analogous definitions hold for d(L-M).

References

Adams, R. J. 1987. "An Evaluation of Color Preference in Early Infancy". *Infant Behavior and Development* 10.143-150.

Barton, R. A. 1998. "Visual Specialization and Brain Evolution in Primates". *Proceedings of the Royal Society of London, Series B* 265.1933-1937.

Bimler, D. L., J. Kirkland & K. A. Jameson. 2002. "Quantifying Variations in Personal Color Spaces: Are there Sex Differences in Color Vision?" *Color Research and Application* 29:2.128-134.

Bonnardel, V. & S. Miller. 2002. "Gender Differences in Colour-naming Task". *Perception* 31.71 Suppl.

Bowmaker, J. K. 1998. "Evolution of Colour Vision in Vertebrates". *Eye* 12.541-547.

Camgoz, N., C. Yener & D. Guvenc. 2002. "Effects of Hue, Saturation, and Brightness on Preference". *Color Research and Application* 27.199-207.

Chandler, A. R. 1934. *Beauty and Human Nature*. New York: Appleton-Century-Crofts.

Dabbs, J. M. J., E. L. Chang, R. A. Strong & R. Milun. 1998. “Spatial Ability, Navigation Strategy, and Geographic Knowledge among Men and Women”. *Evolution and Human Behavior* 19.89-98.

Dominy, N. J. & P. W. Lucas. 2001. “Ecological Importance of Trichromatic Vision to Primates”. *Nature* 410.363-366.

Dorcus, R. N. 1926. “Colour Preferences and Colour Associations”. *Journal of Genetic Psychology* 33.399-434.

Eals, M. & I. Silverman. 1994. “The Hunter-gatherer Theory of Spatial Sex-Differences: Proximate Factors Mediating the Female Advantage in Recall of Object Arrays”. *Ethology and Sociobiology* 15.95-105.

Eysenck, H. J. 1941. “A Critical and Experimental Study of Color Preference”. *American Journal of Psychology* 54.385-391.

Frost, P. 1994. “Preference for Darker Faces in Photographs at Different Phases of the Menstrual Cycle – Preliminary Assessment of Evidence for a Hormonal Relationship”. *Perceptual and Motor Skills* 79.507-514.

Gelineau, E. P. 1981. “A Psychometric Approach to the Measurement of Color Preference”. *Perceptual and Motor Skills* 53.163-174.

Granger, G. W. 1955. “An Experimental Study of Colour Preferences”. *Journal of General Psychology* 52.3-20.

Greene, K. & M. Gynther. 1995. “Blue Versus Periwinkle: Color Identification and Gender”. *Perceptual and Motor Skills* 80.27-32.

Griffin, L. D. 2003. “Males are ‘Noisy Females’ When it Comes to Reporting the Psychological Structure of the Basic Colours”. *Perception* 32.387 Suppl.

Guilford, J. P. & P. C. Smith. 1959. “A System of Color-preference”. *American Journal of Psychology* 72.487-502.

Helson, H. & T. Lansford. 1970. “The Role of Spectral Energy of Source and Background Color in the Pleasantness of Object Colors”. *Applied Optics* 9.1513-1562.

Humphrey, N. K. 1972. “Interest and Pleasure: Two Determinants of a Monkey’s Visual Preferences”. *Perception* 1.395-416.

Jastrow, J. 1897. “The Popular Aesthetics of Color”. *Popular Science Monthly* 50.361-368.

Kimura, D. 1992. “Sex Differences in the Brain”. *Scientific American* 266.81-87.

McBurney, D. H., S. J. C. Gaulin, T. Devineni & C. Adams. 1997. “Superior Spatial Memory of Women: Stronger Evidence for the Gathering Hypothesis”. *Evolution and Human Behavior* 18.165-174.

McGivern, R. F., J. P. Huston, D. Byrd, T. King, G. J. Siegle & J. Reilly. 1997. “Sex Differences in Visual Recognition Memory: Support for a Sex-

Related Difference in Attention in Adults and Children". *Brain and Cognition* 34.323-336.

McManus, I. C., A. L. Jones, J. Cottrell. 1981. "The Aesthetics of Colour". *Perception* 10.651-666.

Mollon, J. D. 1989. "Tho she Kneeld in that Place where they Grew…: The Uses and Origins of Primate Color-vision". *Journal of Experimental Biology* 146.21-38.

Nathans, J. 1999. "The Evolution and Physiology of Human Color Vision: Insights from Molecular Genetic Studies of Visual Pigments". *Neuron* 24.299-312.

Ou, L. C., M. R. Luo, A. Woodcock & A. Wright. 2003. "A Study of Colour Emotion and Colour Preference, Part I: Colour Emotions for Single Colours". *Color Research and Application* 29.232-240.

—, M. R. Luo, A. Woodcock & A. Wright. 2004. "A Study of Colour Emotion and Colour Preference, Part III: Colour Preference Modeling". *Color Research and Application* 29.381-389.

Pereverzeva, M. & D. Y. Teller. 2004. "Infant Color Vision: Influence of Surround Chromaticity on Spontaneous Looking Preferences". *Visual Neuroscience* 21.389-395.

Regan, B. C., C. Julliot, B. Simmen, F. Vienot, P. Charles-Dominique & J. D. Mollon. 2001. "Fruits, Foliage and the Evolution of Primate Colour Vision". *Philosophical Transactions of the Royal Society of London, Series B* 356.229-283.

Sahgal, A. & S. D. Inverson. 1975. "Colour Preferences in the Pigeon: a Behavioural and Psychopharmacological Study". *Psychopharmacologia* 43.175-179.

Saito, M. 1981. "A Cross-cultural Survey on Colour Preference". *Bulletin of the Graduate Division of Literature of Waseda University* 27.211-216.

Silverman, I. & M. Eals. 1992. "Sex Differences in Spatial Abilities: Evolutionary Theory and Data". *The Adapted Mind: Evolutionary Psychology and the Generation of Culture* ed. by J. H. Barkow, L. Cosmides & J. Tooby, 531-549. New York: Oxford University Press.

Smith, V. & J. Pokorny. 1975. "Special Sensitivity of the Foveal Cone Photopigments between 400 and 500 nm". *Vision Research* 15.161-171.

Sumner, P. & J. D. Mollon. 2003. "Did Primate Trichromacy Evolve for Frugivory or Folivory?". *Normal and Defective Colour Vision* ed. by J. D. Mollon, J. Pokorny & K. Knoblauch, 21-30. New York: Oxford University Press.

Thurstone, L. L. 1927. "A Law of Comparative Judgement". *Psychological Review* 34.273-286.

COLOUR ASSOCIATIONS IN THE MEXICAN UNIVERSITY POPULATION

LILIA ROSELIA PRADO-LEÓN, ROSALÍO AVILA-CHAURAND &
ROSA AMELIA ROSALES-CINCO
University of Guadalajara

1. *Introduction*

Colour has effects on a psychological level, with emotional, sensory and cognitive evocations. However, these psychological aspects of colour are not universal, nor are they applicable to any one entire population, since they are constructed with individual as well as collective participation. Although no one doubts that trans-cultural variations exist (Jacobs, Keown, Worthley & Ghymn 1991), in Mexico there do not seem to have been any studies to support or demonstrate the effect that colours have upon people, thus enabling such data to be taken into consideration for design elements appropriate to our population.

At an international level, research conducted in China (Courtney 1986) detected stereotypes for the Chinese population using a pencil-and-paper test that included eight colours. Subjects (n = 784) could select between twelve concepts. Later, Chan and Courtney (2001) studied 117 subjects using ten colour associations with sixteen concepts. Additional studies, related to Western culture, include Bergum and Bergum (1981), Jacobs et al. (1991), Lane (1991) and Mahnke (1996).

To our knowledge, the only research conducted in Mexico is that of Ortiz (1992) in Mexico City, in which results are presented from a study which lasted for ten years and comprised four stages. The author classifies associations attached to colours, according to the extent of their appearance in the results from these four stages. The associations described as ‘durable’ (*permanentes*) are those appearing in three of the four stages, and those considered ‘highly durable’ (*altamente permanentes*) are those appearing in all four stages. The highly durable associations are given below:

1. Associations with red: RESTLESSNESS, LOVE, HEAT, PLEASURE, STRENGTH, AGGRESSIVENESS.

2. Associations with blue: HAPPINESS, MASCULINITY.
3. Associations with black: DEATH, UGLINESS, NIGHT, DEPTH, HATRED, HEAVINESS, FEAR.
4. Associations with white: PEACE, LIGHTNESS (weight), VIRTUE, INNOCENCE, KINDNESS, HEALTH.
5. Associations with pink: FEMININITY.
6. Associations with grey: SADNESS, FATIGUE.

Data obtained in such studies are useful in designing countless objects and environments, with the aim of adapting them to various human pursuits, and achieving high levels of safety, efficiency and comfort for the various activities in which people engage. With this in mind, studies have been undertaken with reference to colour as it is applied to various fields of design; such as those conducted by Braun and Silver (1995), who found that colours relate to levels of risk when they are used in cautionary messages on some products. De Craen, Roos, De Vries and Kleijnen (1996) showed that colours used in antidepressant drugs affect perception of their efficacy as well as users' recollection of proper dosages. Knez and Enmarker (1998) undertook a study into the effects of light upon mood and cognitive performance within the physical environment of an office, finding that it is principally colour which affects mood. Due to the limited research in this field relating to our own cultural context, and the important applications of colour associations in design, the aim of this present study was to recognize such associations among undergraduate students at the University of Guadalajara, via a pencil-and-paper test.

2. *Method*

2.1 *Subjects*

Participating subjects were 1258 students, both males and females, who were in their first or second term in one of the University of Guadalajara's thirty-four undergraduate study programmes: this was to avoid more advanced students in programmes related to the visual arts who might have had academic knowledge of possible colour associations. Two groups were chosen at random from each of the undergraduate degree programmes offered by the University in the Guadalajara metropolitan area.

2.2 *Materials*

We provided students with the following materials:

1. An answer sheet which consisted of two parts: (a) general data for those surveyed, including questions regarding their age, sex, place of residence, whether they paid for the costs of their studies themselves, parents'

occupations, income and academic levels completed; (b) sixteen windows with three lines alongside each for noting down a maximum of three associations.

2. A rectangular letter-size sheet with sixteen 2 x 4 cm rectangles in the following colours: grey, red, blue, pink, purple, green, yellow, black, white, lilac, brown, cream, burgundy, orange, silver and gold. (See Table 1 for Munsell codings).
3. A page listing sixty-six associations, in three versions, each of which varied the order in which the associations were presented. This list was obtained initially from the results of a pilot test.

