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The time course of the influence of colour terms on visual processing

Lewis Forder

Thesis submitted for the degree of Doctor of Philosophy

School of Psychology
University of Sussex

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Declaration

I hereby declare that this thesis has not been and will not be, submitted in whole or in part to another university for the award of any other degree.

Signature:

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Article format thesis declaration

The thesis conforms to an 'article format' in which the first chapter presents an overview of the relevant literature, an outline of the empirical work of the thesis, and discussion of the overall contribution of the thesis to the field. The remaining four chapters consist of discrete papers written for publication in peer-reviewed journals. Two of these chapters have been submitted for publication, and two are prepared for submission.

Chapters and author contributions

Chapter 1 provides an introduction to the relevant literature, along with an outline of the empirical work of the thesis and a discussion of the main findings, implications and conclusions.

Chapter 2 has been submitted for publication in *PLOS ONE* as:

Forder, L., Taylor, O., Mankin, H., Scott, R., & Franklin, A. Colour Terms Affect Detection of Colour and Colour-associated Objects Suppressed from Visual Awareness. *PLOS ONE* (submitted).

The author contributions are as follows: LF was responsible for writing the manuscript, designing the experiment, data collection, and data analysis. OT and HM assisted with data collection. AF provided feedback on the experiment design and manuscript. RS provided feedback on the experiment design.

Chapter 3 is written in a style appropriate for submission to *Psychophysiology:*

Forder, L., He, X., Witzel, C., & Franklin. Speakers of different colour lexicons differ only in post-perceptual processing of colour when colour is attended.

The author contributions are as follows: LF was responsible for writing the manuscript, designing the experiment, data collection, and data analysis. XH and CW provided feedback on the experiment design. AF provided feedback on the experiment design and manuscript.

Chapter 4 has been submitted for publication in *Journal of the Optical Society of America:A* as:

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The author contributions are as follows: LF was responsible for writing the manuscript, designing the experiment, data collection, and data analysis. XH provided feedback on the experiment design. AF provided feedback on the experiment design and manuscript.

Chapter 5 is written in a style appropriate for submission to *Proceedings of the National Academy of Sciences:*

Forder, L., Bosten, J., He, X., & Franklin. A neural signature of the unique hues.

The author contributions are as follows: LF was responsible for writing the manuscript, designing the experiment, data collection, and data analysis. XH provided feedback on the experiment design. JB and AF provided feedback on the experiment design and manuscript.

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UNIVERSITY OF SUSSEX

LEWIS FORDER — PHD PSYCHOLOGY

THE TIME COURSE OF THE INFLUENCE OF COLOUR TERMS ON VISUAL PROCESSING

SUMMARY:

This thesis explores whether colour terms (e.g., "red", "blue", "purple", etc.) influence visual processing of colour, and if so, the time course of any effect. Broadly, this issue relates to debate concerning whether language affects the way we perceive the world (i.e., the theory of linguistic relativity). Three of the experiments conducted used the event-related potential method (ERP), taking electrophysiological measurements of visual processing and visual cognition in human participants. The ERP provides high-resolution information about the timing of neural activity in the brain and can therefore be used to effectively investigate the time course of a potential influence of colour terms on visual processing. The first study, using a behavioural approach, identified that colour terms can influence the detection of colours and colour-associated objects suppressed from awareness by continuous flash suppression. The second study found that a cross-linguistic difference in colour lexicons affected a post-perceptual ERP component (the P2-N2 complex), but not sensory ERP components occurring early in visual processing. However, the third study found that differences in colour naming within a language do affect an early sensory ERP component (the P1). The final study used ERPs to identify a post-perceptual neural marker (in the posterior P2 component) for the unique 'pure' hues (red, yellow, green, and blue), which had previously only been defined and identified linguistically. All of the studies provide evidence that colour terms affect colour processing, and the specific time course of this effect is identified as being task-dependent. These findings have implications for broader debate about the influence of language on visual cognition and perception.

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Chapter 1

Introduction & thesis overview

This thesis presents four papers that outline empirical studies which have been conducted to explore the relationship between colour terms, colour perception and cognition. This chapter first reviews the literature relevant to this field and then summarises the theoretical concepts and methodological techniques that were applied and reported in this thesis. This chapter concludes with a summary of each of the four papers, a description of the contributions this thesis makes to this field of research, and proposes directions for future research.

1.1 Language and thought

The hypothesis that language affects thought goes back a long way. Gellatly (1995) proposes that it can be found as early as the fifth century in the writings of the Greek historian Herodotus. In the modern day, this idea is usually framed in terms of Benjamin Whorf's 'Whorfian hypothesis', also known as the 'Sapir-Whorf hypothesis' (Whorf was a student of Edward Sapir at Yale University), or more generally as 'linguistic relativity'. Before moving on to outlining a more refined hypothesis concerning language and visual perception, which is specific to this thesis, Whorf's ideas are first briefly outlined.

1.1.1   The Whorfian hypothesis

The Whorfian hypothesis may perhaps be best introduced with an often cited quote from Whorf himself. The following is taken from a letter titled 'Science and linguistics' that was penned and published in 1940 in *Technology Review*:

"We dissect nature along lines laid down by our native language. The categories and types that we isolate from the world of phenomena we do not find there because

they stare every observer in the face; on the contrary, the world is presented in a kaleidoscopic flux of impressions which have to be organized by our minds – and this means largely by the linguistic systems in our minds" (Whorf, 1956, p. 213)

Essentially Whorf proposed that language structures thought and that, because languages vary in the way that they semantically segregate the world, speakers of different languages will think about and understand the world differently. Whorf's own work in this area was observational rather than empirical; he studied the writing systems of lost civilizations, such as the Aztecs, as well as writing systems still in use today. Whorf concluded that grammar, as well as words, could affect the way people think. In the decade following his published works there was strong support from some (e.g., Kluckhohn & Leighton, 1946), and sharp criticism from others (e.g., Feuer, 1953; Lenneberg, 1953). One observed development of the Whorfian hypothesis has been the distinction between the 'hard' version of the hypothesis – 'linguistic determinism', which basically holds that thought is entirely determined through language, and the 'soft' version of the hypothesis – 'linguistic relativity', the view of which is that language can structure thought (for a detailed review of these philosophies, see Hickmann, 2000). Fifty years after Whorf's death, debate about the hypothesis continues to have advocates (e.g., Gumperz & Levinson, 1996) and critics (e.g., Pinker, 1995). The Whorfian hypothesis has also generated substantial empirical work, as will be outlined later.

In summary, philosophical debate about the influence of language on thought continues (e.g., Gentner, 2003; Lee, 1996). However, through this debate a more refined question has emerged, one that has attracted sustained, empirical attention. This is the question of whether language affects visual perception. For example, whether language affects the way we 'see' the world, rather than just how we 'think' about the world. The claim that language can affect visual perception is at the heart of this thesis. The principal findings and debate around this topic are accordingly presented next.

1.2 Language and visual perception

It is not clear exactly how far the idea that language affects visual perception goes back, but it is clear that there was an upsurge of research in this domain from the beginning of the 21st century. The following is an outline of some of the primary empirical findings in this area.

One line of investigation has led to arguments that language affects the detection of even such a basic sensory process as the detection of motion. For example, in a study by Meteyard, Bahrami, and Vigliocco (2007) it was shown that participants' perception of moving dots in a motion detection task was affected by words passively-presented during the task. The words were verbs that referred to upwards or downwards motion and the proportion of dots that moved compared to those that were static were at threshold for each participant based on prior psychophysical measurement meaning that the task tapped performance for a stimulus that was just-noticeable. A signal detection analysis of the data, which draws conclusions about the tendency to make a response under conditions of uncertainty (Green & Swets, 1966), found that sensitivity (d') for detecting the correct direction of movement was worse when the words described the opposite direction to which the dots were moving. Meteyard et al. suggest that this represents a link between language and lower-level visual processing because the semantic representations of single words affected perceptual sensitivity.

The effect of language on the perceived detection of motion has also been studied by using the motion aftereffect (MAE). The MAE is an illusion of visual perception that follows adaptation to a moving stimulus. After adaptation, looking at something stationary will produce the impression that it is moving in the opposite direction to the originally-moving stimulus, despite remaining stationary. MAEs and language were investigated by Dils and Boroditsky (2010). In this study participants fixated on a flickering achromatic grating (blended black and white stripes) and were told to imagine that the stripes were either moving up or down for 40 seconds; the participants had previously been shown what the stripes looked like when they actually did move up and down to facilitate this imagination exercise. In the language condition, participants heard short stories that used motion language to describe the movement of imaginary, physical objects, such as "squirrels teeming up the wall". MAEs were found to occur after this adaptation period despite no exposure to a moving visual stimulus.

Further, the strength of the MAEs increased with increased exposure to the stories depicting motion, providing support for the claim that imagining a specific motion is enough to affect visual perception and more so when it has been reinforced by a congruent, linguistic description.

Language has also been shown to mediate performance on visual search tasks, in which participants are asked to correctly identify the location or presence / absence of a target stimulus amongst competing distracter stimuli. Spivey, Tyler, Eberhard, and Tanenhaus (2001) used a visual search task that presented varying numbers of bars on a computer screen, which differed in terms of angle (vertical versus horizontal) and colour (red versus green). A target was always a single bar uniquely defined by its angle and colour (e.g., a horizontal red bar) and presented simultaneously to competing distracters, which were always different to the target. It was found that when information about the target, described via an audio cue was provided before the onset of a trial, performance for correctly identifying the presence of the target was significantly faster than when the audio description was played concurrently with the display. The key finding here is that the target could be identified without the audio description, therefore it appears that language facilitated visual search by reducing the amount of time required on subsequent visual search time. This may represent an example of language priming the detection of a specific stimulus (this possibility is described in greater detail below). The strength of an effect of language on visual perception has also been shown to be increased when participants actively name something they are searching for. Lupyan (2008) showed that response times were slower when a target alphabet letter was spoken out loud during a visual search task in which a target letter was presented amongst distracter letters. This suggests that the act of naming something out loud can affect the speed that things are seen or responded to.

The influence of linguistic categories on visual perception has also been highlighted as evidence that language can affect visual perception. Lupyan, Thompson-Schill, and Swingley (2010) tested the idea that same/different judgements for alphabet letters would be affected by the conceptual category of the letters. It was found that when letters were presented sequentially and came from the same category (e.g., 'B' followed by 'b'), response times for indicating that the two letters were different were significantly longer compared to when they came from a different category ('B' followed by 'p'). Low level feature differences cannot account for this finding as the

stimuli were matched in terms of size, orientation, etc. Thus they argue that the categorical relationship amongst the stimuli affected performance and that this is further evidence that language affects visual perception because categories are essentially a linguistic convention.

All of these studies suggest that language can affect performance on seemingly perceptual tasks. However, a crucial question here is at what point during the processing of a visual stimulus does language have an influence? By pinpointing this time point, it is possible to infer more about the specific mechanism through which language affects visual processing and perception. Establishing the time point is also important to determine the strength of the influence of language.

One possibility is that language influences low-level activity in the visual system (Delorme, Rousselet, Macé, & Fabre-Thorpe, 2004; McCotter, Gosselin, Sowden, & Schyns, 2005). According to this view language can penetrate early, sensory stages of processing that are involved in the processing of the basic physical attributes of visual stimuli (colour, motion, size, etc.). The majority of the studies described above have argued for this view on the basis of their findings (i.e., Lupyan, 2008; Lupyan et al., 2010; Meteyard et al., 2007; Spivey et al., 2001). An alternative view is that language may affect performance on visual perception tasks by actually affecting higher-level cognitive mechanisms or affecting performance at the stage of decision making and response.

The distinction between whether language affects early sensory and perceptual processes or later post-perceptual cognitive processing, decision making and response is hugely important to the broader question of whether language operates independently of perception (e.g., Li & Gleitman, 2002; Pinker, 1995) or whether language and perception operate through interactive processes, whereby language affects bottom-up processing in the visual system in a top-down manner (Lupyan, 2012, see also 2007; Notman, Sowden, & Özgen, 2005; Reber, Stark, & Squire, 1998).

If language does affect activity in the visual system, this alternatively suggests a form of interaction between higher-level cognition and lower-level processing systems (e.g., Kinchla & Wolfe, 1979; McClelland & Rumelhart, 1981; Mesulam, 1998; Stone, Vanhoy, & Van Orden, 1997). Gary Lupyan is a strong advocator of the 'interactive view', which states that visual processing and perception do not operate independently

of language. He has refined this idea by proposing the 'label-feedback hypothesis' (Lupyan, 2012). In this he argues that language has the capacity to affect low-level visual processing and that this occurs because of a top-down effect of language on bottom-up processing in the visual system. This view holds that language can affect the earliest 'sensory' stages of visual processing, and that it can do this by producing transient modulation of ongoing perceptual (and higher-level) processing. Thus, learning the word for an object or category results in the perceptual representations activated when seeing that object / category to become warped by top-down feedback, as the verbal label of the object / category is co-activated. This, he argues, results in a temporary warping of perceptual space with items from the same category being pushed closer together and items from a different category being moved apart, and that viewing a named object / category becomes a hybrid visuo-linguistic experience. The label-feedback hypothesis goes some way to providing a framework to conceptualise the way that language affects visual perception.

Despite emerging empirical support for the idea that language can affect the way the visual system processes information, this idea is not held by all (e.g., Gleitman & Papafragou, 2005). One reason for this is that it is at odds with models of perception that propose the relationship between a stimulus and response is a purely feed-forward process (e.g., Seidenberg & McClelland, 1989; Stone & Van Orden, 1993). It also disagrees with major theories of visual perception, which hold that the visual system functions independently of cognitive processes (Pylyshyn, 1999; Zeki, 1993), as well as those who argue that language processing is best described in terms of a functionally modular human brain (Chomsky, 1965; Fodor, 1983).

The view that language affects 'higher-level' stages of processing is supported by evidence that differences in the way a language uses grammatical gender can affect the left-anterior negativity wave (Boutonnet, Athanasopoulos, & Thierry, 2012; Cubelli et al., 2011). The left-anterior negativity wave is a marker of electrophysiological activity recorded via electrodes placed on the scalp and thought to reflect morphosyntactic processing in post-perceptual (i.e., higher-level cognitive) stages of processing (e.g., Friederici et al., 1993). In the Boutonnet et al. study, participants completed a simple categorisation task, they were presented with two visual stimuli and then categorised whether the third subsequently presented stimulus belonged to the same semantic category as the first two. The key manipulation is that for the Spanish-

English bilinguals only, the grammatical gender (in the Spanish language) of the third stimulus could be manipulated to be consistent or inconsistent with the preceding stimuli (no such manipulation is possible for the other group as the English language does not use grammatically-based articles for nouns). Despite only object stimuli being presented to participants, and not actual written words, the left-anterior negativity wave was significantly more pronounced in Spanish-English bilinguals compared to English monolinguals. This indicates spontaneous access to grammatical gender and that language can affect higher-level mechanisms associated with the way a visual stimulus is processed.

As outlined above, one option is that language affects performance on visual perception tasks because of an influence at the stage of response rather than perception. Evidence in support of this comes from a study that showed that participants can deliberately change the central tendencies of their psychometric functions by introducing a response bias (Morgan, Dillenburger, Raphael, & Solomon, 2012). A psychometric function is a model applied to data from tasks that require participants to make detection or discrimination response and is frequently used to analyse psychophysical data. The function provides information about the probability that a certain response will be made depending on the intensity of a stimulus (Mather, 2009). In Morgan et al.'s study participants were asked to indicate whether the offset direction of three fuzzy patches was clear or not. This was a vernier task that measures visual acuity for the ability to discern disalignment among adjacent stimuli. Importantly, when participants were instructed to favour one of the two responses (clear offset versus unclear offset) when unsure of their answer, a response bias was found that changed the central tendency of the psychometric function. Morgan et al. argue that while this could be concluded to be a 'perceptual' effect between conditions, whereby visual perception is affected differently across the experimental conditions, this was not the case as the manipulation across conditions was one of task strategy, rather than differences in visual stimuli. The ability of researchers to distinguish between 'perceptual' effects in data compared to a response bias had been highlighted previously (Puccetti & Dykes, 1978), and continues to generate discussion (e.g., Mather, Pavan, Marotti, Campana, & Casco, 2013).

In the study described above that used alphabet letters, Lupyan et al. (2010) argue that their findings are not accounted for by decision bias. They compared their

response time data which showed that sequentially presented letters were significantly faster when the letters came from different categories than the same category, to data they collected from trials that presented both letters simultaneously. Unlike sequentially presented stimuli, they found no reliable effect of conceptual categories on simultaneously presented stimuli; there was no significant difference in response times for same- versus different category letter pairs. They argue that a decision bias is unlikely to be responsible for decreasing same-category letter pairs for sequentially presented letters because a decision bias must be present in both simultaneous and sequential presentations. They argue that conceptual categories penetrate both earlier and lower-level stages of visual processing.

Further arguments that language affects low-level perception as opposed to a decision bias, were made in a study by Lupyan and Ward (2013). They used a form of binocular rivalry known as continuous flash suppression (CFS) to hide visual targets from awareness. In this task a target is presented to one eye (e.g., a photo of an object), while the other eye is presented with flashing visual noise (Tsuchiya & Koch, 2005).The outcome is that participants can only perceive the flashing noise for a period of time before the target finally emerges and can be seen. It has been argued that CFS prevents a hidden stimulus from receiving processing from higher-level cognitive processes, such as decision making and stimulus evaluation (Kang et al., 2011). Lupyan and Ward used this masking task to test whether suppressed images of objects could be more or less easily detected (i.e., perceived) if the suppressed object was preceded by a verbal label that either matched the object (e.g., hearing the word "frog" before a frog was presented) or did not match the object (e.g., hearing the word "pumpkin" before a frog was presented). Compared to baseline trials that contained no verbal cue, congruent labels were found to decrease reaction times and increase accuracy of responses, while incongruent labels had the opposite effect. Lupyan and Ward propose that this is evidence that language can interact with early stages of visual processing because some have argued that CFS is thought to disrupt visual processing before higher-level semantic analysis of visual stimuli (e.g., Kang, Blake, & Woodman, 2011). This suggests that language may affect the way a visual stimulus is processed before it is 'seen', indicating an interaction between language and lower-levels of processing.

A number of studies have been outlined here that could suggest that language can affect visual perception. The view that language and visual perception operate

interactively, rather than independently has also been highlighted. The findings reviewed so far cross multiple faculties of vision, such as motion detection, visual search, and the detection of hidden target stimuli. However, of all the faculties of vision, the domain of colour has perhaps been the most fervently studied in relation to debate about language and perception. The influence of colour language on colour perception is a principal concern of this thesis. Therefore, the broad area of research on colour terms and colour categories is reviewed in depth in the following section.

1.3 The effect of language in the domain of colour

Colour is an invaluable tool for investigating the relationship between language, perception and cognition. This is because colour is a continuous spectrum, ranging from blue hues of a shorter wavelength to red hues of a longer wavelength, but it is grouped into a small number of lexical categories (i.e., 'red', 'green', 'yellow', etc.). Importantly, the colour lexicons of the world's languages categorise the colour spectrum differently. For example, whereas the English language makes a distinction between green and blue hues, other cultures such as the Berinmo of Papua New Guinea do not and instead use a single colour term (in this case *'nol'*) to describe these hues (Kay & Regier, 2006). It is therefore possible to carry out empirical research to investigate whether the way that colour terms are used to categorise the continuous spectrum affects the way colour is perceived or thought about. Before outlining some of the key findings in this area, it is important to firstly define what is meant by a 'colour term'.

1.3.1 Basic colour terms

Berlin and Kay's (1969) seminal work on basic colour terms was a review of colour terms across 20 different languages for 330 maximally saturated hues from the Munsell colour system (Munsell, 1912). The Munsell system, like more modern colour spaces such as CIELUV/CIELAB, considers that the psychophysics of colour perception can be described with three parameters: chroma (colourfulness), value (lightness), and hue. The 'World Colour Survey' later expanded on work of Berlin and

Kay to investigate colour terms in 110 non-industrialised languages, also using colours from the Munsell system (Kay, Berlin, Maffi, Merrifield, & Cook, 2009).

Berlin and Kay define a basic colour term as one that is known by all speakers of the language, is monolexemic (e.g., 'red' rather than 'light red'), and is not subordinate to another colour term (e.g., 'maroon' is subsumed in the basic colour term 'red'). Differences in the use of colour terms across languages has been acknowledged for centuries, for example William Gladstone (1858) drew attention to the differential use of colour terms in ancient Greek texts over a hundred and fifty years ago (Deutscher, 2010). However, one of the key strengths of Berlin and Kay's study of colour lexicons is that they applied the same methods and approach to measuring colour naming across multiple languages to enable comparison across these languages. Berlin and Kay reported that despite differences in the way colours are named, the number of basic colour terms in a language predicts which specific colour terms exist in the language. They argued that as a language evolves, more colour terms are acquired and that the acquisition of basic colour terms follows a specific, chronological order: black and white > red > yellow / green > blue > brown > purple / pink / orange / grey (colour terms separated by a forward slash '/' are reversible). For example, the theory posits that languages in the first stage of this classification contain terms distinguishing purely between dark-cool and light-warm colours. Languages, such as English, which Berlin and Kay argue contains 11 basic colour terms (as above), fall in the last stage.

There has been some criticism of the methods employed by Berlin and Kay. Saunders and van Brakel (1997) highlight that the data from 19 out of the 20 languages reported by Berlin and Kay contained only one bilingual speaker and that this is empirically inadequate to consider genuine cross-cultural significance of colour terms. Saunders and van Brakel also argue Berlin and Kay's definition of basic colour terms is too fluid, and highlight a study of speakers of Jarai (of Vietnam and Cambodia), which found that by applying the criteria specified by Berlin and Kay, this language contained 23 basic colour terms (Dournes, 1978), but see Kay and Berlin (1997) for a response to these criticisms. Levinson (2001) further argues that languages such as the Rossel language (of Papua New Guinea), which have only an incipient colour terminology, cast doubt on the universality of the use of basic colour terms. As outlined below, there has been substantial philosophical and empirical debate about whether colour terms are universal (i.e., whether colour terms arise because of the way colour is perceived the

same by all people), or whether the colour spectrum is instead arbitrarily divided into colour categories through language (i.e., the relativist view; Levinson 2001).

There have been subsequent revisions of Berlin and Kay's theory, such as the concept of 'fuzzy sets' that are composite categories that contain one or more hue focus (Kay & McDaniel, 1978), and the proposal that there are alternative developmental routes of basic colour terms (Kay & Maffi, 1999). However, the definition of basic colour terms proposed by Berlin and Kay (1969) continues to be applied broadly in the literature and is the definition used throughout this thesis.

1.3.2 Behavioural studies of colour category effects

Early studies asked whether variation in how speakers of different languages name colours with basic terms leads to differences in colour 'thought' by using a range of behavioural tasks intended to measure colour cognition and perception. For example, Brown and Lenneberg (1954) found that the 'codability' of different colours affected subsequent recognition of them. It was shown that the availability of basic colour terms facilitated performance for remembering and communicating these colours compared to colours that did not match the basic colour terms.

Another classic study was conducted by Kay and Kempton (1984). They showed that subjective judgements about the perceptual difference between colours in native English speakers were distorted around a colour category boundary (blue-green) for colours falling either side of this boundary, whereas speakers of the Tarahumaran language- which makes no such blue-green categorical distinction- showed no such distortion. Kay and Kempton hypothesised that the 'category effect' they found in the English speakers was the result of a naming strategy applied by these participants to complete the task. A 'category effect' is defined as a different response to colour differences depending on the categorical relationship of the colours. For example, in 'categorical perception' it is argued that colours from different categories appear more dissimilar than colours from the same category even when the chromatic difference between colour pairs is equated in a particular metric (e.g., Goldstone, 1994; Harnad, 1987). Such category effects are not unique to performance on colour tasks, for

example it has been argued that categorical perception exists for faces, orientation, speech and other stimuli that fall on a continuum (e.g., Arguin & Saumier, 2000).

In a subsequent task, Kay and Kempton tested their idea that the category effect that they found arose from participants applying a naming strategy when completing the task. They presented two Munsell chips (a green chip and a boundary blue-green chip) and told participants that the green chip was greener than the boundary chip (which they report all participants readily agreed). They also presented a blue chip with the same boundary blue-green chip and told participants that the blue chip was bluer than the boundary chip (participants likewise agreed). When the participants were then asked to judge whether the blueness between the blue chip and the boundary chip or the greenness between the green chip and the boundary was bigger, judgements no longer revealed a category effect despite the same colours being used. Kay and Kempton suggest that naming of the boundary chip in this instance was precluded by being named both green and blue in English speakers. They conclude that this is evidence for explicit linguistic categorisation (the way colours are named) affecting non-linguistic processes (i.e., colour perception).

The early behavioural work described above (Brown & Lenneberg, 1954; Kay & Kempton, 1984; Lenneberg, 1961) potentially goes against the idea that colour terms and their categories are universal (Berlin & Kay, 1969) by showing that cross-linguistic colour naming differences affect performance on tasks probing colour cognition and colour perception. However, as previously mentioned, there has been substantial philosophical and empirical debate on this issue. In support of the ideas of Berlin and Kay, one of the first empirically-based theories to go against the relativist view was the 'prototype theory' proposed by Eleanor Rosch (then Heider) following fieldwork with the Dani of Papua New Guinea (Heider, 1972) and later expanded on (e.g., Rosch, 1975). Rosch's work with the Dani found that this language uses just two colour terms: *mili* (dark-cold) and *mola* (light-warm), and could be considered to be in stage 1 of Berlin and Kay's (1969) model of the evolution of colour terms. Rosch argues that prior findings for the correlation between the codability, communication-accuracy and recognition of colours (e.g., Brown & Lenneberg, 1954), which had been interpreted as evidence for the relativist stance, is due to the existence of universally salient focal colours (a focal colour is the best example of a given colour term, for example focal red is the 'best' red available amongst a selection of different red colours). Rosch reported

that the Dani found it easier to remember good examples (i.e., focal colours) of red, green, yellow, and blue, despite their language containing no words for these colours. This is an important proposition because it suggests that colour terms and their evolution may occur because of the way colour is universally experienced, rather than because of the way a language carves up the colour spectrum.

Rosch's (1972) empirical work and theoretical ideas added support to the view of the universality of colour terms. However, over a series of 12 studies, Roberson, Davies, and Davidoff (2000) refuted the claims made by Rosch with data from speakers of Berinmo (also of Papua New Guinea), which is language thought to contain five basic colour terms. They measured performance on a number of colour tasks (similarity judgements, colour learning, and short-term memory for colour) and provided strong support for the view that performance on these tasks was linguistically relative. For example, while they found that recognition of desaturated colours was affected by colour vocabulary, in contrast to Rosch (1972), when response bias was controlled there was no recognition advantage for focal colours. Further, they found category effects in both English and Berinmo speakers, but only around the boundaries of existing colour terms and their categories. They argued on the basis of this evidence that cultural and linguistic training affects low-level perception by stretching perceptual distances at category boundaries (e.g., Goldstone, 1994; Harnad, 1987; Kay & Kempton, 1984). However, while providing strong support for claims that colour terms affect performance on perceptual or cognitive tasks, the crucial question concerning the specific mechanism underlying this process was left unanswered. From their data with the Berinmo, Roberson et al. do not establish whether this effect is driven by verbal labelling during the task (e.g., Kay & Kempton, 1984), differences in the way colours are memorised (e.g., Brown & Lenneberg, 1954), or differences in colour discrimination resulting from low-level perceptual warping or top-down modulation (e.g., Goldstone, 1994; Harnad, 1987). In other words, it is unclear whether speakers of different languages truly 'see' colour differently, or whether colour terms merely affect the cognitive strategies that participants employ (e.g., how they memorise colour or make decisions on colour differences) when they complete the colour tasks.

In order to address concern that cross-linguistic differences documented in prior research were not clearly at the level of perception, Winawer et al. (2007) adopted a

task which was intended to tap colour perception more directly. They compared native Russian and native English speakers on a task which involved selecting a colour patch that was the odd-one-out compared to two other patches that were the same colour. The Russian and English languages differ in the way they categorise blue hues: The Russian language differentiates between lighter blues (*goluboj*) and darker blues (*sinij*), whereas the English language does not. The two Russian blues have been argued to fulfil Berlin and Kay's (1969) definition of basic colour terms (Davies & Corbett, 1994; Paramei, 2005). In the Winawer et al. study, they found that reaction times in the Russian group were significantly faster for blue hues when the hues straddled the goluboj-sinij boundary compared to when they did not. This effect was not found in the English speaking group. It was argued that Russian speakers had enhanced colour discrimination around the goluboj-sinij boundary as a result of having two colour terms in this region, which produced the effect they reported. However, one limitation of the study is that reaction times were longer on average in the Russian group (1,085 ms) compared to the English group (938 ms), which may indicate that the two groups adopted different strategies to complete the task or that the Russian group found the task more difficult. If the Russian group found the task more difficult this may have amplified differences amongst the stimuli and account for the effect found for Russian speakers and not English speakers.

The effects reported by Winawer et al. could be due to top-down modulation of colour terms on perception (e.g., colour terms activated implicitly during the discrimination task modify the representation of colour). Alternatively, it is possible that this could be due to colour terms inducing long-term perceptual warping of sensitivity to colour difference around category boundaries over time (e.g., Goldstone, 1994; Harnad, 1987). Roberson, Hanley, and Pak (2009) investigated this hypothesis by seeing whether category effects are present in colour discrimination thresholds. The idea here is that if colour terms cause long-term warping of colour sensitivity, this would manifest as smaller (better) discrimination for colours falling towards a category boundary, and larger (worse) colour discrimination thresholds for colours located centrally within categories. They tested native English and native Korean speakers because these languages differ in how they categorise colour, specifically there is an extra colour category in the Korean language corresponding to yellow-green hues. They found no difference in discrimination thresholds between these two groups suggesting

that colour terms do not warp sensitivity for colour difference at the level of colour discrimination. However, one issue with the study is that discrimination thresholds were not in the typical range for adult colour discrimination – they were far lower and beyond the resolution of their monitor and display set up. Therefore there is a lack of clarity on the reliability of these findings.

Another line of investigation has employed the visual search task to investigate whether colour terms really lead to category effects in colour perception. This task does not require colours to be memorised and so it can be used to test whether category effects persist in the absence of colour memory at a more 'perceptual' stage of processing. In a visual search task, participants are presented with multiple visual stimuli at the same time (typically on a computer monitor). The goal is to identify the 'odd-one-out' target by making a spatial judgement (e.g., left or right) or a present/absent response as quickly and accurately as possible. The target will differ from the other stimuli on a particular colour dimension (hue, saturation, or lightness) and researchers investigate the effect of manipulating the size of this difference on the speed and/or accuracy of target detection. This task can also be used to investigate the effect of colour terms on performance by manipulating the categorical relationship of targets and distractors. Several studies using this task suggest that performance is better when targets and distractors come from different categories than from the same category (Bauer, Jolicoeur, & Cowan, 1996; Daoutis, Franklin, Riddett, Clifford, & Davies, 2006; Daoutis, Pilling, & Davies, 2006; Gilbert, Regier, Kay, & Ivry, 2006). These studies argued that category effects occur when it is not necessary to memorise colour stimuli, as was the case in earlier findings (e.g., Brown & Lenneberg, 1954; Lenneberg, 1961), lending stronger support to the claim that colour terms affect colour perception as well as colour cognition.

The use of visual search tasks also led to another line of investigation, where it was found that category effects for colour on visual search tasks were stronger when the target is in the right visual field compared to the left (e.g., Gilbert, Regier, Kay, & Ivry, 2006). Gilbert et al. presented a circular array of 12 square colour patches and on each trial one of the patches (the target) was a different colour to the other 11 patches, and the target and distracters were either same or different category. There was no significant difference in performance for same- and different-category colours when the

target was situated in the left visual field. However, for targets presented to the right visual field there was a category effect, whereby reaction times were significantly faster for different-category colours compared to same-category colours. It is known that visual input to the right visual field is initially projected and processed contralaterally in the left hemisphere, which is known to be more specialised for the processing of language (Corballis, 1993; Hellige, 1993). Consequently, Gilbert et al. argued that the right-visual field lateralised category effect suggests the influence of colour terms on perception in the right visual field.

Gilbert et al. (2006) tested this idea further. Prior findings, such as that of Kay and Kempton (1984) described above (see also Roberson & Davidoff, 2000), showed that categorical perception of colour can be eliminated under conditions designed to interfere with verbal processing. Gilbert et al. included blocks of trials that required participants to memorise and subsequently recall a random string of eight single-digit numbers. This encouraged participants to actively rehearse the sequence while performing the visual search task, making a greater demand on verbal working memory and allowing less cognitive capacity to actively name the colours presented in the task. The category effect they found in the right visual field for trials containing no interference disappeared on the verbal interference trials. Further, they found that reaction times to targets in the right visual field during verbal interference were significantly longer for different-category colours compared to those from the same category, which could be considered a reverse category effect. Gilbert et al. propose that this finding supports the claim that category effects may arise from verbal processing affecting the way colour is perceived.

The stronger category effect reported in the right visual field by Gilbert et al. (2006) has been replicated a number of times across different groups of participants and different colours (Drivonikou et al., 2007; Roberson et al., 2008; Franklin et al., 2008a; Franklin et al. 2008b; Al-Rasheed, Franklin, Drivonikou, & Davies, 2014). For example, Drivonikou et al. (2007) reported a RVF lateralised category effect for colours spanning blue–purple and purple–pink boundaries. Further, Roberson, Pak, and Hanley (2008) found category effects were stronger in the right visual field for Korean speakers, but not English speakers, for colours that are categorically distinct in in the Korean language but not in the English language. An ERP study (Mo, Xu, Kay, & Tan,

2011) and an fMRI study (Siok et al., 2009) have also argued that colour category effects are left hemisphere lateralised. In support of the argument that these left hemisphere lateralised effects are related to language there is evidence that the effect onsets around the time of colour term acquisition. Evidence for this comes from a study of pre-linguistic infants, which found using an eye-movement latency measure that the colour category effect on a visual search task was actually stronger for targets in the left visual field – right hemisphere, than the right visual field – left hemisphere: an opposite pattern to adults   (Franklin et al., 2008a). A subsequent study then found the same pattern of category effect lateralisation as infants for toddlers who had not yet learnt the words for colours, but the adult pattern of category effect lateralisation for toddlers who did know the words for the relevant colour categories (Franklin et al., 2008b). However, this is not the whole story; there are a number of studies that have failed to replicate a stronger category effect in the right visual field than the left in adults (Brown, Lindsey, & Guckes, 2011; Witzel & Gegenfurtner, 2013). It is as of yet unclear why there is discrepancy between these studies, although it is possible that factors such as spatial attention during the task, the size of the chromatic differences, and the amount of practise on the task or the timing of the task could modulate the effect.

There is potentially a crucial issue with the body of behavioural research outlined above, which could undermine reports of an effect of colour terms on colour cognition and perception. This is the issue of how to equate the colour difference for same and different-category colours.   It is critical to any investigation into colour category effects to show that different-category colour differences are not responded to more quickly or accurately than same-category because the colour differences were simply larger. Researchers typically use predefined colour spaces, such as the Munsell system, CIELUV, or CIELAB, to equate colour difference. A key goal of such colour spaces is that the units of difference in this space are perceptually uniform. However, it is known known that there are issues with these colour spaces, whereby they contain areas that are more or less discriminable (Hill, Roger, & Vorhagen, 1997; Mahy, Van Eycken, & Oosterlinck, 1994) and these spaces can only be considered as crudely uniform. One possibility is that some effects in the literature that have been described as 'category effects' are instead due to inequalities in the colour metrics used to equate same- and different-category colour differences (Witzel & Gegenfurtner, 2013).

One way of addressing concerns with colour spaces is to adopt a cross-linguistic approach. Here, the key manipulation does not rely on equal difference between colours, rather it relates to the way that two groups differently name and categorise colours. The lateralised category effects also potentially control for stimulus issues as the same stimuli are seen in left and right visual fields yet category effects are only found in the right visual field in adults. If these category effects were due to stimulus issues then one might expect them to be represented in both visual fields equally. This issue of colour metric and how to equate same and different category colours is discussed later.

In sum, behavioural evidence from a large number of studies spanning several decades has been used to argue that the colour terms spoken affect performance on a range of colour tasks such as colour memory, speeded discrimination and visual search. However, on the basis of this research there is a lack of clarity about the source of these effects: whether they arise from colour terms affecting how colour is seen and sensitivity to colour differences (e.g., colour perception) or whether colour terms affect performance due to verbal labelling during the task or other reasons related to task strategy and unrelated to perception. There is also the question of whether these effects are due to issues with equating the colour difference of same- and different-category colours. Tasks employed in later studies such as the visual search task do a better job of isolating the effect of colour terms to perception rather than cognition, yet even on these tasks there is lack of clarity about the time course of the effect of colour terms, and the effect of language could still be occurring at the stage of decision or response rather than at the stage of perception. In order to address this important issue of the time course of the effect of colour terms, the event-related potential method has been employed. These studies are reviewed in the following section.

1.3.3 Event-related potential studies of colour category effects

Although findings from behavioural studies suggest a link between colour terms and performance on colour tasks, greater precision about the influence of colour terms can be achieved by using the event-related potential (ERP) approach. ERPs provide precise information about the time course of neural activity in the brain (Luck, 2005). ERPs elicited by the presentation of a visual stimulus typically follow a predictable

pattern of components over time, which are traditionally labelled as the direction of voltage deflection (positive or negative) and the order in which they occur (P1, N1, P2, N2, P3, etc.). Researchers typically investigate the mean amplitude (µV) of a component as well as peak latency (ms), which is the specific time point that a component reaches maximum amplitude. Broadly, the P1 and early-phase N1 components are believed to index early sensory processes concerning the physical characteristics of a stimulus and generally occur before 200 ms (e.g., Polich, 1999; Hopf, Vogel, Woodman, Heinze, & Luck, 2002; Johannes, Münte, Heinze, & Mangun, 1995; Key, Dove, & Maguire, 2005). The latter components broadly arising after 200 ms (P2, N2, and P3) are believed to be associated with numerous post-perceptual higher-level cognitive tasks, such as feature detection, stimulus change and short-term memory (Key et al., 2005), as well as stimulus evaluation processes (McCarthy & Donchin, 1981; Patel & Azzam, 2005). Differentiating between whether colour terms affect activity in early or later ERP components provides clarification about the time course of the effect of colour terms on colour perception and cognition. The distinction between whether colour terms affect early or later stages of visual processing has generated research and debate, which will now be considered. Further, the distinction between early and later stages of processing is made throughout this thesis.

One of the first ERP studies to look for a neural correlate of categorical colour perception was carried out by Fonteneau and Davidoff (2007). In the study they aimed to investigate whether the categorical relationship (same- versus different-category) between different colours was evident in ERP amplitude or latency. Participants were tasked with detecting an infrequently occurring cartoon character embedded in blocks of sequentially presented colours, some of which were presented frequently (the standard) and others infrequently (the deviants). This is known as an oddball task and it provides data about the way the brain processes unfamiliar stimuli (i.e., the 'oddball' deviants) in comparison to a frequently presented 'standard' stimulus. The colours were selected from the Munsell system to differ in hue but not in chroma or value (lightness). The categorical relationship of the standard and deviant colours was manipulated. It was found that when presented as a deviant rather than as a standard, the different-category colour elicited a significantly earlier peak latency (195 ms) than the same-category colour (214 ms) over anterior sites, suggesting that the categorical relationship between the stimuli is registered around 200 ms. However, one drawback of the data reported by

Fonteneau and Davidoff is that they only analysed electrophysiological activity up to 300 ms after stimulus onset. This refined window makes it unviable to draw conclusions about the effect of colour terms on later stages of colour processing (such as the P3 component).

Concerning the question of whether the findings of Fonteneau and Davidoff (2006) represent an effect in early 'sensory' ERP components, or whether their effect was in a subsequent post-perceptual stage of processing, Holmes, Franklin, Clifford, and Davies (2009) argue that the effect found by Fonteneau and Davidoff was in a late phase of the N1 component. This, they argue, reflects a post-perceptual stage of processing based on prior work in this area (e.g., Hopf et al., 2002; Vogel & Luck, 2000). Holmes et al. set out to investigate this further. They also measured electrophysiological activity during a visual oddball task, but there were some differences to the study by Fonteneau and Davidoff. Firstly, they used smaller perceptual differences between their colour stimuli to be more in-line with prior behavioural work in this area. Secondly, in each block there were two different deviants rather than one, whereby one of the deviants was the same category as the standard and the other deviant was a different category. Finally, in Holmes et al. participants were tasked with responding to the colour of each stimulus, therefore the stimuli were directly attended to, unlike the study by Fonteneau and Davidoff, in which participants responded to an infrequently-presented cartoon character. Holmes et al. found that both the P1 and N1 peaked significantly earlier in response to the different-category deviant versus the same-category deviant. They also found enhanced P2 and P3 waves for the between-category deviant compared to the same-category deviant. A such, this study found category effects in early ERP components (P1, early-phase N1) as well as subsequent post-perceptual components (P2, P3).

Evidence that the categorical relationship between named colours affects an ERP component known as visual mismatch negativity (vMMN) was reported by Clifford, Holmes, Davies, and Franklin (2010). The vMMN is believed to reflect the processing of stimuli outside of explicit awareness, and has been argued to correspond to a level of preattentive perceptual processing, occurring before post-perceptual stages of processing (Czigler, Balázs, & Pató, 2004; Czigler, Balázs, & Winkler, 2002; Winkler & Czigler, 2012). In the Clifford et al. study, participants completed an oddball task and responded when a central fixation cross changed shape, and there were two colours

presented simultaneously on each trial (the deviants were either same- or different-category). In this study the two colours were presented so that one was above and the other below the fixation cross. This manipulation was included because prior work on the vMMN had revealed differential patterns of activity for stimuli presented to the upper versus lower visual field (Czigler et al., 2004). Clifford et al. replicated the finding for a stronger vMMN response elicited to the different- compared to the same-category deviant. However, this effect was only found when a deviant was presented to the lower visual field, in line with prior research about the vMMN (e.g., Czigler et al., 2004).

Subsequent ERP studies have refined what is known about the effect of colour terms on colour processing. Mo et al. (2011) investigated whether category effects are found in ERP components when the colour stimuli were not explicitly attended. They too used an oddball task but participants were required to respond when a central fixation cross changed shape, therefore the colour stimuli presented on each trial were processed less explicitly. The vMMN was significantly smaller for same-category deviants than different-category deviants. The findings of Mo et al. therefore support the idea that colour terms affect early, preattentive stages of processing.

In sum, findings from a number of early ERP studies suggested that colour terms affect early ERP components (Clifford et al., 2010; Fonteneau & Davidoff, 2007; Holmes et al., 2009; Mo et al., 2011). However, as previously highlighted, there may be metric issues when adopting predefined colour spaces that are known to contain inhomogeneities (e.g., the Munsell system, CIELUV/CIELAB; Hill et al., 1997; Mahy et al., 1994). This is highly relevant to the debate about the effect of colour terms on the time course of colour processing because early ERP components are highly sensitive to differences between stimuli, such as their size and duration (Busch, Debener, Kranczioch, Engel, & Herrmann, 2004). In short, this issue concerning the metric used to equate colour difference limits the conclusions that can be drawn about whether colour terms truly affect colour processing in early visual processes: early effects in these studies may simply be due to the different-category colour differences used being greater than same-category colour differences.

One study that does not suffer from potential stimulus-specific issues is a cross-linguistic study conducted by Thierry et al. (Thierry, Athanasopoulos, Wiggett, Dering,

& Kuipers, 2009). In this study, ERPs were compared between two groups, who categorised the colour stimuli differently. Specifically, the study recruited native Greek and native English speakers because the Greek language divides lighter and darker blue hues into separate categories (Androulaki et al., 2006), while the English language does not. In their study, Thierry et al. found cross-cultural differences in P1, suggesting that the different way the two groups named and categorised the stimuli affected early stages of visual processing. The study also found cross-cultural differences in the vMMN. The participants in the Thierry et al. study were tasked with identifying when a sequence of stimuli changed shape; they therefore focused their attention away from the colour of the stimuli. This provides a strong case for colour terms affecting early, preattentive processes. Further, in a subsequent re-analysis of this data, which grouped the Greek speakers into short- and long-term stay (depending on the length of time spent in the UK), the ERP effects were found to be stronger in the short-stay group compared to the long-stay group suggesting that colour processing changes depending on linguistic environment (Athanasopoulos, Dering, Wiggett, Kuipers, & Thierry, 2010). They propose this represents neural plasticity in the longer stay participants.

There are two further ERP studies that do not suffer from potential metric issues, both carried out exclusively on native English speakers. Clifford et al. (2012) compared ERPs elicited to colours in two groups, one of which had been trained to make a novel (additional) categorical distinction between the stimuli, while the other group had not. The authors therefore manipulated the categorical relationship amongst the stimuli, but importantly all participants saw the same colours. Any differences in ERPs between the groups can therefore be attributed to the way colour terms affect visual processing. The authors found significant differences in the P3 component, which believed to be associated with post-perceptual processing, such as stimulus evaluation of decision making (Donchin & Coles, 1988; Patel & Azzam, 2005; Polich, 2007), and not in earlier ERP components.

He et al. (2014) resolved potential stimulus issues in a different way. They firstly measured colour discrimination thresholds in the form of just-noticeable differences (JNDs) for hues ranging from blue to green. They then used this data to extract colours that were separated in JND units. Consequently, these stimuli were equated in discrimination thresholds and did not suffer from potential inhomogeneities found in adopted colour spaces. Participants were presented with the JND-equated

stimuli in a visual oddball task and significant category effects were found in N2 and P3. These are believed to be post-perceptual ERP components, therefore like Clifford et al. these authors did not find evidence that colour terms affect early stages of visual processing.

To summarise, the ERP method has provided much greater precision about how colour terms affect colour processing and perception. This is a substantial development on what can be inferred from behavioural investigation alone. However, many ERP studies, like many behavioural studies, are plagued by the crucial issue of accurately equating colour difference. To date, this metric issue has only been resolved in three ERP studies (Clifford et al., 2012; He et al., 2014; Thierry et al., 2009). However, while these three studies have produced interesting findings, there is disagreement about the time course that colour terms affect colour processing. Thierry et al. is the only study to find this effect in early ERP components; the other two studies find this effect to reside in later post-perceptual stages of visual processing. Further research is needed to clarify this time course and to investigate whether further evidence for early ERP effects can be found.

1.3.4 Functional magnetic resonance imaging of colour category effects

In addition to behavioural and ERP investigations of the effect of colour terms on colour perception and cognition, functional magnetic resonance imaging (fMRI) has also been adopted as a method to investigate this issue. ERPs have a high temporal resolution; they can measure neural activity in units smaller than a millisecond. However, they have a poor spatial resolution, that is to say they are not ideal for providing precise information about the location of neural colour-processing activity in the brain. Functional magnetic resonance imaging (fMRI) has the opposite characteristics in that it provides data about neural activity in the brain with a high spatial resolution, but limited temporal resolution. In order to discuss the fMRI studies of the effect of colour terms, I first briefly outline what is known about how colour is sensed and perceived by the eye and brain.

The visible spectrum ranges from about 390 – 700 nm. In the human eye there are three types of photoreceptor that are sensitive to different parts of this spectrum.

These are typically labelled as the S-cone, M-cone, and L-cone, corresponding to short, medium and long wavelength peak sensitivities accordingly. Horizontal and bipolar cells transmit this electrical signal to the retinal ganglion cells, which transmit this information to the brain via three channels (Gegenfurtner, 2003): The $L + M$ channel, in which the signals from the L- and M-cones are added to compute information about luminance; the $L - M$ colour-opponent channel, in which the signals are compared to compute the 'red-green' component of a stimulus; and the $S - (L + M)$, in which the sum of the L- and M-cones is compared to the S-cone signal to compute the 'blue-yellow' component of a stimulus. These signals travel via the lateral geniculate nucleus to the occipital lobe in the brain. We still do not fully understand how activity in the brain correlates with colour sensation and perception (Gegenfurtner, 2003). However, we can make a number of observations. Some neurons in the occipital lobe in area V1 (Gouras, 1974) and V2 (Kiper, Fenstemaker, & Gegenfurtner, 1997) have been shown to respond to a refined bandwidth of colour, and neuroimaging data of area V4 often suggests that this is the region that responds very strongly to colour (Brouwer & Heeger, 2009, 2013; Wade, Brewer, Rieger, & Wandell, 2002).

Studies have used fMRI to investigate how colour terms and their categories are represented in the brain and to address debate about how colour, language and perception interact. An early study in this field investigated whether areas of the brain associated with language are differentially activated during colour discrimination for colours that are easier or harder to name (Tan et al., 2008). Three easy- and three hard-to-name colours were selected and participants performed a discrimination task requiring a same- or different-response to be made to two simultaneously presented colours while whole brain fMRI data were acquired. It was hypothesised that if lexical codes are automatically involved in colour discrimination, the availability of lexical information in language processing areas of the brain will be different for easy- versus hard-to-name colours. Specifically, it was predicted that more lexical information would be available (observed through greater activity in language-specific processing regions) for easy-to-name colours. This was confirmed with the finding of greater activity in the left posterior superior temporal gyrus and inferior parietal lobule for the easy- compared to the hard-to-name colours. Both of these regions have been shown to mediate word-finding processes (e.g., Sonty et al., 2003). One issue here is that the perceptual difference between the easy- and hard-to-name colours was different and it is possible

that the effect they report is particular to the colours selected, rather than an effect of automatic lexical processing. The same-different judgement task can also be completed in a number of different ways: for example, on the basis of how the colours look but also on the basis of how the colours are named. If the task has a verbal element to it, it is not surprising that correlates are found in language related regions of the brain.

Another fMRI study used a visual search task with same- and different-category distractors (the one used in Gilbert et al.'s study mentioned earlier). A difference in activation when searching for targets amongst different- than same-category distracters was found in left posterior temporoparietal areas, which is known to be associated with lexical processing. Importantly, the study also found these effects in regions of visual cortex. It was argued that this is evidence that colour terms affect processing of colour in visual cortex. However, unfortunately, the aforementioned issues with equating same- and different-category colours also plague this study and it is unclear whether the effects at visual cortex really are due to the categorical relationship of target and distractors.

Another neuroimaging study used a different approach and examined whether the density of grey matter in the brain increased with the acquisition of novel colour terms (Kwok et al., 2011). Four colours were used that ranged from blue to green and each of the colours was assigned a nonsensical lexical term. Participants completed five training sessions over three days, and were trained to associate the nonsense terms with a specific colour through a listening task, as well as naming and matching. Each participant was scanned before and after training and voxel-based morphometry (VBM), was used to analyse the MRI anatomical images to determine possible brain structure differences indexed by gray matter volume. The two scans revealed a significant difference in visual areas V2/3 and cerebellum: after training the grey matter was significantly larger. Kwok et al. suggest that this is evidence for a structural basis in the brain for previously reported effects of colour terms on colour perception. However, in this study there was no control for general exposure to the colours. It could be the case that the increase found in grey matter density was the result of seeing the colours more, rather than naming them more.

Brouwer and Heeger (2013) measured cortical activity when participants actively named colours or when attention was distracted away from the colours by

another task. They found that the pattern of neural activity in certain visual areas, such as areas VO1 and V4v, was more clustered for colours from the same colour category when participants were actively naming the colours but not when their attention was directed away from the colours. The findings from this study suggest that activity in visual cortex can be modulated by colour terms, at least when participants are actively naming the colours.

Further investigation of the effect of colour categories on activity at visual cortex has supported the view that the categorical relationship of colours is not evident in the neural activity of visual areas when colours are not actively named. Bird, Berens, Horner, and Franklin (2014) acquired fMRI data whilst participants passively viewed two colours within each block that were either from the same category or from different categories. The size of colour difference was also manipulated. It was found that BOLD was greater for different- than same-category colour pairs in the middle frontal gyrus (MFG) in both hemispheres and that this region was unaffected by the size of the colour difference. The size of the colour difference appeared related to the pattern of activity in the visual cortex but was not affected by the categorical relationship between colours. The MFG has been previously been implicated in a range of different types of categorisation, such as the categorisation of dot patterns (Vogels, Sary, Dupont, & Orban, 2002) and semantic categories (Chan et al., 2004). Bird et al. argued that the colour category effect in the MFG was due to domain general categorisation processes related to attention. Importantly, there is no evidence that when colours are passively viewed that their categorical status affects activity at visual cortex (see also Persichetti et al. 2015 for a similar result).

These fMRI studies potentially advance our understanding of the way that colour terms interact with visual processes. The evidence suggests that visual cortex can be modulated by colour terms when colours are named, but that there is no influence of colour terms if colours are passively viewed. However, the conclusions are potentially at odds with Thierry et al.'s ERP study (2009), which found that the categorical relationship of colours affected ERP components thought to correspond to early stages of visual processing in extrastriate regions of visual cortex despite participants not actively naming the colour stimuli.

As can be seen, a very large body of research has investigated whether colour terms lead to category effects on perceptual or cognitive tasks. Across the area multiple methodologies have been applied: behavioural research that includes memory tasks and visual search tasks, the ERP approach combined with the oddball paradigm, as well as fMRI studies. These studies have become progressively better at refining our understanding of colour category effects and their time course. However, several crucial issues need to be addressed: Firstly, the issue of colour metric that limits our understanding of whether previously reported category effects are indeed 'categorical'; Secondly, the time course of these effects need to be known with precision. ERP methods are the most useful for this (ERPs have a very high temporal resolution) but there are discrepancies between the three studies from which effects are clearly categorical. The Thierry et al. (2009) study suggests these effects reside in early stages of visual processing, whereas He et al. (2014) and Clifford et al. (2012) find colour terms affect later, post-perceptual stages of visual processing. Further, data from fMRI studies all suggest that there are no category effects in visual cortex when colour is passively attended (Brouwer and Heeger 2013; Bird et al., 2014; Persichetti et al., 2015), which potentially contradicts the claims from Thierry et al. Therefore, further research that addresses these finer issues is needed. This thesis presents two further ERP studies, which aim to address these issues. The overall goal of these two ERP studies is to clarify the time course of colour category effects. The thesis therefore thus further investigates the influence of colour terms on visual perception by investigating the time course of colour category effects. However, it also further investigates a broader concept related to the interaction of colour categories in language and thought – that of the unique hues. The concept of unique hues and their relationship to the debate about the influence of colour terms on visual perception is outlined in the following section.

1.3.5 The unique hues

One view of colour terms and their categories is that they are organised around a set of four 'unique hues' (e.g., Kuehni, 2004). The unique hues are considered to be four phenomenologically pure colours (Hering, 1878): unique red, yellow, green, and blue. It has been argued that unique hues are special and that only these four colours appear to be unmixed; purple for example always appears to contain both blue and red

(Broackes, 2011). Unique hues can be identified by asking participants to select a hue that is like neither of its neighbouring hues (for example, select a red that is neither yellow nor blue). These unique hue settings (i.e., the specific hue of each of the unique hues) have been attained using monochromatic lights (e.g., Jordan & Mollon, 1995), Munsell surfaces (e.g., Kuehni, 2001), or CRT monitors (e.g., Malkoc, Kay, & Webster, 2005).

Unlike focal colours (the best example of a given colour), which exist at a specific lightness and chromaticity, the unique hues can be defined over different levels of these colour dimensions. Investigation into this area has revealed that the specific hue angle of the unique hues changes over different levels of chroma (i.e., the 'Abney effect'; Abney, 1909). Similarly, the Bezold-Brücke phenomenon describes the way that colour appearance (and unique hue settings) change as a function of the intensity of a colour stimulus (e.g., Walraven, 1961). As such, unique hue settings can be measured over multiple tasks and across different dimensions of colour.

The origin (and very existence) of the unique hues has been debated for decades if not centuries. This debate is relevant to the broader discussion about whether colour terms are universal (e.g., Berlin & Kay, 1969; Heider, 1972), or whether colour terms are a linguistic convention (e.g., Roberson, Davidoff, Davies, & Shapiro, 2005; Roberson et al., 2000).

One idea about the unique hues is that they are perceived as more perceptually salient than other colours (Heider, 1972). Heider reports data from a cross-cultural study in a group of speakers whose language does not contain the colour terms for red, yellow, green, and blue. Despite this, speakers performed better at remembering focal versions of these colours. However, the degree that these focal colours matched the unique hues was not measured. Further, if the unique hues are more perceptually salient than other colours, it might be predicted that: firstly, colour discrimination is better for these colours, which it is not (e.g., Witzel & Gegenfurtner, 2013), and secondly, they can be found more precisely than other hues, which they are not, (e.g., Bosten & Lawrance-Owen, 2014). There is therefore currently little evidence to support the claim that the unique hues are more perceptually salient than other hues.

An early conception of the unique hues was based upon knowledge about cone-opponent mechanisms in the retinal ganglion cells and lateral geniculate nucleus. At this

stage of visual processing, the $L - M$ channel computes the red-green cardinal direction of colour processing, while the $S - (L + M)$ channel computes the blue-yellow channel. It was once thought that the unique hues originate from these opponent processes (e.g., De Valois, Abramov, & Jacobs, 1966), however it is now known that the unique hues do not lie on these cardinal axes (Mollon & Cavonius, 1987; Webster & Mollon, 1994). More recently, it has been proposed that under certain conditions, unique hue settings are related to the relative number of cones in peripheral vision (Otake & Cicerone, 2000) or eye pigmentation (Jordan & Mollon, 1995). However, Webster, Miyahara, Malkoc, and Raker (2000) argue that the large variation found in unique hue settings across and within observers imply that the strength of these factors on determining the unique hues must be relatively weak.

A study by Wool et al. (2015) looked at a possible neural representation of the unique hues by measuring local field potentials (LFPs) in the primary visual cortex of rhesus macaques. LFPs are a measurement of the electrical activity from populations of neurons recorded extracellularly. LFPs were recorded in response to chromatic patches corresponding to the four unique hues. It was found that unique yellow peaked significantly earlier than the other unique hues. However, a limitation of this study is that LFPs were recorded to the unique hues only, therefore it was not possible to compare this data to that elicited by 'non-unique' hues. A different approach was taken by Stoughton and Conway (2008). They measured single-unit responses in areas of the macaque visual cortex in response to 46 colours that ranged around a hue circle. They found that activity in a population of glob cells (regions that show high response to the chromaticity of stimuli) had a strong explicit representation for three out of the four unique hues (red, green, and blue) in the posterior inferior temporal cortex. The representation of unique yellow was somewhat weaker. This appeared to be the first evidence for a neural representation of the unique hues. However, their claims were challenged by Mollon (2009). Mollon plotted the colour stimuli used in this study in the MacLeod-Boynton (1979) chromaticity diagram. This highlighted that the colours used in the study were situated as a triangle (in reference to the background whitepoint) and that the three furthest points of the triangle corresponded to the larger activation reported for unique red, green, and blue by Stoughton and Conway. Mollon argued for the need of a stimulus set that lies on a circle in an appropriate chromaticity space.

Identifying a neural representation of the unique hues has proved elusive, and scientists have questioned whether such a representation will be found (Bosten & Boehm, 2014; Mollon, 2006; Saunders & van Brakel, 1997; Wool et al., 2015). Yet, Stoughton and Conway suggest that if the unique hues are truly 'special' for human colour perception, there will be some form of neural representation of them in the brain. One problem with the concept of the unique hues is that tasks used to identify them are linguistic (e.g., participants are asked to find a red that contains no yellow or blue). As there has been no evidence that the unique hues are more perceptually salient than other hues, and so far there has been solid neurophysiological evidence for them, it is not clear whether the unique hues are simply a linguistic construct. For example, would someone who does not have the words for red, yellow, green, and blue, still have hues within these categories that are phenomenologically pure and not appear as mixtures of other hues?

In order for the field to understand whether unique hues are more than just a construct of colour terms and colour language, we need evidence for their existence on a task that does not refer to colour terms. This thesis investigated whether evidence can be provided using the ERP technique. If unique hues are found to exist in ERPs, in that they are processed differently to non-unique hues, one important question is the time course of their existence and whether this would be found in early ERP components or later post-perceptual components. If evidence for the unique hues is found in early, sensory ERP components then then this would be the first evidence that these hues are perceptually privileged. Alternatively, if evidence for the unique hues is found in later occurring ERP components, it would suggest they are more of an attentional, post-perceptual or cognitive construct. If a neural marker for the unique hues can be found it will enable their origin and their relationship to colour terms to be further investigated.

1.4 Summary of current state of the art of research on language on perception

This preceding review of the literature has identified three main conclusions about the current state of the art of research which investigates the effect of language on perception. First, the research area is broad and encompasses investigation of a range of different perceptual domains including motion (Meteyard et al., 2007; Dils & Boroditsky, 2010), visual search (Spivey et al., 2001) and sequentially presented letters

(Lupyan et al., 2010). A range of different effects have been identified. For example, there is evidence that language affects judgements on seemingly low-level perceptual tasks (e.g., Meteyard et al.), that it may enhance the ability to search for certain stimuli (Spivey et al.) or that it can boost detection of objects otherwise suppressed from visual awareness (Lupyan & Ward, 2013). However, despite this range of effects being reported, there is still substantial debate about how language affects performance on these tasks, and whether sensory and perceptual processes are affected or whether language interacts with performance at later stages cognitive processing, decision making or response. Convincing evidence that early sensory and perceptual stages are affected by language is still perhaps scarce and future research should investigate further the generality of these effects. For example, Lupyan and Ward show that object labels boost detection of objects suppressed from visual awareness. However, what is the generality of this effect and does it extend to other types of labels and stimuli?

Second, in the domain of colour, there is ample behavioural evidence that colour terms are associated with category effects on a range of colour tasks such as colour memory, speeded discrimination and visual search. However, these studies provide little information about the processes underlying these effects. As with the behavioural studies in other domains (Meteyard et al. 2007; Spivey et al. 2001; Lupyan et al. 2010), effects of language could be due to terms influencing sensory or perceptual stages of processing or later stages related to cognitive processing, decision making and response. More recent ERP studies have attempted to provide greater precision on this issue by attempting to unravel whether colour terms lead to category effects in early visual ERP components or subsequent post-perceptual components. This distinction has implications for clarifying the manner in which language and perception operate through interactive processes. However, the findings from the majority of ERP studies, as well as behavioural studies, may actually reflect the way that same- and different-category colour differences were equated in colour spaces that are known to contain inhomogeneities. This limits the conclusions that can be drawn from these findings. To date, three ERP studies do not suffer from this potential 'metric' issue but there is disagreement about whether colour terms affect early ERP components (Thierry et al., 2009), or whether they affect subsequent post-perceptual processes (Clifford et al., 2012; He et al., 2014). Data from fMRI studies suggest that colour terms affect regions of visual cortex but only when colour is actively named. There is therefore a substantial

lack of clarity about whether colour terms affect the processing of colour at the level of visual cortex, or whether colour terms instead affect higher-level cognitive responses to colour. Resolving this debate will be key to furthering our understanding of the broader debate about whether language operates independently of or interactively with perception.

Third, in addition to debate about colour category effects in sensation and perception, there has also been substantial research into the question of the origin of colour terms and their associated categories. One key idea is the notion that there are a set of four unique hues and that these provide a focus for 'universal' colour categories. However, despite decades of research the existence of unique hues has only ever been shown on a task which makes explicit reference to colour terms – unique hues are defined linguistically. Despite concerted effort, neurophysiological evidence of the unique hues has never been provided. Therefore, it appears possible that unique hues are just a linguistic construct and support Relativist theories that colour categories result from language.

1.5 Thesis overview

This thesis presents four papers that outline empirical studies which have been conducted to further explore the relationship between colour terms, colour perception and cognition and the issues outlined above. The first paper presents a study which further investigates whether Lupyan and Ward's finding that language boosts detection of objects suppressed from visual awareness can be replicated in the domain of colour. The aim is to establish the replicability and generality of the effect. The second and third papers present two ERP studies which further investigate the time course of colour category effects, with the aim of bringing greater clarity on whether colour terms really do induce category effects in early sensory and perceptual processes. The final paper presents an ERP study of unique hues in order to provide a neural marker for unique hues. The aim is to establish when in processing it is that unique hues are processed differently to non-unique hues. The overall aim of the thesis is to clarify the effect of colour terms on colour perception and cognition, and to clarify the time course and nature of such effects. Before providing an overview of the findings of each of these

four papers, I first outline the main methods employed in the thesis and the rationale for choosing these methods.

1.5.2 Research methods

The experiments in this thesis employ three main methods to investigate the interaction of colour terms and colour perception and cognition: the event-related potential method; psychophysical measurement of discrimination thresholds; and continuous flash suppression. In addition, the experiments also draw on knowledge of colour spaces and the use of precise colorimetry to ensure that stimulus issues are appropriately controlled. Each of these methods is outlined below.

1.5.2.1 Colour spaces and colorimetry

Colour has three perceptual dimensions. One dimension corresponds to the lightness of a colour. The other two dimensions describe a colour at a specific lightness in terms of the hue of the colour and its colourfulness (referred to as saturation in some colour spaces, and chroma in others). Considering these last two dimensions, a colour of a specified lightness can be plotted in a 2D space in either Cartesian or polar coordinates. In both cases, the centre of the 2D plot is achromatic and saturation increases with distance from this centre point. Polar coordinates indicate a position in 2D space by specifying angle (either in degrees or radians) and radius (the distance from the centre of a colour space). Angle therefore refers to the specific hue of a particular colour (i.e., hue angle) and the radius corresponds to saturation/chroma. Polar coordinates are useful for describing experimental stimuli that are isoluminant and isosaturated, and therefore only vary in hue (i.e., hue angle).

There exist a number of predefined colour spaces, which are models for organising colour so that specific colours can be specified and replicated, such as the Munsell system (Munsell, 1912), Derrington Krauskopf and Lennie space (i.e., DKL space; Derrington et al., 1984), and MacLeod-Boynton space (MacLeod & Boynton, 1979). The principal colour space used in this thesis to define (but not equate colour differences) is the 1976 CIELUV colour space. The Commission Internationale de

l'Eclairage (CIE; International Commission on Illumination) is the international authority on the science of colour, light, illumination, vision, and image technology. Unlike earlier colour spaces produced by the CIE (such as the CIE 1931 XYZ colour space), CIELUV represents the coordinates of a particular coloured surface when viewed under a specified illuminant and therefore takes into account both the colour of a surface and the colour of the light that illuminates it. It attempts to be perceptually uniform so that Euclidean distance in this colour space corresponds to perceptual colour difference. In other words, moving from a position in CIELUV by a certain Euclidean distance is equal to the perceptual difference of moving to a different coordinate of the same Euclidean distance. However, there are known in homogeneities in the space and it has been argued that it does not achieve perceptual uniformity especially for large chromatic differences (Hill et al., 1997). When describing a particular colour in CIELUV, $L*$ refers to the perceived lightness of a colour, while $u*$ and $v*$ correspond to Cartesian coordinates of perceptual redness–greenness and blueness–yellowness respectively. It is possible to convert between Cartesian and polar coordinates. When presented as polar coordinates, hue angle in CIELUV is denoted by h_{uv} and in degrees. The radial distance chroma is denoted $C*uv$. Throughout this thesis CIELUV colour coordinates are specified as polar coordinates.

In order to render colours accurately, calibrated CRT monitors were used in all experiments reported in this thesis. Calibration was achieved by mathematically linearizing outputs from the red, green, and blue electron guns, and verified through measurement with a colorimeter. Many colour studies do not adopt this approach, which is essential to ensure that the colours rendered and presented in experimental colour research accurately reflect the colour space chosen to define colour stimuli.

1.5.2.2 Event-related potentials

Three out of the four studies presented in this thesis use event-related potentials (ERPs) to investigate the effect of colour terms and their associated categories or unique hues on the time course of colour processing in human participants. As briefly mentioned earlier, ERPs are an electrophysiological response time-locked to a stimulus, such as its presentation or a manual action made in response to the stimulus. ERPs are extracted from the electroencephalogram (EEG), which is the continuous recording of

electrical activity that travels from the brain, through the skull to the scalp. EEG is recorded through electrodes situated over the scalp (participants wear a cap with electrodes fitted in specific locations). At any one time the EEG reflects the activity from all (measureable) ongoing brain processes, as such the data is averaged over a number of trials in order to extract the signal relevant to the processing associated with experimental stimuli. ERPs are calculated by converting information about the frequency of neural activity (EEG) into the time domain and therefore provide information about the precise time course of neural processing (Luck, 2005).

ERPs are a non-invasive method of recording brain function. They are used by clinicians to check brain function following trauma, and by researchers to investigate how the brain responds to stimuli and how it processes information. Specific waveform components have been identified for different types of stimulation (visual, tactile, auditory, olfactory) and this has enabled researchers to investigate specific questions about the timing of neural events in the brain. One commonly adopted approach in this area is the 'oddball task', first reported by Squires, Squires, and Hillyard (1975). As outlined earlier, this task has a stimulus (known as the 'standard') which is presented on the majority of trials and occasional, different 'oddball' (also known as 'deviant') stimuli are interspersed. These oddball stimuli typically elicit differences in the magnitude and timing of ERPs compared to the stimulus presented frequently, and this provides a tool for researchers to investigate how the brain responds to different and unfamiliar stimuli. This task has been used in two studies presented in this thesis. The oddball task has been used because it provides a powerful tool for investigating how the visual system may encode the categorical relationship between colour stimuli (Fonteneau and Davidoff, 2007). For example, this method enables two different oddball colours to be presented in one block, one of which is the same category and the other a different category to the standard. A comparison of the ERP activity elicited by these two oddballs is essentially asking whether the brain processes colour differences if they belong to the same or a different colour category. This is a key method that can be applied for the broader question of how and when colour terms affect colour processing.

1.5.2.3 Discrimination thresholds and just-noticeable differences

The thesis also uses the psychophysical approach of measuring discrimination thresholds and the resulting just-noticeable differences (JNDs). JNDs of discrimination thresholds are the smallest difference between two stimuli that is just discriminable (Mather, 2009). A staircase procedure is often used to determine the JND on discrimination tasks. For this, the perceptual difference between a test stimulus and the comparison stimulus on sequential trials is changed by a predefined factor in order to arrive at a point where the difference between the target and comparison stimulus is just noticeable. This difference represents one JND. The staircase procedure used in this thesis is known as a 'three-up-one-down' method. During a block, participants indicate which colour patch (the target) is the odd-one-out from competing, identical patches presented simultaneously with the target. Because a response must be made on all trials and to avoid those correct responses that may occur through chance, participants are required to correctly identify the target three times successively. If this is achieved, the perceptual difference in colour between the target and the comparison stimuli becomes smaller on the subsequent trial (i.e., the task becomes harder). Again, three successive correct responses are required for a further change in the degree of colour difference between the target and comparison stimuli. However, one incorrect response elicits an increase in the perceptual difference between the colours on the subsequent trial (the task becomes easier). Each point that the difference in colour between the target and comparison changes direction (either by increasing or decreasing) is referred to as a reversal point. In this thesis, JNDs were measured over five reversal points with a JND corresponding to the mean colour difference at the reversal points. Alternative methods have been devised to measure JNDs, such the 'method of constants', in which several stimulus levels are chosen a priori by the researcher for testing, and the 'method of limits', in which a threshold is obtained on the first trial that an incorrect response is made following successive responses (Levitt, 1971). The three-up-one-down method presented in this thesis does not make assumptions about the size of the perceptual difference between different colours and therefore does not require step sizes to be specified a priori. The difference in colour that occurs at a reversal point is corresponds to a factor of 0.259, which represents the Weber fraction ascertained in previous colour discrimination studies (Witzel & Gegenfurtner, 2013).