Common name of colour	Munsell code
Grey	6.0 BG 3/4
Red	6.0 R 4/20
Blue	8.0 B 2/8
Pink	5.0 R 6/6
Purple	4.0 P 1/10
Green	2.0 G 4/18
Yellow	4.0 Y 8/16
Black	N 1/
White	N 9/
Lilac	3.0 RP 2/8
Brown	8.0 YR 2/6
Cream	3.0 Y 8/4
Burgundy	3.0 R 1/10
Orange	9.0 R 5/18
Silver	*
Gold	2.0 Y 4/10

*Does not appear in the *Munsell Book of Color*.

Table 1: *Colours included in the research and their* Munsell Book of Color *codes.*

2.3 *Procedure*

2.3.1 *Exclusion Criteria*

Before the survey was administered, potential participants were asked if they had any visual problem, such as colour blindness, which would impede their accurate perception of the colours. Any such prospective subjects were excluded from participation.

2.3.2 *Instructions*

Instructions were given to subjects requesting that they place the answer sheets on top of the colour sheets, in such a way that the windows in each answer sheet aligned with the coloured rectangles. They were asked to write general data at the beginning of the answer sheet and, later, to write as many as three associations, selected from a list, that each colour evoked for them. It was made clear that, if a colour evoked an association that was not on the list, they could include it on their answer sheet.

Time was tabulated from the start of the test until the last subject completed it, with a mean completion time of twenty-two minutes (SD= ± 4.69 min.).

3. *Results*

3.1 *Characteristics of the subjects*

Participating subjects were 1258 students (48.8% women and 51.2% men), aged between seventeen and forty-five years, with a mean age of twenty years (SD= ± 2.98). The mode was nineteen years of age, and none of the subjects reported visual problems related to colour perception.

As for the economic characteristics of the subjects, 31.4% worked in order to pay their tuition fees, 65.0% were supported by parents, and 2.6% were supported by others, such as relatives. 91.4% resided in Guadalajara’s metropolitan area and 8.6% lived outside the city. Data showed that the majority of parents were office workers (23.6%), business owners (17.0%), trades-people (for example, carpenters, plumbers, and housepainters (17.0%)), or independent professionals (15.5%). Other occupations were industrial work, police-work and teaching. The most frequently reported occupation for mothers was housewife (67.3%), and their other principal occupations were office work, business employee and teacher. Data on household income is not included, as 62.1% of the surveys showed that subjects had no knowledge of this.

3.2 *Colour Associations*

In applying the test, 399 associations were elicited in response to the presented stimuli. As many of these were semantically related, they were classified together, until a final fifty-four conceptual categories remained. For example, under the concept of LOVE were classified the associations (as submitted by the subjects) of AFFECTION (*cariño*), ROMANTIC (*romántico*) and ROMANCE (*romance*); and, under the concept of BEAUTY, were classified ATTRACTIVE (*atractivo*), BEAUTIFUL (*bello*), PRETTY (*bonito*), LOVELY (*hermoso*), AGREEABLE-LOOKING (*agradable*) and GORGEOUS (*vistoso*). After this had been done, the total of the associations for each colour was taken as

100% and, from this base, particular percentages were calculated for each association with the given colour.

The associations for each colour varied widely. No very high percentages were obtained, since each colour generally had diverse associated concepts, with results falling within a range of sixteen to thirty-two associations, although a minimum percentage of 0.9 and a maximum of 28.7 figured in the results. Associations with percentages of between 0.9 and 4.4 were excluded, in order to show the more important ones, and to better summarize the findings. Tables 2.1 and 2.2 show the thirty-three associations reported for each colour with a percentage greater than or equal to 4.5. A chi square test was applied to each of these thirty-three concepts, with the result that each one was associated with each colour at a significance level of $p< 0.001$, except lilac, which had a significance of $p< 0.05$.

The range of associations that were greater than or equal to 4.5% for each colour varied from three to eight. The colour brown elicited the fewest associations, while the colours grey and purple were assigned the most. The well-determined associations of more than 20% were: RED-SEXUALITY, GOLD-WEALTH, BLACK-DEATH, WHITE-INNOCENCE, GREEN-NATURE, BROWN-DIRTINESS. Less determinate associations with percentages of 10 to 20 were: GREY-SADNESS, PINK-FEMININITY, CREAM-PASSIVITY, YELLOW-BRIGHTNESS, BURGUNDY-SEXUALITY, BLUE-PASSIVITY, ORANGE-ACTIVITY. Associations of between 5% and 10% were: SILVER-BRIGHTNESS, LILAC-SEXUALITY and PURPLE-ACTIVITY.

One interesting finding was that there were statistically significant differences observed between men and women (see Tables 3.1, 3.2, 3.3 and 3.4), following application of the chi square test ($p< 0.05$). In Table 3.3 it may be observed, for example, that, of the total of PINK-FEMININITY associations, 55.2% were given by men and only 34% by women. In contrast, of the total of BLUE-MASCULINITY associations, 22.8% were given by women, and 17% by men (see Table 3.2). Furthermore, of the associations of SEXUALITY with pink, 23.4% were by men and only 6.3% by women (see Table 3.4), contrasting with the associations of INNOCENCE with the same colour, 44.2% of which were given by women and 20% by men (see Table 3.3). Although the associations attributed to lilac were not very determinate, it may be observed that 21.1% of those obtained for SEXUALITY were from men and only 9.6% from women (see Table 3.2). Thus, for Mexican male students, the colours red, pink and lilac are more strongly associated with SEXUALITY, while, for women, only red has a strong association with this concept.

4. *Discussion*

According to Bergum and Bergum (1981), primary colours attract the greatest number of associations, based on the physiology of colour perception. In this study, red, blue, yellow, green, and black exhibited six associations each, and white five; higher than the mean number of associations of 4.5.

As can be seen, some colours were found to have associations with particularly high percentages, suggesting more strongly established concepts tending toward the stereotypical. Among these were white, with its associations of PASSIVITY and INNOCENCE, brown, associated with DIRTINESS, red with SEXUALITY, gold with WEALTH, and green with NATURE and LIFE; all of which obtained percentages above 20. On the other hand, there were colours like lilac and purple, for which all associations were below 10%. Notwithstanding the chi square test, according to the mean percentages obtained, no stereotype could be established for these colours, only tendencies, since the criterion of a 66% minimum was taken for determining an effective stereotype (Bergum & Bergum 1981). Stereotypes have been found in previous research (Bergum & Bergum 1981; Courtney 1986; Chan & Courtney 2001), but this was probably a result of the procedure employed, which consisted in a closed test with very few (eight to sixteen) associations. In the present study, the subjects could choose between sixty-six concepts and could also add others, as they considered necessary. Obviously, this has the advantage of permitting knowledge of a considerable number of other concepts associated with colour, although it has the disadvantage of not obtaining elevated percentages; there is also the possibility that subjects may not include a meaning that could be useful for the researcher, such as those included in the above-mentioned studies.

There are, however, several similarities between the results from the present study and those reported by Courtney (1986) and Chan and Courtney (2001). In all three studies, the colour red is associated with HEAT and AGGRESSIVENESS (or DANGER, in the Chinese population). Mexicans, as well as Chinese, associated the colour yellow with HEAT and CAUTION, and the present study also encountered the association ENERGY, which compares in some measure with the Chinese association RADIATION. In the same manner, orange was associated, for both Mexicans and Chinese, with RADIATION and ENERGY, along with HEAT. As for the colour pink, Chan and Courtney (2001) found the association DULLNESS, and the present study found a certain similarity, with the association WEAKNESS. Similarly, the colour grey is associated, in both studies, with COLD and WEAKNESS. For white, the association in the study of the Chinese population was found to be DULLNESS, and, in the Mexican population, PASSIVITY, which is somewhat similar. With purple, likewise, the Chinese association was BRIGHTNESS and the Mexican was ACTIVITY. Chan and Courtney (2001) found that pink, purple and grey had low percentages. In our study also, lilac and purple (together coinciding with Chan and Courtney's purple category) were those showing the lowest percentages. No comparison could be made for lilac alone, as the Chinese population was not evaluated for associations with this colour. Thus, it may be observed that, despite these being completely distinct cultures, there exist certain trans-cultural similarities.

In comparing this study's results with other research conducted in Western cultures, Mahnke (1996) found that red and red-violet had a high percentage association with LOVE (81%), which is compatible with the findings of the present study in which the strongest associations for red were SEXUALITY (28.7%) and LOVE (14%). Mahnke also found that blue, blue-green and green were mainly associated with PEACE / TRANQUILITY, and, in our study, the highest percentage for blue was for PASSIVITY (12.1%). Nevertheless, some trans-cultural differences were also observed in colour associations, insofar as Mahnke found that only black and grey were associated with MOURNING / SORROW, but, in our study, brown was also associated with SADNESS (6.2%), even more so than black (5.1%). It is interesting that Mahnke reports that the same test was conducted in Europe in 1993 (Germany, Austria and Switzerland), and, in that study, brown and violet appeared to be associated with MOURNING / SORROW.

Regarding gender, from the results obtained in this study, it is suggested that there are colour associations which differ according to sex. In our review of the literature, very little supporting research was found for this last aspect. Ellis and Ficek (2001) refer to preferences for certain colours, and mention that men prefer blue, while women's preferences are divided between blue and green. In our study, since it is not a study of colour preferences, we could only make some inexact comparisons related to the statistically significant number of associations elicited from men and women. In some instances, our results bore comparison with those of Ellis and Ficek, as in the case of green. The results for its association with LIFE turned out to be significantly higher for women than for men.

In general, therefore, the results of this study seem to support the supposition upon which the work was based: that not all colour associations are universal, since they are constructed in the context of multiple social and cultural influences. Because of this, designers must consider the specific group of users for whom the product is destined, avoiding the extrapolation of associations from other populations.

References

Bergum, B. O. & J. E. Bergum. 1981. “Population Stereotypes: an Attempt to Measure and Define”. *Proceedings of the Human Factors Society* 25.662-665.

Braun, C. C. & N. C. Silver. 1995. “Interaction of Signal Word and Colour on Warning Labels: Differences in Perceived Hazard and Behavioural Compliance.” *Ergonomics* 38:11.2207-2220.

Chan, Alan & Alan J. Courtney. 2001. “Color Associations for Hong Kong Chinese.” *International Journal of Industrial Ergonomics* 28:3-4.165-170.

Courtney, Alan J. 1986. “Chinese Population Stereotypes: Color Associations.” *Human Factors* 28:1.97-99.

De Craen, Anthony J. M., Pieter J. Roos, A. Leonard De Vries & Jos Kleijnen. 1996. “Effect of Colour of Drugs: Systematic Review of Perceived Effect f Drugs and of their Effectiveness.” *British Medical Journal* 313:7072.1624-1626.

Ellis, Lee & Christopher Ficek. 2001. “Colour Preferences According to Gender and Sexual Orientation.” *Personality and Individual Differences* 31:8.1375-1379.

Jacobs, Lawrence, Charles Keown, R. Worthley & K. Ghymn. 1991. “Cross-cultural Color Comparisons: Global Marketers Beware.” *International Marketing Review* 8:3.21-30.