JNDs reported here correspond to the smallest difference in colour that needs to be applied for a colour to be reliably discriminable from a comparison colour. This difference can be measured for any of the three dimensions of colour (hue, saturation, and lightness). JNDs can be measured in different ways and this affects the size of a JND. For example, stimuli presented in a serial fashion produce larger JNDs than those presented simultaneously, such as in a four-alternative forced choice task (i.e., identify the odd-one out in four stimuli). By measuring JNDs over a range of colours, it is possible to extract specific colours separated by a specified number of JNDs. Thus it is possible to extract three colours, for example a red, a purple, and a blue, with the same specified number of JNDs in between them (e.g., red <> 3 JNDs <> purple <> 3 JNDs <> blue). This provides a powerful, alternative method of equating colour difference to using predefined colour spaces, such as the Munsell system, DKL space, and CIELUV/CIELAB, which are known to contain inhomogeneities reflected as areas of greater or lesser discriminable colour difference (Hill et al., 1997; Mahy et al., 1994). In this thesis JNDs were therefore considered to be a better alternative than predefined colour spaces and were applied in those studies presented that required the difference between colour stimuli to be perceptually equivalent. Specifically, JNDs were used for two purposes: (1) To investigate whether colour terms affect colour discrimination by comparing JNDs across two groups of speakers who categorise colour differently. (2) For the formulation of JND-equated stimuli (i.e., colours separated by the same number of discrimination thresholds) for use in the ERP oddball tasks. This was considered essential because it is known that early ERP components are especially sensitive to the physical attributes of a stimulus. Therefore, the effective equating of colour difference was considered paramount to the relevant studies conducted as part of this thesis.

1.5.2.4 Continuous flash suppression

This thesis also employs the method of continuous flash suppression in order to further investigate the finding of Lupyan and Ward (2013). As outlined briefly earlier, binocular rivalry is the phenomenon found to occur when a different visual stimulus is presented to either eye (also known as dichoptic presentation). Wade (1996) suggests that this phenomenon was first reported by Porta in 1593. Typically, rather than seeing a composite of the two stimuli, people perceive one of the stimuli for a period of time

before the other stimulus is perceived. For two not too dissimilar stimuli, perception switches back and forth between the two. Continuous flash suppression (CFS), first reported by Tsuchiya and Koch (2005) is a form of binocular rivalry that is very effective at masking a stimulus presented to one of the eyes. It achieves this by presenting one eye with rapidly changing visual noise and the other with a target stimulus. When the visual noise is presented at the right frequency (around 7 – 12 Hz; Arnold, Law, & Wallis, 2008), the target cannot be perceived for a period of time despite the target being present on the retina and therefore receiving a degree of visual processing (the exact level of processing that the hidden stimulus receives is currently unknown). Because it can successfully suppress a stimulus from awareness for long periods of time, CFS has been adopted as a method for investigating the degree of processing of targets hidden from conscious awareness, such as emotional faces (Yang, Zald, & Blake, 2007), colour after images (Tsuchiya & Koch, 2005), and objects (Lupyan & Ward, 2013). As outlined earlier, it has been argued that CFS prevents a hidden stimulus from receiving processing from higher-level cognitive processes, such as decision making and stimulus evaluation (Kang et al., 2011). This is relevant to the debate about whether colour terms affect processing in early stages, prior to semantic analysis, or whether they affect later post-perceptual processes. CFS was therefore adopted in a study presented in this thesis to investigate whether colour terms affect the detection of colour and colour-associated stimuli suppressed from awareness through CFS.

1.6 Overview of the empirical work of this thesis

Here, I provide an overview of the four empirical papers of this thesis, their findings and the implications for debate about colour terms.

1.6.1 Paper 1 – Colour terms affect detection of colour and colour-associated objects suppressed from visual awareness

A range of approaches across a range of domains have been adopted to investigate the broad issue of how language and perception interact. As outlined earlier, in one key study, Lupyan and Ward (2013) demonstrated that a verbal object-category

cue affected the detection of objects (presented on a computer monitor) that were suppressed from visual awareness using CFS. Specifically, performance was better if the cue matched the suppressed object compared to baseline (no cue) trials, and performance was worse if the cue did not match the object compared to baseline trials. This is relevant to the debate about the influence of language on visual processing because it has been argued that CFS prevents semantic (i.e., post-perceptual) processing of a suppressed stimulus (Kang et al., 2011). Therefore if the linguistic cues affect detection of the hidden targets this may support the idea that language penetrates earlier, sensory stages of visual processing prior to semantic processing (e.g., Lupyan, 2007, 2012). Paper 1 is an investigation into the generality of this effect and investigates whether colour terms affect the detection of coloured stimuli and colour-associated objects that have been suppressed from visual awareness. Three experiments are reported that used continuous flash suppression (CFS) to hide target stimuli from visual awareness. At the start of each trial participants were presented with an audio cue, which was either a label that matched the suppressed target (congruent condition), did not match the target (incongruent condition), or it was audio noise (baseline condition). Detection sensitivity was calculated through a signal detection analysis of the data. Data from reaction times, accuracy, and false alarm rates are also presented.

Experiment 1 was a replication of the aforementioned study by Lupyan and Ward (2013), whereby images of objects were suppressed from visual awareness. The principal difference between Experiment 1 presented in this thesis and that by Lupyan and Ward was the use of different masking stimuli in Experiment 1 (achromatic noise; Arnold et al., 2008), rather than segmented lines (Lupyan and Ward). The reason for this was twofold: (1) To assess the robustness of the effect reported by Lupyan and Ward; (2) To examine whether achromatic noise was an effective masking stimulus because this style of mask was preferable for experiments involving chromatic stimuli (e.g., Experiment 2). The audio labels were object labels (or audio noise) and the effect reported by Lupyan and Ward was generally replicated; it was found that detection performance was significantly worse on incongruent trials compared to congruent trials and baseline noise trials. In Experiment 2 the same method was applied to investigate the effect of colour terms (e.g., "pink", "yellow", etc.) on the detection of suppressed colours. The stimuli were colour patches. Like the first experiment, performance was significantly worse on congruent trials compared to the other conditions. However,

reaction times were significantly faster for congruent trials compared to the other conditions. These data are interpreted as evidence that colour terms affect the detection of hidden stimuli and expand the generality of the effect reported previously and replicated here in Experiment 1. In Experiment 3, the generality of this effect was tested further by using indirect cues to suppressed stimuli. Colour terms were again used as audio labels but the hidden stimuli were achromatic photos of objects. The objects were all strongly associated with a single colour (e.g., carrots are associated with the colour orange, frogs are associated with the colour green etc.). It was found that detection sensitivity was significantly poorer on incongruent trials compared to the other two conditions.

The data reported in Paper 1 confirm the generality of the effect first reported by Lupyan and Ward, that linguistic cues affect the detection of suppressed visual stimuli. This potentially adds support to the view that language can affect visual processing and may support the claim that language affects early stages of processing (e.g., Lupyan, 2012; Thierry et al., 2009), if it is the case that CFS prevents semantic (i.e., post-perceptual) evaluation (Kang et al., 2011). This is the first demonstration of the strength of the association between colour terms and suppressed colour stimuli. Further, prior work in this area has focused on investigating how direct cues affect the detection of a suppressed stimulus (e.g., its shape or object category). Experiment 3 expands on previously reported findings by showing that an indirect linguistic cue about a physical characteristic that a suppressed object is associated with can affect detection of the suppressed object.

Although the finding that colour terms affect the detection of colours and colour associated objects suppressed from visual awareness could potentially provide support for the argument that language affects the very early stages of information processing, there is still some concern on whether CFS really prevents post-perceptual stages of processing (Costello et al., 2009; Bahrami et al., 2010). It also remains possible that the effects found by Lupyan and Ward and in the current paper could be at the stage of response. In order to provide greater clarity and precision about the time course of the effect of colour language on visual processing, papers 2 and 3 employ an ERP approach to investigate the time course of colour category effects.

1.6.2 Paper 2 – Speakers of different colour lexicons differ only in post-perceptual processing of colour when colour is attended

As outlined earlier, colour terms have been argued to affect colour cognition (e.g., Brown & Lenneberg, 1954; Kay & Kempton, 1984) as well as colour perception (e.g., Clifford, Holmes, Davies, & Franklin, 2010; He, Witzel, Forder, Clifford, & Franklin, 2014; Thierry, Athanasopoulos, Wiggett, Dering, & Kuipers, 2009; Winawer et al., 2007). Paper 2 builds on this work. It is a cross-linguistic comparison of colour processing between two groups who categorise colour differently. The study presents two experiments that compare responses in native Russian speakers and native English speakers. These languages categorise blue hues differently; the Russian language separates lighter (*goluboj*) and darker blue hues (*sinij*) into distinct colour categories, whereas the English language does not.

The paper presents data for colour naming in native Russian speakers for the two Russian blues and the boundary between them in the supplementary section. This data was collected before Experiment 1 and 2 to facilitate the selection of colours used in these experiments. For this a range of blue hues were presented to participants. These ranged in chroma and lightness in CIELUV, but not in hue angle. Participants nominated each hue as either *goluboj* or *sinij*. They also judged the degree to which each test colour was a good example of these colours. This was carried out with a group of native Russian speakers, who did not take part in the subsequent experiments, and provided a means of assuring that the stimuli used in the subsequent experiments spanned the boundary between the two Russian blues.

Experiment 1 presents a comparison of discrimination thresholds across the two groups. Participants completed a four-alternative forced choice task that measured JNDs over a set of stimuli that ranged across the two Russian blues and the boundary between them. It has been proposed that colour category effects may arise because of long-term warping of colour perception at category boundaries and compression in category centres (Goldstone, 1994; Harnad, 1990; Roberson, Hanley, & Pak, 2009). If so, it was predicted that JNDs in the Russian group would be significantly smaller (better discrimination) around the boundary between the two Russian blues compared to JNDs for hues from within these colour categories and that the same pattern would not be present in the English group. The results indicated that there was no significant

difference in JNDs between the two groups nor an advantage for the Russian group around the boundary between the two Russian blues.

Experiment 2 uses a visual oddball task that presented three blue hues varying in lightness whilst ERPs were recorded. One of the hues (the standard) was presented on the majority of trials and two deviant blue hues were infrequently presented. The key manipulation was that for the Russian group, one of these deviants was a different category (*goluboj*) to the frequently-presented stimulus and the other was the same category (*sinij*), whereas for the English group the three hues were all the same category (*blue*). The three hues were chosen such that adjacent hues were equally different from each other in number JNDs and therefore supra-threshold colour differences were equated in terms of discriminable units at threshold. Participants were tasked with attending to the stimuli and counting the number of deviant stimuli (the stimuli presented infrequently). If colour terms affect early, sensory stages of visual processing (e.g., Clifford et al., 2010; Holmes, Franklin, Clifford, & Davies, 2009; Thierry et al., 2009) it was expected that there would be a category effect in the Russian group, but not the English group, in early ERP components (P1, early-phase N1; Hillyard, Teder-Sälejärv, & Münte, 1998), whereby there was a different ERP amplitude or latency elicited to the different-category deviant compared to the other two hues. If colour terms affect post-perceptual stages (e.g., Clifford et al., 2012; He et al., 2014), this should be evident in subsequent ERP components (P2, N2, P3; Patel & Azzam, 2005). The results indicated a significant category effect in the Russian group, that was evident in the amplitude difference elicited by the three hues between 280 and 320 ms. Specifically, the different-category deviant elicited a significantly larger amplitude than the other two hues and no such difference was found in the English group; responses to both deviants in this group did not significantly differ. This effect is at a post-perceptual stage of processing (Clifford et al., 2010; He et al., 2014; Patel & Azzam, 2005); no significant category effects were found in earlier ERP components. A behavioural version of the same task, whereby participants made a manual response to the stimuli, indicated no significant differences in performance on the task between the two groups.

Overall, the study found no effects of colour terms on colour discrimination thresholds and no effect on early, sensory ERP components. The effect reported is that colour terms affect a subsequent, post-perceptual stage of colour processing. The study does not provide any support to the argument that colour terms lead to long term

warping of colour discrimination or that they affect early stages of visual processing. One possible explanation for the lack of early category effect in this study is the length of time that the Russian speakers had been residing in England. It is possible that this exposure to the English colour lexicon which does not have two basic blues has weakened their categorical distinction in Russian. Alternatively, it could be that Thierry et al. found early category effects for Greek participants whereas the current study did not because of differences in the tasks employed. For example, Thierry et al. used a task where attention was directed away from the colour whereas in the current study participants actively attended the colours. Paper 3 of this thesis further investigates the existence of early category effects.

1.6.3 Paper 3 – Colour categories are reflected in sensory stages of colour perception when stimulus issues are resolved

Previous studies have highlighted substantial variance in the way speakers of the same native language name colours (e.g., Lindsey & Brown, 2014). Paper 3 is an investigation into whether such differences in speakers of the same language affect the time course of colour processing. It presents the data from a visual oddball ERP task in two groups of native English speakers, who reliably named the colour stimuli differently. Three hues were chosen so that the supra-threshold colour difference between each adjacent hue was equated in terms of discriminable units at threshold and consequently differed from each other by the same number of JNDs. All participants reliably named one of the stimuli *green,* another *blue,* but the two groups named the central stimulus differently: One group reliably named this stimulus *green* while the other reliably named it *blue.* Participants completed a passive task; attention was directed towards a fixation dot that occasionally changed shape, while the three colour stimuli were presented in a randomised sequential fashion. The stimulus named differently by the two groups (i.e., the standard) was presented on the majority of trials, while the blue deviant and green deviant stimuli named the same by both groups were infrequently presented. Therefore, the categorical relationship (i.e., same-category versus different- category) of the deviants and standard differed between the two groups but all participants saw exactly the same stimuli. The study investigates category effects across ERP components, evidence for which would be found by a differential response

to the different-category deviant compared to the standard or same-category deviant in either ERP amplitude or latency.

The study outlined in this paper also resolved the issue of colour metric by calibrating same- and different-category colour difference using discrimination thresholds. Three published ERP studies also do not suffer from potential metric issues (Clifford et al., 2012; He et al., 2014; Thierry et al., 2009). Only in Thierry et al. is an effect of colour terms apparent on early stages of visual processing. The findings of the study presented in paper 3 support this claim; there was a significant category effect in P1 (peaking at 100 ms), whereby the different-category deviant elicited a significantly different mean amplitude than both the same-category deviant and the standard. The P1 is an early visual-evoked ERP component. A further category effect was found over frontal sites around 250 ms after stimulus onset. These category effects are interpreted as suggesting that colour terms for unattended stimuli affect multiple stages of visual processing including the early stages of processing. Like Thierry et al., this paper presents data from a task in which colour processing was more implicit (attention was directed away from the colour stimuli). One potential explanation for the post-perceptual effect of colour terms on colour processing reported by Clifford et al. and He et al. is the result of explicit attention to the colour stimuli (in these studies participants counted the deviant stimuli). This may suggest a level of categorical encoding in earlier stages of visual processing for unattended stimuli. This is the first time that individual differences in colour naming for speakers of the same native language have been used as a method for investigating the relationship between colour categorisation and colour processing by measuring ERPs.

Papers 2 and 3 both consider the time course of colour category effects, and combined suggest that colour terms may lead to category effects early on in sensory and perceptual processing but only when attention is not directed to the colour. I propose a hypothesis to account for this potential modulation by attention, but the role of attention deserves further investigation. Paper 4 looks at the issue of the interaction of colour categories in language and perception from a different angle and investigates the concept of 'unique' hues.

1.6.4 Paper 4 – A neural signature of the unique hues

Paper 4 is a study that used electrophysiology to investigate the long-standing debate of whether the unique hues (pure examples of red, yellow, green, and blue) are differentially processed (as evidenced through ERP mean amplitude or peak latency) compared to four 'intermediate' hues (orange, lime, teal, and purple) or whether they are mere linguistic constructs. In Experiment 1 the location of these eight hues were measured in each participant on a psychophysical task in CIELUV colour space. The hues varied only in hue angle (chroma and lightness were constrained to be equal). Measuring the unique hues for each individual is important since there can be substantial variation across individuals. In Experiment 2 each participant was presented their own specifically-calibrated eight hues in a randomised order while ERPs were recorded. In each block participants were tasked with responding to one of the eight hues (these trials were removed from subsequent analyses to avoid contamination of the ERP waveforms from the execution of a motor action).

The findings indicated that the four unique hues all reached peak latency earlier than the intermediate hues in the posterior P2 component 230 ms after stimulus onset. No equivalent effects are reported for earlier components. The data are interpreted as evidence for a neural signature of the unique hues at a post-perceptual stage of colour processing. This is the first solid neural evidence for the unique hues. A fundamental question for future research will be to investigate whether this effect arises through top-down effects of language, perhaps through the active naming of colour, which may have been a strategy applied by participants to complete the task. For this account to work the unique hues would need to be more easily named than the non-unique hues. That potential explanation is discussed but considered unlikely for several reasons which are expanded upon in the paper. The identification of a neural marker for unique hues has important theoretical implications for the debate about the saliency of colours (Heider, 1972), as well as the debate about whether colour terms are universal (Berlin & Kay, 1969), or a linguistic construct (e.g., Roberson, Davidoff, Davies, & Shapiro, 2005; Roberson, Davies, & Davidoff, 2000), because it provides a platform for future research to investigate fundamental questions about the contribution of language, neural hardwiring, and the environment to the origin of the unique hues. For example, the question of whether speakers of all languages have unique hues regardless of whether they have red, green, blue and yellow terms in their colour lexicons could not be

addressed with the behavioural tasks used in prior research. This is because tasks used in the past identified unique hues by reference to the colour terms. Now that paper 4 has established a neural maker for unique hues on a task which does not make reference to colour terms, whether or not unique hues exist in speakers without red, green, blue and yellow colour terms can be investigated. This will bring greater clarity on whether unique hues are linguistic constructs or whether they are universal regardless of colour terms.

1.7 Research contributions

The papers in this thesis contribute to several issues of debate: the issue of how colour terms affect colour processing; our understanding of the unique hues; and the broader issue of how language and perception interact. Each of these is discussed in turn.

1.7.1 Contribution to research on how colour terms affect the processing and perception of colours

A number of observations about the effect of colour terms on colour processing are reported in this thesis. Firstly, in response to the specific research question of whether colour terms affect early, sensory stages of visual processing, or whether colour terms affect subsequent post-perceptual stages, the findings are mixed. In paper 1, if the assumption that CFS limits post-perceptual processing of suppressed stimuli is correct, then the data support the idea that colour terms affect early stages of visual processing. This finding was supported in an ERP study for unattended colours reported in paper 3, whereby the findings indicated an effect of colour terms on P1, 100ms after stimulus onset, which is one of the earliest visual ERP components. In contrast to this, the cross-cultural study presented in paper 2 found no evidence that colour terms affect colour discrimination thresholds or early ERP components. The effect found was that colour terms affected ERPs at post-perceptual stages of colour processing. The question here is why were there different outcomes with regards to time course across these studies? One of the main differences between papers 2 and 3 which investigate the time course of colour category effects concerns the task completed by the participants. In paper 2,

participants actively attended to the colour of the stimuli, whereas in paper 3 they attended to a fixation dot, therefore the colour stimuli were not directly attended. A novel contribution of the thesis is the idea that the contradictory findings reported previously in this domain may be the result of differences in how much colour is attended during the task: colour terms lead to category effects in early sensory processes when colour is not explicitly attended but not when colour is attended.

This hypothesis may not seem logical, why would the categorical relationship between colours be encoded when colour is not explicitly attended and colours are processed to a greater degree outside of awareness? One possibility is that categorical processing is more greatly recruited under conditions of greater stimulus uncertainty. There is some support for this view; colour category effects were found to be stronger in participants on a behavioural task when they were less familiar with the colour stimuli compared to participants who were highly trained with the stimuli (Witzel & Gegenfurtner, 2015). It is tempting to speculate that the visual system may have evolved this way; it may increase the chances of survival if a change in the visual scene, which is outside of one's direct focus, is registered categorically (e.g., threat versus no-threat), so that a threatening stimulus is brought faster into awareness. These ideas deserve to be explored further and the thesis provides a testable hypothesis for further research on the role of attention in colour category effects.

Another novel contribution of the thesis to the question on the influence of colour terms on colour processing is the exploration of the impact of individual differences in colour naming. In paper 3 the ERPs elicited in two groups of native English speakers, who differed in their naming of a standard colour, were compared on a visual oddball task. This method can be adapted and applied more generally by future researchers to investigate different questions about colour processing and perception, such as whether individual differences in colour naming are associated with differences in performance on visual search tasks and colour memory tasks. Further, the mechanism underpinning individual differences in colour naming remains unknown. Possible candidates could be biological (e.g., the individual physiology of the eye and visual system), environmental (e.g., exposure to colour throughout development), linguistic (e.g., the way that specific colours, especially category boundary colours, are associated with colour terms), or social (e.g., the way colour terms are used in a society to describe colours and objects). The finding that individual differences in colour naming are

associated with different ERP responses also highlights the necessity for research using colour to collect appropriate data on colour naming. This is so as to rule out the possibility that data may be contaminated by the assumption (often made but not verified by researchers) that all participants, who speak the same language, name colours in the same way.

1.7.2 Contribution to research on unique hues

An original and potentially fundamental contribution of the thesis is its contribution to the investigation of unique hues. There have been competing explanations for the origin of the unique hues spanning decades. Some argue that they are represented very early in the visual system, in the retina and lateral geniculate nucleus (De Valois et al., 1966), while other proposed they are represented in the visual cortex (Stoughton & Conway, 2008). Others suggest that they may exist because of the statistics of the natural environment (Mollon, 2009), and some question whether they may exist because of greater frequency of word use than other colour terms (Wool et al., 2015). However, in paper 4, a specific neural signature of the unique hues is identified, whereby the posterior P2 component over the parieto-occipital lobe peaked significantly earlier for the unique than for the intermediate hues. This finding is crucial because it is the first solid evidence to reconcile a basic theory in colour science (that there are four phenomenologically pure hues: red, yellow, green, and blue) with observable, neural measurements.

At this stage and without further investigation it remains unclear what the specific process is that results in the unique hues reaching peak latency earlier than non-unique hues. The fundamental contribution that this paper makes is to identify a neural marker which means that further research can investigate crucial questions on the original of the unique hues. For example, are the unique hues also privileged in pre-linguistic infant colour perception? Do speakers of colour lexicons that lack basic colour terms for red, green, blue and yellow also experience the unique hues? Are the unique hues consequential of the statistics of natural scenes? These are important questions for future research to investigate.

1.7.3 Contribution to research on language and visual perception

The data presented in this thesis support the view that language and perception operate in an interactive manner (e.g., Kinchla & Wolfe, 1979; McClelland & Rumelhart, 1981; Mesulam, 1998; Stone, Vanhoy, & Van Orden, 1997). This is in opposition to models of perception that view the visual system as a strictly feed-forward process (e.g., Seidenberg & McClelland, 1989; Stone & Van Orden, 1993). Further, it contradicts the idea that the visual system functions independently of cognitive processes (e.g., Pylyshyn, 1999; Zeki, 1993). In sum, the findings reported in this thesis are likely best applied to models of perception that can account for the way language interacts with visual processing. One such model is Lupyan's (2012) label-feedback hypothesis. The hypothesis proposes that language continuously modulates visual processes and that this can start in early stages of visual processing. Here, converging evidence for this hypothesis is provided in the domain of colour.

1.8 Future research

Following the investigations reported in this thesis there are a number of questions for future research to resolve. The following is an outline of these questions and an outline of future research directions.

A central question of the thesis is whether colour terms affect the processing and perception of colours. Evidence for colour terms modulating both early and later stages of processing is provided. A key avenue for future research will be to identify the variable(s) responsible for these different outcomes. One possibility is that the effect of colour terms that manifests in early stages of visual processing (papers 1 and 3) is due to implicit, rather than explicit, colour processing. In the experiment reported in paper 3 participants fixated to a dot rather than the colour of the stimuli, and therefore the stimuli were less attended. However, it cannot be argued they were entirely unattended because it is plausible that a degree of attention was applied to the colours although it is assumed that attention to colour was to a greater degree implicit than the procedure adopted in paper 2. A future ERP study should be able to answer this question by using the same stimuli, which are either attended in one condition (such as counted, as in paper 2), while in another condition they are superfluous to completing the task while

attention is fixated to a different stimulus. It might be possible to adopt a within-subjects design, whereby task order is counter-balanced, providing that an adequate task can be devised that uses exactly the same stimuli across this experimental manipulation. However, there is the case for potential cross-contamination between tasks; greater attention to colour stimuli may occur in a 'non-attended' condition if participants had previously completed the 'attended' version. A between-subjects design would obviously not suffer from this issue. There now exists two papers that provide convincing evidence for the influence of colour terms just 100 ms after colour onset. It is now important to more fully characterise this effect and understand the conditions under which it occurs. This is important for determining the conditions under which language penetrates early processing of visual information.

In paper 4, a neural signature of the unique hues is reported in posterior P2. Future research is needed to clarify the mechanism that underpins this finding. There are a number of different avenues available for future research. Firstly, it could be argued that the unique hues peaked earlier than non-unique hues because they recruit different attentional resources. This could be investigated further by designing a similar ERP task to that reported but one that uses a task in which the colour of the stimuli is not relevant to completing the task. For example, participants could be directed to attend to the shape of the stimuli and respond when a different shape is presented, rather than the colour. This task would more greatly measure implicit colour processing, rather than explicit processing. The question here is whether the effect reported is specific to when colour is attended. The role of language in the unique hue effect requires further exploration. It could be argued that the effect reported is due to the unique hues being more nameable than the other hues, which facilitated processing and produce an earlier posterior P2 peak latency. While the unique hues are all 'basic colour terms' and therefore highly nameable, it is appears unlikely that nameability can account for this finding because two of the intermediate hues were also basic colour terms (orange and purple). Nonetheless, this deserves further investigation. The colours presented to participants in the study reported in this thesis were isoluminant, as such some were better examples of a prototypical colour category than others (i.e., a focal colour). For example, the unique red would be named as pinkish due to the lightness at which it was defined. The nameability of unique hues will vary depending on the degree to which they match the focal version of the colour category, and this could be manipulated by

varying the lightness of the stimuli (but still comparing colours within one lightness level). If the unique hue effect found is present irrespective of the lightness level, and therefore irrespective of how nameable the unique hues are, this would suggest that the unique hue effect is not due to naming.

A cross-linguistic study would also clarify the role of language in the unique hues. The goal here would be to compare speakers of different languages, one of whom categorise the unique hues as four separate categories (e.g., the English language), to speakers of a language that does not. Unique hues are typically conceived as being pure, elemental sensations, and would therefore be predicted to be experienced the same regardless of the naming tendencies of a language. Therefore it is plausible that someone, who does not have basic colour terms for red, yellow, green, and blue, and does not have named hues in those regions, will nonetheless consider the unique hues to be purer than other hues. This has not been tested previously because prior tasks used colour terms to ask about colour purity. Another possibility for testing whether unique hues are linguistically constructed would be to test pre-linguistic infants, who have not yet learnt the colour terms of red, yellow, green, and blue. ERPs can be recorded from pre-linguistic infants; therefore the same approach outlined with the cross-linguistic design could be applied to the measurement of ERPs for unique and intermediate hues in this group of participants.

In the broader area there are questions that remain for future research. It has been argued that the data reported in this thesis support interactive models of language and perception (e.g., Lupyan, 2012), rather than strictly feed-forward models of perception (e.g., Seidenberg & McClelland, 1989; Stone & Van Orden, 1993). Yet the specification of this interaction on a neural level remains undetermined. This is clearly a highly desirable goal for future research. It is unlikely that ERP or EEG data will provide the information to determine these processes because of the poor spatial resolution of this method. It is also unlikely that fMRI data will clarify this area because of the poor temporal resolution of this method, which is unable to determine delicate, fast, and subtle communication between brain regions (which presumably is what an interaction between language and visual processing entails). One possibility here is the combined ERP/fMRI method, whereby EEG is recorded in an MRI scanner, which provides more precise details about both the timing and location of neural activity. Further, techniques are being developed that enable single-trial data from conjoint

ERP/fMRI studies to be feasibly analysed (e.g., Debener, Ullsperger, Siegel, & Engel, 2006). This approach may provide greater clarification on the interaction between language, visual processing and perception.

1.9 Conclusion

Over the course of a number of experiments, this thesis has aimed to contribute to debate on the relationship between language and visual processing. Specifically, the thesis focused on colour terms and how they affect the processing of colour. Across the experiments, multiple methods were applied to investigate a number of refined research questions: (1) Do colour terms affect the speed and accuracy of the detection of colour stimuli or colour-associated stimuli that are suppressed from visual awareness? (2) Do speakers of different languages process colour differently if their colour lexicons differentially categorise the continuous colour spectrum, and if so what is the time course of this effect? (3) Do colour terms within a language induce category effects in early sensory and perceptual processing of colour or just later post-perceptual stages? (4) Do ERPs reveal a neural representation of the unique hues, and if so when in colour processing are unique hues represented?

A large proportion of the research conducted used event-related potentials as an index of visual processing. Evidence from two of the ERP studies suggests that colour terms affect both early and later stages of visual perception. Further support for the claim that colour terms affect early stages was reported in a behavioural task that suppressed colour stimuli from visual awareness. A theory was proposed that colour terms affect earlier stages of colour processing when attention is not explicitly directed towards the colour. The thesis has also provided the first solid evidence that the unique hues have a special neural representation in the brain; the unique hues all reached peak latency earlier than non-unique hues in posterior P2, which is a post-perceptual stage of visual processing. This provides a platform for future research to investigate more fundamental questions about the unique hues, such as their neural hardwiring and to further understand the relationship of colour terms and unique hues. Taken together, the data reported in this thesis supports the idea that language and perception operative in an interactive manner (e.g., Lupyan, 2012). This contradicts the idea that perception is purely a feed-forward process (e.g., Seidenberg & McClelland, 1989; Stone & Van

Orden, 1993), and further highlights the need for any global model of visual perception to be able to incorporate the effect of language on visual processing.

Chapter 2

Paper 1: Colour Terms Affect Detection of Colour and Colour-associated Objects
Suppressed from Visual Awareness

Forder, L., Taylor, O., Mankin, H., Scott, R., & Franklin, A. *PLOS ONE* (submitted)

2.1 Abstract

The idea that language can affect how we see the world continues to create controversy. The specific time course of the influence of language on visual processing has received sustained attention. A potentially important development in this field has shown that object labels ('leaf, 'sink', etc.) boost otherwise invisible images of those objects into visual awareness and may suggest that language can affect early-stages of vision. We replicated this paradigm and also investigated whether colour terms ('red', 'yellow', etc.) likewise influence the detection of colours or colour associated-object images suppressed from visual awareness by continuous flash suppression. In Experiment 1 we suppressed greyscale photos of objects and these were either preceded by a congruent object label, an incongruent object label, or white noise. Detection sensitivity (d') and hit rates were significantly poorer for suppressed objects preceded by an incongruent label compared to a congruent label or noise. In Experiment 2, we extended this finding. Targets were coloured circles preceded by a colour term. Detection sensitivity was significantly worse when a colour term did not match a suppressed colour patch compared to congruent and noise trials, and reaction times were significantly faster for congruent trials compared to incongruent and noise trials. In Experiment 3 we tested the strength of this effect by using an indirect cue to a suppressed stimulus. Targets were suppressed greyscale object images and were preceded by a colour term. On congruent trials the colour term was diagnostic of the object's characteristic colour (e.g., 'orange' for a basketball), whereas on incongruent trials the colour term was not. Detection sensitivity was significantly poorer on incongruent trials compared to congruent trials. These findings suggest that colour

terms affect awareness of coloured stimuli and colour- associated objects, and contribute to debate about the interaction of language and perception.

2.2 Introduction

The idea that language can affect how we see the world continues to create controversy (Lee, 1996; Lucy, 1997; Lupyan, 2012; Pinker, 1995). One reason for this is that it is at odds with models of perception that propose the relationship between a stimulus and response is a purely feed-forward process (e.g., Seidenberg & McClelland, 1989; Stone & Van Orden, 1993). If language does affect how we see the world, this alternatively suggests a form of interaction between higher-level cognition and lower-level processing systems (e.g., Kinchla & Wolfe, 1979; McClelland & Rumelhart, 1981; Mesulam, 1998; Stone, Vanhoy, & Van Orden, 1997). This debate has substantial implications for our understanding of the way that we perceive and interact with the external world.

There is a growing body of behavioural research, which supports the idea that language affects visual perception. For example, people tend to be faster at identifying target letters on a search task when they actively name the letters (Lupyan, 2008), suggesting that the linguistic activity of verbalising can affect visual identification. The way people make same/different judgements for dot-cross configurations suggests there is a relationship between lexicalized spatial categories ("up", "left", etc.) and the perceptual processing of categorical and spatial relations (Kranjec, Lupyan, & Chatterjee, 2014). Further, there appears to be direct relationship between the way different cultures talk about the world and performance on tasks exploring visual perception. This has been shown for the way colour is responded to; speeded colour discrimination (Winawer et al., 2007) as well as short- and long-term memory recall (Roberson, Davidoff, Davies, & Shapiro, 2005) tends to be better around language-specific colour category boundaries. On one side these data point towards a relationship between language and visual perception; however, a fundamental question here is whether language directly affects activity in the visual processing system in an interactive manner (e.g., McClelland & Rumelhart, 1981; Mesulam, 1998; Stone et al., 1997), or whether language instead affects perception after visual processing, in a

manner consistent with feed-forward models of perception (e.g., Seidenberg & McClelland, 1989; Stone & Van Orden, 1993).

In the label-feedback hypothesis, Lupyan (2012) argues that language has the capacity to affect low-level visual processing. According to this hypothesis, observable differences in behaviour on tasks probing visual perception, such as those reported above (Kranjec et al., 2014; Lupyan, 2008; Roberson et al., 2005; Winawer et al., 2007), occur because language exerts a top-down influence on bottom-up neural activity in the visual processing system. Critically, this view holds that language can affect the earliest 'perceptual' stages of visual processing. However, an issue here is that from behavioural data it is often difficult to differentiate between whether language genuinely affects activity in the visual system, or whether language instead affects subsequent higher-level 'post-perceptual' activity, such as attention, semantic processing or decision making (Mather, Pavan, Marotti, Campana, & Casco, 2013; Morgan, Dillenburger, Raphael, & Solomon, 2012). These contrasting views explicitly differ in what they say about the specific timing of the relationship between language and visual processing. In other words, does language affect early stages of visual processing (Lupyan, 2012), or does this effect reside in later post-perceptual processes (Mather et al., 2013; Morgan et al., 2012)?

Electrophysiological measurements provide precise information about the time course of visual processing activity (Luck, 2005). As such, they can be used to help clarify the time course of the relationship between language and visual perception. There are several studies in this area that suggest that language does affect activity in early stages of visual processing. Thierry, Athanasopoulos, Wiggett, Dering, and Kuipers (2009) compared colour processing in native Greek speakers and native English speakers by measuring event-related potentials. These languages differentially categorize the colour blue: unlike the English language, the Greek language divides this colour into two distinct colour categories for lighter and darker shades (Androulaki et al., 2006). These authors showed that this linguistic difference in colour categorisation was associated with different patterns of neural activity for these colours as early as 100 ms. Similar effects were reported in a study of native English speakers on a colour processing task (Clifford, Holmes, Davies, & Franklin, 2010) and an object recognition task (Boutonnet & Lupyan, 2015). Importantly, at this time point in visual processing (i.e., 100 ms) activity in the visual system is thought to reflect early, lower-level

processes (Di Russo, Martínez, Sereno, Pitzalis, & Hillyard, 2002; Hopf, Vogel, Woodman, Heinze, & Luck, 2002; Johannes, Münte, Heinze, & Mangun, 1995). Higher-level post-perceptual processes are thought to occur several hundred milliseconds later (Donchin & Coles, 1988; Patel & Azzam, 2005).

There is also evidence that language effects activity in areas of the brain known to be specialised for vision. In a colour naming task, functional magnetic resonance imaging (fMRI) revealed that cortical activity in human ventral area V4 and VO1, which are known to play a specific role in colour processing (Zeki, 1974; 1990), was modulated when participants actively named the colour of the stimuli (Brouwer & Heeger, 2013). On one hand this may suggest a direct link between language and visual perception, and strong evidence that language affects low-level activity in the visual processing system. However, there is debate in this area. The effects in V4 and VO1 reported by Brouwer and Heeger were found when participants actively named (and therefore attended to the visual stimuli). In contrast, no modulation of neural activity in visual cortex was found when attention was directed away from colour stimuli. Likewise, in two studies in which participants passively attended to colours, no modulation of cortical activity was found in visual cortex (Bird, Berens, Horner, & Franklin, 2014; Persichetti, Thompson-Schill, Butt, Brainard, & Aguirre, 2015). This contrasts to prior findings that language and cognitive processing occur regardless of whether attention is deployed to a task (for a recent review, see Pulvermüller & Shtyrov, 2006). Likewise, there are some electrophysiological studies fail to find effects in early stages of visual processing and instead find effects in later post-perceptual processes (Clifford et al., 2012; He, Witzel, Forder, Clifford, & Franklin, 2014).

A different approach to identifying whether language affects activity in early visual processes or later post-perceptual processes was adopted by Lupyan and Ward (2013). Rather than measuring neural activity, these authors deliberately suppressed images from visual awareness using a form of binocular rivalry known as continuous flash suppression (CFS; Tsuchiya & Koch, 2005). Importantly, CFS is believed to disrupt visual processing prior to semantic (i.e., post-perceptual) analysis (Kang, Blake, & Woodman, 2011). The authors investigated whether verbal labels affected whether participants would eventually perceive the suppressed images compared to audio noise (the baseline condition). The verbal labels either matched or did not match the image. For example, participants would hear the word "pumpkin" before a suppressed image

was displayed, which was either a pumpkin or a different image. It was hypothesised that if language penetrates early stages of visual processing, the verbal label would affect whether participants detected the presence of the suppressed image. Alternatively, if language instead affects post-perceptual mechanisms, the verbal labels were predicted to have no effect on detection. They found that the type of audio cue affected performance; detection was significantly better when a verbal label was congruent to the suppressed image compared baseline noise trials. Further, performance was significantly worse on incongruent trials compared to baseline trials.

To date one study has replicated this method. Sun, Cai, and Lu (2015) explored whether this effect would replicate and whether it occurs more strongly for suppressed images presented to the right visual field compared to the left visual field. They chose to compare stimuli presented to the left and right visual fields because it is known that visual input to the right visual field is projected and processed contralaterally in the left hemisphere, which is known to be more specialised for the processing of language (Corballis, 1993; Hellige, 1993). Further, prior findings suggest that this affects performance on tasks probing visual perception (Drivonikou et al., 2007; Gilbert, Regier, Kay, & Ivry, 2006). In their study (Sun et al., 2015), they replicated the effect reported by Lupyan and Ward and showed that the detection of suppressed images is affected by the congruency of a preceding verbal label. However, in contrast to prior studies investigating hemispheric asymmetry, they found that performance to stimuli presented to the left visual field was more greatly influenced by verbal labels, rather than the right visual field. While the implications of this finding for the debate about language and perception remain to be resolved, an issue here is that there is evidence for a right hemispheric dominance in the processing of spatial attention (Becker & Karnath, 2007; Ringman, Saver, Woolson, Clarke, & Adams, 2004), which may alternatively account for this finding.

In the study by Lupyan and Ward (2013) and by Sun et al. (2015), language affected the detection of suppressed stimuli and this effect appears to reside from a top-down affect of language on early, perceptual stages of visual processing (e.g., Kang et al., 2011). This is clearly important to the debate about language and perception. If this finding represents a general rule in the influence of language on vision then it should also generalise to other types of label-stimulus associations. The current study aimed to investigate this over the course of three experiments. In Experiment 1 we investigated

whether we could replicate this effect, and used greyscale photos of objects. These were suppressed from awareness by using CFS and preceded by an audio cue, which was either a verbal label that matched or did not match the object, or it was audio noise. On half of trials there was no object present in order to investigate detection performance. In Experiment 2 we adopted the same method but instead investigated if the effect would generalise to different stimuli. We used patches of colour and tested whether colour terms affected whether the patches of colour were detected. In both of these experiments the verbal labels were direct cues to a suppressed stimulus: in Experiment 1 (object label) it was a direct cue to the spatial configuration of a suppressed stimulus and in Experiment 2 (colour term) it was a direct cue to the colour of the stimulus. In contrast to this, in Experiment 3 we tested the strength of this effect by investigating whether an *indirect* cue to a suppressed stimulus also affected detection. For this we suppressed greyscale images of objects and these were preceded by a colour term (or audio noise), which either matched or did not match the object's characteristic colour.

2.3 Experiment 1: Object targets and object labels

Experiment 1 aimed to replicate the finding of Lupyan and Ward (2013) using a highly similar method. Using CFS, we suppressed greyscale photos of objects from visual awareness and measured participants' performance at detecting them. The objects were either preceded by a congruent object label (e.g., hear 'frog' before 'frog' image), an incongruent object label that did not match the object (e.g., hear 'frog' before 'dog' image), or white audio noise. Noise trials act as a baseline condition for subsequent comparison to congruent and incongruent trials. There were a larger proportion of congruent trials versus incongruent trials so that the object labels were predictive of a hidden object. On half of all trials there was no hidden object. These object-absent trials are necessary to identify participants, who might have a tendency to report that they saw a suppressed object on a trial when they had not. Further, by combining these performance data with data from object-present trials, it is possible to calculate a measure of detection sensitivity (d'). This measure is valuable because it takes into account a bias that may exist to respond in a particular way under conditions of uncertainty. Here, data from 'hits' and 'misses' (the correct and incorrect response on object-present trials respectively) are combined with data from 'correct rejections' and

'false alarms' (the correct and incorrect response on object-absent trials) to calculate d'. By measuring d', as well as hit rates (accuracy) and reaction time, we investigated whether object labels affected participants' performance for detecting hidden objects, as was reported by Lupyan and Ward.

The current study had a few minor differences in the method to Lupyan and Ward's study. First, we used a mirror stereoscope to present visual noise to one eye and an object to the other eye, rather than red-cyan anaglyph glasses. This served two goals: to examine the reliability of the effect reported by Lupyan and Ward across experimental hardware; and to provide a suitable method to investigate the generality of their findings for different stimuli (see Experiment 2 and 3). We also used square random white noise patterns as visual noise to mask the target objects, rather than coloured, curved line segments. These square noise patterns provide a strong image signal and contain a broad distribution of high spatial frequency content. Further, unlike the curved line segments used by Lupyan and Ward, they have previously been investigated in a psychophysical paradigm to ensure successful masking (Arnold, Law, & Wallis, 2008). We anticipated that, if the effect reported by Lupyan and Ward is reliable, we would observe a similar pattern of results. Specifically, compared to baseline trials, we predicted that detection would be significantly better in congruent trials and significantly worse on incongruent trials.

2.3.1 Methods

2.3.1.1 Participants

Twenty British English speakers took part (16 female; mean age = 20.4; SD = 0.7; Range = 19 – 22). Participants were recruited from the University of Sussex. All participants were screened for colour vision deficiencies using the Ishihara test (Ishihara, 1987) and the City University Test (Fletcher, 1980) presented under natural daylight. Observers were naive to the purpose of the study, provided written informed consent and their time was reimbursed with money or research credits. The study was approved by the Cluster-based Ethics Research Committee of Psychology and Life Sciences at the University of Sussex.

2.3.1.2 Stimuli and set up

Participants were seated in a dark room, the only source of light was a 22" Diamond Pro 2070SB CRT monitor (Mitsubishi, Tokyo, Japan; colour resolution: 8 bits/channel; spatial resolution: 1280 × 1024; refresh rate: 100 Hz) located at a distance of 55 cm. Participants viewed dichoptic stimuli through a mirror stereoscope (NVP3D, La Croix-sur-Lutry, Switzerland) fixed to a chin rest. The background grey was metameric with illuminant C and had a luminance of 40 cd/m^2. Both dichoptic stimuli were boxes (5.4° × 5.4°) surrounded by a black border (0.4°) with a horizontal gap between the boxes of around 8° (this varied to suit participants individually). When viewed through the stereoscope each eye viewed a different box but participants perceived there to be a single box (the two boxes fused binocularly). To align both boxes with each participant's eyes, both boxes could be moved by pressing computer keys. The same four vertical and four horizontal white lines (width: 0.3°) were added to the border of both boxes to assist binocular fusion as was a fixation cross (1° × 1°) in the centre of both boxes. During trials the dominant eye was presented with a masking stimulus that changed at a rate of 10 Hz. We used a similar approach to generate the masking stimulus as Arnold, Law, and Wallis (2008), whereby the masking stimulus was a grid of 27 × 27 greyscale squares (each 0.2° × 0.2° and metameric with illuminant C) that filled the entire space inside the border of the box. Each time that the masking stimulus changed, the luminance of each greyscale square was randomly selected from 27 possible luminance values, which ranged from black (0.6 cd/m^2) through to white (69.2 cd/m^2) in steps of near 2.5 cd/m^2. Luminance and chromaticity coordinates were verified with a CRS ColourCal (Cambridge Research Systems, Rochester, UK). Targets were greyscale photographs of an object. There were 30 object categories (e.g., 'frog', 'lemon', see Table 2.2 in supplementary for full list) and five different examples of each category creating 150 different stimuli (mean width = 2°; mean height = 4°). The stimuli came from several online databases: The Bank of Standardized Stimuli (Brodeur, Dionne-Dostie, Montreuil, & Lepage, 2010), Object Categories (Konkle, Brady, Alvarez, & Oliva, 2010), and Shutterstock Inc. (www.shutterstock.com). All visual stimuli were prepared with Matlab (The MathWorks Inc., 2012) with the Psychophysics toolbox (Brainard, 1997). Audio cues (volume-normalised) were recordings of a native British English speaker speaking the same 30 object category labels as the photographs (e.g., "frog") plus one sample of white noise generated using

Audacity software (www.audacityteam.org) and of a duration of 400 ms. Audio cues were presented via HD201 headphones (Sennheiser electronic GmbH & Co. KG, Wedemark, Germany). Participants responded during the trials with a custom-made button box.

2.3.1.3 Procedure

We measured participants' ability to detect target objects suppressed from visual awareness. For a graphic of the procedure see Figure 2.1. There were 300 randomised trials of which half contained a target; each of the 150 stimuli was therefore displayed once. At the start of every trial an audio cue was played. For object-present trials, half (i.e., 75 trials) contained an object label (e.g., "basketball") and the other half contained white noise. For object-present trials preceded by an object label, the label matched the object 80% of the time (congruent condition) and did not match it 20% of the time (incongruent condition). This ensured that a label was predictive of the suppressed object. For object-absent trials, 75 were preceded by white noise and 75 by a randomised object label. After the audio cue the fixation crosses were removed and the masking stimuli began to flash to the dominant eye. On object-absent trials only the background grey was displayed inside the box presented to the non-dominant eye and the masking stimuli continued to flash to the dominant eye until the end of the trial (or until the participant made a response). On object-present trials a randomised delay ranging $1 - 2$ seconds was implemented after the audio cue before the target was ramped up to its maximum value (i.e., no transparency) over a period of 4.5 seconds. Once fully revealed and if no detection-response had been made the target remained on screen for a further second. If a detection response was made during the masking period, the masking stimuli and target were removed. If the detection response was "Yes", a written recognition-probe was then displayed asking whether the object seen matched the audio label (e.g., "Was the object a basketball?"). On noise trials the recognition probe was randomised. On trials where no detection response was made before the end of the masking period the target and masking stimuli were replaced with a written prompt asking whether an object had been seen.
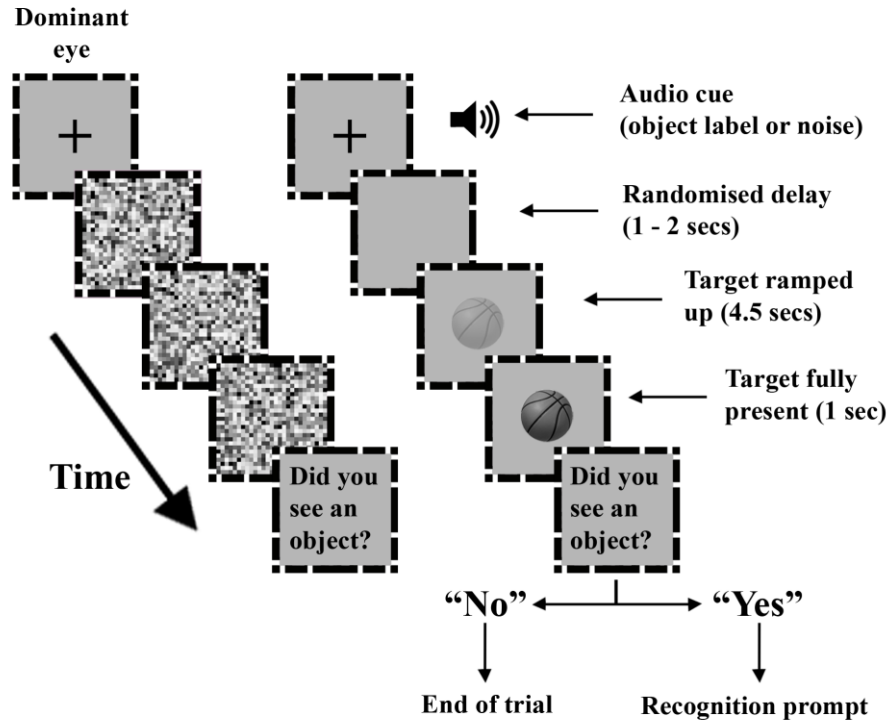
Figure 2.1. Experiment 1 task procedure for object-present trials. An audio cue (either an object label or white noise) was presented over headphones before the dominant eye was presented with flashing (10 Hz) square random noise patterns. On half the trials the audio cue was an object label and on the other half the audio cue was white noise.

2.3.2 Results

We investigated four measures of detection performance for all three experiments: Firstly, for each participant we analysed reaction times for object-present trials where a response was made before the trial timed out. We excluded trials from this analysis which timed out to avoid contaminating this measure with data recorded after a participant had read and comprehended the written prompt "Did you see an object?"; Secondly, hit rates (accuracy) for all object-present trials were analysed; Thirdly, detection sensitivity (d') was calculated with the data from object-present and object-absent trials. Finally, we analysed false alarm rates for object-absent trials. The three factors of Reaction time, Hit rate, and Detection sensitivity were each analysed separately with a repeated-measures ANOVA containing three levels corresponding to

the three audio cue conditions (congruent trials, incongruent trials, and white noise). The factor or False alarm rate was analysed as a paired-samples t-test to compare this measure on trials containing white noise versus trials containing an (randomised) object label. Where appropriate, Greenhouse-Geisser corrections were applied for violations of sphericity. Significant main effects were followed up with planned comparisons comprising paired-samples t-tests and alpha was adjusted by the Bonferroni correction for multiple comparisons ($\alpha = .05/3$).

Reaction time: There was no significant effect of audio cue on the speed that participants correctly saw a target, $F(2, 38) = 2.7$, $p = .079$. See Figure 2.2a.

Hit rate: There was a significant effect of audio cue on hit rates, $F(1.4, 27.1) = 10.7$, $p = .001$. Planned comparisons revealed that performance on incongruent trials ($M = 0.89$; $SEM = 0.02$) was significantly poorer than congruent trials ($M = 0.95$; $SEM = 0.01$; $p = .006$) and on trials preceded by noise ($M = 0.95$; $SEM = 0.01$; $p = .01$). Congruent and noise trials did not differ ($p = .99$). See Figure 2.2b.

Detection sensitivity: There was a significant effect of audio cue on d', $F(2,38) = 9.9$, $p < .001$. Planned comparisons revealed the same trend as hit rates; performance on incongruent trials ($M = 3.45$; $SEM = 0.13$) was significantly poorer than on congruent trials ($M = 3.94$; $SEM = 0.15$, $p < .001$) and noise trials ($M = 3.90$; $SEM = 0.12$; $p = .008$), but congruent and noise trials did not differ ($p = .99$). See Figure 2.2c.

False alarm rate: The number of false alarms did not significantly differ for trials preceded by a verbal label ($M = 0.17$; $SEM = 0.004$) compared to noise ($M = 0.18$; $SEM = 0.004$), $t(19) = -0.16$, $p = .87$.
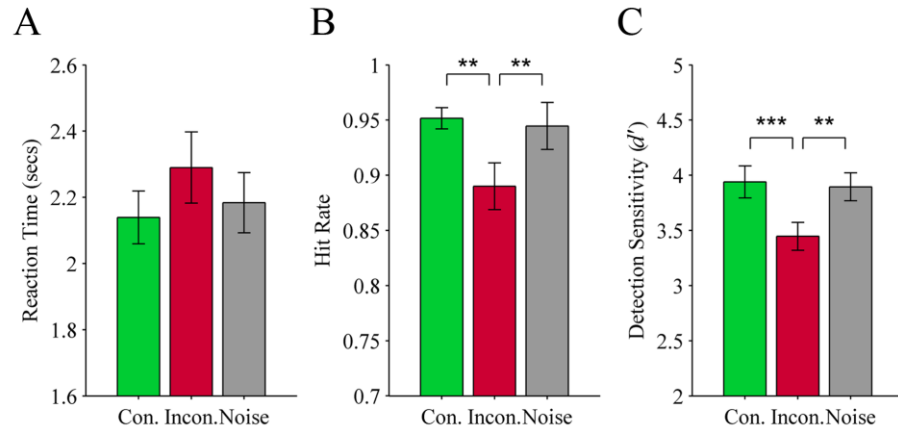
Figure 2.2. Results from Experiment 1 (object targets preceded by an object label or noise). Three measures of performance for detecting greyscale objects suppressed from visual awareness through CFS: (A) Reaction time, (B) Hit rate, and (C) Detection sensitivity (d'). The objects were preceded by one of three types of audio cue: Con. (congruent object label; green), Incon. (incongruent object label; red), or Noise (grey). Error bars show $\pm$ 1 SEM. ** $p < .01$; *** $p < .001$.

2.3.4 Discussion

The type of audio cue presented prior to a suppressed object affected participants' performance at detecting the object. This supports the findings of Lupyan and Ward (2013), who likewise reported that audio cues influence the detection of suppressed objects. There were however subtle differences between the results of the two studies. Similarly to Lupyan and Ward, we found that hit rates and detection sensitivity were poorer on trials when an object label did not match a hidden object (incongruent trials) compared to baseline noise trials and when they did match (congruent trials). However, we did not replicate the finding that detection is improved when a label matches a hidden object (congruent trials) relative to baseline trials. In other words, we do not find like Lupyan and Ward that appropriate language boosts detection, but rather find that inappropriate language impedes detection. Further, we did not find a significant effect of audio cue on reaction times.

2.4 Experiment 2: Colour targets and colour terms

In Experiment 1, we found that object labels affected the detection of greyscale objects hidden from visual awareness, with incongruent labels impeding detection of the objects. A central question here is whether this effect occurs exclusively for objects preceded by object labels, or whether this effect generalises to other types of stimuli and language-stimulus associations. This question is important as if the finding represents a general rule of the effect of language on vision then it should generalise across different types of visual stimulus. In Experiment 2 we tackled this question by suppressing patches of colour, which were preceded by a colour term or by white audio noise. We specifically chose to use colour stimuli because of the extensive debate about the time course that colour terms affect colour processing. For example, as outlined in the introduction, there is some evidence that colour terms can affect early, perceptual stages of visual processing (Thierry et al., 2009), yet others have failed to replicate these early effects, finding an influence of colour terms only at later, so-called 'post-perceptual' stages of visual processing (He et al., 2014). In the current experiment, by suppressing colour patches through CFS, the colour stimuli are first presented outside of awareness. Consequently, if colour terms do affect early, unconscious processes (Thierry et al.), colour terms would be expected to affect the detection of colour stimuli suppressed with CFS. Conversely, if colour terms only affect later post-perceptual processes (He et al.), they might not be expected to affect detection of visually suppressed coloured stimuli.

2.4.1 Methods

2.4.1.1 Participants

Twenty British English speakers took part (15 female; mean age = 21.3; SD = 1.5; Range = 20 – 26). None of the participants took part in Experiment 1. Participants were recruited from the University of Sussex. All participants were screened for colour vision deficiencies using the same tests as Experiment 1. Observers were naive to the purpose of the study, provided written informed consent and their time was reimbursed with money or research credits. The study was approved by the Cluster-based Ethics Research Committee of Psychology and Life Sciences at the University of Sussex.

2.4.1.2 Stimuli and set up

The only difference in hardware and set up compared to Experiment 1 was the use of a mirror stereoscope with OptoSigma mirrors (OptoSigma, Santa Ana, USA). All aspects of the dichoptic stimuli were the same as Experiment 1 except that targets were circular patches of colour (2° × 2°), the edges of which were blurred with a Gaussian filter (σ = 0.08º). The target colours were the eight chromatic basic colours proposed by Berlin and Kay (1969): Red, orange, yellow, green, blue, purple, pink, and brown, plus white and black. The chromaticity coordinates of these stimuli were taken from data from Sturges and Whitfield (1995), who investigated English speakers' focal colours using the Munsell colour system. Focal colours are the best example of a colour when the three dimensions of colour (lightness, saturation and hue) can be varied (Kuehni, 2005; Miyahara, 2003). We converted these Munsell values into CIE x,y,Y values based on an assumed white point of illuminant C of a luminance of 40 cd/m^2. For those focal

Table 2.1. Chromaticity coordinates (CIE1931, x,y,Y) of colour patch targets from Experiment 2.

Focal colour name	x	y	Y
Red	0.579	0.330	4.8
Orange	0.549	0.395	12.0
Yellow	0.451	0.475	27.4
Green	0.258	0.399	4.8
Blue	0.179	0.189	7.9
Purple	0.278	0.181	4.8
Pink	0.372	0.296	17.2
Brown	0.434	0.402	2.6
White	0.310	0.316	69.2
Black	0.310	0.136	0.58

colours located outside of the monitor's gamut, saturation was reduced until the colour could be displayed (see Table 2.1 for final CIE *x,y,Y* values). The audio colour cues were likewise these 10 colour terms recorded from a native British English speaker (e.g., "red"). The same background grey and software was used as Experiment 1.

2.4.1.3 Procedure

Participants completed 320 trials. Like Experiment 1, half the trials contained targets and half of these colour-present trials were preceded by an audio cue of which 80% matched the colour shown (congruent trials). All other aspects of the procedure were the same as Experiment 1, except that verbal cues were colour terms, and targets were circular patches of colour.

2.4.2 Results

Reaction time: The speed that participants correctly saw a target was significantly affected by the type of audio cue preceding the target, $F(2 ,36) = 19.6$, $p < .001$. On congruent trials ($M = 1.80$ seconds; $SEM = 0.15$) performance was significantly faster than both incongruent trials ($M = 2.10$ seconds; $SEM = 0.16$; $p < .001$) and noise trials ($M = 2.04$ seconds; $SEM = 0.16$; $p < .001$). Although reaction times were slowest for incongruent trials, this did not differ significantly from noise trials ($p = .57$). See Figure 2.3a.

Hit rate: There was a significant main effect of audio cue on hit rates, $F(1.2, 21.1) = 4.3$, $p = .046$. Hit rates were highest on congruent trials ($M = 0.97$; $SEM = 0.010$) and lowest on incongruent trials ($M = 0.92$; $SEM = 0.022$), though this difference did not survive Bonferroni correction. Performance on noise trials fell in the middle ($M = 0.96$; $SEM = 0.014$). See Figure 2.3b.

Detection sensitivity: There was a significant main effect of audio cue on *d'*, $F(1.5, 27.6) = 11.0$, $p = .001$. Like the first experiment, *d'* was significantly lowest on incongruent trials ($M = 3.71$; $SEM = 0.16$) compared to congruent trials ($M = 4.23$; $SEM = 0.16$; $p = .001$) and noise trials ($M = 4.22$; $SEM = 0.16$; $p = .003$), but congruent and noise trials did not differ significantly ($p = .90$). See Figure 2.3c.

False alarm rate: There was no significant difference in false alarm rates on trials with a colour term ($M = 0.19$; $SEM = 0.011$) compared to noise trials ($M = 0.10$; $SEM = 0.004$), $t(18) = 1.03$, $p = .32$.
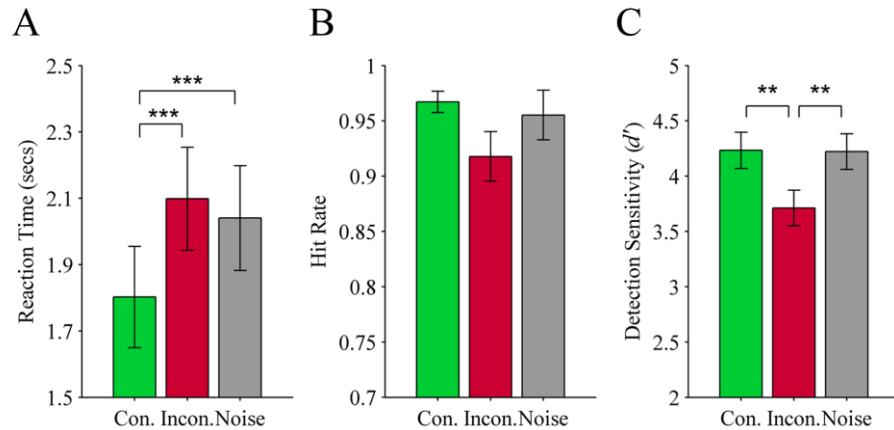

Figure 2.3. Results from Experiment 2 (colour targets preceded by a colour term or noise). Three measures of performance for detecting circular colour patches suppressed from visual awareness through CFS: (A) Reaction time, (B) Hit rate, and (C) Detection sensitivity (d'). The colour patches were preceded by one of three types of audio cue: Con. (congruent colour term; green), Incon. (incongruent colour term; red), or Noise (grey). Error bars show ± 1 SEM. ** $p < .01$; *** $p < .001$.

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2.4.3 Discussion

Hearing colour terms affected the detection of coloured patches suppressed from visual awareness with CFS. Specifically, when a colour term matched the colour of a suppressed target, participants respond significantly faster than when the colour term did not match the target or when just noise was heard. This effect was considerable; participants responded around 300 ms faster on congruent trials compared to incongruent trials, and around 250 ms faster compared to noise trials. For both detection sensitivity and hit rates there was a different pattern of results compared to reaction time. Here, the pattern was similar to Experiment 1, whereby colour terms hindered

performance on these measures (significantly so for detection sensitivity) when a colour term did not match the colour of a suppressed target (incongruent trials) compared to congruent and noise trials. Overall, these data suggest that the strength of association between a colour term and a colour is strong enough to affect detection of a coloured patch suppressed from visual awareness. We next investigated whether a similar effect of language could be found when the association between the verbal label and the object is potentially weaker by assessing whether coloured labels also affects the detection of suppressed images of coloured-associated objects presented in greyscale.

2.5 Experiment 3: Object targets and colour terms

The first two experiments found that a verbal cue, which either matched or did not match the object identity of a target (Experiment 1) or the colour of a target (Experiment 2), significantly affected performance at detecting the target when suppressed from visual awareness. In Experiment 3, we aimed to test whether this effect would generalise a step further. We investigated whether a verbal cue which refers not to the identity of an object but to an associated characteristic, such as its typical colour, likewise affects detection of that object when presented in greyscale. We used the same object stimuli as Experiment 1, but here the objects were preceded by a colour term. The objects were all associated with a single particular colour. For example, carrots are typically orange; frogs are typically green, and so forth. Importantly, like Experiment 1, the objects were greyscale and therefore contained no chromatic information. As such, the colour term was a cue to a physical characteristic associated with the hidden object, rather than a direct cue towards the identity of the object. On congruent trials the colour term matched the object's typical colour and on incongruent trials it did not. We used objects and colour terms because there is evidence that suggests that there is a strong association between colour and object identity. For example, it has been shown that memory of an object's typical colour modulates the actual appearance of the object (Hansen, Olkkonen, Walter, & Gegenfurtner, 2006; Olkkonen, Hansen, & Gegenfurtner, 2008). Further, a neural representation of object memory colour has also been found in activity in area V1 suggesting that prior knowledge of an object's colour influences early visual processing (Bannert & Bartels, 2013). This experiment consequently aimed to further investigate whether the association between colour and

object identity is strong enough for colour terms to affect the detection of object images when suppressed from visual awareness. As the label-target association relates to a characteristic of the target image rather than its identity, this manipulation further tests the limits of the effect found in Experiments 1 and 2.

2.5.1 Methods

2.5.1.1 Participants

Twenty British English speakers took part (17 female; mean age = 20.7; SD = 0.7; Range = 19 − 22). None of the participants took part in Experiment 1 or 2. Participants were recruited from the University of Sussex. All participants were screened for colour vision deficiencies using the same tests as Experiment 1. Observers were naive to the purpose of the study, provided written informed consent and their time was reimbursed with money or research credits. The study was approved by the Cluster-based Ethics Research Committee of Psychology and Life Sciences at the University of Sussex.

2.5.1.2 Stimuli and set up

The visual stimuli were the same greyscale objects used in Experiment 1. These objects were selected a priori because they were each strongly associated with a single, particular colour (verified through pilot testing). Recall the stimuli in Experiment 1 comprised 30 object categories (e.g., 'banana') and there were five different examples of each category (150 stimuli in total). Out of the 30 categories, five were associated with green (frog, lettuce, peapod, broccoli, and pear). There were therefore 25 individual green-associated stimuli. The same was the case for the colours red, orange, yellow, pink, and brown (see Table 2.2 in supplementary for full list of objects and colours). Note that targets were greyscale and contained no chromatic information. Audio cues were these six colour terms (e.g., "red"). The same hardware and all other aspects of the visual stimuli were the same as Experiment 1.

2.5.1.3 Procedure

Participants completed 300 trials. Like Experiments 1, half the trials contained objects of which half were preceded by an audio cue and half by white noise. On congruent trials the audio colour cue matched the object's characteristic colour (e.g., "orange" for basketball; "yellow" for banana etc.). On incongruent trials the colour cue did not match the object's characteristic colour. As with the prior experiments, on object-present trials preceded by a colour cue, 80% were congruent, 20% were incongruent, and on object-absent trials the audio cue was randomised (half were white noise).

2.5.2 Results

Three participants did not follow the task instructions and deliberately responded after each trial had timed out. They were consequently excluded from subsequent analysis.

Reaction time: There was no significant main effect of audio cue on reaction times, $F(1.2, 18.5) = 2.10$, $p = .163$. See Figure 2.4a.

Hit rate: There was a marginal main effect of audio cue on hit rates, $F(2, 32) = 3.12$, $p = .058$. The trend was similar to the prior experiments in that hit rates were lowest on incongruent trials ($M = 0.86$; $SEM = 0.026$) compared to congruent ($M = 0.90$; $SEM = 0.018$) and noise trials ($M = 0.91$; $SEM = 0.026$). See Figure 2.4b.

Detection sensitivity: There was a significant main effect of audio cue on detection sensitivity, $F(2, 32) = 4.56$, $p = .018$. Planned comparisons revealed d' was significantly higher on congruent trials ($M = 3.75$; $SEM = 0.20$) compared to incongruent trials ($M = 3.47$; $SEM = 0.19$; $p = .015$), but not noise trials ($M = 3.67$; $SEM = 0.19$; $p = .343$). The difference in d' between noise and incongruent trials did not reach significance ($p = .056$). See Figure 2.4c.

False alarm rate: There was no significant difference in false alarm rates on audio cue trials ($M = 0.02$; $SEM = 0.018$) compared to noise trials ($M = 0.02$; $SEM = 0.020$), $t(16) = -1.00$, $p = .33$.
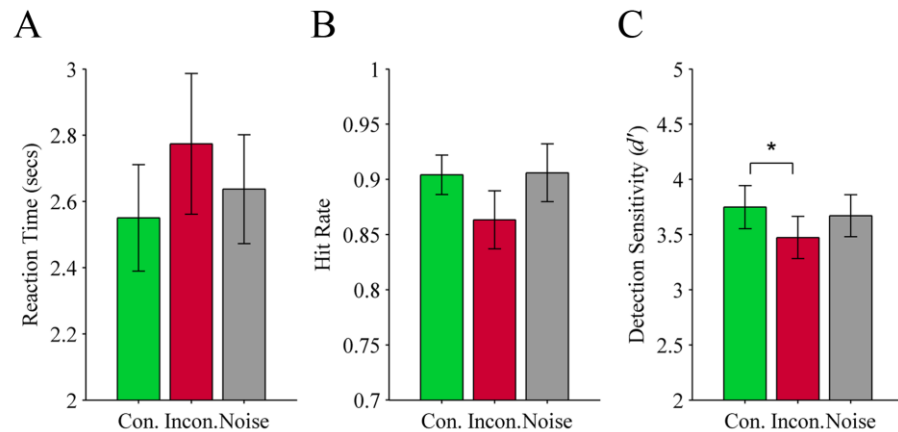
Figure 2.4. Results from Experiment 3 (object targets preceded by a colour term or noise). Three measures of performance for detecting greyscale objects suppressed from visual awareness through CFS: (A) Reaction time, (B) Hit rate, and (C) Detection sensitivity (*d'*). The objects were each associated with a single colour (e.g., a banana is associated with yellow) and were preceded by one of three types of audio cue: Con. (congruent colour term; green), Incon. (incongruent colour term; red), or Noise (grey). Error bars show ± 1 SEM. * $p < .05$.

2.5.3 Discussion

In the previous experiments, observers were given a verbal cue that either matched or did not match the identity of a hidden target. In Experiment 3 we instead investigated whether the association between colour terms and object identity is strong enough to affect detection of hidden objects. The verbal cue was a colour term that either matched, or did not match the typical colour associated with a hidden object. Importantly, target objects were greyscale, therefore the colour term was an indirect cue to a physical characteristic associated with the object, rather than a direct cue. We found that, despite no chromatic information being available to assist detection, colour terms affected the detection of hidden, greyscale objects. Specifically, detection sensitivity was significantly worse on incongruent compared to congruent trials. For example, hearing the cue "yellow" impeded the detection of an object not typically associated with that colour relative to the detection of an object associated with that colour. There was however, no difference in the effect of verbal label on detection relative to just

hearing noise. A similar, though marginal effect was found for hit rates, and like Experiment 1 we did not find that the verbal cues significantly affected reaction times to hidden targets. Given the lack of significant effects for two of the measures, and the lack of significant difference between the verbal labels and noise, the evidence for the effect of terms on the detection of suppressed stimuli appears less convincing for colour term-object associations than for when terms directly relate to the identity of an object.

One possibility for the weaker effect in Experiment 3 may be the weaker association between colour labels and objects compared to colour labels and colours or object labels and objects. For example while a carrot may typically be associated with the colour orange it may also be associated with the green colour of its foliage. Another point to consider is whether the colour-to-object priming reported in Experiment 3 would similarly occur for object-to-colour priming. This alternative paradigm would consist of hearing an object prime before the presentation of a suppressed colour patch that matched or mismatched the characteristic colour of the object. For example, on congruent trials participants would hear frog before a green patch was presented. This paradigm deserves further investigation because it would provide further insights into the strength of the association between colours and objects. Without further investigation is it unclear whether colour-to-object or object-to-colour associations are stronger, but this paradigm could be used to investigate this area.

2.6 General Discussion

Previous studies have found that hearing an object label affects detection of an object suppressed from visual awareness through CFS (Lupyan & Ward, 2013; Sun et al., 2015). Importantly, in both these studies it was found that the object label both improved detection when the label matched the object, and inhibited detection when it did not. In Experiment 1 we partially replicated this effect. Unlike these previous studies, we did not find evidence that detection is improved by a congruent object label, but we did find that detection was worse when a label did not match a suppressed image. However, in Experiment 2, in which colour patches were suppressed and preceded by a colour term or noise, like Lupyan and Ward (2013), and Sun et al. (2015), we found that language can both facilitate detection (reaction times were significantly faster on congruent trials compared to the other conditions), as well as hinder detection

(*d'* was significantly lower on incongruent trials compared to the other conditions). One possibility here is that the colour stimuli used in Experiment 2 were each presented 16 times, whereas the stimuli in Experiments 1 and 3 were presented just once. This may have resulted in greater predictive power of the colour terms and the effect we report for suppressed colour stimuli. In Experiment 3, we found a weaker effect. For both reaction times and hit rates we found verbal labels to the typical colour of a suppressed, greyscale object had no significant effect on detecting the objects compared to baseline. Detection sensitivity was however affected. Here, the trend was for colour terms to impede detection on incongruent trials compared to congruent trials.