Knez, Igor & Ingela Enmarker. 1998. “Effects of Office Lighting on Mood and Cognitive Performance and a Gender Effect in Work-related Judgment”.*Environment and Behavior* 30:4.553-567.

Lane, Randall. 1991. “Does Orange Mean Cheap?”. *Forbes* 148:14.144-147.

Mahnke, Frank. 1996. *Color, Environment and Human Response*. New York: John Wiley.

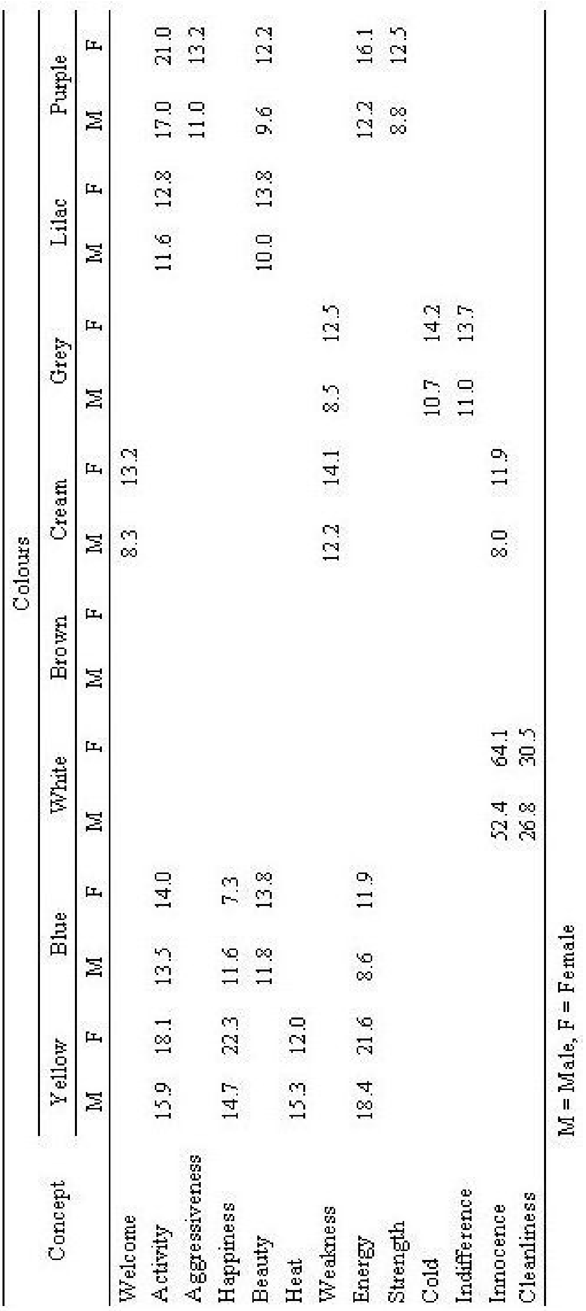
Ortiz, Georgina. 1992. *El significado de los colores*. Mexico City: Trillas.

	Colour															
Concept	Blue	Pink	Red	Grey	Burgundy	Orange	Brown	Cream	White	Lilac	Yellow	Black	Purple	Green	Silver	Golden
Passivity	12.1	5.5		11.7			6.5	16.7	20.9	7.0				7.1		
Masculinity	9.2															
Infinity	7.0															
Activity	6.4		5.7			11.8				6.6	8.0		9.7			
Beauty	5.9	5.6								6.5			5.7			4.6
Femininity		19.0														
Tenderness		17.0														
Innocence		13.5						4.9	22.8							
Weakness		7.3		4.7				6.5								
Sexuality		6.4	28.7		13.0	5.2		5.4		8.4			6.7			5.2
Love			14.0													
Heat			8.4			8.4					6.5					
Aggressiveness			7.0		11.2	5.0							6.3			
Energy	4.7		6.3		5.7	8.9					9.4		7.3		8.8	7.4
Sadness				19.1			6.2	4.6				5.1				
Happiness	4.5					6.3					8.7			4.6		

Table 2.1: *Association percentages for each colour evaluated (≥ 4.5%).*

	Colour															
Concept	Blue	Pink	Red	Grey	Burgundy	Orange	Brown	Cream	White	Lilac	Yellow	Black	Purple	Green	Silver	Golden
Fear				6.6	5.7							11.4	6.2			
Cold				5.6											9.2	
Indifference				5.5												
Death				5.0								23.1				
Strength					8.3								5.6			
Elegance					5.8							10.6			5.5	7.7
Dirtiness				4.5			22.6									
Comfort								5.2								
Cleanliness									11.2							
Brightness									8.9		15.2				10.0	5.0
Life									6.9					22.3		
Caution											4.9					
Darkness												9.2				
Evil					5.6							6.8	5.3			
Nature														22.7		
Fertility														6.7		
Wealth					4.9									5.4	10.0	27.9

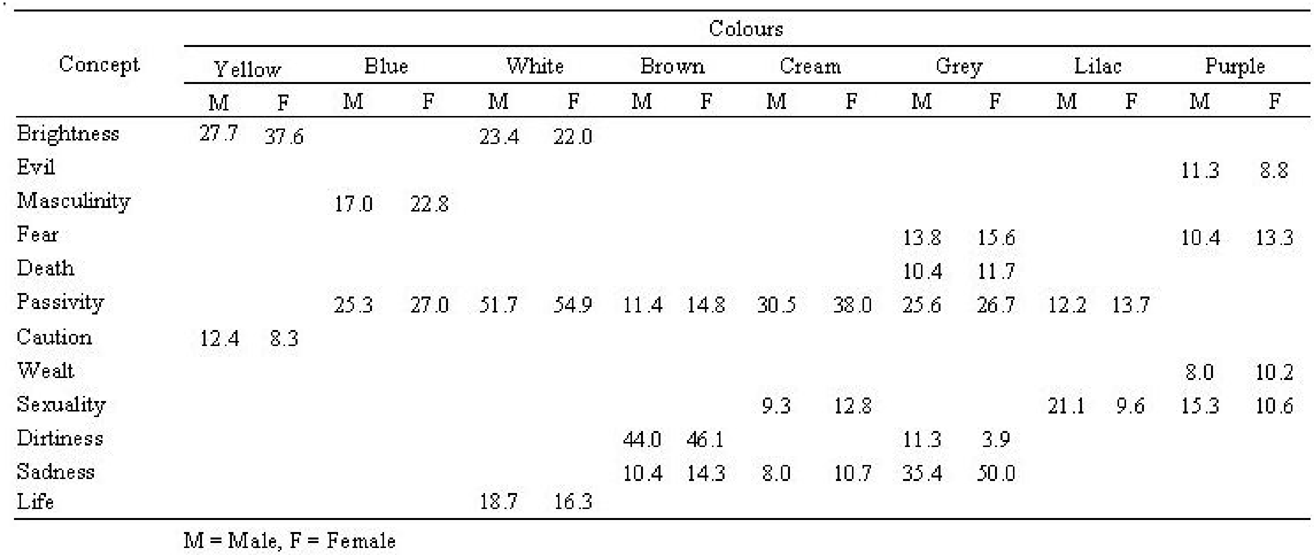
Table 2.2: *Association percentages for each colour evaluated(≥ 4.5%).*



Concept	Yellow		Blue		White		Brown		Cream		Grey		Lilac		Purple	
	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F
Welcome									8.3	13.2						
Activity	15.9	18.1	13.5	14.0									11.6	12.8	17.0	21.0
Aggressiveness															11.0	13.2
Happiness	14.7	22.3	11.6	7.3												
Beauty			11.8	13.8									10.0	13.8	9.6	12.2
Heat	15.3	12.0														
Weakness									12.2	14.1	8.5	12.5				
Energy	18.4	21.6	8.6	11.9											12.2	16.1
Strength															8.8	12.5
Cold											10.7	14.2				
Indifference											11.0	13.7				
Innocence					52.4	64.1			8.0	11.9						
Cleanliness					26.8	30.5										

M = Male, F = Female

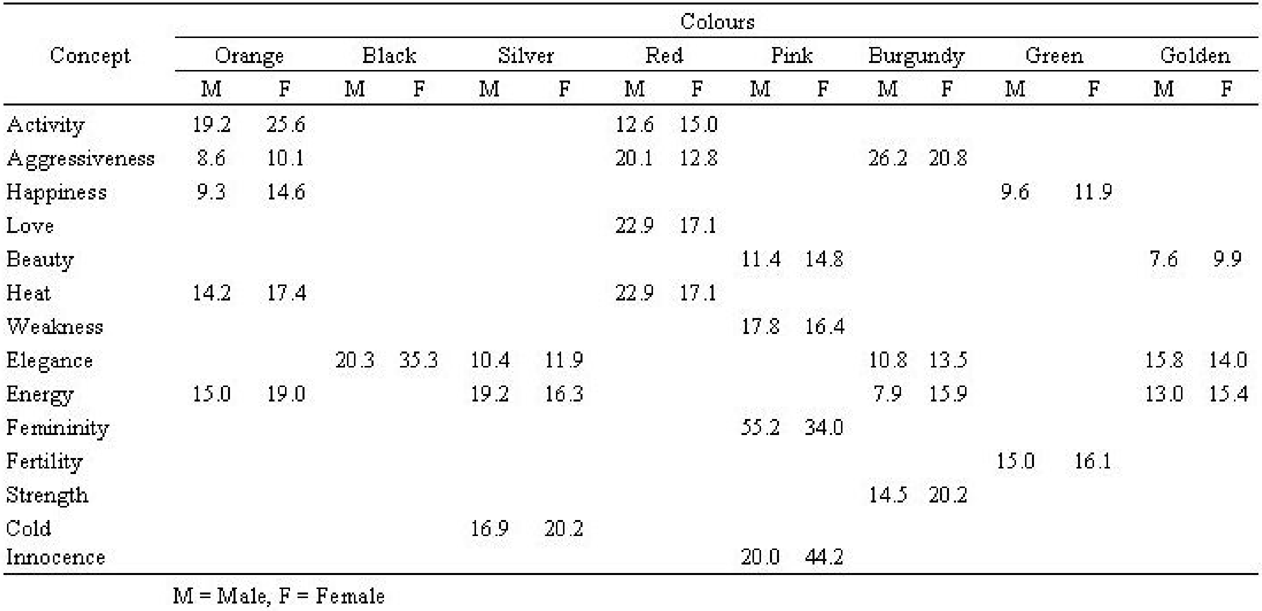
Table 3.1: *Comparison between colour association percentages ($p \leq 0.05$) in males and females.*



Concept	Colours															
	Yellow		Blue		White		Brown		Cream		Grey		Lilac		Purple	
	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F
Brightness	27.7	37.6			23.4	22.0										
Evil															11.3	8.8
Masculinity			17.0	22.8												
Fear											13.8	15.6			10.4	13.3
Death											10.4	11.7				
Passivity			25.3	27.0	51.7	54.9	11.4	14.8	30.5	38.0	25.6	26.7	12.2	13.7		
Caution	12.4	8.3														
Wealt															8.0	10.2
Sexuality									9.3	12.8			21.1	9.6	15.3	10.6
Dirtiness							44.0	46.1			11.3	3.9				
Sadness							10.4	14.3	8.0	10.7	35.4	50.0				
Life					18.7	16.3										