In the present study we extend the finding that verbal labels affect the detection of suppressed objects by demonstrating that this effect generalises to colour stimuli and colour-associated objects preceded by a colour term. This suggests that the association between a colour term and a colour is strong enough to affect whether and when a coloured patch will be perceived when it is suppressed from awareness through CFS. There has been much debate about the time course that colour terms might affect colour processing; some data suggest colour terms affect early stages of visual processing (Thierry et al., 2009), while some indicate this effect resides in later, post-perceptual stages of processing (He et al., 2014). It has been proposed that CFS disrupts processing prior to semantic analysis (e.g., Kang et al., 2011; for further discussion see below). If so, the present study provides further support for colour terms affecting earlier stages of processing (i.e., Thierry et al.). We also show that the association between objects and colour terms is strong enough to affect detection of suppressed colour-associated objects. This supports prior findings that memory of an object's typical colour is enough to affect the appearance of an object (Hansen et al., 2006; Olkkonen et al., 2008), and may be related to the finding of colour-associated neural activity in area V1 that was elicited in response to greyscale colour-associated objects (Bannert & Bartels, 2013).

The difference between boosting detection on congruent trials and inhibiting detection on incongruent trials has important theoretical implications because it likely speaks to the mechanism underlying how language can affect the detection of a suppressed stimulus. If language modulates bottom-up processing in the visual system by affecting neural signals associated with processing a stimulus (Boutonnet & Lupyan, 2015; Lupyan, 2012), the question is how is this achieved? One possibility for the finding that language can improve detection in Experiment 2 and in the studies by

Lupyan and Ward, and by Sun et al., is that language may advance the specific signal associated with processing the suppressed stimulus compared to background neural noise in the visual processing system. According to Kersten and Yuille (2003), this is consistent with some electrode-recording experiments, which show that activity from higher-level areas can reduce (and refine) activity in early visual processing areas (Lee, Yang, Romero, & Mumford, 2002). A candidate for this process is population encoding (Pouget, Dayan, & Zemel, 2000).

In the current study we find stronger evidence that language can obstruct detection, rather than facilitate detection. One possible account of this finding of obstruction is that an incongruent label adds further noise to the visual system, which hinders visual awareness. If the higher-level visual areas in extrastriate cortex represent hypotheses about visual stimuli, which are tested against information in earlier stages of vision such as area V1 (e.g., Grill-Spector, Kourtzi, & Kanwisher, 2001), ambiguity in early visual signals will not be resolved as successfully on incongruent trials compared to congruent trials because the hypothesis is incorrect (the verbal label does not match the stimulus). In this view, feed-forward pathways, which contain both the neural signal and the residual error signal between predictions, may contain greater error in the signal (e.g., Rao & Ballard, 1999).

The proposal that language feeds back to earlier stages of visual processing (Lupyan, 2012; Lupyan & Ward, 2013) begs the question of which higher and lower-level visual areas are responsible for this process. Lupyan and Ward propose a potential higher-level candidate for the finding that language affects the detection of suppressed object stimuli is the ventral occipito-temporal cortex. This region has previously been related with object processing (Chao, Haxby, & Martin, 1999; Gainotti, Silveri, Daniel, & Giustolisi, 1995; Sartori, Miozzo, & Job, 1993). The idea here is that this region may feedback to earlier stages of visual processing through a mechanism such as population encoding (e.g., Pouget et al., 2000) or hypothesis / prediction testing (e.g., Grill-Spector et al., 2001). If this is the case, feedback from this region to lower-level areas could also be responsible for the finding that the detection of colour stimuli (Experiment 2) is similarly affected because this region has also been shown to be associated with colour processing (Anllo-Vento, Luck, & Hillyard, 1998). Concerning the effect we find in Experiment 3, whereby a colour term affected detection of greyscale, colour-associated objects, it was previously highlighted that lesions of inferior occipito-temporal cortex

are associated with cerebral achromatopsia, which is a sensory impairment characterised by an inability to perceive the colour of objects (Anllo-Vento et al., 1998; for a review, see Zeki, 1990). A possibility here is that the association we find between objects and colour may arise from feedback from this region.

While potential candidates for the higher-level representation of language that drives the effects reported in the present study have been discussed, it remains unclear which lower-level stage(s) of visual processing language may penetrate. Kersten and Yuille (2003) suggest that higher-level areas could feedback to area V1, while attention has been shown to modulate activity even earlier, in the lateral geniculate nucleus (O'Connor, Fukui, Pinsk, & Kastner, 2002). Concerning our finding that colour terms affect colour detection, a key question for future research will be to clarify whether the same low-level area(s) is involved as that for suppressed objects, or whether feedback occurs to alternative areas. For example, it is possible that the lower-level area could be one that is highly specialised for the processing of colour, such as area V4 (Brouwer & Heeger, 2009; Conway, Moeller, & Tsao, 2007; Zeki, 1974).

An essential foundation of the conclusions made by Lupyan and Ward is that CFS disrupts processing prior to semantic analysis and that the effect of verbal labels found on detection must occur in earlier, lower-level stages of visual processing. But is this necessarily the case? There are a number of studies that support this view. They fail to find an observable effect on behaviour from a suppressed prime, which suggests that semantic processing is inhibited for suppressed stimuli. For example, no priming effects were reported for suppressed objects (Cave, Blake, & McNamara, 1998), and binocular rivalry, more generally, has been reported to obstruct semantic processing of words (Zimba & Blake, 1983). This has also been demonstrated by measuring electrophysiological activity, whereby the N400 component, which is associated with language processing (for a review see, Kutas & Federmeier, 2011), was absent for words suppressed through CFS (Kang et al., 2011). However, there are several contrary findings that show a priming effect (and presumably semantic processing) for stimuli suppressed through CFS. This has been shown for suppressed words (Costello, Jiang, Baartman, McGlennen, & He, 2009), as well as numbers (Bahrami et al., 2010). The findings of Bahrami et al., and Costello et al., dispute the view that images and colours suppressed through CFS receive no semantic processing. These findings cast doubt on whether the paradigm used in the present study truly tapped early-stages of visual

processing. Resolving these conflicting findings will be essential for clarifying the mechanism underlying CFS and whether it is a valid tool for exploring the time course that language can affect visual processes.

The method that allows us to be precise about the effect of language on perception has proved to be elusive. It has been argued that the effect of language on the detection of stimuli suppressed by CFS indicates that language affects early-stages rather than post-perceptual stages of visual processing (Lupyan & Ward, 2013; Sun et al., 2015). In the present study we sought to add to this debate by testing the generality of this effect. While we replicated and extended this effect, albeit with some differences, we are more cautious in interpreting this as evidence that language affects early-stages of processing during CFS. Given that participants were required to respond once a suppressed stimulus was perceived, we cannot rule out the possibility that verbal labels may act at the stage of decision rather than detection itself (Mather et al., 2013; Morgan et al., 2012). On the other hand, in Experiment 2 reaction times were 300 ms faster in the congruent condition compared to the incongruent condition, and this substantial length of time appears unlikely to be accounted for purely by post-perceptual decision-making processes. Further research into the neural locus of this effect will likely shed light on this question. For example, transcranial magnetic stimulation has previously been used successfully to disrupt processing in areas, such as the inferior occipito-temporal cortex, which are relevant to this discussion, (Duncan, Pattamadilok, & Devlin, 2010; Mancini, Bolognini, Bricolo, & Vallar, 2011). This could prove a valid tool whether this area plays a role in the effects reported here, as proposed by Lupyan and Ward. Likewise, neuroimaging studies will be crucial for investigating whether language (via verbal cues) is fed back to earlier stages of vision. While fMRI data suggests this is the case for attention on visual search (Melloni, van Leeuwen, Alink, & Muller, 2012), it remains to be clarified whether it is also the case for language. This will prove a valuable goal for increasing our understanding of the relationship between language, visual processing and perception.

2.7 Supplementary: Category listing for stimuli in Experiments 1 and 2

Table 2.2 Category listing for stimuli in Experiments 1 and 3.

Banana	(yellow)	Pea pod	(green)
Basketball	(orange)	Pear	(green)
Broccoli	(green)	Pig	(pink)
Carrot	(orange)	Piggy Bank	(pink)
Chocolate	(brown)	Pine cone	(brown)
Coconut	(brown)	Pineapple ring	(yellow)
Corn on cob	(yellow)	Prawn	(pink)
Fire engine	(red)	Pumpkin	(orange)
Fire extinguisher	(red)	Rubber Duck	(yellow)
Flamingo	(pink)	Santa Hat	(red)
Ham	(pink)	Strawberry	(red)
Frog	(green)	Tiger	(orange)
Lemon	(yellow)	Tomato	(red)
Lettuce	(green)	Traffic cone	(orange)
Moose	(brown)	Violin	(brown)

Table notes: The colour terms in parentheses refer to the pairing between object and colour on congruent trials in Experiment 3.

Chapter 3

Paper 2: Speakers of different colour lexicons differ only in post-perceptual processing of colour when colour is attended

Forder, L., He., X., Witzel., C., & Franklin., A. *Psychophysiology* (in preparation)

3.1 Abstract

Speakers of different colour lexicons differ in their behavioural response to differences in colour. An important question is whether cross-linguistic differences occur at early perceptual or later post-perceptual stages of processing. We compared just-noticeable differences (JNDs) for native Russian and native English speakers on a 4-alternative forced-choice task. JNDs were measured in a colour region spanning two basic linguistic colour categories for Russian speakers, but which is named "Blue" by English speakers. We found no cross-linguistic difference in JNDs that could be accounted for by language. Secondly, we measured Event-Related Potentials (ERPs) for Russian and English speakers on a visual oddball task where participants attended to three colours: one colour presented on 83.5% of trials (the standard), and two colours presented less frequently (the deviants), one of which was a different-category to the standard for Russian speakers. The standard-deviant colour difference was equated in JNDs. We found no cross-linguistic difference within early perceptual ERP components (P1, N1). However, there was an effect within the later P2-N2 complex (280-320 ms) where Russian speakers had significantly greater amplitude for the deviant which was different-category for them than the same-category deviant, while there was no such effect for English speakers. This suggests that language only modulates post-perceptual processing of attended colour differences and has implications for broader debate on the interaction of language and perception.

3.2 Introduction

For many years, the idea that language can affect visual perception has generated debate and it continues to do so (see for example, Lupyan, 2012; Pinker, 1995). One contentious issue is the point at which language affects visual processing. There is currently dispute about whether language affects early sensory stages of visual processing (Boutonnet, Athanasopoulos, & Thierry, 2012; Clifford, Holmes, Davies, & Franklin, 2010; Thierry, Athanasopoulos, Wiggett, Dering, & Kuipers, 2009), or whether it operates at later post-perceptual and cognitive stages (Clifford et al., 2012; He, Witzel, Forder, Clifford, & Franklin, 2014). This distinction is important because it is relevant to the broader question of whether language operates independently of perception (e.g., Li & Gleitman, 2002; Pinker, 1995) or whether language and perception operate through interactive processes (Lupyan, 2012, see also 2007; Notman, Sowden, & Özgen, 2005; Reber, Stark, & Squire, 1998).

Findings from behavioural research have been inferred by some to indicate that language affects visual perception (e.g., Lupyan, 2012). For example, the act of saying a verbal object label out loud during a visual search task was shown to improve performance compared to not saying a verbal label, providing that the label matched the target object (Lupyan & Swingley, 2012, see also Lupyan, 2008). Participants have also been shown to perform worse at detecting motion after hearing a word that describes the incorrect direction of the movement (Meteyard, Bahrami, & Vigliocco, 2007). Likewise, results from a speeded colour discrimination task (Winawer et al., 2007; see also Daoutis, Franklin, Riddett, Clifford, & Davies, 2006; Daoutis, Pilling, & Davies, 2006) suggest that the way a language categorises colour affects speed of response to colour difference. However, while these findings have been shown across multiple types of visual stimuli, they do not clarify whether language is affecting a higher-level cognitive process, such as decision making (e.g., Mather, Pavan, Marotti, Campana, & Casco, 2013), or whether language is penetrating earlier stages of visual processing.

One method that can provide greater clarity about the effect of language on the time course of visual processing is the event-related potential (ERP) technique. ERPs provide high temporal resolution measurements of the electrophysiological activity that occurs during visual and cognitive processing (Luck, 2005). ERPs elicited by the presentation of a visual stimulus typically follow a predictable pattern of waveform

components over time. These components are traditionally labelled in terms of the direction of their voltage deflection (positive or negative) and the order in which they occur (P1, N1, P2, N2, P3, etc.). In broad terms, the P1 and N1 components are believed to index early sensory processes influenced predominantly by the physical characteristics of a stimulus and generally occur before 200 ms (e.g., Polich, 1999; Hopf, Vogel, Woodman, Heinze, & Luck, 2002; Johannes, Münte, Heinze, & Mangun, 1995; Key, Dove, & Maguire, 2005). The latter components (P2, N2, and P3) broadly arising after 200 ms are believed to be associated with numerous post-perceptual higher-level cognitive tasks, such as feature detection, stimulus change and short-term memory (Key et al., 2005), as well as stimulus evaluation processes (McCarthy & Donchin, 1981; Patel & Azzam, 2005).

One domain particularly suited to the debate about the time course of the effect of language on processing is colour because the continuous visible spectrum is divided into distinct, linguistic colour categories ('red', 'green', etc.). A category effect is the finding of a different response to two colours from different categories compared to two colours from the same category, despite the perceivable difference between the colours being equated in a particular colour metric (Harnad, 1987). By searching for category effects across multiple ERP components, it is possible to establish the time-course of the effect of colour terms on colour processing. However, studies in this area disagree on whether language affects early, sensory stages of colour processing (Athanasopoulos et al., 2010; Clifford et al., 2010; Holmes et al., 2009; Mo et al., 2011; Thierry et al., 2009; Zhong, Li, Li, Xu, & Mo, 2015), or whether language affects subsequently occurring, post-perceptual processes (Clifford et al., 2012; He et al., 2014).

An important issue with the majority of ERP studies investigating categorical colour processing is that the category effects they report may instead be the result of limitations of the metric used to equate colour difference, rather than genuine category effects (He et al., 2014; Witzel & Gegenfurtner, 2013). The colour spaces used to equate colour differences such as the Munsell system and CIELUV/CIELAB were designed to be perceptually uniform, however these colour spaces are known to contain inhomogeneities, which are revealed as areas of greater and lesser discrimination sensitivity (Hill, Roger, & Vorhagen, 1997; Mahy, Van Eycken, & Oosterlinck, 1994). This is of great importance to the debate about the time course of category effects because early visual processes are known to be highly sensitive to the physical

characteristics of stimuli (Busch, Debener, Kranczioch, Engel, & Herrmann, 2004). Importantly, different-category colours in prior ERP studies may simply have been more dissimilar than the same-category colours. This 'metric' issue needs to be controlled or ruled out in order for differences in the ERP response elicited by the colour pairs to be confidently attributed to the categorical relationship between colours.

One study that that does not suffer from potential stimulus issues is a cross-linguistic study conducted by Thierry et al. (2009). These authors compared speakers of different languages that categorise colour differently. The study compared native Greek and native English speakers because the Greek language divides lighter and darker blue hues into separate categories (Androulaki et al., 2006), while the English language does not. The participants in the study by Thierry et al. were tasked with focusing on the shape of the stimuli rather than the colour and the study aimed to measure preattentive or 'unconscious' processing of the colour stimuli. Thierry et al. found a category effect for Greek speakers and cross-linguistic differences in the P1 (at 100 – 130 ms), suggesting that language affects early stages of processing, and in the visual mismatch negativity (vMMN). The vMMN is an ERP waveform starting in early visual processing and is known to be sensitive to changing stimuli presented outside of attention (for a review, see Czigler, 2013). The category effects found for the Greek speakers and the resulting cross-linguistic differences cannot be attributed to stimulus issues since the English and Greek speakers saw the same stimuli. Further, in a subsequent re-analysis of this data, which split the Greek participants into two groups depending on the length of time they had spent in the UK, it was found that this ERP effect was stronger for short-stay Greek speakers compared to those who had been in the UK for longer (Athanasopoulos et al., 2010).

Thierry et al.'s conclusion that colour terms affect early ERP components is central to the debate about the time course that colour terms affect colour processing. However, it is at odds with another two other ERP studies, which also do not suffer stimulus issues (Clifford et al., 2012; He et al., 2014).

He et al. (2014) measured just-noticeable differences (JNDs) over a range of blue and green colours in native English speakers; a JND is the smallest perceptual difference in colour that can be perceived. These measurements were then used to select colours for an oddball task in which participants saw the same 'standard' colour on the

majority of trials and were required to count occasionally-occurring deviant stimuli. The deviants were either same- or different-category to the standard, and the standard-deviant colour difference was equated in the number of JNDs. This provides a method of investigating the effect of colour terms on supra-threshold colour differences and the time course of such category effects without the stimulus issues that arise from relying on colour spaces to equate colours. The earliest category effect that was found was in posterior N2 (230 – 246 ms), suggesting that language did not affect earlier, sensory stages of processing, rather it affected subsequent, post-perceptual stages.

In the study by Clifford et al. (2012), a group of participants were trained over a period of time to categorise colours into two new categories. Like He et al., they used an oddball task that required participants to count deviant stimuli. They found that compared to a control group, who had not received the same training, category effects resulting from the newly trained categories were only present in later, post-perceptual ERP components, rather than early components. Stimulus issues are unlikely to account for these findings because both groups saw exactly the same hues and the groups differed only in the way that they categorised those hues.

There is therefore disagreement about whether colour terms affect early stages of visual processing (Thierry et al., 2009) or subsequent post-perceptual stages (Clifford et al., 2012; He et al., 2014). One possible explanation for the lack of category effects in early ERP components in Clifford et al.'s study is that the categories had only recently been trained and were therefore not as 'cognitively ingrained' as established colour terms. However, this cannot account for the differences in Thierry et al. and He et al.'s studies: one could argue that the blue-green categorical distinction is more basic than that of the categorical distinction between blues in Greek, and therefore that one might expect early category effects should be stronger in He et al. than Thierry et al.'s study. Another possible explanation for differences in conclusion across studies may lie with differences in the tasks. In Thierry et al.'s study reporting early category effects, participants attended to the shape of the stimuli, whereas in those studies reporting later category effects, participants attended to the colour of the stimuli. This raises the possibility that early category effects only occur when colour is not attended. Another possibility is that comparing speakers of different languages rather than comparing same- and different-category colour responses within a language is more sensitive to early category effects.

The current study aims to investigate these issues further. In particular the study aims to seek further evidence that cross-linguistic differences in colour lexicons result in differences in early ERP components as so far this has only been shown in the one investigation by Thierry et al. (and the re-analysis by Athanasopoulos et al., 2010). We compared native English speakers and native Russian speakers because the Russian language, like the Greek language, divides lighter (*goluboj*) and darker (*sinij*) blue hues into two distinct categories (Davies & Corbett, 1994; Paramei, 2005), whereas the English language does not. We firstly ran a colour naming study in the blue region to enable us to precisely locate *sinij*, *goluboj*, and the boundary between them in CIELUV space (see Supplementary 1). Next, so as to create JND-equated colour stimuli for the oddball task, we measured discrimination thresholds (i.e., JNDs) in native English and native Russian speakers over a range of blue hues (Experiment 1). These were in the region of the light/dark blue category that exists in the Russian language. These measurements also provided an opportunity to assess whether language affects discrimination thresholds. Two prior studies that investigated the effect of categories on discrimination thresholds found no systematic category effects on JNDs (Roberson, Hanley, & Pak, 2009; Witzel & Gegenfurtner, 2013), which may be supportive of He et al.'s (2014) argument that language only affects post-perceptual processes. Based on Thierry et al.'s (2009) finding of language affecting P1, one might expect that cross-linguistic differences in colour categorisation could affect JNDs as well. For example, if perceptual differences are stretched around a category boundary and condensed within categories (e.g., Goldstone & Hendrickson, 2010; Harnad, 1987)**,** this perceptual 'warping' of colour may result in heightened sensitivity to colour difference in Russian speakers, but not in English speakers, around the boundary between the two Russian blues. In other words, native Russian speakers may have smaller JNDs (i.e., better discrimination) than English speakers in the boundary region where the two categories are distinguished.

Next, we used the approach of He et al. (2014) and equated colour stimuli in JNDs and participants completed an oddball task where the colours were attended (Experiment 2). We compared the electrophysiological activity elicited in response to three blue hues around the boundary between the two Russian blues. We analysed multiple ERP components (P1, N1, P2-N2, P3) to examine whether a category effect occurs in early ERP components (e.g., Thierry et al., 2009), or in later components (e.g.,

He et al., 2014). In other words, does the categorical relationship of the colours affect the amplitude and/or latency of ERP components elicited by those colours, and does that result in cross-linguistic differences that align with differences in Russian and English naming of blues? We also measured behavioural responses on a subsequent supra-threshold oddball task in the same participants for the same colours used in the ERP task.

3.3 Experiment 1: Effect of colour terms on chromatic discrimination thresholds

3.3.1 Overview

We compared chromatic discrimination thresholds (JNDs) in native Russian and native English speakers in a light blue − dark blue region of colour space where the Russian colour lexicon makes a distinction between lighter (*goluboj*) and darker blue hues (*sinij*), whereas the English colour lexicon has just one basic colour term (*blue*). If colour categorization results in a warped perception of colour, whereby there is heightened discriminability in the region of the category boundary and reduced discriminability within categories (Goldstone & Hendrickson, 2010; Harnad, 1987), then we expect that JNDs for Russian speakers will be smaller around the goluboj-sinij category boundary than for hues more centrally within either of these categories, and that JNDs for English speakers will not show this pattern.

3.3.2 Methods

3.3.2.1 Participants

Eight native Russian speakers (5 female; mean age = 22.5 years; *SD* = 4.1 years; range = 18 − 29) and 10 native British English speakers (5 female; mean age = 23.9 years; *SD* = 5.5 years; range = 19 − 33) participated in this experiment. Participants were recruited from the University of Sussex and the surrounding area. All observers were screened for colour vision deficiencies using the Ishihara test (Ishihara, 1987) and the City University Test (Fletcher, 1980) under natural daylight. Observers were naive to the purpose of the study, provided written informed consent and their time was reimbursed with money or research credits. The study was approved by the Cluster-

based Ethics Research Committee of Psychology and Life Sciences at University of Sussex (AF0811).

3.3.2.2 Set up

Participants were seated in a dark room; the only source of light was a gamma-corrected 20" Diamond Pro 2070SB CRT monitor (Mitsubishi, Tokyo, Japan; spatial resolution: 1600×1200; refresh rate: 100 Hz) driven by an Quadro FX1800 graphics card (NVIDIA, Santa Clara, USA) with a colour resolution of 8 bits per channel. Participants sat at a distance of 57 cm and used a chin rest. All programming was carried out in Matlab (The MathWorks Inc., 2007) using the Psychophysics toolbox (Brainard, 1997).

3.3.2.3 Stimuli and design

Test stimuli were 17 colours that ranged across the two Russian blue terms '*sinij*' (darker blue) and '*goluboj*' (lighter blue). We used the colour space CIELUV as a basis and then measured colour discrimination around the test colours so that our data were based on psychophysical measurements and not constrained to CIELUV. In this colour space the test stimuli were isochromatic (C^*uv = 35) and had the same hue angle ($h$uv = 231°). The test stimuli differed only in lightness and this ranged from $L^* = 29$ to $L^* = 61$ in increments of $\Delta L^* = 2$ units. The stimuli and task instructions were presented on a background grey metameric with illuminant D65 and of a luminance of 16.7 cd/m^2. Participants were tasked with correctly identifying one stimulus (the 'odd-one-out'), which differed in lightness from three other identical stimuli. With this design, if the odd-one-out can be reliably identified, the odd-one-out is modified on subsequent trials to be more similar to the three stimuli until a point is reached where any further change results in the stimuli being too similar to be reliably differentiated. This point is referred to as a detection threshold or a 'just-noticeable difference' (JND). We used a 3-up-1-down version of the 4-Alternative Forced-Choice (4AFC) discrimination task reported by Krauskopf and Gegenfurtner (1992). In this approach, three correct responses in a row results in the ΔL^* units between the odd-one-out and the test lightness on the subsequent (fourth) trial being reduced (i.e., on the subsequent fourth trial the task

becomes more difficult). One incorrect response results in the ΔL^* units being increased to make the subsequent trial more easy. For each test lightness, there were two staircases (ascending versus descending in lightness), except for the test hues of the lowest ($L^* = 29$) and highest lightness ($L^* = 61$), for which there were single staircases (descending and ascending respectively). At the start of each staircase, the difference in lightness between the odd-one-out and the three isoluminant circles was always the same ($\Delta L^* = 3$). For example, for the test lightness of $L^* = 45$, the first trial of an ascending staircase would display three isochromatic circles of $L^* = 45$, and one odd-one-out of $L^* = 42$. In the descending staircase the odd-one-out would be $L^* = 48$. To measure detection thresholds we used five reversal points for each staircase. A reversal point occurs between trials that differ in detection performance. For example, after three correct responses, ΔL^* is decreased on the subsequent trial. If an incorrect response is then made on this subsequent trial, ΔL^* is increased, and this corresponds to a reversal in performance (i.e., decreasing to increasing ΔL^* or increasing to decreasing ΔL^*). A staircase ended after the completion of these five reversal points. The specific ΔL^* applied at each step on the staircase corresponded to a factor of 0.259. This represents the Weber fraction ascertained in previous colour discrimination studies (Witzel & Gegenfurtner, 2013). A JND was calculated as the mean of these reversal points (Levitt, 1971).

3.3.2.4 Procedure

We measured JNDs for the same 17 test hues in each participant. Participants were first dark-adapted for five minutes; during this time they read the task instructions, which were presented to each participant in their native language. Instructions were translated from English to Russian by a competent bilingual speaker, and back-translated into English by a second bilingual speaker to confirm accuracy. Each trial began by presenting a black, central fixation point for 1,000 ms. The test stimuli were then presented for 500 ms in a 2×2 grid (see Figure 3.1 for stimuli dimensions). Three were identical and their lightness corresponded to one of the 17 test hues, while one differed in lightness from the other three (the odd-one-out). The position of the odd-one-out on the grid was always random. Participants identified the odd-one-out by using their dominant hand on a numeric keyboard to specify its location (each of the four

positions was assigned an individual key, e.g., "1" for bottom-left, "9" for top-right, etc.). Participants were asked to respond on all trials. Feedback was provided after each response: the fixation point turned a lighter grey than the background for correct responses or a darker grey for incorrect responses. There were 17 blocks (one for each of the 17 test hues) and in each block ascending and descending trials were randomised (except the two for which a single staircase was used).
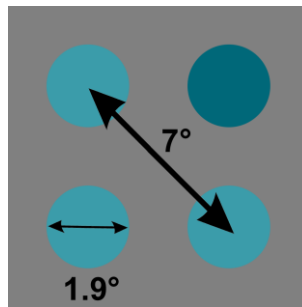

Figure 3.1. Example and dimensions of stimuli in visual angle used in the 4AFC task in Experiment 1. Four circles were presented on an achromatic background and the target was always the odd-one-out (here located top-right).

3.3.3 Results

The data from two Russian participants and one English participant were excluded due to a software error. For the remaining 15 participants we calculated the size of their mean JND for each of the 17 test hues by averaging all relevant reversal points. We excluded the first reversal point of each staircase to remove artefacts (Levitt, 1971; Witzel & Gegenfurtner, 2013). JNDs are reported as ΔL^*: the distance in perceived lightness between the test and comparison stimuli.

We were primarily interested in whether JNDs around the boundary between the two Russian blues were smaller in native Russian speakers compared to native English speakers. We consequently grouped the data from the 17 test hues into three groups: JNDs for darker blue hues from L^* 29 – 39 (i.e., *sinij*), JNDs for lighter blue hues from L^* 51 – 61 (i.e., *goluboj*) and those JNDs falling towards the boundary between the two

Russian blues (*L** 41 − 49). This manner of grouping was established in an earlier colour naming study, which mapped the location of the two Russian blues in CIELUV (see Supplementary 1). We ran a mixed ANOVA containing the within-subjects factor of Colour with three levels (*sinij*, *goluboj,* and the boundary), and the between-subjects factor of Group (2-levels [Russian versus English speakers]). There was a main effect of Colour, $F(2,26) = 102.4$, $p < .001$, see Figure 3.2a. Bonferroni-corrected paired-samples *t*-tests ($\alpha = .05/3$) were subsequently run on the data collapsed over the factor of Group. These showed that JNDs for the group of darker blue hues (*sinij*; *L** 29 − 39; $M = 3.00$; $SD = 0.55$) were significantly larger than JNDs for hues in the boundary region (*L** 41 − 49; $M = 2.54$; $SD = 0.45$, $p = .001$) as well the group of lighter blue hues (*goluboj*; *L** 51 − 61; $M = 1.84$; $SD = 0.46$; $p < .001$). JNDs for the boundary hues were also significantly larger than those in the group of lighter blue hues ($p < .001$). The main effect of Group was not significant, $F(1,13) = 1.69$, $p = 0.22$, and neither was the Colour × Group interaction, $F(2,26) = 2.46$, $p = 0.11$.
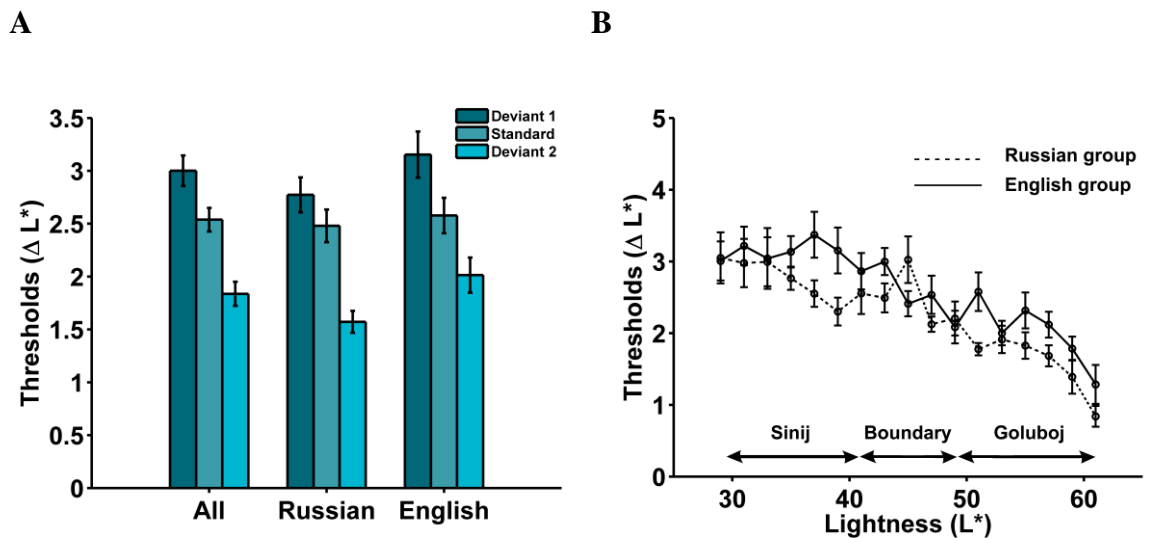
Figure 3.2. JNDs averaged across participants. (A) JNDs grouped into three groups (ascertained from prior pilot work, see Supplementary 1) corresponding to the Russian blues (*sinij: L** 29 − 39; *goluboj: L** 51 − 61) and the boundary between the two (*L** 41 − 49), and presented separately for native Russian and native English speakers, as well as the combined average (All) for all participants. (B) JNDs for all 17 test hues presented separately for native Russian speakers (dotted line) and native English speakers (bold line). JNDs are calculated as Euclidean

distances (*y*-axis) in the perceived lightness from the test hues (*x*-axis) in CIELUV. Errors bars represent ± 1 SEM.

We also analysed the data without grouping the test hues into categories to examine whether grouping the data obscured any subtle effects (Figure 3.2b). We ran a mixed ANOVA containing the within-subjects factor of Lightness (17-levels) and the between subject factor of Group (2-levels [Russian versus English speakers]). We found a significant effect of Lightness, $F(16,224) = 15.7$, $p < .001$. To follow this up we ran 17 one-sample *t*-tests that compared JNDs at each test lightness to the grand averaged JND for the whole sample ($M = 2.730$; $SD = 1.109$). We applied the Bonferroni correction for multiple comparisons ($\alpha = .05/17$). Four comparisons were significant ($L^* = 53$, $p = .0014$; $L^* = 57$, $p = .0018$; $L^* = 59$, $p = 4.50E\text{-}05$; $L^* = 61$, $p = 2.54E\text{-}06$). There was no significant difference in the size of the JNDs between the two groups, $F(1,13) = 1.8$, $p = .20$, and no Lightness × Group interaction, $F(16,224) = 1.61$, $p = .071$.

3.3.4 Discussion

We compared discrimination thresholds (JNDs) in native Russian and native English speakers for a range of blue hues that spanned two colour categories in the Russian language but a single category in the English language. We found no significant difference in the size of JNDs between the two groups, and no suggestion that the Russian JNDs were smaller than English only in the region of the Russian blue category boundary. The two groups exhibited a similar trend: We found JNDs to be smallest (i.e., the task was easiest) when test stimuli approached isoluminance with the background grey. This is likely due to the well-documented finding that the size of a JND is proportional to the intensity of a stimulus; JNDs are smaller if a stimulus is less intense and larger when it is more intense (i.e., Weber's Law, see Fechner, 1860). In summary, we did not find that the way colour is categorized in language affects colour discrimination at threshold.

3.4 Experiment 2: Oddball tasks

3.4.1 Overview

Experiment 2 aimed to further clarify the time course of the potential effect of colour terms on colour processing of supra-threshold colour differences by measuring cortical activity elicited to different hues. We investigated category effects by comparing ERPs elicited to three blue hues that varied in lightness in native Russian and native English speakers. Stimuli were chosen such that one of the blue hues was a different lexical category (*goluboj;* deviant 2) to the other two hues (*sinij;* the standard and deviant 1) for Russian speakers but that all three hues were the same lexical category for English speakers (*blue*). If colour terms affect colour processing then we would expect an analysis of ERP components to reveal a difference in amplitude or latency elicited to the deviant that is from a different category (deviant 2) to the standard than the deviant from the same-category (deviant 1) as the standard according to Russian colour terms, and that this effect would be found for the native Russian speakers only (i.e., a category effect). The stimuli were equated in JNDs using the discrimination data from Experiment 1.

3.4.2 Methods

3.4.2.1 Participants

Thirteen native Russian speakers (7 female: mean age = 25.2; *SD* = 5.3; range = 18 – 35) and eighteen native British English speakers (7 female: mean age = 23.6, *SD* = 4.5; range = 18 – 33) took part in this study. None of the participants took part in Experiment 1 and all other details concerning participant recruitment were the same as Experiment 1. The mean score on the Nation (1990) vocabulary test for the 12 Russian participants included in the final analysis was 72/90 (*SD* = 9.8; range = 58 – 88). This is towards the 8,000-word level. The mean years spent living in the UK was 2.3 (*SD* = 1.4 years; range = 0.5 – 5.0 years) and the mean years spent learning English was 6.6 (*SD* = 3.5 years; range = 1.5 – 12.0 years).

3.4.2.2 Set up

Participants were seated in a dark room, the only source of light was a 22" Diamond Plus 230SB CRT monitor (Mitsubishi, Tokyo, Japan; colour resolution: 8 bits∕channel; spatial resolution: 1024 × 768; refresh rate: 75 Hz). Participants were seated 77 cm away from the monitor. All materials were prepared with e-Prime 2 (Psychology Software Tools, Inc.).

3.4.2.3 Stimuli and design

Participants completed the same oddball task two times. In the first instance the spontaneous electroencephalogram (EEG) was recorded for subsequent analysis (i.e., as ERPs), and in the second instance behavioural performance was recorded. In the oddball tasks three blue hues, which varied from each other in lightness, were sequentially-presented a large number of times in a randomized order. One of the hues was presented on the majority of trials (referred to as 'the standard'), while the other two hues (referred to as 'deviants') were occasionally presented. The standard was the middle lightness, one deviant was lighter than the standard and the other deviant was darker than the standard. The key manipulation is that for native English speakers, the stimuli all comprise the same colour category *blue*, whereas for native Russian speakers, the standard and one of the deviants are from the same lexical colour category (the standard and 'deviant 1': *sinij*), and the standard and other deviant ('deviant 2': *goluboj*) are from a different categories. The categorical relationship between the standard and deviants was based on Russian colour naming data (see Supplementary 1), and based on a naming consensus criterion of > 62% (see Figure 3.3). The three hues were each separated by 2.5 JNDs based on the discrimination data obtained in Experiment 1.The same background grey was used as Experiment 1. The chromaticity coordinates for the three hues are displayed in Table 3.1.