M = Male, F = Female

Table 3.2: *Comparison between colour association percentages ($p \leq 0.05$) in males and females.*



Concept	Colours															
	Orange		Black		Silver		Red		Pink		Burgundy		Green		Golden	
	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F
Activity	19.2	25.6					12.6	15.0								
Aggressiveness	8.6	10.1					20.1	12.8			26.2	20.8				
Happiness	9.3	14.6											9.6	11.9		
Love							22.9	17.1								
Beauty									11.4	14.8					7.6	9.9
Heat	14.2	17.4					22.9	17.1								
Weakness									17.8	16.4						
Elegance			20.3	35.3	10.4	11.9					10.8	13.5			15.8	14.0
Energy	15.0	19.0			19.2	16.3					7.9	15.9			13.0	15.4
Femininity									55.2	34.0						
Fertility													15.0	16.1		
Strength											14.5	20.2				
Cold					16.9	20.2										
Innocence									20.0	44.2						

M = Male, F = Female

Table 3.3: *Comparison between colour association percentages ($p \leq 0.05$) in males and females.*

Concept	Colours															
	Orange		Black		Silver		Red		Pink		Burgundy		Green		Golden	
	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F
Brightness					23.6	16.9									8.2	10.7
Evil			20.1	15.0							14.4	8.8				
Fear			27.3	32.3							10.4	13.7				
Death			63.8	56.6												
Nature													52.7	52.8		
Darkness			25.6	22.3												
Passivity									9.3	16.9			15.3	17.6		
Wealth	8.8	9.7			19.0	21.2							13.6	11.5	52.3	54.3
Sexuality	11.0	8.6					68.1	67.6	23.4	6.3	22.9	31.6			9.7	10.1
Tenderness									31.5	49.2						
Sadness			12.1	14.5												
Life													48.9	55.1		

M = Male, F = Female

Table 3.4: *Comparison between colour association percentages ($p \leq 0.05$) in males and females.*

SYNAESTHESIA, NEUROLOGY AND LANGUAGE

CHRISTIAN KAY & CATHERINE MULVENNA
University of Glasgow and University College London

> Far from being a mere curiosity, synaesthesia may provide a window into perception, thought and language. (Ramachandran & Hubbard 2001b:3)

1. *Introduction: the subject (Kay)*

Synaesthesia is an uncommon condition whereby an otherwise ‘normal’ individual experiences automatic and involuntary sensations in one modality of the brain when a different modality is stimulated (Cytowic 1989 [2002]; Ramachandran & Hirstein 1999; Armel & Ramachandran 1999; Ramachandran & Hubbard 2001b).[1] This cross-modal pattern can be between or within the senses of vision, hearing, touch, and taste. For instance, the sound of different musical notes may always be automatically accompanied by the sensation of particular colours or shapes, or the sight of individual written graphemes or words may be consistently and automatically joined by the experience of groups of colours or tastes. More colloquially, this condition is sometimes referred to as cross-wiring within the brain.

Kay writes: I have been synaesthetic for as long as I can remember. Like most synaesthetes, I grew up without realizing that my perceptual apparatus was anything out of the ordinary. Although synaesthesia often runs in families, neither of my siblings is affected by it, nor, as far as I know, were my parents.

---

[1] Estimates of the number of synaesthetes in the population vary widely, from 1 in 25,000 (Motluk 1994), 1 in 2000 (Baron-Cohen, Burt, Smith-Laittan, Harrison & Bolton 1996), 1 in 100 (Mulvenna, Ramachandran & Pollick 2004) and 1 in 33 in 2005 (Simner, Mulvenna, Savig, Tsakanikos, Whitherby, Fraser, Scott & Ward, submitted). Lower estimates may reflect a reluctance to broach the subject. Since this paper was presented in 2004, Kay has discovered nine synaesthetes among friends and colleagues. Apart from a sibling pair, their condition was either unrecognized or undiscussed. One declared that it was a great relief to be able to talk about it.

My strongest associations are between written or spoken language and colours. Thus numbers, letters, sequences such as days of the week and months of the year, and certain individual words, including names of people, places and languages, have consistent colour associations. The written form is dominant, and the colour of the whole is often influenced by the first letter, as is commonly the case (Frith & Paulesu 1997:129, 138).[2] Kathryn and <k>, for instance, are a dark cherry red colour, whereas Catherine and <c> are a deep salmony pink. I also have a less strong association between sounds and shapes, or, occasionally, colours.

Like most synaesthetes, I had two reactions to the condition. The first was surprise that non-synaesthetes should find it strange, and even have difficulty comprehending it. The second was astonishment that my fellow synaesthetes should have different perceptions from mine – that the world actually contained people who thought that Wednesday was red and five was yellow when both are self-evidently green.[3] In an article recounting a conversation with one of the most famous synaesthetic subjects, the painter Elizabeth Stewart-Jones, Alison Motluk, herself a synaesthete, records such perceptions: “For me, the proud emerald green of the city name Edinburgh triumphs over the simpering yellow of London; Kathryn is dark and woody, while Catherine is like dirty beach sand” (1997:269). Worse still, her Wednesdays are pink, and her year is roller-coaster shaped, whereas for me (and Stewart-Jones) the year is circular (though proceeds clockwise in her case and counter-clockwise in mine) (1997:276). The delicacy of Motluk’s categorization is notable. It has been estimated that the average person can distinguish at least half a million colours, and synaesthetes are often particularly sensitive in this respect (McGilvray 1994, in Smith 2002).

So what does all this mean? It certainly makes life more interesting and is mildly useful for such things as remembering telephone numbers and people’s names. An interest in patterns and connections may also have led to my

---

[2] This form of synaesthesia also appears to be language-specific. A German colleague and I agree that ‘Germany’ and ‘Deutschland’ are different colours (though not on what they are).

[3] One of the few studies which suggests otherwise is Pečjak (1970), reported by Osgood, who studied subjects from seven speech communities and found that “there were definite clusters between the Colors and Days. GREY goes with MONDAY for six of the seven communities but never with SATURDAY, GREEN and BLUE tend to go with WEDNESDAY (5 communities) but never with SATURDAY, YELLOW and GREEN go with THURSDAY (5 communities) but again never with SATURDAY – but RED *does* go with SATURDAY (6 of the 7 communities), yet *never* goes with MONDAY or SUNDAY!” (Osgood 1980:217).

subsequent interest in linguistics.[4] My associations are largely conscious. If somebody asks “What colour is Thursday?” I can reply immediately (yellow), but I am not continually aware of colours when reading at normal speed. More extreme cases are less fortunate. The Russian psychologist Luria worked for many years with an extreme case, Shereshevsky, whose communication skills were severely impaired by the continual diversion of colour associations (Luria [1968] 1987; Dann 1998:163). However, I have to confess that when I was writing this paper and having to focus on what I normally do automatically, I occasionally got somewhat confused. For example, the word *synaesthesia* as a unit is a light yellow colour, probably influenced by the fact that the letter <s> is yellow, but it can also be separated into different coloured letters; sorting these out took several attempts.

2. *The psychologist (Mulvenna)*

2.1 *What is synaesthesia?*

Until recently, synaesthesia has been described mainly by the reported experiences and behaviours most common amongst individuals with the condition, collected from researchers’ observations (often case-studies) and tests over the long history of synaesthesia’s scientific documentation (see e.g. Galton 1883). However, the current wave of neuroscientific research into synaesthesia is now providing insightful new perspectives on the condition. Furthermore, clarification of its neurological basis may lead towards understanding the fundaments of broader neurological, cognitive, behavioural and linguistic patterns that we all experience.

From its Greek roots (*syn* = ‘together’ + *aisthesis* = ‘perception’), *synaesthesia* refers to a union of experiences within or between an individual’s senses (vision, taste, smell, touch, hearing).[5] As opposed to any general indistinctness between them, the physical stimulation of one sense will systematically activate the experience of a second sensation. The pairs of sensations will be idiosyncratic to each synaesthete (Martino & Marks 2001) and remain consistent across time (e.g. Baron-Cohen, Wyke & Binnie 1987).

---

[4] I also have another mnemonic system based on the category headings in Roget’s (1852) *Thesaurus of English Words and Phrases*, which has been a staple of my research for many years. Telephone extension 4150, for example, is Hearing blue black green white.

[5] There is a growing controversy over whether the definition should be relaxed to include less orthodox subtypes, such as sensations triggering an emotion or evoking an association of gender or personality type (Calkins 1895; Day 2005; Sagiv 2005). As these do not involve a link between two *sense* modalities, we do not include them in synaesthesia here.

For example, if the sound of the letter <k> activates the perception of a cherry red colour, as it does for Kay (see Section 1), it will never change to a different colour, though, for a different synaesthete, it might activate the taste of tuna, or a light green colour. This will happen automatically (Motluk 1997; Odgaard, Flowers & Bradman 1999) and will have occurred since childhood (Maurer [1993] 1997; Baron-Cohen 1996). It is also unidirectional (Mills, Boteler & Oliver 1999), so, every time Kay sees the particular shade of cherry red, it will not trigger the sound of the letter <k>. Such a phenomenon will not seem unusual to the individual experiencing it, although they are aware that the second sensation is not present in the 'real' world, and synaesthetes are frequently surprised to learn that others do not perceive the world in the same way.[6]

Current understanding is that each instance of synaesthesia can involve triggers from any of the senses of vision (including colour, shape and movement), taste, sound, smell, or touch (including texture and temperature) (Harrison & Baron-Cohen 1997; Ramachandran & Hubbard 2001b; Rich & Mattingley 2002; Robertson & Sagiv 2004). Individuals may have several subtypes of synaesthesia (e.g. music-colour, letter-taste, day-colour, music-shape) or just one.

The most common and widely researched triggered sensation is that of colour. For such synaesthetes, colours can be generated by everyday exposure to letters, words, numbers, music, and other stimuli, depending on their own individual sub-type. These can be simple, such as the sight of the letter <A> triggering a dark red colour, or more complex, such as a sequence of pitches inducing experience of the colours "gold, yellow and white moving rapidly upwards at an angle, like a rippling stream" (Mulvenna & Walsh 2005). Personal experience and the literature on synaesthesia suggest that synaesthetes tend to be very specific in reporting their triggered colours, which is noticeably different from non-synaesthetes when asked to generate an associated colour for a word or letter. For example, for synaesthete ET the name Rachael is "black with red surrounding it", in contrast to the single, major colour-term dominance in non-synaesthetes' responses (Mulvenna, 2003). Baron-Cohen, Harrison, Goldstein & Wyke (1993) observed that even a chart of over 250 colours was not sufficient to cover the variety of specific colour descriptions synaesthetes experienced.

---

[6] For example, one individual we worked with said she could remember arguing with her father when she was very young over the colour of Germany, while neither of them knew *why* it was the colour they 'knew' it to be.

From this information, the fundamental characteristics of synaesthesia would appear to be automatic sensory cross-activations that are consistent over time, consciously present since childhood and occur in everyday life.[7] Beyond this, the differences between cases of synaesthesia remain plentiful (Dixon & Smilek 2005; Hubbard, Arman, Ramachandran & Boynton 2005), which undoubtedly added to the initial difficulty researchers experienced in attempting to characterize the phenomenon. These differences include the range and proportions of subtypes (for an exhaustive list see Day 2005; Mulvenna 2004), whether a triggered colour is projected into space or viewed within 'the mind's eye' (Dixon, Smilek & Merikle 2004), or at which stage of perceptual processing synaesthesia occurs (Grossenbacher & Lovelace 2001; Ramachandran & Hubbard 2001b).

2.2 *What is not synaesthesia?*

Sensory experiences *not* indicative of synaesthesia include memories triggered by sensations, such as a song reminding someone of a person, place or a particular time in their life. Also not included are cross-sensory associations that are clearly acquired with adult life experience, such as the sound of the word *summer* reminding one of the shade of blue of a new suitcase. Such a sensory pairing would not have the synaesthetic characteristics of *activating* the experience of the shade of blue, being automatic (because the logical connection is consciously made) or being present since childhood (before the suitcase was bought). In contrast, in developmental synaesthesia, there must have been an initial experience that triggered each synaesthetic pairing (as we are not born knowing the alphabet). This will have happened in early childhood and, inexplicably, remained fixed (Rich, Bradshaw & Mattingley 2005). This is distinct from simple sensory memory. A recent study trained a synaesthete to associate and remember various sense-pairs not synaesthetically experienced. Even after training, these could not be reported with the same consistency as their synaesthetic sense-pairs, thus not only highlighting the extraordinary durability of synaesthesia, but also distinguishing it from strong sensory

---

[7] It must be noted that the authors are describing what is often referred to as 'developmental' synaesthesia. Some claim that synaesthesia can be acquired after exceptional circumstances such as brain damage, eye diseases, migraines or meditative states (e.g. Jacobs, Karpik, Bozian & Gothgen 1981; Armel & Ramachandran 1999; Podoll & Robinson 2002; Walsh 2005). However, until there is evidence for the underlying mechanisms of such 'acquired synaesthesia' being similar, we prefer to differentiate between the two. This paper, therefore, refers only to the synaesthesia inexplicably present since childhood, that is what Martino and Marks (2001) call 'strong synaesthesia' or Baron-Cohen et al. (1996) call 'developmental synaesthesia'.

memory in the same synaesthete (Ward & Simner 2003).

Interestingly, a somewhat similar ‘merging of the senses’ is reported by users of hallucinogenic drugs (Hartman & Hollister 1963; Rang & Dale 1987). However, to our knowledge, no reports have been made of consistent sense pairings over different substance uses. While the outward experience of this phenomenon may have something in common with that of developmental synaesthesia, without this definitive characteristic it is likely to differ in its basis.

A further comparison is often made with cross-sensory metaphors. While synaesthesia research may shed light on the basis of this area of linguistics (Ramachandran & Hubbard 2001b; see also section 3 below), the condition appears to be more complex than an extension of typical metaphor (Cytowic 1997). Metaphors, even cross-sensory ones, are not known to activate the experience of their subject. To produce or understand the metaphor *juicy red* is different from the sound of the word *red* having reliably and automatically produced the sensation of the taste of (a particular flavour of) juice for as long as one can remember. Also, unlike metaphor, which aids and enhances understanding of one concept by describing it as another concept with related attributes, any obvious connection between synaesthetic sense-pairs can be quite absent, even to the synaesthetes themselves.

2.3 *Testing for synaesthesia*

For actual classification, it is the trait of consistency over time that is most easily and frequently measured. Synaesthesia sense-pairs appear to be consistent across months and even years. Baron-Cohen et al. created the ‘Test of Genuineness’ as a standardized consistency test of associations for grapheme-colour and word-colour synaesthetes. When asked to describe the synaesthetic sensation experienced in response to over 100 stimuli on two different occasions, synaesthetes show ~90% consistency in their reports, while non-synaesthetes asked to produce an associated colour are only 35-40% consistent (Baron-Cohen et al. 1987). Researchers can adopt this method for classifying other sub-types of synaesthesia (Mulvenna 2004; Asher, Aitken, Farooqi, Kurmani & Baron-Cohen 2005; Ward, Simner & Auyeung 2005; Simner et al., submitted).

Other methods of classification try to test the actual perceptual nature of the synaesthetic experience. Experiments including applications of the Stroop task (Wollen & Ruggiero 1983) compare the difference between synaesthetes’ pupil diameter (Paulsen & Laeng 2005) or reaction time between naming the colour of a letter when it is presented in the ‘correct’ synaesthetic colour or in a different, ‘incorrect’ colour. Other tests focus on the enhanced ability to differentiate identically coloured items in visual searches due to their contrasting synaesthetic colours (e.g. Ramachandran & Hubbard 2001a; Palmeri, Blake, Marois, Flanery & Whetsell 2002; Laeng, Svartdal & Oelmann 2004; Hubbard et al. 2005). The general results of such tests indicate that synaesthetes cannot consciously suppress their activated colours and this can be used to distinguish a synaesthete from a non-synaesthete (Wollen & Ruggiero 1983; Mills et al. 1999; Odgaard et al. 1999; Smilek & Dixon 2002; Sagiv, Heer & Robertson 2005; Mattingley, Payne & Rich 2005).

Recent application of advances in brain imaging is now allowing synaesthesia researchers to add a different level of description to the phenomenon. Given the assumption that (1) every conscious human experience corresponds to a specific pattern of brain activity, and (2) the reported experiences of synaesthetes are genuinely different to those of other people, then a distinctive pattern of brain activity should be observable in synaesthetes when having synaesthetic experiences, compared to non-synaesthetes (Jacobs et al. 1981; Frith & Paulesu 1997). The first experiments to take this approach revealed just this, and marked a change in the scientific credibility of the condition. For example, Positron Emission Tomography (PET), which detects brain activity by changes in regional cerebral blood flow, was used while blindfolded word-colour synaesthetes (n=6) listened to the sound of words (Paulesu, Harrison, Baron-Cohen, Watson, Goldstein, Heather, Frackowiak & Frith 1995). The perceptual experiences reported from synaesthetes were both auditory (the sounds of words) and visual (their synaesthetic visualizations of colour), but only auditory for a group of non-synaesthetes. The neurological results reflected the behavioural reports and showed different areas of activation in the brains of synaesthetes (bilateral superior occipital gyrus / superior parietal lobe, bilateral posterior inferior temporal cortex). In keeping with the concept of functional segregation (different kinds of information are localized in different brain areas) all participants showed activation in areas strongly associated with auditory perception, but word-colour synaesthetes also showed activation in areas associated with *visual* perception. Finally, the synaesthetes were played an additional auditory stimulus that they had reported did *not* activate visual experiences (pure tones). This time their neural activity was only indicative of auditory perception, demonstrating the very specific nature of the synaesthetic experience, in contrast to overall cross-sensory fusion.

More recent experiments have applied functional Magnetic Resonance Imaging (fMRI) with heightened precision in identifying anatomical location. Activation of areas precisely associated with the perception of colour, V4 / V8

(Zeki & Marini 1998; Hadjikhani, Liu, Dale, Cavanagh & Tootell 1998), was observed in word-colour synaesthetes listening to words, but not in either naïve non-synaesthetes or non-synaesthetes extensively trained to imagine colours in response to the sound of words (Nunn, Gregory, Brammer, Williams, Parslow, Morgan, Morris, Bullmore, Baron-Cohen & Gray 2002). Recently, similar activation of colour selective cortex has been demonstrated for grapheme-colour synaesthesia (Hubbard et al. 2005).

Overall, the evidence indicates that the synaesthete brain responds reliably and systematically differently to certain stimuli, consistent with subjective reports and objective demonstrations of the perceptual reality of synaesthesia. Future studies will tell us if this is consistent across all sub-types of synaesthesia.

2.4 *Theories of the basis of synaesthesia*

With a neurological distinction evident, the next questions are *how* and *why* does one sensation trigger another? Speculative theories draw on current understanding of how the brain works, but no techniques are sophisticated enough to observe connectivity in actual pathways in the brain. The neurological evidence of synaesthesia demonstrates cross-activation of very specific areas in the brain, but how and why they are communicating is (experimentally) unknown.

The Neonatal Synaesthesia (NS) hypothesis claims that all human infants (up to around four months) naturally experience sensory input in an undifferentiated way, having dense interconnections between sensory systems in their brains (Maurer [1993] 1997; Maurer & Mondloch 2005). Adult synaesthesia could, therefore, be the product of sensory differentiation (modularity: Fodor 1983) never reaching typical maturity, through delayed apoptosis or a partial failure of the normal pruning process that naturally eliminates the neural connections (Baron-Cohen 1996; Ramachandran & Hubbard 2001b).

If this is correct, then, to a neurological extent, we are all synaesthetes in the first few months of life, which could explain why synaesthetes often report ‘growing out of it’ at some point. It is not uncommon for individuals to report only experiencing synaesthesia as a child or, if they still do, that it was much more vivid when they were younger. This could be the delayed outward manifestation of sensory modularization. What the NS hypothesis cannot offer yet is an explanation of why modularization would be delayed in some individuals and not others.

Ramachandran and Hubbard (2001b) go further to postulate that such a pattern of ‘hyperconnectivity’ might be localized to neural areas that correspond to synaesthetes’ verbal reports. For example, a grapheme-colour synaesthete would have hyperconnectivity between an area known to respond to colours and an area known to respond to the vision of graphemes. Support for this theory comes from independent research claiming that these two areas both lie in the fusiform gyrus of the brain (Lueck, Zeki, Friston, Deiber, Cope, Cunningham, Lammertsma, Kennard & Frackowiak 1989; Zeki & Marini 1998; Hadjikani et al. 1998; Allison, McCarthy, Nobre, Puce & Belger 1994; Nobre, Allison & McCarthy 1994; Pesenti, Thioux, Seron & De Volder 2000) and are, therefore, spatially close. This does not account for other sub-types of synaesthesia, but it could potentially be the reason for the high proportion of grapheme-colour synaesthesia.

Alternatively, the Disinhibited-Feedback theory (Grossenbacher 1997; Armel & Ramachandran 1999; Grossenbacher & Lovelace 2001) suggests that there are no additional connections responsible for the synaesthetic experience. It claims that synaesthesia employs neural connections which also exist in the non-synaesthete adult brain: ‘feedback’ pathways, which are typically inhibited to pass information only ‘one way’, serve as a direct link between the affected sensory areas.