3.4.2.4 Procedure

Participants first completed a visual oddball task during which spontaneous electroencephalogram (EEG) was recorded for subsequent analysis (ERPs). Participants

were presented with a randomised sequence of the three blue hues and required to count the number of deviants (see Figure 3.4 for a graphic of the task procedure). On 83.5% of trials the stimulus was the standard, and on remaining trials it was one of the two deviants (equally balanced). On each trial the stimulus ($7.5° \times 7.5°$) was presented for 400 ms, with a randomised inter-stimulus interval ranging from $1200 - 1600$ ms. The
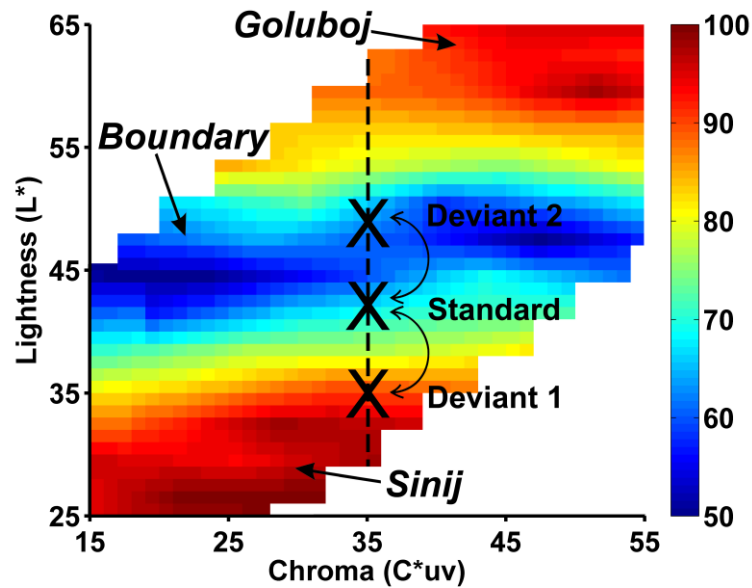

Figure 3.3. Defining the three blue hues for the oddball tasks. The heat map displays the degree of naming agreement (%) amongst native Russian speakers for a range of blue hues as being either *sinij* or *goluboj* ascertained by measuring their location in CIELUV (for further details see Supplementary 1). Higher agreement for s*inij* can be seen as the cluster of high consensus indicated in red towards bottom-left; lower naming agreement indicated in blue for hues falling towards the sinij-goluboj boundary; and higher naming agreement in red for *goluboj* is towards top-right. Dotted line displays the range over which discrimination thresholds were measured (Experiment 1). Three hues were defined so as to be spaced 2.5 JNDs apart (indicated by the double-headed arrows) and their location in CIELUV is identified by rotated crosses and labelled accordingly (Deviant 1, Standard, and Deviant 2). As can be seen in the figure, deviant 1 and the standard were named as *sinij*, whereas deviant 2 was named as *goluboj*.

background remained the same grey throughout. There were eight blocks each of 100 trials. The first eight trials in each block were always the standard. The following trials were pseudo-randomised so that a deviant was always followed by the standard. In each block the number of deviants ranged from 15 to 18. These frequencies each featured twice during a testing session. After each block, participants were asked to report the number of deviants they had counted. Participants first completed a practice block during which three green hues, approximately equivalent in lightness and chroma to the experimental stimuli, were presented on the same grey background in the same format as the experimental trials.

Table 3.1. Chromaticity coordinates for the three hues used in Experiment 2 in CIE1931 (x,yY) and CIELUV (lightness: L^*; chroma: C^*uv). Luminance (Y) is cd/m^2.

Stimulus name	x	y	Y	L^*	C^*uv
Deviant 1	0.216	0.257	4.61	34.79	35
Standard	0.232	0.268	6.88	42.00	35
Deviant 2	0.241	0.275	9.40	48.37	35

Background grey: $x = 0.313$, $y = 0.329$, $Y = 16.72$ cd/m^2; Whitepoint: $Y = 50$ cd/m^2.

After completing this EEG version of the oddball task, participants next completed four further blocks of the same task but EEG was not recorded and participants were instead required to make a manual response to deviant stimuli, rather than count them. All other aspects were the same as the previous task. Participants were asked to respond as quickly and accurately to each stimulus and to identify the stimulus as the standard with the 'c' keyboard key, or a deviant with the 'm' key (counterbalanced across participants). Data from this task were not included in the analysis of the EEG data.

Following this task, the Russian participants completed two further tasks. Firstly they completed a 2AFC colour naming task, whereby each of the three hues used in the earlier experiments were presented individually 25 times in a random order. Participants were asked to indicate whether the stimulus (7.5° × 7.5°) was *goluboj* or *sinij* by pressing the 'c' or 'm' keyboard key (counterbalanced across participants). On each trial the stimulus remained onscreen until a response had been made. Following this task, these participants then completed the 90-item English vocabulary proficiency test (Nation, 1990), which measures vocabulary across five different levels. These range from the 2,000-word level (less proficient) to the 10,000-word level (more proficient) and is scored out of 90.
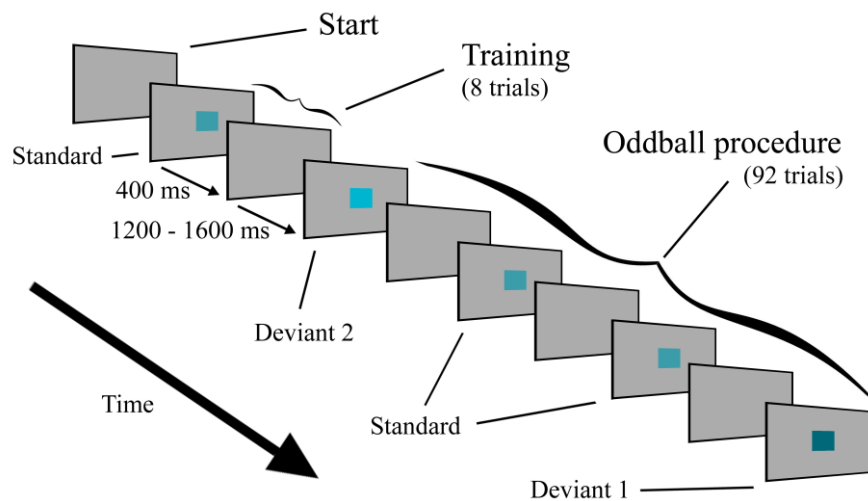
Figure 3.4. Task procedure for one block of trials for the visual oddball task (Experiment 2). Participants were tasked with counting the number of deviant stimuli in the EEG version of the task. In the behavioural version they responded to deviants on a keyboard. One deviant was lower and the other deviant higher in lightness than the standard. These hues span a single colour term in the English language (*blue*) while Russian participants reliably named both the standard and deviant 1 as '*sinij*' (darker blue) and deviant 2 as '*goluboj*' (lighter blue). Each block started with 8 training trials of the standard. The remaining 92 trials were quasi-randomised so that a deviant was always followed by the standard.

3.4.2.5 Data Recording and Processing

EEG data was recorded and processed with NeuroScan SynAmps[2] amplifiers and SCAN 4.3 software (NeuroScan/Compumedics, Inc.) at a digitizing rate of 1000 Hz. A physical band-pass filter was applied to online recording (0.15 − 30 Hz). EEG was recorded from 30 electrode sites: FP1, FPz, FP2, F7, F3, Fz, F4, F8, FCz, T7, C3, Cz, C4, T8, CP3, CPz, CP4, P7, P3, Pz, P4, P8, PO7, PO3, POz, PO4, PO8, O1, Oz, O2, using Ag-AgCl electrodes, as well as the average of the left and right mastoid references (re-referenced offline). Eye blinks and eye movements were monitored via one bi-polar horizontal electro-oculogram (EOG) channel located laterally of the canthi and one mono-polar vertical electro-oculogram channel located below the left eye. Impedance of each channel was reduced below 5kΩ prior to data collection. Following EEG recording, a zero phase-shift low-pass filter with amplitude cut off frequency of 30 Hz and 24dB/oct roll-off was applied to the data. The EEG data were analysed as segments and epoched off-line with a window extending 800 ms after stimulus onset, relative to a 100 ms pre-stimulus baseline. Trials containing a voltage exceeding ±60 µV at any electrode site were identified as artefacts and removed from subsequent analysis. ERPs were generated by averaging EEG activities over trials time-locked to stimulus onset.

3.4.3 Results

Twelve native Russian speakers (6 female, mean age = 25.7, *SD* = 5.4; range = 18 - 35) and twelve native British English speakers (6 female, mean age = 24.5, *SD* = 5.0; range = 18 − 33) were included in the final analysis. An additional seven participants were excluded: Two elicited strong alpha waves (8 − 13 Hz EEG rhythmic activity) which contaminated the ERP waveforms substantially. Two exhibited a very poor signal-to-noise ratio following averaging due to the presence of artefacts in the EEG data. One Russian participant's naming did not follow the same trend as the other participants and instead named the standard *goluboj*. It was crucial to the hypothesis that the Russian participants named the test stimuli in the same manner and so this participant was excluded. Finally, two participants had very poor performance on the EEG counting task, i.e., they were not able to discriminate the deviants from the standard stimulus.

3.4.3.1 Colour naming

The 12 Russian participants included in the final analysis reliably named the stimuli as predicted: Both deviant 1 ($M = 100\%$; $SD = 0.0\%$) and the standard ($M = 90.3\%$; $SD = 15.1\%$) were reliably named *sinij* (i.e., darker blue) and deviant 2 ($M = 93.3\%$; $SD = 14.2\%$) was reliably named *goluboj* (i.e., lighter blue).

3.4.3.2 EEG oddball task

ERP components were calculated by averaging mean amplitudes at electrode sites separately for each of the three stimuli across those time windows demonstrating pronounced activities. This is a standard method of analysis for both general ERP data (e.g., Luck, 2005; Rugg & Coles, 1996) as well as ERP data for categorical colour perception tasks (e.g., Fonteneau & Davidoff, 2007; He et al., 2014; Holmes et al., 2009). Time windows and electrode sites were chosen based upon prior findings (Clifford et al., 2010; He et al., 2014), and following visual inspection of the grand averaged ERP waveforms presented in Figure 3.5. We analysed mean amplitudes of all components, as well as peak latency of P1, and P2 because these components had discernible peaks. The analyses were mixed ANOVAs containing the within-subjects factor of Stimulus with three levels (the standard, deviant 1 and deviant 2), and the between-subjects factor of Group with two levels (English speakers versus Russian speakers). Where appropriate, the within-subjects factors of Hemisphere (right versus left) and Region were included in the analyses to investigate whether effects were more or less pronounced over different areas of the scalp. A main effect of Stimulus indicates different ERP responses were elicited to the three different blue hues. A main effect of Group reveals general differences in the ERP component between the two groups, rather than a specific effect of language. More crucial to the hypothesis is the finding of an interaction between Stimulus and Group. This is specifically revealed as a language-specific category effect characterised by a significantly different ERP response in the Russian group to deviant 2 (i.e., the different-category hue for Russian speakers) than to the other two stimuli (the standard and deviant 1, which are the same-category stimuli for Russian speakers). No such pattern would here by found for the English speakers. Greenhouse-Geisser corrections were applied to those instances in which the assumption of sphericity had been violated and all significant main effects
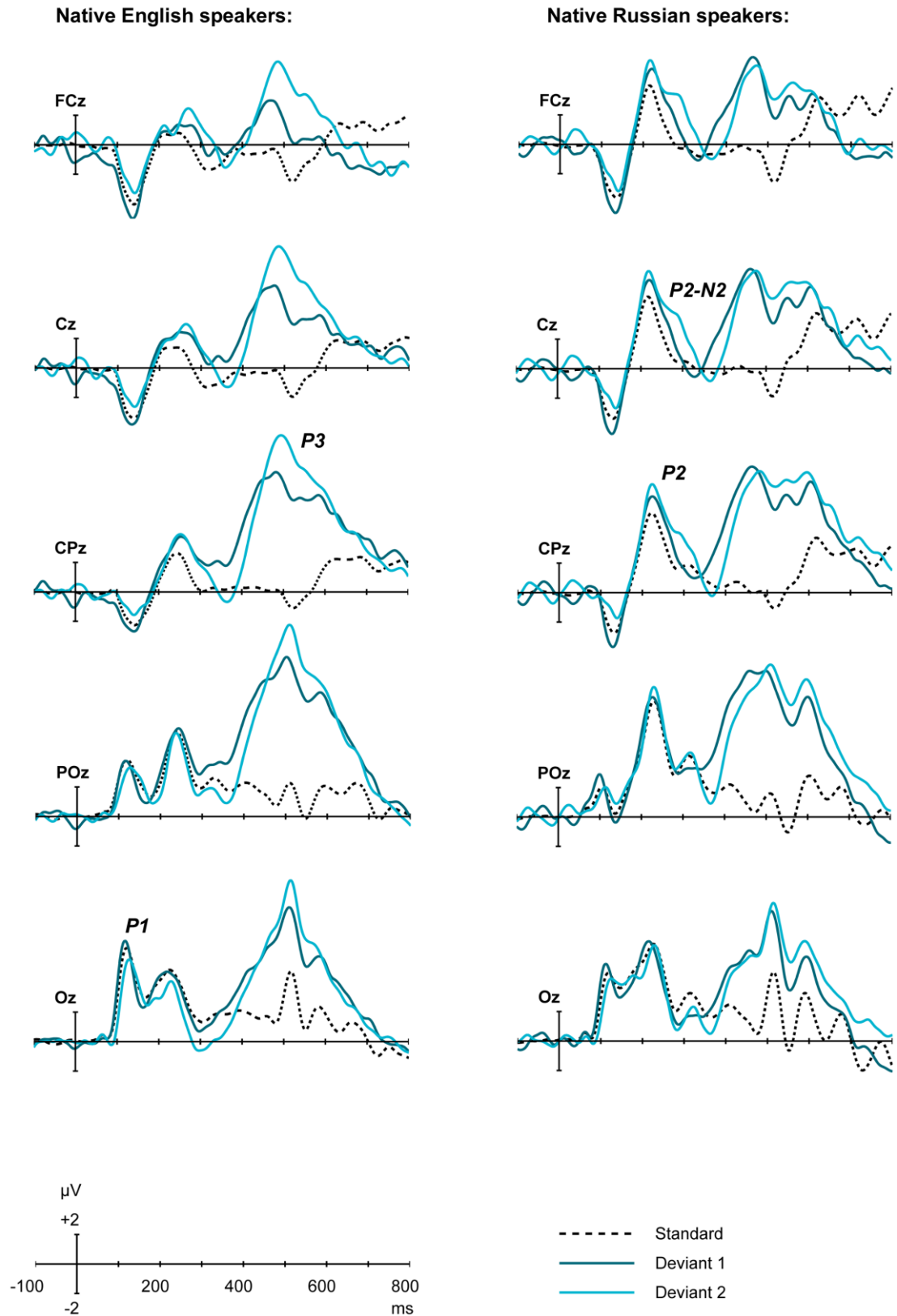
Native English speakers: **Native Russian speakers:**

Figure 3.5. Representative ERP waveforms at five electrode locations presented separately in the left column for native English (*n* = 12) and in the right column for native Russian (*n* = 12) speakers. Electrode locations are specified above the

y-axis (e.g., Oz). ERPs elicited to the standard (black dotted line), deviant 1 (solid dark blue line) and deviant 2 (solid light blue line) are displayed. ERP components (e.g., P1) are labelled on one waveform each.

were followed up with pairwise comparisons using Fisher's least significant different (LSD) post-hoc test.

P1 analyses: Peak amplitude occurred maximally at occipital sites at 100ms for Russian participants and 110ms for English participants. A time window of 90-110 ms was selected for the Russian group, and 100-120 for the English group to reflect maximal deflection, and both were averaged over three occipital sites (O1, Oz, O2). There was no evidence of a language specific category effect in P1 amplitude as there was no significant interaction between the factors of Group and Stimulus, $F(2,44) = 0.18$, $p = .84$. There was also no main effect of Group, $F(1,22) = 1.63$, $p = .22$. There was however a main effect of Stimulus, $F(1.35, 28.95) = 17.48$, $p < .001$ (see Figure 3.6a). Pairwise comparisons found that the darkest stimulus (deviant 1) elicited a significantly larger amplitude ($M = 4.18$ µV; $SD = 3.19$ µV) than both the standard ($M = 3.39$ µV; $SD = 2.61$ µV*; p = .006$) and deviant 2 ($M = 2.25$ µV; $SD = 2.53$ µV; $p < 001$). P1 amplitude was also significantly larger in response to the standard than to deviant 2 ($p < .001$). For P1 peak latency, there was also a significant main effect of Stimulus that followed a reliable pattern, $F(1.33, 29.22) = 6.79$, $p = .009$. ERPs peaked significantly earlier in response to the darkest stimulus (deviant 1; $M = 113.6$ ms; $SD = 16.1$ ms) than both the standard ($M = 118.3$ ms; $SD = 14.3$ ms, $p = .021$) and deviant 2 ($M = 124.1$ ms; $SD = 19.0$ ms, $p = .009$). The standard also produced a significantly earlier peak latency than deviant 2 ($p = .043$). There was no main effect of Group on peak latency, $F(1,22) = 2.46$, $p = .131$, and no Stimulus × Group interaction, $F(2,44) = 0.48$, $p = .62$, see Figure 3.6b.

Given that the non-significant Stimulus x Group interaction is critical to the hypothesis that colour terms affect early stages of visual processing, we also used Bayesian statistics to examine the degree to which the null, $p(H_0 | D)$, or alternative hypotheses, $p(H_1 | D)$, were more-or-less likely (Masson, 2011), based on guidelines outlined by Raftery (Raftery, 1999). We consequently calculated the Bayesian information criterion (BIC) for the Stimulus x Group interaction, and this revealed

strong support in favour of the null hypothesis (ΔBIC = 7.34, $p(\text{H}_0 \,|\, \text{D})$ = .98) for mean amplitude. For peak latency, there was also strong support for the null for the Stimulus x Group interaction (ΔBIC = 6.71, $p(\text{H}_0 \,|\, \text{D})$ = .97).
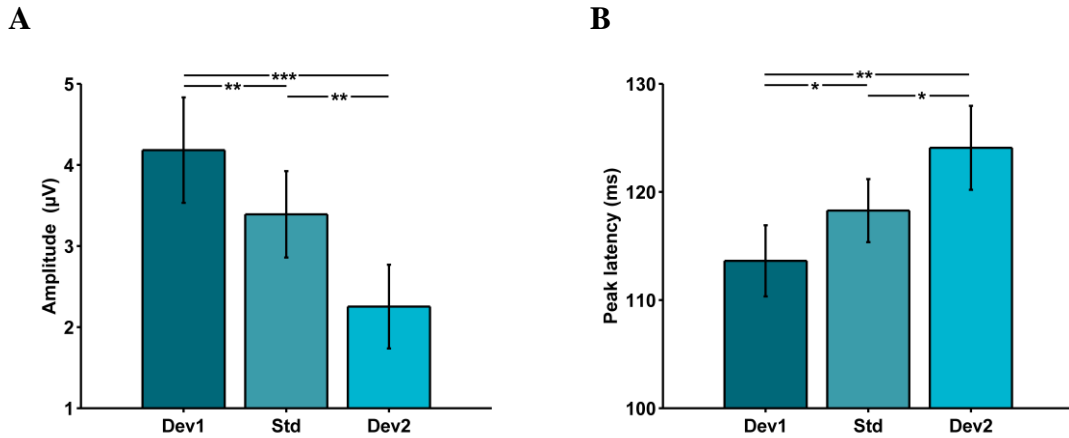
A **B**

Figure 3.6. P1 component (Experiment 2) for three blue hues varying in lightness elicited in native Russian (n = 12) and native English (n = 12) speakers: Deviant 1 (Dev1), the standard (Std), and deviant 2 (Dev2). No significant differences were found between the two groups, therefore the data are presented collapsed across both groups (for figures presenting the data separately for each group, see Supplementary 2). (A) Mean amplitude (μV). (B) Peak latency (ms). Significant differences denoted by asterisks (* $p < .05$, ** $p < .01$; *** $p < .001$). Error bars represent ± 1 SEM.

P2 analyses: The P2 peaked around 250 ms and ranged maximally from central to parietal areas. The specific peak differed slightly across the two groups, consequently we used a window of 220 – 240 ms for the Russian group and 240 – 260 for the English group, over three electrode sites (collapsed across CP3, CPz and CP4, and from Cz and Pz). This reflected the maximal activity of this component in both groups. Despite a visible difference between the amplitude of P2 across the two groups (see Figure 3.5), the main effect of group in a three-way ANOVA did not reach significance, $F(1,22)$ = 3.95, p = .06. Like the earlier peaking P1 component, there was a main effect of Stimulus on mean amplitude, $F(2,44)$ = 7.96, p = .001, however here the pattern was

different. Post hoc analysis revealed that the standard (M = 3.91 μV; SD = 3.41 μV) elicited a significantly smaller P2 than both deviant 1 (M = 4.93 μV, SD = 3.96 μV; p = .006) and deviant 2 (M = 5.30 μV, SD = 3.72 μV; p = .001). The two deviants did not significantly differ (p = .35). This indicates a general oddball effect (a different response to deviant stimuli compared to the standard), rather than a category effect. The main effect of Region on mean amplitude was significant, $F(1.15, 25.25) = 78.83$, $p < .001$, and this was due to greater activity over parietal areas versus central and centro-parietal sites, rather than a category effect. There were no two- or three-way interactions between the factors (all Fs < 1) in the analysis of mean amplitude. Analysis of peak latency revealed no main effect of Stimulus, $F(2,22) = 1.85$, $p = .17$, or Group, $F(1,22) = 0.92$, $p = .35$. There was a significant Stimulus × Group interaction, $F(2,44) = 3.62$, $p = .035$, suggesting a potential language-specific category effect, however post hoc analysis found no significant main effect of Stimulus on peak latency in either the Russian participants, $F(2,22) = 2.83$, $p = .080$, or the English participants, $F(2,22) = 1.73$, $p = .20$, consequently no post-hoc pairwise comparisons were carried out.

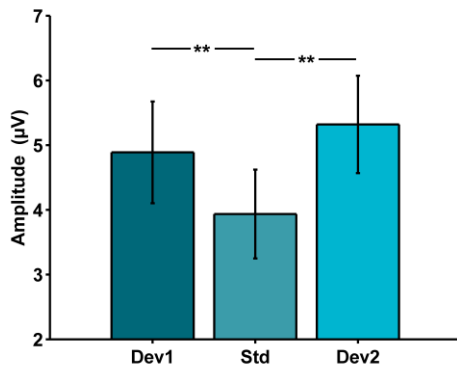Figure 3.7. Mean amplitude (μV) for the P2 component elicited in response to three blue hues in native Russian and native English speakers (Experiment 2). No significant differences were found between the two groups, therefore the data are presented collapsed across both groups. (** $p < .01$). Error bars represent ±1 SEM.

P2-N2 analyses: We observed a difference in mean amplitude between the two groups for the falling curve following peak P2 amplitude descending towards peak amplitude of the N2 over central areas. Like the subtle difference in peak amplitude between the groups in the P1 and P2 components, this deflection also occurred at slightly different times for the two groups. Time windows were chosen to reflect this maximal activity accordingly, corresponding to a window of 290 – 320 ms for the Russian group, and 280 – 310 ms for the English group, collapsed over central areas (C3, Cz, C4). A two-way ANOVA found no main effect of Group, $F(1,22) = .01$, $p = .91$, but there was a main effect of Stimulus, $F(2,44) = 8.13$, $p = .001$. This was the result of deviant 2 ($M = 2.06$ µV; $SD = 3.63$ µV) eliciting a significantly larger amplitude than both the standard ($M = 0.31$ µV; $SD = 2.97$ µV; $p < .001$) and deviant 1 ($M = 0.83$ µV; $SD = 3.56$ µV; $p = .025$) in the data collapsed across the two groups, while the standard and deviant 1 did not significantly differ ($p = .198$). More crucial to the hypothesis was a significant Stimulus × Group interaction, $F(2,44) = 3.39$, $p = .043$, and subsequent post hoc analysis revealed a language-specific category effect. This was shown by a significant main effect of Stimulus for both the Russian, $F(2,22) = 4.88$, $p = .018$, and the English group, $F(2,22) = 7.22$, $p = .004$. However, when these one-way ANOVAs were followed up with pairwise comparisons, they revealed the category effect was specific to the Russian group. In this group deviant 2 elicited a significantly larger mean amplitude ($M = 2.37$ µV; $SD = 3.87$) over this window than both the standard ($M = 0.81$ µV; $SD = 3.03$ µV; $p = .042$) and deviant 1 ($M = 0.24$ µV; $SD = 4.10$ µV; $p = .029$), while the standard and deviant 1 did not significantly differ ($p = .33$). This pattern was different in the English group for whom deviant 2 ($M = 1.76$ µV; $SD = 3.52$ µV) was not significantly different to deviant 1 ($M = 1.42$ µV; $SD = 3.0$ µV; $p = .57$) but both deviant 1 ($p = .014$) and deviant 2 ($p = .003$) were significantly larger in amplitude than the standard ($M = -0.20$ µV; $SD = 2.96$ µV). In other words, there was a language-specific category effect in the Russian group, and a general oddball effect in the English group, see Figure 3.8.
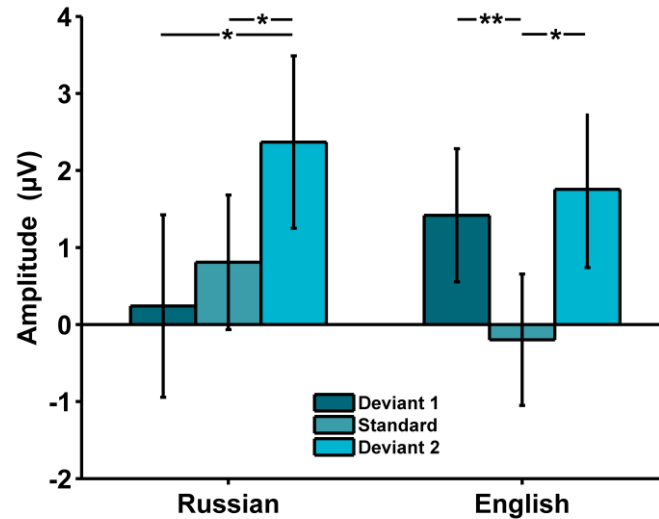
Figure 3.8. Mean amplitude (µV) elicited by the three stimuli (standard, deviant 1, and deviant 2) between the peak P2 and peak N2 component. There was a different trend across the two groups. In the Russian group there was a language-specific category effect, whereby deviant 2 (the different-category deviant for this group) was significantly larger than the other two stimuli. In the English group, the two deviants did not significantly differ. (* $p < .05$, ** $p < .01$). Error bars represent ±1 SEM.

P3 analyses: We observed a long-lasting positive deflection from 380 ms onwards in both groups that appeared maximal at centro-parietal (CP3, CPz, CP4), parietal (P3, Pz, P4) and parieto-occiptal (PO3, POz, PO4) sites. Due to the length of this component, we divided it into two separate time windows for analysis: early (380 – 440 ms) and late (500 – 560 ms). This was adopted to highlight effects, which would otherwise be masked by analysing the P3 as a whole. This procedure was previously adopted by He et al. (2013) to highlight significant colour category effects in P3. Peak latencies were not analysed in this component. In summary, there was no evidence for a category effect in either time window. There was a significant main effect of Stimulus on mean amplitude in the early, $F(2,44) = 17.92$, $p < .001$, and late, $F(2,44) = 68.04$, $p < .001$, time windows, and post hoc analysis revealed a similar trend: In both windows, an oddball effect was found; the standard in the early window ($M = 1.13$ µV; $SD = 1.99$ µV) elicited a significantly lower amplitude than both deviant 1 ($M = 5.66$ µV; $SD =$

5.30 µV; *p* < .001), and deviant 2 (*M* = 3.73 µV; *SD* = 3.89 µV; *p* = .002), see Figure 3.9a. In the late window, the standard (*M* = -0.36 µV; *SD* = 2.10 µV) also elicited a significantly lower amplitude than deviant 1 (*M* = 6.59 µV; *SD* = 4.71 µV, *p* < .001), and deviant 2 (*M* = 8.19 µV; *SD* = 4.16 µV, *p* < .001), see Figure 3.9b. The only difference was that, in the early window, deviant 1 elicited a larger amplitude than deviant 2 (*p* = .005), whereas in the late window, deviant 2 elicited a larger amplitude than deviant 1 (*p* = .019).
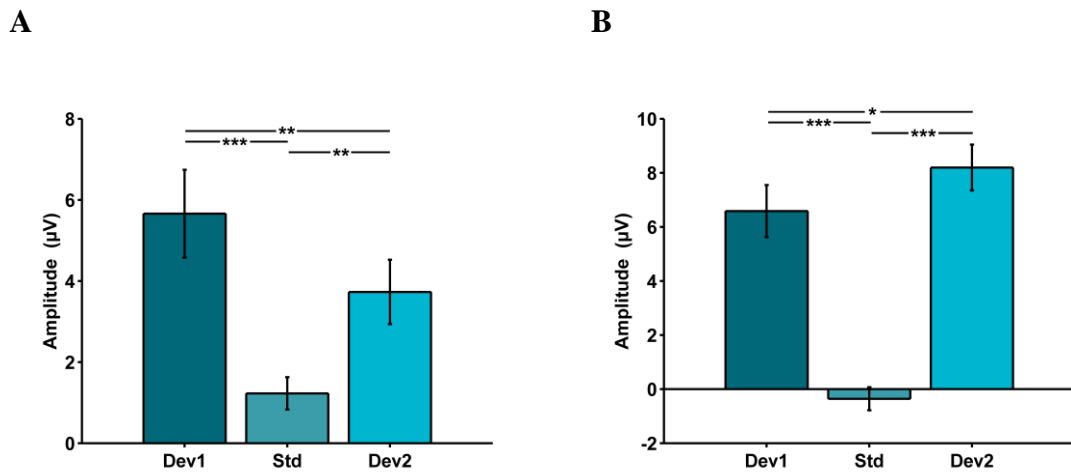
A   **B**

Figure 3.9. Mean amplitude (µV) of the P3 component in native Russian and native English speakers. (A) Early P3 window (380 – 440 ms). (B) Late P3 window (500 – 560 ms). No significant differences were found between the two groups, therefore the data are presented collapsed across both groups. (* *p* < .05; ** *p* < .01; *p* < .001). Error bars represent ±1 SEM.

3.4.3.3 Behavioural oddball task

One participant included in the ERP oddball analyses, failed to complete the subsequent behavioural version of the task due to time constraints, therefore for this analysis N = 23. We analysed reaction times (RTs) and hit rates (HRs) in a similar way to the ERP data by using a two-way mixed ANOVA containing the within-subjects factor of Stimulus with three levels (the standard, deviant 1 and deviant 2), and the between-subjects factor of Group with two levels (English speakers versus Russian speakers). For RTs, we analysed correct responses only. There was no main effect of Group on RTs, $F(1,21) = 0.87$, $p = .361$, but there was a main effect of Stimulus,

$F(1.43,29.98) = 77.55$, $p < .001$. Pairwise comparisons revealed a general oddball effect, whereby RTs were significantly faster to the standard ($M = 422.4$ ms; $SD = 80.3$ ms) compared to both deviant 1 ($M = 515.7$ ms; $SD = 70.8$ ms; $p < .001$) and deviant 2 ($M = 521.5$ ms; $SD = 66.1$ ms; $p < .001$), see Figure 3.10a. The deviants did not differ significantly ($p = .303$), and there was no Stimulus × Group interaction, $F(2, 42) = 2.30$, $p = .131$.
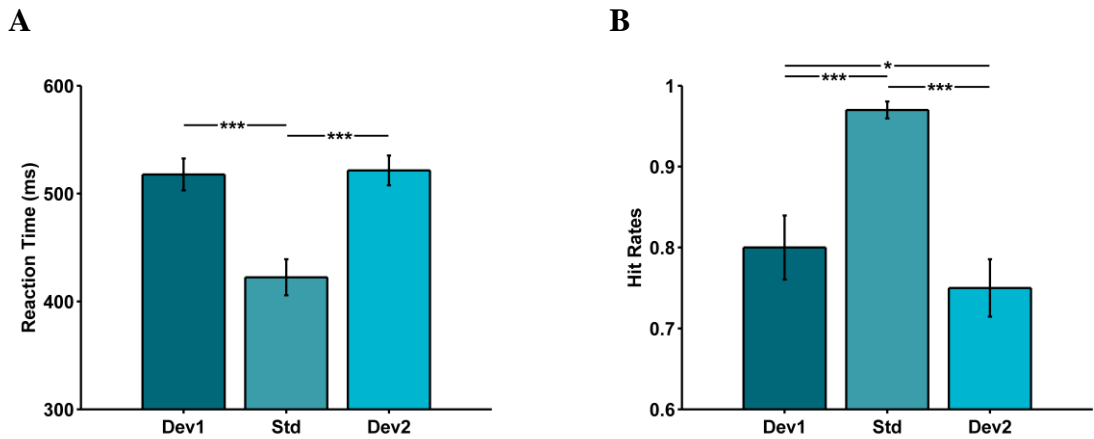

Figure 3.10. Behavioural data from native Russian and native English speakers on an oddball task. (A) Reaction times. (B) Hit rates. No significant differences were found between the two groups, therefore the data are presented collapsed across both groups. (* $p < .05$; ** $p < .01$; *** $p < .001$). Error bars represent ±1 SEM.

The analysis of HRs produced a similar outcome; there was no main effect of Group, $F(1,21) = 0.493$, $p = .490$, no Stimulus × Group interaction, $F(2,42) = 1.507$, $p = .223$, but there was a main effect of Stimulus, $F(1.48, 31.02) = 23.29$, $p < .001$. This was the result of significantly larger HRs (i.e., better performance) in response to the standard ($M = 0.97$; $SD = 0.05$) compared to deviant 1 ($M = 0.80$, $SD = 0.19$; $p < .001$) and deviant 2 ($M = 0.75$; $SD = 0.17$; $p < .001$), see Figure 3.10b. HRs for deviant 1 were significantly higher than deviant 2 ($p = .048$). Overall the analyses of behavioural data indicated a general oddball effect, rather than a language-specific category effect restricted to the Russian group.

3.4.4 Discussion

In the present experiment we sought clarify the time course of the influence of colour terms on visual processing by measuring ERPs elicited to three blue stimuli, which varied in lightness, in two groups who named and categorised the hues differently. The three hues were equated in JNDs to be equally discriminable. We recruited native Russian speakers because the Russian language makes a distinction between lighter and darker hues and compared their ERPs elicited on a visual oddball task to native English speakers because no such lexical distinction is made in the English language. We found a significant category effect in the Russian group when we analysed mean amplitude between P2 and N2 over central sites (290 – 320 ms for the Russian group; 280 – 310 ms for the English group). During this time, deviant 2 which was a different category to the other two hues for the Russian speakers only, elicited a significantly larger amplitude that the other hues in the Russian group. The same effect was not found in the English group; during this time ERP amplitudes for both deviants did not significantly differ from each other. There were no such language specific category effects in earlier ERP components.

3.5 General discussion

In Experiment 1 we measured discrimination thresholds (JNDs) in native Russian and native English speakers across a range of blue hues that varied in lightness in CIELUV. We found no group differences in how the size of the JNDs varied across the range of stimuli despite the fact that the Russian language divides the stimuli into two separate categories, while the English language does not. In Experiment 2 we measured ERPs on an oddball task that presented three different blue hues, which were categorised differently by Russian and English speakers. We found a category effect in a post-perceptual stage of visual processing between 280 and 320 ms but no evidence for a category effect occurring in earlier, sensory stages.