Current investigations are also looking at the question of an identifiable gene-expression leading to the development of synaesthesia by causing one of these neurological patterns. Research is ongoing, but synaesthesia running in families has been demonstrated (e.g. Baron-Cohen et al. 1996; Ward & Simner 2005). Theories have included an X-linked dominant mode of inheritance (see Ward & Mattingley 2005), but genetic research has failed to substantiate this (Asher et al. 2005). Early studies frequently suggested that more females than males had synaesthesia, from a 3:1 to an 8:1 ratio (Galton 1883; Baron-Cohen et al. 1987; Cytowic 1989 [2002]; Baron-Cohen et al. 1993; Bailey & Johnson 1997; Harrison 2001; Rich et al. 2005), but, very recently, this has been questioned on methodological grounds. When samples of the population were tested at random for synaesthesia, in contrast to depending on individuals who come forward for testing, the female bias decreased dramatically to 1:1.1 (Simner et al., submitted). Previous gender bias may have actually been for willingness to take part in psychological experiments rather than for having synaesthesia (Mulvenna 2004), which has been noted previously in general research (Dindia & Allen 1992).

2.5 *Are there effects of having synaesthesia?*

Whether synaesthesia involves either atypical neural connections, or unusual uses of typical connections, there appears to be a neurological distinction involving neural connectivity. Synaesthetes could thus constitute an important population to investigate, with respect to the cause and effect of such atypical neurology.

Interestingly, a pattern of traits has been observed in synaesthetes during the course of the condition's scientific documentation (e.g. Geschwind & Galaburda 1987; Domino 1989; Dailey, Martindale & Borkum 1997; Root-Bernstein & Root-Bernstein 1999; Ramachandran & Hubbard 2001b; Cytowic [1989] 2002; Burrack, Knoch & Brugger 2005), some of which have associations with what we might call 'conceptual connectivity'. For example, the presence of additional sensations acts as an extra cue for memory (Smilek, Dixon, Cudahy & Merikle 2002; Mills, Innis, Westendorf, Owsianieki & McDonald 2005), causing many synaesthetes to anecdotally report it as advantageous for remembering day-to-day things like phone-numbers (see Section 1).

Another example is repeated reports of a relationship with creativity (Domino 1989; Dailey et al. 1997; Mulvenna et al. 2004). In fact, synaesthesia was once dismissed as nothing more than 'creative' people describing typical perception in an atypical way. Public attention was drawn to seemingly eccentric comments from high profile creative individuals, as when Oliver Messiaen stated, "Colors are very important to me because I have a gift – it's not my fault, it's just how I am – whenever I hear music or even if I read music, I see colors" (Cytowic [1989] 2002:308).

However, now that a neurological distinction is clear, the frequent reporting of synaesthesia among poets, novelists, artists and musicians (such as Rimbaud, Baudelaire, Kandinsky, Nabakov, Scriabin, Messiaen and Hockney) could be the result of more than a coincidence or media bias. Rather than simply looking at the level of creative achievements in synaesthetes, initial investigations have attempted to empirically compare synaesthetes to similar non-synaesthetes by testing their predisposition to creativity through creative thinking.

When investigating a characteristic such as creativity, the standard method of recruiting individuals to take part in scientific studies causes a potential confounding variable: individuals with synaesthesia who self-select themselves for research may be the more 'creative' synaesthetes and not representative of the rest. For this reason, previous conclusions that synaesthetes score higher on creativity tests (Domino 1989; Dailey et al. 1997) have been open to criticism and often discarded (see Ramachandran & Hubbard 2001a).

In an attempt to combat this problem, Mulvenna screened a large number of university students (n=445) for synaesthesia, to directly compare those found to have synaesthesia (n=4) with matched non-synaesthete students (n=4) (Mulvenna et al. 2004). Self-selection effects were avoided by gaining responses from each individual, and implementing a surprise Test of Genuineness (Baron-Cohen et al. 1987) on every student who reported experiences indicative of synaesthesia, with a ten-week retest period. Another group which identically matched each synaesthete student on key characteristics (age, gender, nationality, year-group, academic subject of study, faculty membership and time of lectures attended) was exposed to the same test to formally classify them as non-synaesthetes. In a further attempt to avoid biasing the results, neither the experimenter nor the participant knew their group allocation when implementing a recognized test of creative thinking (Torrance, Orlow, Ball & Safter 1992). This involved seven pencil and paper tasks requiring as many responses as possible within a time limit. Tasks included:

> In the middle of this page is a sketch of a stuffed toy elephant. It is about six inches tall and weighs about half a pound. List the cleverest, most interesting and unusual ways you can think of for changing this toy elephant so that children will have more fun playing with it. Do not worry about how much the change would cost. Think only about what would make it more fun to play with as a toy.

Each individual response was allocated three separate scores on three aspects of creative thinking: flexibility, or the ability to produce a variety of types of ideas; fluency, or the ability to produce a large number of relevant ideas; and originality, or the ability to produce ideas away from the obvious and established.

The results revealed a significant difference between the creative thinking scores of synaesthetes and those of matched non-synaesthetes. This strongly supports there being more than a coincidental relationship between synaesthesia and creativity (Domino 1989; Dailey et al. 1997) and that, as a group, they may have specific cognitive abilities (Grossenbacher & Lovelace 2001). Additional studies need to be carried out to establish if this is the case for different aspects of creativity and other reported synaesthetic traits, such as higher spatial memory and intelligence, and poorer navigation and left / right differentiation (Cytowic [1989] 2002). The creativity study tentatively suggests a link between neural connectivity and conceptual connectivity, by using synaesthetes as an example of both. We need to question further if this is a causal relationship, or an indirect result of the heightened sensory experience of having synaesthesia in daily life.

As neurological research continues to substantiate synaesthesia as having recognizable underlying mechanisms, we look forward to an increase of research into what exactly this means for the individual with synaesthesia, and what we can learn about other human characteristics from studying it.

3. *The linguist (Kay)*

Apart from my personal interest in synaesthesia, the subject interests me from the point of view of linguistics, and especially semantics. Interestingly, synaesthesia studies and semantics have followed similar pathways, the development of both from the 1920's to 1960's being inhibited by the dominance of behaviourism and the consequent dismissal of subjects not considered suitable for scientific investigation (Harrison & Baron-Cohen 1997:4). Linguistics has often drawn inspiration from Psychology, especially in the development of Cognitive Linguistics over the last forty years or so (for an overview, see Croft & Cruse 2004). Within this paradigm, the emphasis is on making theoretical linguistic explanations compatible with what is known of mental processing. As our knowledge of mental processes grows, so do the possibilities of making further interdisciplinary connections. Work on the localization of brain functions and their interconnectivity is relevant here, as is Ramachandran's theory of hyperconnectivity characterizing the synaesthete brain (Ramachandran & Hubbard 2001b). One consequence of this cross-fertilization is the fact that some previously no-go areas of linguistics, even the ultimate taboo subject of speculation on the origins of language, are becoming almost respectable. Some of these areas are discussed below.

3.1 *Folk etymology*

One such phenomenon is folk etymology. Here people attempt to make sense of a strange word by re-interpreting it. Thus, in some dialects of English, asparagus is referred to as ‘sparrow-grass’ – this makes no real sense, since asparagus has nothing to do with either sparrows or grass, but it makes more sense to the users than the Greek word from which it derives. Similarly, in standard English we have a crustacean called the crayfish. The element ‘cray’ is meaningless and it is not a fish – in fact the word derives from a French word *crevisse*, which recognizes the creature's habit of hiding in crevices. Such examples used to be dismissed as mildly interesting historical byways, but within a cognitive framework they become more interesting as examples of one group of speakers creating different mental pathways or activating different mental spaces from another (see further Rundblad & Kronenfeld 2000).

3.2 *Sound symbolism*

Another area of interest to both linguists and psychologists is that of sound symbolism (for a linguistic overview and many examples, see Jakobson & Waugh 1978:ch.4). Linguists have an ambivalent attitude here. We are brought up to believe that language is largely arbitrary – that there is generally no connection between the form of the word and the idea it expresses – but every so often we have to confront examples where this appears not to be so. For vowels, for example, there seems to be a correlation between sound and size: if people are presented with pairs like ‘ding dong’ (of a bell) or ‘clip clop’ (of horses’ hooves), they will almost always agree that the first sound is quieter and less ‘heavy’ than the second. Research at various periods in the history of the subject has suggested a correlation between activities in the vocal tract and semantic associations of sounds, such as the correlation in English and many other languages between front vowels and small size, in words such as *little, teeny, petite* and so on. Ramachandran describes this kind of connection between mechanism and meaning as synaesthetic, writing:

> We would also point out that lip and tongue movements and other vocalizations may be synaesthetically linked to objects and events they refer to in closer ways than we usually assume and this may have been especially true early in the evolution of the proto-language of ancestral hominids, e.g. words referring to something small often involve making a synaesthetic small /ɪ/ with the lips and a narrowing of the vocal tracts … whereas the opposite is true for words denoting large or enormous (Ramachandran & Hubbard 2001b:20).

Similar mappings are observed in other areas, such as the connection between speech sounds and visual appearance or synkinetic motor maps, as when jaw movements mimic those of the hand. Thus, while there is no claim that all language is synaesthetic in origin, such factors might have provided “the initial impetus for language evolution” (Ramachandran & Hubbard 2001b: 21).

Words such as ‘ding-dong’ often have no clear etymology and are thought to be mimetic or onomatopoeic in origin. They are sometimes distinguished from words exhibiting phonaesthesia, a term first used by J. R. Firth for cases where particular meanings are incrementally associated with certain sounds. Thus, for many English speakers, the set containing *slip, slither, slimy, sly, sleazy, slobber* and many more has connotations of both material and abstract unpleasantness, possibly arising from the associations with salivation and then more general wetness. Firth also proposes a ‘kinaesthetic background’ for the <str-> phonaestheme, suggestive of effort in words like *stress, strain, stretch* (Firth [1930] 1964:186). In both cases, a link is being made between the physical circumstances of the sound, its meaning in the material universe, and a more abstract or evaluative meaning, in a way similar to that described by Ramachandran above. The extension into evaluation is noted elsewhere in the literature. Although he does not use the term phonaesthesia, Luria's multiply synaesthetic subject was apparently affected by the appropriateness or otherwise of words for their meanings. *Svinya*, for example, the Russian for 'pig', he regarded as too elegant a word to denote such a creature, whereas *khavronya* 'sow' and *khazzer*, Yiddish for pig, were more appropriate (Luria, [1968] 1987:29, 87).

3.3 *Metaphor*

Sounds are often described in terms of touch or vision – they can be soft or hard, light or dark. Colours in turn are expressed by sound or touch: loud, vibrant, soft, warm, hard, harsh, cold. Traditionally, these are described as synaesthetic metaphors. They have long been a subject of study and evidence has been collected to show that they are widespread in both ancient and modern languages (Ullman 1957:ch.5).[8] The fact that such metaphors "combine, unify and synthesize the various sensory domains" (Ullman 1957:267) was noted in earlier studies, but interest tended to focus on their use in literary texts. More recent work raises the question of whether they are synaesthetic in origin in the psychological sense.

One of the most thoroughly researched areas in cognitive linguistics in recent years has been metaphor, where superficially different meanings are brought together in order to shed new light on a concept. Many such metaphors are drawn from the senses, such as 'shedding light on a concept', where metaphor links the physical perception of light to mental understanding. Such metaphors may originate from individual flashes of genius, but can become so embedded in a language that whole groups of words embody the metaphor: a 'flash of genius' is another example of the light metaphor, while 'embody' and 'embed' derive from other common sources (see further Kay 2000; Allan 2003; Hough 2004). When this happens, the metaphors are referred to as conceptual metaphors, forming part of our basic cognitive structure. By this stage, speakers are usually unaware that they are using a metaphor; there is, after all, no other way of expressing an abstract idea than to refer it to the physical world.

The pioneering book in this area was Lakoff and Johnson (1980), *Metaphors We Live By*. More recently, in *Philosophy in the Flesh* (1999), they

---

[8] Among other examples, Ullman points out that synaesthetic literary excesses were a subject of jest in Shakespeare's time. In *A Midsummer Night's Dream*, v, i, Pyramus says "I see a voice: now will I to the chink, To spy an [if] I can hear my Thisbe's face" (Ullman 1957:269-270).

have proposed an integrated theory of primary metaphor, incorporating four developments in the subject. The first of these is Christopher Johnson's (1997) conflation theory, which goes against the generally accepted view that abstract metaphors follow concrete experience, by proposing that young children go through a period of conflation when the abstract and concrete are fused. Thus, for example, the warmth of physical affection is correlated with the corresponding abstract emotion, leading to associations between the two domains that persist when they are differentiated later in the child's cognitive development. Second is Grady's (1999) theory of primary metaphor, which suggests that the primary metaphors of everyday experience develop into more complex ones through a process of conceptual blending. Third is Naranayan's neural theory of metaphor, which postulates "permanent neural connections being made across the neural networks that define conceptual domains" (Lakoff & Johnson 1999:46), and fourth is Fauconnier and Turner's (2002) theory of conceptual blending. Also of interest here is the fact that many basic metonymies, such as those involved in spatial organization, are now regarded as pre-linguistic cognitive structures lying at the root of metaphor and other cognitive processes (Ungerer & Schmid 1996:ch.3). Lakoff and Johnson write:

> We acquire a large system of primary metaphors automatically and unconsciously simply by functioning in the most ordinary ways in the everyday world from our earliest years. We have no choice in this. Because of the way neural connections are formed during the period of conflation, we all naturally think using hundreds of primary metaphors (1999:47).

This theory, and especially the conflation element, has obvious implications for synaesthesia, suggesting as it does that primary sensual experiences are initially indistinguishable from later metaphorical perceptions in sensory or other domains. In addition to 'Affection Is Warmth', other primary metaphors from Grady's (1999) list which might be linked to the infant's early experiences of mother, feeding and bodily functions include 'Important Is Big', 'Happy Is Up', 'Intimacy Is Closeness', 'Bad Is Stinky', and 'More Is Up'.[9] One might also hypothesize a connection between human flesh tones and 'warm' colours, as opposed to the 'cool' colours of the more remote environment, and explain the prevalence of synaesthetic metaphors in languages by the fact that "… the newborn's senses are not well-differentiated but are instead intermingled in a synaesthetic confusion" (Maurer [1993]

---

[9] For the full list, with Grady's explications of the primary experiences, see Lakoff & Johnson (1999:51-52). Compare also Ramachandran & Hubbard 2001b on 'disgusting'.

1997:227). To make the jump from infants to primitive languages, one might quote Cytowic:

> In this view, synaesthesia is the conscious awareness of a normally holistic process of perception that is prematurely displayed. That is, it is awareness before the terminal target, before the final stage of neural transformation and mental mediation. If this is correct, then we are all unknowingly synaesthetic (Cytowic [1996] 1997:38).

4. *Conclusion*

However one explains the examples above, they all indicate a high degree of connectivity between areas of the brain, some common to all language users, others the preserve of groups, or, in extreme cases such as poets or synaesthetes, of single individuals. Combining the insights of psychology and linguistics will undoubtedly lead to greater understanding of these vital connections.

References

Allan, Kathryn. 2003. *An Examination of Metaphor from Old English to Present Day English, Focusing on Notions of Intelligence / Cleverness and Stupidity*. Ph.D. dissertation, University of Glasgow.

Allison, T., G. McCarthy, A. Nobre, A. Puce & A. Belger. 1994. “Human Extrastriate Visual Cortex and the Perception of Faces, Words, Numbers and Colours”. *Cerebral Cortex* 4.543-544.

Armel, K. C. & V. S. Ramachandran. 1999. “Acquired Synesthesia in Retinitis Pigmentosa”. *Neurocase* 5.293-296.

Asher, J., M. R. F. Aitken, N. Farooqi, S. Kurmani & S. Baron-Cohen. 2005. “Diagnosing and Phenotyping Visual Synaesthesia: a Preliminary Evaluation of the Revised Test of Genuineness (TOG-R)”. *Cortex*. http://www.cortex-online.org

Bailey, M. E. & K. J. Johnson. 1997. “Synaesthesia: Is a Genetic Analysis Feasible”? Baron-Cohen & Harrison 1997.182-207.

Baron-Cohen, S. 1996. “Is There a Normal Phase of Synaesthesia in Development?” *Psyche* 2.27. http://psyche.cs.monash.edu.au/v2/psyche-2-27-baron_cohen.html

—, L. Burt, F. Smith-Laittan, J. Harrison & P. Bolton. 1996. “Synesthesia: Prevalence and Similarity”. *Perception* 25.1073-1080.

— & J. E. Harrison, eds. 1997. *Synaesthesia: Classic and Contemporary Readings*. Oxford: Blackwell.

—, J. Harrison, L. H. Goldstein & M. Wyke. 1993. “Coloured Speech Perception: Is Synesthesia What Happens When Modularity Breaks Down”? *Perception* 22.419-422.

—, M. A. Wyke & C. Binnie. 1987. “Hearing Words and Seeing Colours: an Experimental Investigation of a Case of Synaesthesia”. *Perception* 16.761-767.

Burrack, A., D. Knoch & P. Brugger. 2005. “Mitempfindung in Synaesthetes: Co-incidence or Meaningful Association?” *Cortex*. http://www.cortex-online.org

Calkins, M. W. 1895. “Synaesthesia”. *American Journal of Psychology* 7.90-107.

Croft, William & D. Alan Cruse. 2004. *Cognitive Linguistics*. Cambridge: Cambridge University Press.

Cytowic, R. E. [1989] 2002. *Synesthesia: a Union of the Senses*. 2nd edn. New York: Springer-Verlag.

— 1997. “Synaesthesia: phenomenology and neuropsychology - a review of current knowledge.” Baron-Cohen & Harrison 1997.17-39.

Dailey, A., C. Martindale & J. Borkum. 1997. “Creativity, Synesthesia, and Physiognomic Perception”. *Creativity Research Journal* 10.1-8.

Dann, Kevin T. 1998. *Bright Colours Falsely Seen: Synaesthesia and the Search for Transcendental Knowledge*. New Haven & London: Yale University Press.

Day, S. 2005. “Some Demographic and Socio-cultural Aspects of Synaesthesia”. Robertson & Sagiv 2005.11-33.

Dindia, K. & M. Allen. 1992. “Sex Differences in Self-disclosure: a Meta-analysis”. *Psychological Bulletin* 112.106-124.

Dixon, M. J. & D. Smilek. 2005. “The Importance of Individual Differences in Grapheme-colour Synaesthesia”. *Neuron* 45.821-823.

—, D. Smilek & P. M. Merikle. 2004. “Not All Synaesthetes are Created Equal: Projector vs Associator Synaesthetes”. *Cognitive, Affective and Behavioral Neuroscience* 4.335-343.

Domino, G. 1989. “Synesthesia and Creativity in Fine Art Students: an Empirical Look”. *Creativity Research Journal* 1.7-29.

Fauconnier, G. & M. Turner. 2002. *The Way We Think: Conceptual Blending and the Mind’s Hidden Complexities*. New York: Basic Books.

Firth, J. R. 1964. *The Tongues of Men* [1937] & *Speech* [1930]. London: Oxford University Press.

Fodor, J. A. 1983. *The Modularity of Mind*. Cambridge, Mass.: MIT Press.

Frith, C. D. & E. Paulesu. 1997. “The Physiological Basis of Synaesthesia”. Baron-Cohen & Harrison 1997.123-147.

Galton, F. 1883. *Inquiries into Human Faculty and its Development*. London: Dent.

Geschwind, N. & A. M. Galaburda. 1987. *Cerebral Lateralization: Biological Mechanisms, Associations, and Pathology*. Cambridge, Mass.: MIT Press.

Grady, J. 1999. "A Typology of Motivation for Conceptual Metaphor: Correlation vs. Resemblance". *Metaphor in Cognitive Linguistics* ed. by Raymond W. Gibbs & Gerard J. Steen, 79-100. Amsterdam & Philadelphia: John Benjamins.

Grossenbacher, P. G. 1997. "Perception and Sensory Information in Synaesthetic Experience". Baron-Cohen & Harrison 1997.148-172.

— & C. T. Lovelace. 2001. "Mechanisms of Synesthesia: Cognitive and Physiological Constraints". *Trends in Cognitive Sciences* 5.36-41.

Hadjikani, N., A. K. Liu, A. M. Dale, P. Cavanagh & R. B. H. Tootell. 1998. "Retinotopy and Colour Sensitivity in Human Visual Cortical Area V8". *Nature Neuroscience* 1.31-44.

Harrison, J. 2001. *Synaesthesia: the Strangest Thing*. New York: Oxford University Press.

— & Simon Baron-Cohen. 1997. "Synaesthesia: an Introduction". Baron-Cohen & Harrison 1997.3-16.

Hartman, A. M. & L. E. Hollister. 1963. "Effect of Mescaline, Lysergic Acid Diethylamide and Psilocybin on Color Perception". *Psychopharmacologia* 4.441-451.

Hough, Carole. 2004. "New Light on the Verb 'Understand'". *New Perspectives on English Historical Linguistics (2): Lexis and Transmission* ed. by Christian J. Kay, Carole A. Hough & Irené A. W. Wotherspoon, 139-149. Amsterdam & Philadelphia: John Benjamins.

Hubbard, E. M., C. Arman, V. S. Ramachandran & G. M. Boynton. 2005. "Individual Differences among Grapheme-Color Synesthetes: Brain-behavior Correlations". *Neuron* 45.975-985.