The finding that JNDs did not significantly differ for Russian speakers compared to English speakers supports a previous cross-cultural study by Roberson et al. (2009). In their study they compared JNDs in Korean speakers to English speakers for test colours ranging from green to blue (the Korean language has three categories in this

region: *chorok, cheongnok,* and *parang*, whereas the English language has two: *green* and *blue*). They found no significant difference in the pattern of JND size across the stimulus range between the two groups. This finding and that of the present study contradict the idea that colour terms lead to long term perceptual warping of colour discrimination such that discrimination sensitivity is heightened at the category boundary and is reduced within categories (Goldstone & Hendrickson, 2010; Harnad, 1987). The effect of colour terms on colour differences at threshold may not be seen even though category effects are found in studies where colour differences are supra-threshold (e.g., Winawer et al., 2007) because supra-threshold colour differences capture categorical relationships more effectively than smaller colour differences at threshold: it is more clear that colours are from different categories the larger the colour difference. What our findings suggest is that the source of the category effect in studies that have used supra-threshold colour differences are not likely due to category effects in discriminability.

Unlike Thierry et al. (2009), we did not find that the blue test hues elicited a significantly different pattern in P1 in the two groups. The effect we find in P1 was for deviant 1 to elicit the greatest amplitude and deviant 2 to elicit the smallest amplitude in both groups (see Supplementary 2). It is possible the finding we report in P1 represents equivalent processes within the two groups that relate to the physical characteristics of the stimuli (e.g., Hopf et al., 2002; Johannes et al., 1995). Deviant 1, which elicited the greatest amplitude and earliest peak latency, was the darkest test stimulus. Although the study by Johannes et al. found the opposite pattern to this (their lightest stimulus elicited greater amplitudes in early ERP components), in their study they used a background grey that had a lower lightness than their test stimuli whereas in the present study we used stimuli that were darker than the background. The pattern of ERP responses we found in early ERP components (and those by Johannes et al.) may therefore be explained by lightness contrast between test stimuli and background.

One possibility is that the difference in the findings of the studies is due to the languages compared. In the present study we compared native Russian speakers and native English speakers, whereas in the study by Thierry et al. (2009) they compared native Greek and native English speakers. The critical assumption in both studies is that both the Russian and Greek languages distinguish between lighter and darker blue hues and that these two blues constitute basic colour categories in these languages (see

Supplementary 1 for an outline of basic colour categories). Data reported from a list task and a colour naming task in Russian speakers (Davies & Corbett, 1994), as well as a review of psycholinguistic studies (Paramei, 2005), suggest that there are two basic blue colours in the Russian language. Likewise, an investigation into the basicness of the Greek blues across a number of measures (naming agreement, naming time, and frequency) concluded that there are two basic blue categories in the Greek language (Androulaki et al., 2006). There is no evidence from these studies that the blue distinction is less basic in Russian than in Greek and therefore we consider this an unlikely explanation for the lack of an early category effect in the current study.

It could be argued that the lack of significant effects in early ERP components in the present study was due to three blue hues being less reliably named than the blue hues used in the study by Thierry et al. It is not possible to verify this as Thierry et al. do not report naming agreement data for their test stimuli (though the hues they used were verified as being good examples of the two Greek blues). Given that the Russian participants in the present study had an average naming agreement of over 90% for the each of the three test hues used in Experiment 2 in the present study we consider this potential explanation highly unlikely.

Another possibility is that the participants in the two studies differed in terms of their experience of the English language. Thierry et al. report that their Greek participants scored on average 66/90 on a vocabulary test (Nation, 1990). In the present study, the Russian group's mean score was slightly higher: 72/90, suggesting greater familiarity with the English language. Also, in Thierry et al. the mean time spent in the UK by the Greek participants was 18 months and in the present study it was longer at 27 months. It is possible that a greater aptitude with the English language and longer time spent in the UK by the Russian participants in the present study may have reduced the effect of colour terms on early ERP components. This possibility is supported in the re-analysis of the data in Thierry et al. by Athanasopoulos et al. (2010), which showed that the effects reported by Thierry et al. were absent in the longer-stay Greek participants who had been in England for on average 3 years or longer compared to those who had spent a shorter time in the UK. Ideally, future cross-linguistic investigations should compare only monolingual speakers

Differences in the tasks of the two studies should also be noted. In Thierry et al., participants were required to attend to the shape of the stimuli, rather than the colour. The shape occasionally changed and responses were required when this occurred. In the present study participants were required to count the deviants and therefore directly attend to the colour of the stimuli to complete the task. Differences in the amount of attention to colour across the two studies is potentially indicated by the presence of the visual mismatch negativity (vMMN) in Thierry et al.'s study but not the current one: the vMMN is an ERP waveform thought to indicate preattentive processing for stimuli presented outside of attention (Czigler, 2013). It is therefore possible that early category effects are stronger the less attention is focussed on the stimuli. In support of this proposal, both He et al. (2014) and Clifford et al. (2012) used tasks where the colour was attended to and both report no early category effects.

The proposal that early category effects depend on colour being not attended may seem to go against intuition: one might argue that category effects should be stronger the more attended stimuli are as the observer is more aware of the categorical status of the stimuli. However, it is plausible that categorical processing could be recruited more under conditions where there is greater uncertainty about the stimulus. There is some support for the hypothesis that categorical influences are stronger the more stimulus uncertainty, for example, weaker colour category effects were found on a behavioural task in participants who were highly familiar with the stimuli due to more experimental testing than participants who had seen and interacted with the stimuli less (Witzel & Gegenfurtner, 2015). The influence of attention on the time course of categorical colour processing deserves further investigation.

In the present study we found a category effect at a post-perceptual stage of visual processing and not in early ERP components. This finding combined with a lack of cross-linguistic differences in discrimination thresholds and on a supra-threshold visual oddball task, challenges the generality of the claim that colour terms affect early processing of colour. While several studies have reported early effects (Clifford et al., 2010; Holmes et al., 2009; Mo et al., 2011), it is plausible that these effects may reside in metric issues related to equating colour difference. To date, there is only one study which avoids potential metric issues that can unequivocally provide support for the claim of early category effects (Thierry et al., 2009; see also the reanalysis of this data by Athanasopoulos et al., 2010). The ERP evidence from the present study, as well as

that from He et al. (2014) and Clifford et al. (2012) only provide evidence that colour terms influence the later stages of processing that may reflect post-perceptual processes such as stimulus evaluation or decision making. The field is still lacking a substantial body of unequivocal evidence that the colour terms that we speak affect the early stages of how we 'see' colour.

3.6 Supplementary 1: Mapping the two Russian blues

3.6.1 Overview

The Russian language makes a distinction between lighter (*goluboj*) and darker (*sinij*) blue hues. They have been argued by Davies and Corbett (1994) and Paramei (2005) to fulfil Berlin and Kay's (1969) requirements to constitute basic colour categories, whereby they are known to all speakers of a language, are monolexemic and are not subordinate to other colour terms. We investigated their location in CIELUV space by asking Russian speakers to name a range of blue hues varying in their chroma and lightness. We measured naming agreement as well as confidence ratings in order to determine the location of *goluboj* and *sinij* as well as the boundary between the two.

3.6.2 Methods

3.6.2.1 Participants

12 native Russian speakers (9 women; mean age = 25.5 years; SD = 9.3 years; range = 18 − 46) studying at University of Sussex took part in this experiment. The mean time spent in the UK was 4.25 years (SD = 3.6 years; Range = 1 − 13) and mean time learning English was 13.9 years (SD = 8.2; Range = 6 − 36). None of the participants took part in Experiment 1 or 2. All participants were screened for colour vision deficiencies using the Ishihara test (Ishihara, 1987) and the City University Test (Fletcher, 1980) under natural daylight. Participants were naive to the purpose of the study, provided written informed consent and their time was reimbursed with cash or research credits. The study was approved by the Cluster-based Ethics Research Committee of Psychology and Life Sciences at University of Sussex (AF0811).

3.6.2.2 Set up

Participants were seated in a dark room; the only source of light was a gamma-corrected 20" Diamond Pro 2070SB CRT monitor (Mitsubishi , Tokyo, Japan; spatial resolution: 1600×1200; refresh rate: 100 Hz) driven by an Quadro FX1800 graphics card (NVIDIA, Santa Clara, USA) with a colour resolution of 8 bits per channel. Participants sat at a distance of 57 cm. All programming was carried out in Matlab (The MathWorks Inc., 2007) using the Psychophysics toolbox (Brainard, 1997).

3.6.2.3 Stimuli and design

Participants completed a colour naming paradigm for 89 different blue hues (hue angle: 231°), which varied in lightness and chroma only. The hues were defined in CIELUV, and were displayed on a mid-grey background metameric to illuminant D65 ($x = 0.3127$, $y = 0.3290$, $Y = 16.72$ cd/m^2). The chromaticity coordinates of the blue hues were defined by those available with monitor gamut.

3.6.2.4 Procedure

Observers were first adapted to the dark conditions for five minutes prior to commencing testing. During this time they read the instructions presented in Russian. On each trial one of the blue hues was presented as a circle (4.8°) until the participant indicted that the hue was *sinij* or *goluboj* on a computer keyboard. Participants were then asked to rate their confidence that the hue constituted a good example of the nominated colour on a 9-point scale (1 = very unconfident and 9 = very confident). All 89 blue hues were presented four times in a randomised order.

3.6.3 Results

Out of a total of 4,272 responses, 31 were removed due to an unsystematic bug in the programme that resulted in the binary choice being recorded in place of a confidence rating. This represented 0.7% of the data. The test stimuli varied along two dimensions: lightness and chroma. Naming agreement tended to be higher for hues

towards the lowest and highest lightness values (Figure 3.11a), but can be seen to be much more random when plotted against chroma (Figure 3.11b). Confidence ratings were higher for those hues of a higher lightness (Figure 3.11c) and greater chroma (Figure 3.11d). When plotted as heat maps so that both chroma (*y*-axis) and lightness (*x*-axis) are represented, naming agreement can be seen to be around 50% (i.e., no consensus) for hues ranging from around $L*$ 41 to 49 (Figure 3.11e). This represents the boundary region between *sinij* and *goluboj*. In Figure 3.11e hues named reliably as *sinij* can be clearly seen as the cluster of higher naming agreement values at the bottom-left of the figure, and *goluboj* can be clearly seen as the cluster towards the top-right. Confidence ratings increased with chroma (Figure 3.11f).

3.6.4 Discussion

The goal of the naming experiment was to locate the two Russian blues in CIELUV colour space and the boundary in between the two in order to ascertain chromaticity coordinates for subsequent research (Experiments 1 and 2). To this end we calculated naming agreement across native Russian speakers for a range of blue hues as well as confidence ratings for whether the hues were a good example of the colour category they had been named. We found that naming agreement for the range of hues we had selected was more influenced by lightness than chroma: lighter hues were named *goluboj* and darker hues *sinij*. Confidence ratings tended to be more influenced by chroma, whereby hues of a higher chroma, rather than a lower chroma, tended to be rated as being good examples of either *sinij* or *goluboj*. Naming agreement approached 50% around $L*41 – 49$, this represents the sinij-goluboj boundary.
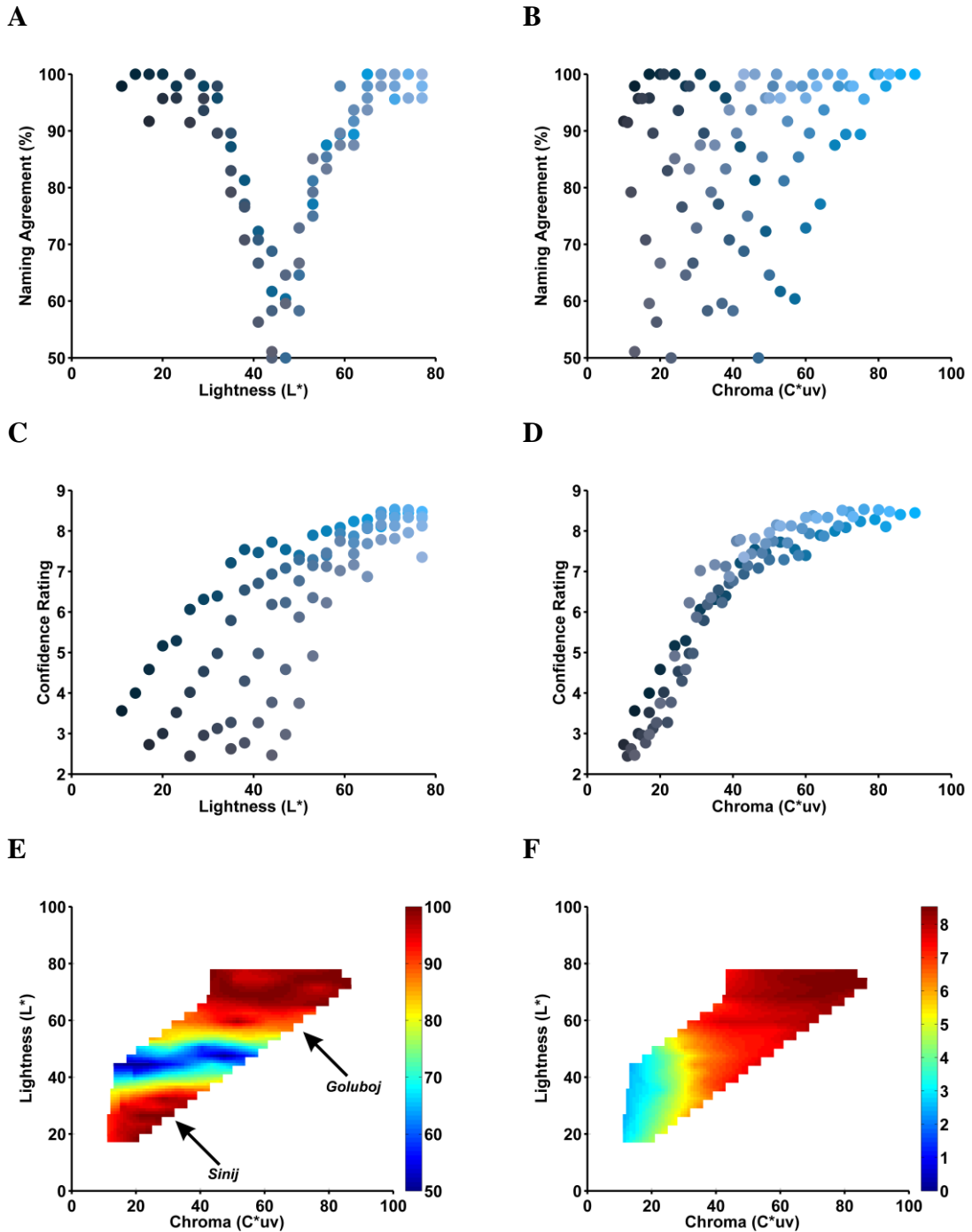
Figure 3.11. Mapping the two Russian blues. Data from native Russian speakers (N = 12) for a colour naming task in which 89 blue hues were nominated as being either *sinij* (darker blue) or *goluboj* (lighter blue). Data is presented for naming agreement (%) and a subsequent confidence rating (1 [very unconfident] – 9 [very confident]) asking whether each test hue was a good example of the nominated colour category. All hues were defined in CIELUV, had a hue angle of 231°, and varied in lightness (*L**) and chroma (*C**uv). (A) Naming agreement plotted against lightness. (B) Naming agreement plotted against chroma. (C) Confidence

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rating plotted against lightness. (D) Confidence rating plotted against chroma. The colours of the markers in A- D are for display purposes. (E) Naming agreement (%) depicted as a heat map plotted against lightness and chroma. The Russian blues are labelled in italics. (F) Confidence rating $(1 - 9)$ depicted as a heat map plotted against lightness and chroma. The selection of test hues was limited to those hues that were available with monitor gamut.
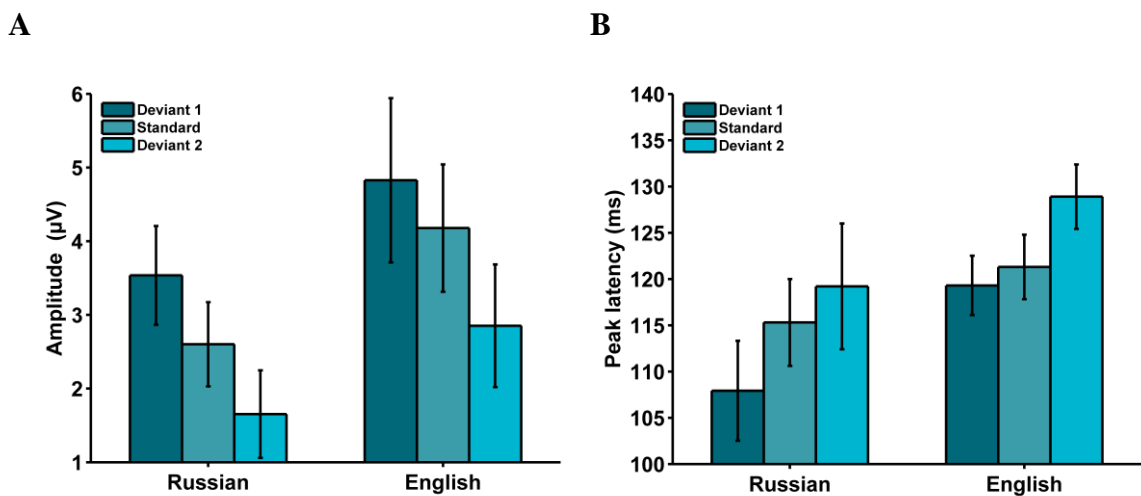
3.7 Supplementary 2: P1 component separated across groups

A

B

Figure 3.12. P1 component presented separately for native Russian speakers and native English speakers. (A) Mean amplitude (µV). (B) Peak latency (ms). Inferential analysis revealed no significant main effect of Group (Russian vs. English) and no significant Stimulus (Deviant 1, Standard, and Deviant 2) by Group interaction for either mean amplitude or peak latency in P1. The data are displayed here to highlight the similar ERP responses in both groups in this component.

Chapter 4

Paper 3: Colour categories are reflected in sensory stages of colour perception when stimulus issues are resolved

Forder, L., He, X., & Franklin, A. *Journal of the Optical Society of America: A*
(submitted)

4.1 Abstract

Debate exists about the time course of the effect of colour categories on visual processing. We compared two groups who differed in whether they categorized a blue-green colour as the same- or different-category to a blue and green. Colour differences were equated to be equally discriminable. We analyzed event-related potentials for these colors on a passive visual oddball task and investigated the time course of categorical effects. Category effects were found 100 ms after stimulus onset in the P1 component, and over frontal sites around 250 ms, suggesting that colour naming affects early sensory and later stages of chromatic processing.

4.2 Introduction

We perceive millions of different colors (Linhares, Pinto, & Nascimento, 2008), but we necessarily use a limited number of colour terms (categories) to describe them ('blue', 'yellow', 'orange', etc.). There has been much debate on whether our naming of colour affects how we see it (Kay & Maffi, 1999; Kay & Regier, 2003). A common assertion is that colors are more easily distinguished if they are named with different terms (different-category) than with the same term (same-category) even if the colour differences are equated in some kind of colour metric (Daoutis, Pilling, & Davies, 2006; Drivonikou et al., 2007; Gilbert, Regier, Kay, & Ivry, 2006). There is a plethora of evidence for these so called 'colour category effects' on behavioral tasks where observers judge the difference between colors, memorize or search for colors (Roberson, Davidoff, Davies, & Shapiro, 2005; Winawer et al., 2007). However, one crucial question is the extent to which colour terms affect how we perceive colour and the time course of any effect. Colour terms may simply affect 'post-perceptual' processes such as attention, task strategy or the stage of decision making (Mather, Pavan, Marotti, Campana, & Casco, 2013; Morgan, Dillenburger, Raphael, & Solomon, 2012). Alternatively, colour terms may affect early sensory and perceptual stages of colour processing (Lupyan, 2012).

The argument that language affects sensory and perceptual stages of processing has found support in domains other than colour (Kranjec, Lupyan, & Chatterjee, 2014; Lupyan & Ward, 2013). However, for colour, the evidence is currently mixed. To investigate this issue, studies have employed the event-related potential (ERP) approach, which is an electrophysiological technique that provides precise millisecond data about the timing of visual processes in response to an event or stimulus (Luck, 2005). Studies have measured event-related potentials elicited in response to colored stimuli that vary in their categorical relationship with each other, and category effects in the elicited ERP waveforms have been examined. The timing and polarity of ERP waveform components gives an indication of stage and type of processing related to that component. For example, the P1 ERP component is a component with a positive deflection that occurs roughly 100ms after stimulus onset, and the P1 is thought to correspond to activity in early sensory stages of colour processing in the visual cortex, prior to visual awareness (Luck, Woodman, & Vogel, 2000). A number of ERP studies have claimed to find colour category effects throughout early ERP components such as

the P1 and early-phase N1 whereby the categorical relationship of colour differences appears to modulate the amplitude or latency of these components (Clifford et al., 2010; Fonteneau & Davidoff, 2007; Holmes, Franklin, Clifford, & Davies, 2009; Thierry et al., 2009). Other studies have claimed that such colour category effects only occur in later 'post-perceptual' components such as the P2 (He, Witzel, Forder, Clifford, & Franklin, 2014) and P3 (Clifford et al., 2012) which correspond to attention, stimulus evaluation, memory or decision making (Anllo-Vento, Luck, & Hillyard, 1998; Dunn, Dunn, Languis, & Andrews, 1998; Polich, 2007).

Although there are now a number of ERP studies of colour category effects, the majority of these studies are plagued by an important stimulus issue: same- and different-category colour differences are equated in colour metrics which have known inhomegeneities (Hill, Roger, & Vorhagen, 1997; Mahy, Van Eycken, & Oosterlinck, 1994; Witzel & Gegenfurtner, 2013). For example, although the colour metrics used in category studies such as CIELUV, CIELAB and Munsell attempt to be perceptually uniform, inhomogeneities are known to exist within such spaces, and these manifest as areas of greater and lesser discrimination sensitivity. Early ERP components are known to be highly sensitive to the physical differences between stimuli (Busch, Debener, Kranczioch, Engel, & Herrmann, 2004; Hopf & Mangun, 2000). Therefore, effects which have been labeled as 'category effects' could instead be due the different-category colour differences being greater than same-category colour differences when 'equated' in the colour metrics used in prior studies (He et al., 2014).

There have only been three ERP studies so far which cannot potentially be explained by stimulus issues and the findings of these studies disagree. Thierry et al. (2009) compared ERP components elicited in response to colors in native Greek and native English speakers. Greek and English differs in the categorization of the colour blue; the Greek language contains an additional colour category dividing lighter and darker shades (Androulaki et al., 2006). Observers were required to detect a square amongst serially-presented colored circles whilst ERPs were recorded. It was found that for Greek speakers, a blue colour difference which was different-category in the Greek language elicited a stronger visual mismatch negativity (vMMN) ERP component (around 160 – 230 ms), than colour differences which were the same category, with no such effect for English speakers. A similar 'category' effect was also found for Greek speakers in the P1 ERP component. Both the vMMN and P1 components are thought to

be pre-attentive (Czigler, Balázs, & Pató, 2004; Czigler, Balázs, & Winkler, 2002). The apparent category effect for Greek speakers cannot be explained by stimulus issues since the English speakers, for whom there was no such effect saw the same colors. However, one potential issue with the study has been identified by Clifford et al. (2012) who argue that the ERP waveforms for Greek and English observers suggest that the English observers attended more to the colour differences than Greek observers (there appears to be an attention-related P3 component for English but not Greeks). Therefore, stronger 'pre-attentive' ERP components for Greek than English speakers for certain colour differences could potentially be due to different amounts of attention to colour during the task rather than cross-linguistic differences in colour terms. Nevertheless, further evidence for the early effects of language was provided by Thierry and colleagues in a re-analysis of their original study (Athanasopoulos, Dering, Wiggett, Kuipers, & Thierry, 2010) where they find that the strength of the category effect for the Greek speakers was modulated by how long Greek observers had lived in England. Category effects were weaker for a group of bilingual Greeks who had lived in England for 18 months or longer than a group of bilingual Greeks who had lived in England for less than a year.

A second ERP study, conducted by Clifford et al. (2012) investigated the time course of category effects for newly trained colour categories. Observers were trained to categorize a set of colors varying in hue and lightness into two new categories with new terms, and ERPs were then measured to colors which varied in their categorical relationship according to these newly trained terms. Within a block of trials, one hue was presented frequently (the standard) and two infrequently presented hues (the deviants) were either from the same new category as the standard or from a different category. Observers were required to count the number of deviant stimuli and therefore attend to the colour differences. The categorical relationship of the deviant hues with the standard was only found to modulate post-perceptual ERP components 350 – 600 ms after stimulus onset. No such category effects were found for a separate sample of observers who were not trained to categorize the hues into new categories, or for either group in an untrained hue region. These effects cannot be explained by stimulus issues since category effects were only found for those who underwent category training yet all observers saw the same stimuli.

The third ERP study which cannot be explained by stimulus issues is that of He et al. (2014). They used the same task as Clifford et al., but tested for category effects related to the blue-green categorical distinction in English speakers. To address concern over stimulus issues, same- and different-category colour differences between the standard and deviant hues were equated in number of just noticeable differences (JNDs) rather than relying on other colour metrics. As in Clifford et al., category effects, indicated by greater ERP amplitude for deviants from a different-category to the standard than the same-category, were found only in post-perceptual components, and were found 230 ms after stimulus onset..

In sum, whilst two studies claim that colour terms only affect post-perceptual processing of colour when stimulus issues are controlled (Clifford et al., 2012; He et al., 2014), another study which draws on cross-linguistic differences in colour terms claims that colour terms do affect early stages of colour processing (Thierry et al., 2009). Further research is needed to explore this apparent discrepancy. One possibility is that the documented early effects are due to cross-linguistic differences in attention and are not related to naming (Clifford et al., 2010). The studies also differ in their task: the study which claimed to find early category effects used a task where observers were required to attend to the shape not the colour of the stimuli, whereas the two studies which only find post-perceptual category effects required observers to attend the changes in colour. Therefore, another possibility is that early 'category' effects are only found when attention is directed away from colour and processing of colour is more implicit.

In the current study, we use a task where observers were not required to attend to colour (as in Thierry et al., 2009). However, rather than comparing speakers of different languages who differ in their colour terms and potentially also in other factors, we investigate the impact of differences in colour term usage for observers speaking the same language. Intra-language colour term use can vary substantially: A recent study in native American English speakers found only 31% of 330 colour samples were named the same by all participants despite constraining responses to just 11 basic colour terms (Lindsey & Brown, 2014). Having intra- rather than inter- language comparisons means that any effect of language that we find is more likely to be due to colour term usage rather than other group differences such as task strategy that could arise from cognitive or cultural difference. Relevant to the present study, differences in colour naming will

result in differences in colour categorization when the colour in question is in the boundary region between two colour categories. For example, in this region a particular colour may reliably be named *yellow* by one observer and reliably as *orange* by another. When presenting this colour alongside a different colour named *orange* by both observers, the first observer will see two colors from different colour categories (yellow and orange), whereas the second observer will see two colors from the same category (orange and orange) even though the two colors are the same for both observers.

In the present study we used three colors: A green, a blue, and a boundary colour in between the two. We selected these colors because green and blue are often the colour terms applied to the largest number of colour samples by native English speakers (Boynton & Olson, 1990; Lindsey & Brown, 2014), and it has been observed that the location of the boundary between these colour categories can vary across British English speakers (Bird, Berens, Horner, & Franklin, 2014; He et al., 2014). As in He et al., we equated the colour differences between the standard and deviant stimuli in just-noticeable differences. Observers completed a passive 'visual oddball' task. Participants were presented with the boundary colour on the majority of trials (called the 'standard' stimulus). Two groups of observers reliably named this boundary stimulus differently to each other – either as blue or green. On a smaller number of 'oddball' trials, participants were presented with the blue and the green colors (the infrequent 'deviants') for which the two groups agreed in their naming. According to how observers named the boundary colour, the blue and green deviant colors were either same- or different-category to the standard. We recorded and compared the ERPs elicited by each of the three stimuli, and assessed whether the categorical relationship of the standard and deviant colors, which varied across the two groups, modulated the amplitude and latency of the ERP component.

As in Thierry et al. (2009), attention to the colour changes was not required as observers were tasked with making a manual response when a central fixation dot changed. The stimuli were presented simultaneously as pairs, with one colour presented to the upper visual field (UVF), and another to the lower visual field (LVF). We included this manipulation of visual field because prior work has shown that ERPs differ depending on which visual field a stimulus is presented to (Clifford et al., 2010; Czigler et al., 2004). After the ERP task, we measured whether the participants named the three colors as blue or green. Participants named each stimulus 25 times so that we

could establish the degree of colour naming consistency. This was important because we wanted to analyze potential category effects in people who reliably categorize colors. We analyzed all available visual ERP components to specifically investigate when category effects occur in visual processing. If category effects occur in early sensory stages of visual processing, a category effect would be found in early components (e.g., P1 or early-phase N1, as in Thierry et al., 2009). Alternatively, category effects could be restricted to later 'post-perceptual' components (P2, N2, as in Clifford et al., 2012; He et al., 2014).

4.3 Methods

4.3.1 Participants

Thirty-four native British English speakers (24 female; mean age = 21.3; SD = 2.96), who were naive to the purpose of the study, took part. Participants were recruited from the University of Sussex. All participants were screened for colour vision deficiencies using the Ishihara test (Ishihara, 1987) and the City University Test (Fletcher, 1980). Participants provided written informed consent and were compensated with cash or course credits. The study was approved by the Cluster-based Ethics Research Committee of Psychology and Life Sciences at the University of Sussex.

4.3.2 Stimuli and set up

Participants were seated in a dark room, the only source of light was a 22" Diamond Plus 230SB CRT monitor (Mitsubishi, Tokyo, Japan; colour resolution: 8 bits∕channel; spatial resolution: 1024 × 768; refresh rate: 75 Hz), located 77 cm away from participants. Gamma correction was applied after measuring monitor primaries with a CRS ColorCal (Cambridge Research Systems, Rochester, UK). The CIE1931 chromaticity coordinates and luminance of the monitor primaries were (R: 0.626, 0.337, 14.24; G: 0.281, 0.614, 45.51; B: 0.151, 0.071, 5.28). All materials were prepared with e-Prime 2 (Psychology Software Tools, Inc.). Test stimuli were three isoluminant, isosaturated colors varying in hue in CIELUV space and presented on a grey background. Adjacent hues were separated by 3 JNDs following previous

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psychophysical measurement (for details, see He et al., 2014). The colors spanned the colour categories of blue and green (for colour chromaticity coordinates see Table 4.1). The central boundary colour was anticipated to be named *blue* by some participants and *green* by others. Note that the boundary colour is henceforth referred to as the 'standard' due to a greater frequency of presentation (see Design and procedure below).

Table 4.1. Chromaticity coordinates (x,y,*Y* CIE1931) of test stimuli and background.

Colour name	*X*	*y*	*Y*
Green deviant	0.237	0.380	9.21
Boundary / Standard	0.222	0.333	9.21
Blue deviant	0.220	0.292	9.21
Background	0.313	0.329	20.37

4.3.3 Design and procedure

4.3.3.1 Passive oddball task

Participants first completed a passive visual oddball task. The stimuli and task procedure are illustrated in Figure 4.1. An oddball task presents the same stimulus on the majority of trials (referred to as the 'standard'), while different 'oddball' stimuli are occasionally presented (referred to as 'deviants'). On each trial there was the simultaneous presentation of two colored squares (length: 1.93° visual angle) for 200 ms towards the centre of the screen and ordered vertically such that the space between

them was equal to their size. This resulted in one square being presented towards the upper visual field (UVF) and the other the lower visual field (LVF; see Figure 4.1). For 90 trials in each block both upper and lower squares were the standard (boundary) colour. Half of the 20 deviant trials presented the blue deviant and the other half the green deviant, with equal probabilities shown in the upper or lower visual field. In each block the fixation dot (0.13° in diameter) remained in the centre of the screen and changed to a horizontal bar at the onset of 10 random trials (0.46° × 0.13°). Observers were asked to attend to a black fixation dot while the colour stimuli were flashed above and below the dot. This design is referred to as passive because participants are not required to attend to or make decisions about the colored stimuli. Participants were asked to respond quickly and accurately when the fixation changes took place by pressing the space key with both hands, and were told that the colors were not relevant to the task. A randomized interval ranging from 800 to 1,200 ms was used between trials. In each block of trials the trial sequence was pseudo-randomized so that the first 8 trials were always standard trials and no consecutive deviant trials were allowed. In total there were 18 blocks of 110 trials.
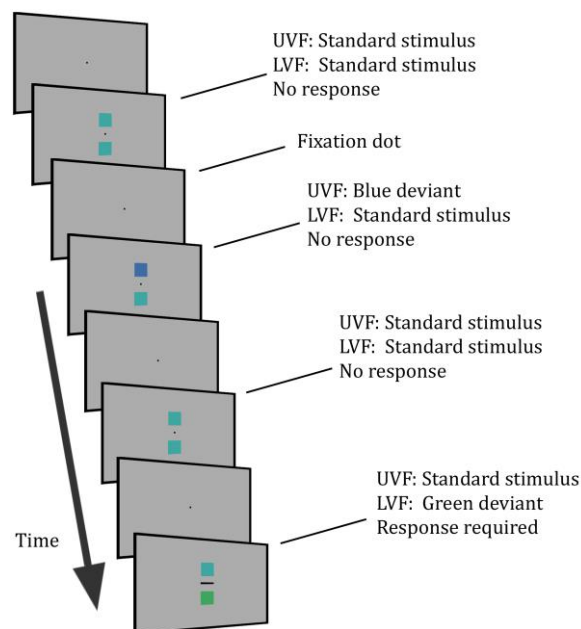

Figure 4.1. General task procedure of the passive visual oddball task. Two colored squares were simultaneously presented for 200 ms to both the upper visual field (UVF) and lower visual field (LVF). Participants attended to a fixation dot and

responded on those trials in which it changed shape. For the majority of trials in a block both squares comprised the standard stimulus. The remaining trials presented either a green or blue deviant stimulus to the UVF or LVF. Stimuli were presented for 200 ms with a randomized interstimulus interval of 1,000 ms ± 200 ms.

4.3.3.2 Colour naming task

Following the oddball task participants completed a colour naming task, whereby each of the three colour stimuli were presented 25 times in a randomized order. Participants were asked to indicate if the stimulus was green or blue by pressing the "c" or "m" key (counterbalanced across participants). Stimuli were presented as a colored square (7.5° × 7.5°) in the centre of the screen and remained onscreen until a response had been made with an interstimulus interval of 1,500 ms. The same background grey was used as the oddball task.

4.3.4 EEG recording and analysis

EEG data was recorded and processed with NeuroScan SynAmps^2 amplifiers and SCAN 4.3 software (NeuroScan/Compumedics, Inc.) at a digitizing rate of 500 Hz. A physical band-pass filter was applied to online recording (0.10 – 100 Hz). EEG was recorded from 62 electrode sites: FP1, FPz, FP2, AF3, AF4, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FT7, FC5, FC3, FC1, FCz, FC2, FC4, FC6, FT8, T7, C5, C3, C1, Cz, C2, C4, C6, T8, TP7, CP5, CP3, CP1, CPz, CP2, CP4, CP6, TP8, P7, P5, P3, P1, Pz, P2, P4, P6, P8, PO7, PO5, PO3, POz, PO4, PO6, PO8, O1, Oz, O2, I1 and I2, using Ag-AgCl electrodes, as well as the average of the left and right mastoid references (re-referenced offline). Eye blinks and eye movements were monitored via one bi-polar horizontal electro-oculogram (EOG) channel located laterally of the canthi and one bi-polar vertical EOG channel located above and below the participant's left eye. Impedance of each channel was reduced below 5kΩ prior to data collection. Following EEG recording, a zero phase-shift low-pass filter with amplitude cut off frequency of 30 Hz

and 48dB/oct roll-off was applied to the data. The recorded EEG data were analyzed as segments extending 800 ms after stimulus onset relative to a 100 ms pre-stimulus baseline, averaged over trials in each experimental condition. Trials were rejected as artefacts when voltage exceeded ±60 µV at any electrode. Criteria for artifact rejection were determined on the basis of previous research (e.g., He et al., 2014), from which ERPs were used to successfully investigate colour category effects. ERPs were generated by averaging EEG activities over trials time-locked to stimulus onsets.