Jacobs, L., A. Karpik, D. Bozian & S. Gothgen. 1981. "Auditory-visual Synesthesia: Sound-induced Photisms". *Archives of Neurology* 38.211-216.

Jakobson, Roman & Linda Waugh. 1978. *The Sound-shape of Language*. Bloomington: Indiana University Press.

Johnson, Christopher. 1997. "Metaphor vs. Conflation in the Acquisition of Polysemy: the Case of SEE". *Cultural, Typological and Psychological Issues in Cognitive Linguistics* ed. by M. K. Hiraga, C. Sinha & S. Wilcox, 155-169. Amsterdam & Philadelphia: John Benjamins.

Kay, C. 2000. "Metaphors We Lived By: Pathways between Old and Modern English". *Essays on Anglo-Saxon and Related Themes in Memory of Dr Lynne Grundy* ed. by J. Nelson & J. Roberts, 273-285. London: King's.

Laeng, B., F. Svartdal & H. Oelmann. 2004. “Does Color Synesthesia Pose a Paradox for Early-selection Theories of Attention?” *Psychological Science* 15.277-281.

Lakoff, George & Mark Johnson. 1980. *Metaphors We Live By*. Chicago: University of Chicago Press.

— & Mark Johnson. 1999. *Philosophy in the Flesh: the Embodied Mind and its Challenge to Western Thought*. New York: Basic Books.

Lueck C. J., S. Zeki, K. J. Friston, M. P. Deiber, P. Cope, V. J. Cunningham, A. A. Lammertsma, C. Kennard & R. S. Frackowiak. 1989. “The Color Centre in the Cerebral Cortex of Man”. *Nature* 340.386-389.

Luria, A. R. [1968] 1987. *The Mind of a Mnemonist: a Little Book about a Vast Memory*. Cambridge, Mass. & London: Harvard University Press.

McGilvray, J. 1994. “Constant Colours in the Head”. *Synthese* 100.197-239.

Martino, G. & L. E. Marks. 2001. “Synesthesia: Strong and Weak Forms”. *Current Directions in Psychological Science* 10.61-65.

Mattingley, J. B., J. Payne & A. N. Rich. 2005. “Attentional Load Attenuates Synaesthetic Priming Effects in Grapheme-colour Synaesthesia”. *Cortex*. http://www.cortex-online.org

Maurer, Daphne. 1993. “Neonatal Synaesthesia: Implications for the Processing of Speech and Faces”. Baron-Cohen & Harrison 1997.224-242.

— & C. Mondloch. 2005. “Neonatal Synesthesia: a Re-evaluation”. Robertson & Sagiv 2005.193-213.

Mills, C. B., E. H. Boteler & G. K. Oliver. 1999. “Digit Synaesthesia: a Case Study Using a Stroop-type Test”. *Cognitive Neuropsychology* 16.181-191.

—, J. Innis, T. Westendorf, L. Owsianiecki & A. McDonald. 2005. “Effects of a Synesthete’s Photisms on Name Recall”. *Cortex*. http://www.cortex-online.org

Motluk, Alison. 1994. “The Sweet Smell of Purple”. *New Scientist* 13.33-37.

—. 1997. “Two Synaesthetes Talking Colour”. Baron-Cohen & Harrison 1997.269-277.

Mulvenna, C. 2003. *The Relationship between Synaesthesia and Creativity*. Undergraduate dissertation, University of Glasgow.

—. 2004. *The Prevalence and Diversity of Synaesthesia*. M.A. dissertation, University of Glasgow.

—, E. M. Hubbard, V. S. Ramachandran & F. Pollick. 2004. “The Relationship between Synaesthesia and Creativity”. Paper presented at the Eleventh Annual Meeting of the Cognitive Neuroscience Society, San Francisco, California, April 2004.

— & V. Walsh. 2005. “Synaesthesia”. *Current Biology* 5.399-400.

Narayanan, S. 1997. *Embodiment in Language Understanding: Sensory-motor Representations for Metaphoric Reasoning about Event Descriptions*. Ph.D. dissertation, University of California.

Nobre, A. C., T. Allison & G. McCarthy. 1994. “Word Recognition in the Human Inferior Temporal Lobe”. *Nature* 372.260-263.

Nunn, J. A., L. J. Gregory, M. Brammer, S. C. R Williams, D. M. Parslow, M. J. Morgan, R. G. Morris, E. T. Bullmore, S. Baron-Cohen & J. A. Gray. 2002. “Functional Magnetic Resonance Imaging of Synesthesia: Activation of V4/V8 by Spoken Words”. *Nature Neuroscience* 5.371-375.

Odgaard, E. C., J. H. Flowers & H. L. Bradman. 1999. “An Investigation of the Cognitive and Perceptual Dynamics of a Colour-digit Synaesthete”. *Perception* 28.651-664.

Osgood, C. E. 1980. “The Cognitive Dynamics of Synesthesia and Metaphor”. *Cognition and Figurative Language* ed. by Richard Honek & Robert R. Hoffman, 203-238. Hillsdale, N.J.: Erlbaum Associates.

Palmeri, T. J., R. Blake, R. Marois, M. A. Flanery & W. Whetsell. 2002. “The Perceptual Reality of Synesthetic Colors”. *Proceedings of the National Academy of Science* 99.4127-4131.

Paulesu, E., J. Harrison, S. Baron-Cohen, J. D. G. Watson, L. Goldstein, J. Heather, R. S. J. Frackowiak & C. D. Frith. 1995. “The Physiology of Coloured Hearing: a PET Activation Study of Colour-word Synaesthesia”. *Brain* 118.661-676.

Paulsen, H. G. & B. Laeng. 2005. “Pupillometry of Grapheme-color Synaesthesia”. *Cortex*. http://www.cortex-online.org

Pečjak, V. 1970. “Verbal Synesthesiae of Colours, Emotions & Days of the Week”. *Journal of Verbal Learning and Verbal Behaviour* 9.623-626.

Pesenti, M., M. Thioux, X. Seron & A. De Volder. 2000. “Neuroanatomical Substrates of Arabic Number Processing, Numerical Comparison, and Simple Addition: a PET Study”. *Journal of Cognitive Neuroscience* 12.461-479.

Podoll, K. & D. Robinson. 2002. “Auditory-visual Synaesthesia in a Patient with Basilar Migraine”. *Journal of Neurology* 249.476-477.

Ramachandran, V. S. & W. Hirstein. 1999. “The Science of Art: a Neurological Theory of Aesthetic Experience”. *Journal of Consciousness Studies* 6.15-51.

— & E. M. Hubbard. 2001a. “Psychophysical Investigations into the Neural Basis of Synaesthesia”. *Proceedings of the Royal Society of London B* 268.979-983.

— & E. M. Hubbard. 2001b. “Synaesthesia – a Window into Perception, Thought and Language”. *Journal of Consciousness Studies* 8.3-34.

Rang, H. P. & M. M. Dale. 1987. *Pharmacology*. Edinburgh: Churchill Livingstone.

Rich, A. N., J. L. Bradshaw & J. B. Mattingley. 2005. “A Systematic, Large-scale Study of Synaesthesia: Implications for the Role of Early Experience in Lexical-colour Associations”. *Cognition* 98:1.53-84.

— & J. B. Mattingley. 2002. “Anomalous Perception in Synaesthesia: a Cognitive Neuroscience Perspective”. *Nature Reviews: Neuroscience* 3.43-52.

Robertson, L. & N. Sagiv. 2005. *Synesthesia: Perspectives from Cognitive Neuroscience*. Oxford: Oxford University Press.

Roget, P. M. [1852] 1982. *Thesaurus of English Words and Phrases* ed. by Susan M. Lloyd. London: Longman.

Root-Bernstein, R. S. & M. M. Root-Bernstein. 1999. *Sparks of Genius: the Thirteen Tools of the World’s Most Creative People*. Boston: Houghton Mifflin.

Rundblad, Gabriella & David B. Kronenfeld. 2000. “Folk-etymology: Haphazard Perversion or Shrewd Analogy?” *Lexicology, Semantics and Lexicography: Selected Papers from the Fourth G. L. Brook Symposium* ed. by Julie Coleman & Christian J. Kay, 19-34. Amsterdam & Philadelphia: John Benjamins.

Sagiv, N. 2005. “Synesthesia in Perspective”. Robertson & Sagiv 2005.3-10.

—, J. Heer & L. Robertson. 2005. “Does Binding of Synesthetic Color to the Evoking Grapheme Require Attention?” *Cortex*. http://www.cortex-online.org.

Simner, J., C. Mulvenna, N. Sagiv, E. Tsakanikos, S. A. Whitherby, K. Fraser, K. Scott & J. Ward. Manuscript submitted. “On Segregation of the Senses: When Modularity Breaks Down”.

Smilek, D. & M. J. Dixon. 2002. “Towards a Synergistic Understanding of Synaesthesia: Combining Current Experimental Findings with Synaesthetes’ Subjective Descriptions”. *Psyche* 8 http://psyche.cs.monash.edu.au/v8/psyche-8-01-smilek.html

—, M. J. Dixon, C. Cudahy & P. M. Merikle. 2002. “Synaesthetic Color Experiences Influence Memory”. *Psychological Science* 13.548-552.

Smith, N. 2002. *Language, Bananas & Bonobos: Linguistic Problems, Puzzles and Polemics*. Oxford: Blackwell.

Torrance, E. P., E. Orlow, H. Ball & Tammy Safter. 1992. *Torrance Tests of Creative Thinking*. Bensenville, Ill.: Scholastic Testing Service.

Ullman, Stephen. 1957. *The Principles of Semantics*. 2nd edn. Oxford: Blackwell & Glasgow: Jackson.

Ungerer**,** Friedrich & H-J. Schmid. 1996. *Introduction to Cognitive Linguistics*. London: Longman.

Walsh, R. 2005. “Can Synaesthesia be Cultivated?: Indications from Surveys of Meditators”. *Journal of Consciousness Studies* 12.5-17.

Ward, J. & J. B. Mattingley. 2005. “Synaesthesia: an Overview of Contemporary Findings and Controversies”. *Cortex*. http://www.cortex-online.org

— & J. Simner. 2003. “Lexical-gustatory Synaesthesia: Linguistic and Conceptual Factors”. *Cognition* 89.237-261.

— & J. Simner. 2005. “Is Synaesthesia an X-linked Dominant Trait with Lethality in Males?” *Perception* 34.611–623.

—, J. Simner & V. Auyeung. 2005. “A Comparison of Lexical-gustatory and Grapheme-colour Synaesthesia”. *Cognitive Neuropsychology* 22.22-48.

Wollen, K. A. & F. T. Ruggiero. 1983. “Colored-letter Synaesthesia”. *Journal of Mental Imagery* 7.83-86.

Zeki, S. & L. Marini. 1998. “Three Cortical Stages of Colour Processing in the Human Brain”. *Brain* 12.1669-1685.

AUTHOR INDEX

SUBJECT INDEX