4.4 Results

4.4.1 Colour naming task

Although this task was completed after the ERP task, it is reported here first because performance on the colour naming task determined whether a participant was included in the analysis of the ERP data. The blue deviant was consistently named *blue* ($M = 98.1\%$; $SD = 4.5\%$) and the green deviant *green* ($M = 98.6\%$; $SD = 2.7\%$). As expected, naming of the standard was variable across participants, it was named *blue* 48.7% ($SD = 36.4\%$) of the time. However, the tendency for an individual to name the standard consistently *green* or consistently *blue* was high ($M = 81.9\%$; $SD = 16.7\%$).

4.4.2 EEG passive oddball task

Recall that the goal of the study is to investigate ERPs elicited to colors that vary in their categorical relationship in two groups who reliably categorize colors differently. Consequently, a naming consistency threshold for the standard of ≥80% was selected for inclusion in the analysis of the ERP data. This approach is common in colour ERP literature (e.g., Fonteneau & Davidoff, 2007). Additionally, this threshold is higher (more conservative) than other colour ERP studies (e.g., Athanasopoulos et al., 2010). This serves the benefit of identifying category effects in the data that would otherwise be attenuated by including non-reliable namers. Thirteen participants had a naming consistency of the standard colour below this threshold ($M = 62.8\%$; $SD = 6.0\%$) and were excluded. Of the remaining 21 participants, three were excluded as they elicited strong alpha waves (8 – 13 Hz EEG rhythmic activity), which substantially

contaminated the ERP waveforms. Consequently, the EEG analysis comprised nine participants, who reliably named the standard *blue* (the Blue Namers: 7 female; mean age = 21.2; *SD* = 3.2), and nine participants, who reliably named the standard *green* (the Green Namers: 8 female; mean age = 22.2; *SD* = 4.3). For the Blue Namers, a deviant trial consisting of the simultaneous presentation of the standard (i.e., named blue) as well as the blue deviant is a same-category deviant trial. For the Green Namers this is a different-category trial. This pattern is reversed on trials that present the green deviant. Classifying stimuli as same- or different-category on the basis of an individual's naming was previously adopted to analyze colour category effects in fMRI (Bird et al., 2014) and ERP data (He et al., 2014). Unless otherwise stated, the ERP data were analyzed to investigate category effects: Data were combined across all participants (N = 18) with three conditions: 1. ERPs elicited to the standard (i.e., both squares are the boundary colour); 2. ERPs elicited on same-category deviant trials; 3. ERPs elicited on different-category deviant trials (see Figure 4.2a). This is referred to as the factor of Category with three within-subjects levels (standard, same-category, and different-category).
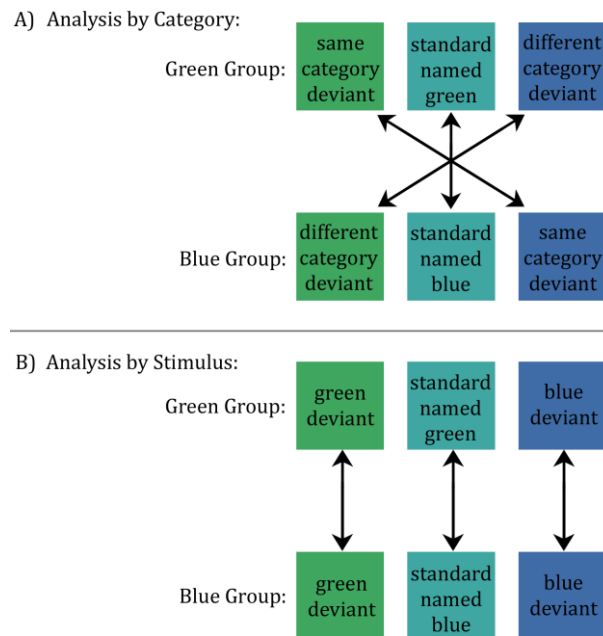

Figure 4.2. (A) Analysis by Category. ERP data were grouped (same- or different-category) to form three conditions for subsequent analysis: ERPs elicited to the standard, to the same-category deviant, and to the different-category deviant.

Arrows denote grouping of data for inferential analysis. (B) Analysis by Colour. ERPs elicited to a stimulus were grouped independently of naming to analyze effects arising from the physical difference in hue across the stimuli and ERPs. Arrows denote grouping of data for inferential analysis.

A category effect is demonstrated by a significant main effect of Category, with subsequent post-hoc analysis revealing a significant difference between the ERP responses elicited to the different-category deviant compared to both the same-category deviant and the standard stimulus. This finding would suggest that the categorical relationship between the stimuli modulates a particular ERP component. Data were analyzed with mixed ANOVAs containing the factor of Category, as well as the between-subjects factor of Naming Group (2-levels [Blue Namers vs. Green Namers]). The within-subjects factors of Hemisphere (2 levels) and Region (n levels) were included where appropriate. Trials requiring a manual response were excluded from analysis to avoid contamination of ERPs from electrical activity arising from the execution of a motor response. Greenhouse-Geisser corrections were applied to those instances in which the assumption of sphericity had been violated and significant main effects were followed up with pairwise comparisons comprising Fisher's least significant different (LSD) post-hoc test. The analysis focuses on mean amplitude (μV). Peak latency was not analyzed because it was not possible to discern reliable peaks across a suitable number of participants. ERP waveforms for LVF stimuli are presented in Figure 4.3. The UVF waveforms are presented in Figure 4.4. We analyzed several ERP components that were elicited by the stimuli and the task: the P1, anterior and posterior N1, anterior and posterior N2, frontal positivity, and P3.
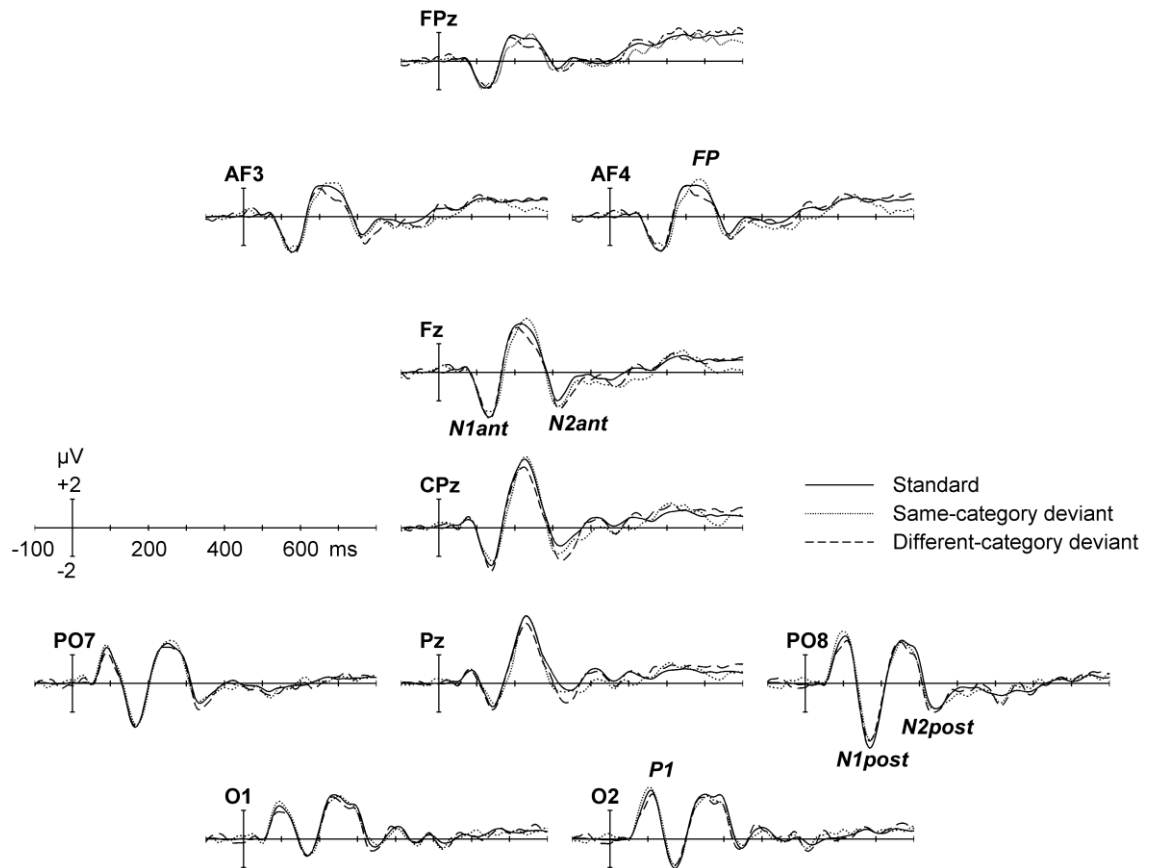
Figure 4.3. Lower visual field. Grand-averaged ERP waveforms elicited for 800 ms following stimulus onset summarized over eight representative electrode locations in response to standard and deviant colors presented to the lower visual field. Data were grouped by the factor of Category in terms of same- and different-category deviants corresponding to the way the standard was named individually by participants (green or blue) and averaged for all participants (N = 18). Electrode locations are provided towards the top of the y-axes. ERP components (e.g., P1) are labeled on one waveform each. N1ant denotes the anterior N1 component, N1post denotes the posterior N2, FP denotes frontal positivity, N2ant denotes the anterior N2, and N2post denotes the posterior N2.
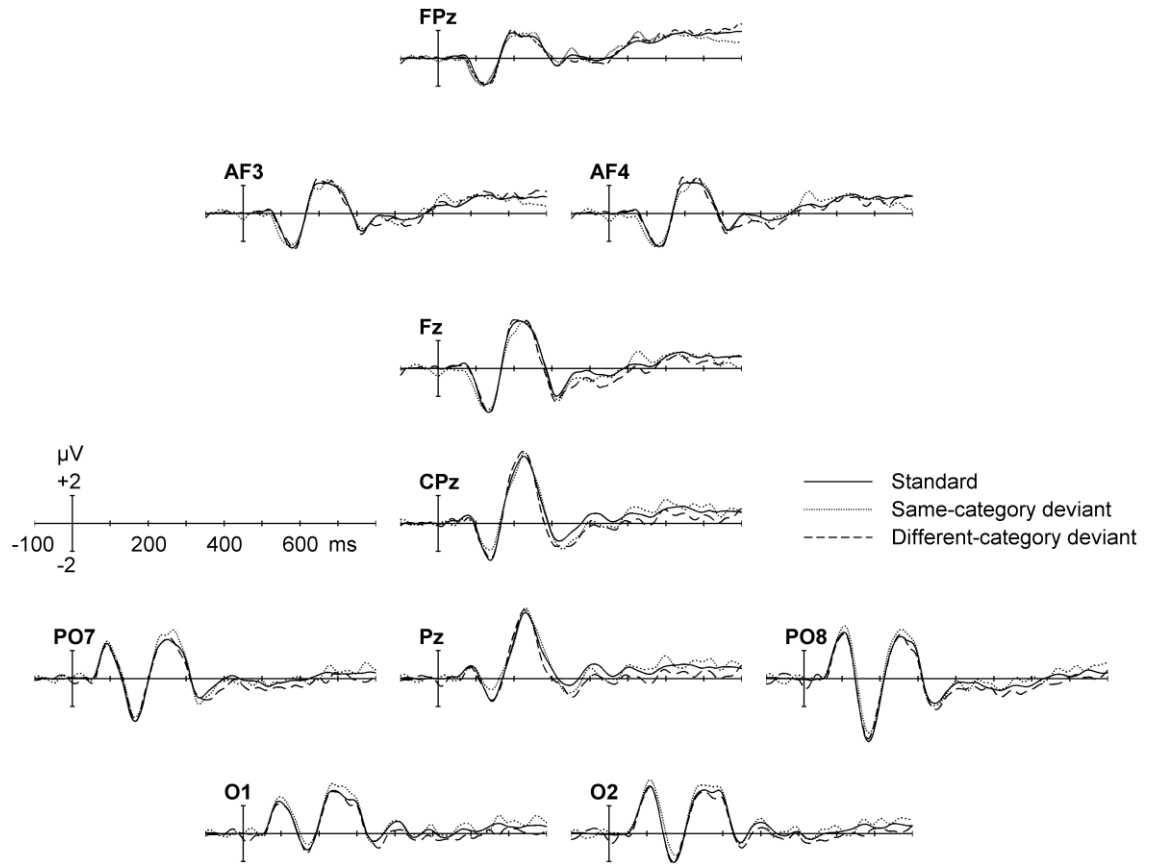
Figure 4.4. Upper visual field. Grand-averaged ERP waveforms elicited for 800 ms following stimulus onset summarized over eight representative electrode locations in response to standard and deviant colors presented to the upper visual field. Data were grouped by the factor of Category in terms of same- and different-category deviants corresponding to the way the standard was named individually by participants (*green* or *blue*) and averaged for all participants (*N* = 18). Electrode locations are provided towards the top of the y-axes.

P1 analyses: Peak amplitude of P1 had a lateral distribution maximal over parieto-occipital and occipital sites around 100 ms following stimulus onset. A difference in amplitude between the conditions was apparent in the waveforms across a highly refined period. An analysis window (94 – 104 ms) and electrodes (PO7, PO5, PO3, PO4, PO6, PO8, O1, and O2) were chosen to reflect these maximal ERP activities in P1. A three-way ANOVA (Category × Group × Hemisphere) was run separately on the

UVF and LVF data. The main effect of Category was not significant in the UVF data (p = .30), the main effects of Hemisphere and Group were not significant in either visual field (all ps > .11), and all interactions between the factors were non-significant in both visual fields (all ps > .10). There was however a marginal main effect of Category in the LVF, $F(1, 21) = 3.60$, $p = .063$, suggesting that a category effect may be present in P1. A category effect in this component is clearly important to the debate concerning the time course that category effects are found in colour processing, consequently, these data were investigated further in two ways.

Firstly, Manly's Unrestricted Permutation of Observation test (Manly, 1991) was run for 10,000 permutations on the factor of Category (collapsed over the factors of Hemisphere and Group) to produce one amplitude average for each participant for each of the three conditions. The original F value (3.60) fell within the upper 5% of the F distribution computed from the permutations, suggesting that rejecting the null hypothesis is appropriate. Subsequent post hoc pairwise comparisons indicated a category effect: The different-category deviant ($M = 2.2$ μV; $SD = 1.7$ μV) was significantly more negative than both the standard ($M = 2.7$ μV; $SD = 1.4$ μV; $p = .005$) and the same-category deviant ($M = 2.9$ μV; $SD = 1.4$ μV; $p = .047$), see Figure 4.5a. The standard and same-category deviant did not differ significantly ($p = .410$).

Secondly, the mean amplitude data in P1 were reanalyzed by instead grouping by the factor of Colour, rather than by the factor of Category (see Figure 4.2b). This approach examines whether P1 amplitude is affected by the colour of the stimuli, instead of the categorical relationship between them. The factor of Colour has three-levels: Mean amplitude elicited to the green deviant, to the blue deviant, and to the standard. A main effect of Colour would suggest that the three colors elicited different amplitudes. A main effect of Group (Blue Namers vs. Green Namers) would suggest that, overall, mean amplitude is larger in one of the groups. A category effect would be supported by the finding of an interaction between the factors of Colour and Group, whereby the pattern of P1 amplitudes elicited to the three colors differs between the Blue and Green Namers. A three-way ANOVA (Colour × Group × Hemisphere) found no main effects of Colour ($p = .57$), Group ($p = .69$), or Hemisphere ($p = .12$), suggesting that mean amplitude did not significantly differ across the three colors or the two groups in either hemisphere. There was however a significant Colour × Group interaction, $F(2,32) = 3.60$, $p = .039$. This suggests a category effect in P1; the pattern

of ERPs elicited by the three stimuli differed across the Blue and Green Namers (see Figure 4.5b). A separate one-way ANOVA was run for each group collapsed over the factor of Hemisphere; the main effect of Colour was not significant for either group (both ps > .13). All other remaining interactions between the factors were non-significant (all ps > .12).

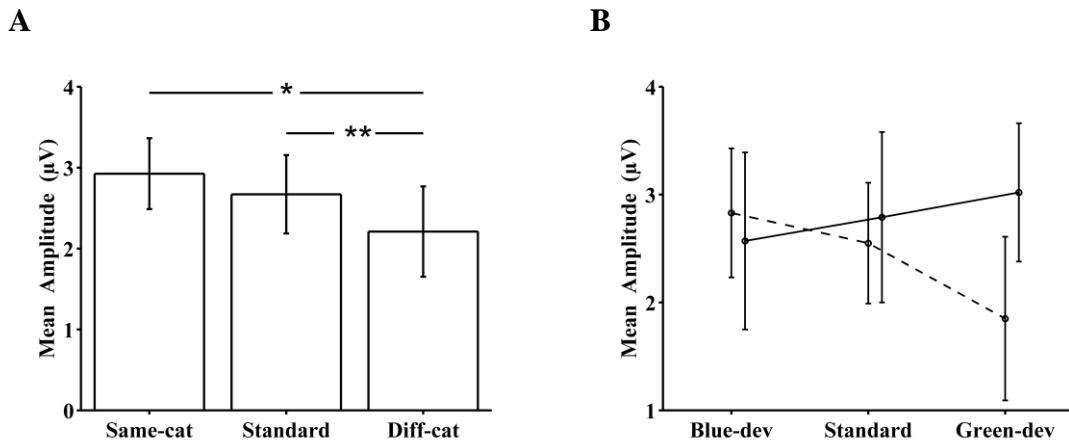**A**   **B**

Figure 4.5. P1 component for three colour stimuli presented to the lower visual field. (A) Data grouped by Category. (B) Data grouped by Colour, whereby the standard was named green (solid line) or blue (dashed line). Significant differences denoted by asterisks (* p < .05, ** p < .01). No equivalent effects were found for stimuli presented to the upper visual field. Error bars represent ±1 SEM.

Anterior N1 analyses: The anterior N1 showed peak amplitude 135 ms over frontal and central areas. A time window of 120 – 150 ms was selected and averaged over nine electrode sites (F1, Fz, F2, FC1, FCz, FC2, C1, Cz, and C2) to reflect this maximal activity. A three-way mixed ANOVA (Category × Group × Hemisphere) on the data grouped by Category found no main effects in either visual field (all ps > .62). All interactions between factors were also non-significant in both visual fields (all ps > .11).

Posterior N1 analyses: A lateralized posterior N1 component was evident in the grand-averaged ERP waveform over parieto-occiptal sites. An analysis window of 160 – 180 ms and electrodes PO7, PO5, PO6, and PO8, were selected to reflect the maximal activity in posterior N1. A three-way mixed ANOVA (Category × Group ×

Hemisphere) found no evidence for a category effect; the main effect of Category was non-significant in either visual field (both ps > .34). There was a significant interaction between Category and Group in the UVF data, $F(2,32) = 3.73$, $p = .035$, however this did not represent a category effect. Rather, the interaction was driven by an overall difference in amplitude elicited in response to the green deviant (-2.7 μV) compared to the blue deviant (-3.5 μV) and the standard (-3.4 μV). In other words, the amplitude of this component changed depending on the colour of the stimuli, rather than the categorical relationship between them. Asides from a main effect of Hemisphere in the UVF, $F(1,16) = 4.97$, $p = .040$, (LVF: $p = .055$), due to a stronger posterior N1 in the right hemisphere, all other main effects and interactions were non-significant (all ps > .25).

Frontal positivity analyses: In the grand average waveforms of the LVF data over frontal sites (see Figure 4.3) it was observed that a different pattern of activity was elicited by the same- and different-category deviants over a range of around 100 ms. Specifically, the same-category deviant appeared more negative than the standard and different-category deviant in an earlier window (160 – 200 ms), while the different-category deviant appeared more negative than the standard and same-category deviant in a later window (220 – 260 ms). These analysis windows were chosen to reflect maximal frontal positivity activities, and because of previously reported significant category effects in frontal positivity activity around a similar time period (He et al., 2014). To investigate these potential category effects the factor of Time Window (2-levels [160 – 200 ms vs. 220 – 260 ms]) was included in a three-way ANOVA (Category × Group × Time Window) on the data averaged over electrodes AF3 and AF4. The observation was supported by a significant Category × Time Window interaction in the LVF data, $F(1,21) = 19.7$, $p < .001$ (Figure 4.6). A separate one-way ANOVA was subsequently run on the factor of Category for each time window. There was a significant main effect of Category in the later window, $F(2,34) = 3.31$, $p = .049$, which was driven by a category effect, whereby the different-category deviant elicited a significantly weaker mean amplitude (1.3 μV; $SD = 1.7$ μV) than both the same-category deviant (2.4 μV; $SD = 3.0$ μV; $p = .048$) and the standard (2.0 μV; $SD = 1.7$ μV; $p = .035$). The main effect of Category did not reach significance in the earlier time window ($F = 2.0$, $p = .15$), though in this window a different trend was found: Here, the

same-category deviant (0.40 µV; *SD* = 2.5 µV) elicited the weakest amplitude compared to the different-category deviant (1.0 µV; *SD* = 2.1 µV) and the standard (1.1 µV; *SD* = 1.8 µV). All other main effects and interactions in the LVF were non-significant as were all main effects and interactions in the UVF data, asides from a main effect of Time Window, which occurred due to an overall larger mean amplitude in the later window (2.1 µV) than the earlier window (1.0 µV).
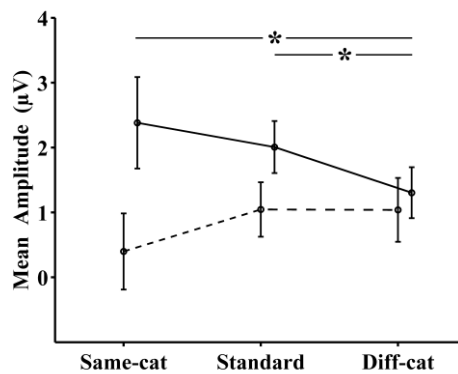

Figure 4.6. A significant interaction (*p* < .001) over frontal sites between the factors of Category and Time-window highlighting different amplitude responses to colour categories between (a) 160 − 200 ms (dashed line) and (b) 220 − 260 ms (solid line). Stimuli were presented to the lower visual field. No effects were found for stimuli presented to the upper visual field. Significant differences in the later time window (220 − 260 ms) denoted by asterisks (* *p* < .05). Error bars represent ±1 SEM.

N2 analyses: Both an anterior N2 ranging from frontal to centro-parietal areas (316 − 356 ms) and a lateralized posterior N2 over parieto-occipital sites (330 − 360 ms) were evident and analyzed. In both cases there was no significant category effect; the main effect of Category was not significant at anterior or posterior sites in either the LVF or UVF (all *p*s > .30). There was however a significant interaction between the factors of Category and Group in the LVF data of the posterior N2, *F*(2,32) = 3.64, *p* = .038. Like

the mean amplitude of the UVF data for the posterior N1, the amplitude of this component changed depending on the colour of the stimuli, rather than the categorical relationship between them. The pattern of amplitude differences in the posterior N2 LVF data was different to that observed in the posterior N1 UVF data: Here, the green deviant (-1.8 µV) rather than the blue deviant (-1.0 µV) elicited the strongest response, and like the posterior N1 the mean amplitude of the standard fell in between the mean amplitude of the two deviants (-1.3 µV).

Behavioral performance analyses: Hit rates from participants included in the ERP analysis for target trials were very high ($M = 99.8\%$; $SD = 0.3$) suggesting participants attended to the fixation dot throughout testing. False alarm rates were likewise very low ($M = 0.04\%$; $SD = 0.03$). Mean response time to targets was 389 ms ($SD = 28.8$ ms).

4.5 Discussion

We measured ERPs on a passive oddball task to blue and green colors equated in JNDs that varied in their categorical relationship for two groups of observers who differed in colour naming. The earliest indication of a category effect was 100 ms after stimulus onset in the P1. Because attention was directed away from the colors during the task, the effect in the P1 likely reflects an early, pre-attentive process that encodes the categorical relationship between colour stimuli. A category effect was also found at frontal sites around 250 ms, indicating that post-perceptual processing also responds to the categorical relationship between stimuli. In all cases, these category effects were found for stimuli presented to the LVF, rather than the UVF, which supports prior findings that ERPs differ depending on which visual field a stimulus is presented to (Clifford et al., 2010; Czigler et al., 2004).

The earliest indication of a category effect in visual processing was found in the P1 component. Here, the different-category deviant elicited a significantly more negative amplitude than both the same-category deviant and the standard stimulus. The P1 component in this study likely corresponds to unconscious, pre-attentive processes (Luck, Woodman, & Vogel, 2000) and to neural activity in extrastriate cortical areas (Mangun, Hopfinger, Kussmaul, Fletcher, & Heinze, 1997). The finding of greater negativity elicited to a different-category deviant compared to a same-category deviant

has been reported previously on visual oddball tasks in the visual mismatch negativity (vMMN; Czigler, 2007). The vMMN has been suggested to arise from the automatic processing of unattended visual stimuli and as a marker of low-level, pre-attentive perceptual processing (Clifford et al., 2010; Czigler et al., 2002). It is thought to be characterized by a posterior distribution and occur from around 100 – 250 ms (Clifford et al., 2010; Czigler, 2013; Folstein & Van Petten, 2007). A question here is whether the finding of greater negativity for the different-category deviant in the present study in P1 over posterior sites should be viewed as a category-related vMMN response (Clifford et al., 2010; Czigler, 2013). In the present study, and unlike prior reports, this response was limited to P1, rather than continuing over a longer period of visual processing. For example, greater negativity for different-category deviants has been shown in posterior sites up to 250 ms after stimulus onset (Clifford et al., 2010). One possible explanation for this difference in findings is the use of stimuli equated to be equally discriminable in the present study, which may result in more subtle differences in ERP amplitudes.

Further evidence for categorical processing was found in the present study over frontal sites from 220 – 260 ms. Here, significantly greater negativity was elicited in response to the different-category deviant compared to the same-category deviant and the standard. A post-perceptual category effect was also found in He et al.'s study (2014) which also used blue and green stimuli equated in JNDs, and also found a significant effect over frontal sites from 210 – 260 ms but when colour differences were attended. However, the pattern was different across the two studies; in the present study the different-category deviant elicited a significantly smaller amplitude than the other stimuli, whereas in the study by He et al., the different-category deviant elicited significantly greater amplitude than the other stimuli. Without further investigation the reason for this difference cannot be clarified, however one possibility is that it may arise because of different task demands: the effect may be modulated by whether or not colour changes need to be attended during the task.

In the present study we found a colour category effect in P1, which corresponds to early stages of visual processing, and this therefore suggests that the categorical relationship between colour stimuli is registered in early sensory stages of visual processing. This effect appears to be related to how participants named the colors. However, very importantly, the direction of the relationship between colour naming and the early sensory category effects remains to be clarified. It remains unclear whether

this early sensory category effect is due to physiological differences in the visual system across individuals that give rise to differences in colour naming, or whether colour naming modulates early sensory processes. In other words, the early sensory category effects could be the cause rather than result of the group differences in colour naming. Cone pigment (Jameson, Highnote, & Wasserman, 2001), macular pigmentation (Sharpe et al., 1998), the optical density of retinal photopigments (He & Shevell, 1995), eye pigmentation (Jordan & Mollon, 1995), as well as the relative number of L and M cones (Otake & Cicerone, 2000), are known to vary across individuals and might account for such differences. However, others have not found a link between physiological differences and colour naming. For example, it has been shown that individual differences in unique hue settings (pure examples of the terms red, green, blue and yellow) do not relate to individual differences in the sensitivity of the spectral sensitivities of the cones (Malkoc, Kay, & Webster, 2005; Webster, Miyahara, Malkoc, & Raker, 2000). A task for future research will be to clarify the relationship between these low-level physiological attributes and colour naming.

It has previously been shown using fMRI that explicit naming of attended colors modulates activity at V4 and VO1 (Brouwer & Heeger, 2013), although representation in these regions was found to be non-categorical when attention was directed away from the colors. Likewise, several fMRI studies have failed to find an effect of colour categories on visual cortex when colors are passively viewed (Bird et al., 2014; Persichetti, Thompson-Schill, Butt, Brainard, & Aguirre, 2015). However, our result does suggest some form of relationship between colour naming and early sensory processes even when colour changes do not need to be attended. Further investigation of the neural basis of our effect at P1 and the neural representation of colour categories will be important to establish the conditions under which language really does interact with our early sensory visual processing and the underlying mechanisms of such an effect. Shedding light on this question has the potential to address more fundamental issues about how colour is perceived (e.g., the source of individual differences in colour perception), as well as the degree to which language has the capacity to affect the way we see the world.

Chapter 5

Paper 4: A neural signature of the unique hues

Forder, L., Bosten, J., He, X., & Franklin, A. *PNAS* (in preparation)

5.1 Abstract

A dominant theory in human colour vision is that there are four perceptually pure "unique" hues: red, yellow, green, and blue, and that all other hues are perceived as mixtures of these four hues. However, research has not yet provided solid evidence for a neural representation that separates the unique hues from other colors. We measured event-related potentials elicited from unique hues and the 'intermediate' hues in between them. We find a neural signature of the unique hues 230 ms after stimulus onset at a post-perceptual stage of visual processing. Specifically, the posterior P2 component over the parieto-occipital lobe peaked significantly earlier for the unique than for the intermediate hues ($Z = -2.9$, $p = .005$). Having identified a neural marker for unique hues, fundamental questions about the contribution of neural hardwiring, language and environment to the unique hues can now be addressed.

5.2 Introduction

For over one hundred years colour science has been influenced by the idea that there are four phenomenologically pure "unique" hues (Hering, 1878): red, yellow, green, and blue. It is claimed that unique hues are elemental qualities in colour perception because they cannot be described in terms of any other hues (Wyszecki & Stiles, 1982), and that all other hues can be described as mixtures of these four hues (Sternheim & Boynton, 1966). Unique hues have a different definition to 'focal' colors, which are the best examples of a given colour term and are found at specific levels of lightness or saturation. However, average unique hues are similar in hue to focal red, green, blue and yellow (Kuehni, 2005; Miyahara, 2003; Witzel & Franklin, 2014). Results from cross-cultural studies suggest that the focal colors have a degree of universality, showing conservation across different colour lexicons (Kay & Regier, 2003). The assumed universality of phenomenological colour experience as well as the cross-cultural results on focal colors have led to the assumption that there is a 'hardwired', neural representation of the unique hues somewhere in the visual system (Stoughton & Conway, 2008).

It was once thought that the unique hues must be represented at an early stage in the visual processing system, in the retina and lateral geniculate nucleus (De Valois, Abramov, & Jacobs, 1966). Since we now know that the retino-geniculate "opponent processes" are tuned to the intermediate colour directions violet-chartreuse and cherry-teal, rather than to the unique hues (Jameson & D'Andrade, 1997; Mollon & Cavonius, 1987), models for the combination of retino-geniculate colour mechanisms that result in a cortical colour representation of the unique hues have been proposed (De Valois & De Valois, 1993; Valberg, 2001; Wuerger, Atkinson, & Cropper, 2005).

Only one study to date has reported evidence of a neural representation of unique hues; Stoughton and Conway (2008), took single-unit recordings in macaques and found that neurons in posterior inferior temporal cortex are preferentially tuned to unique red, green and blue, though not to unique yellow. However, Mollon (2009) challenged Stoughton and Conway's conclusions on the basis of limitations with their stimuli. Specifically, Mollon advocated the need for a set of colour stimuli that lie on a circle in an appropriate chromaticity space. In short, identifying a neural representation of the unique hues has proved elusive, and scientists have questioned whether such a

representation will be found (Bosten & Boehm, 2014; Mollon, 2006; Saunders & van Brakel, 1997; Wool et al., 2015). Finding neural evidence for the unique hues remains a key objective in contemporary colour science.

The current study aimed to reveal a neural representation of the unique hues by measuring event-related potentials (ERPs) elicited in response to eight different hues: the four unique hues and the four intermediate hues (orange, lime, teal, and purple). We firstly accounted for individual variation in the positions of the unique and intermediate hues by adopting a psychophysical task similar to that of Malkoc, Kay, and Webster (2005). For each of the eight hues, observers selected a hue that was like neither of its neighboring hues on the hue circle (e.g., a red that is neither too orange nor too purple). For each observer ($N = 23$) we then measured the electrophysiological activity elicited in response to their specific unique and intermediate hues. Observers viewed each hue presented in isolation on a neutral background. Observers were required to manually respond to a target hue that varied across blocks. Response trials were excluded from subsequent analysis to avoid the contamination of ERP waveforms from the electrophysiological activity elicited by making a manual response. By analyzing multiple visual ERP components (P1, anterior N1, and posterior P2) we aimed to identify the time at which a neural signature of the unique hues arises during visual processing.

5.3 Methods

5.3.1 Participants

Twenty-three native British English speakers took part (10 male; mean age = 19.7; $SD = 1.36$). Observers were recruited from the University of Sussex. All observers had normal colour vision, assessed using the Ishihara test (Ishihara, 1987) and the City University Test (Fletcher, 1980) presented under natural daylight. Observers were naive to the purpose of the study, provided written informed consent and their time was reimbursed with money or research credits.

5.3.2 Set up

Observers were seated in a dark room, the only source of light was the 22" Diamond Plus CRT monitor (Mitsubishi, Tokyo, Japan), which was used to present the stimuli (colour resolution: 8 bits/channel; spatial resolution: 1024×768; refresh rate: 75 Hz) and located 40 cm away from observers. Gamma correction was achieved using a CRS ColorCal (Cambridge Research Systems, Rochester, UK).

5.3.3 Task 1: Hue setting

5.3.3.1 Stimuli

Stimuli were annuli of 100 equally-sized colored segments with an outer diameter of 22° and inner diameter 14°. Each segment was an isosceles trapezoid with a circular top and base covering an area of $2 \times 2°$. The segments had a geometric angle of 2.6° of the annulus and between them were 1° gaps. The segments were isoluminant (28 cd/m^2), isosaturated in the CIELUV uniform chromaticity space (L* = 130; Chroma = 110) and always sequentially circumnavigated the CIELUV hue circle in equal-sized steps of a hue angle of 3.6°. The hue circle was randomly rotated on each trial so that the exact chromaticity coordinates of the colors would vary and would not appear in the same location on each trial. The background grey was metameric with D65 and had a luminance of 14cd/m^2. The experiment was written in Matlab (The MathWorks Inc., 2012) with the Psychophysics toolbox (Brainard, 1997).

5.3.3.2 Design and procedure

At the start of each block observers were instructed to select a particular hue in comparison to its neighboring hues, for example, "an orange that is neither too red nor too yellow". On each trial observers selected the specified hue by clicking a segment in the annulus with the mouse cursor. The colour terms (red, orange, yellow, yellow-green, green, blue-green, blue, and purple) were the same as those used by Malkoc et al. (2005). Once selected, a light grey highlighter (35 cd/m^2 and metameric with D65) was displayed outside the annulus with a gap of 2° to the annulus. An alternative segment could be selected in which case the highlighter moved, or the same segment was tapped

again to complete a trial. One hue was measured in each block of 20 trials. There were 16 blocks: the order was randomized so that the first eight and last eight blocks each contained all of the eight hues, and each block was different to the last. If participants forgot the target colour, they could hold the spacebar during a trial to temporarily show the instructions.

5.3.4 ERPs

5.3.4.1 Stimuli

Stimuli were the four unique hues (red, yellow, blue, and green) and four intermediate hues (orange, lime, teal, and purple) for each observer. The chromaticity coordinates of the eight hues were each observer's median hue selections from the hue selection task. Test materials were presented with e-Prime 2 (Psychology Software Tools, Inc.).

5.3.4.2 Design and procedure

At the start of each block one of the eight hues was selected randomly as the target hue. The eight hues were presented centrally as squares (2 x 2°) for 400 ms on each trial, with a randomized interstimulus interval of 1200-1600 ms. In a block, all hues were presented 10 times each in a random order. The observer was asked to make a manual response only to the target hue by pressing the space bar with both hands. There were 16 blocks, so each hue was presented a total of 140 times as the distracter and 20 times as the target. Prior to testing, observers completed 40 practice trials during which the target was black (metameric with D65 with a luminance of 0.60 cd/m^2).

5.3.4.3 EEG recording and analysis

EEG data was recorded and processed with NeuroScan SynAmps^2 amplifiers and SCAN 4.3 software (NeuroScan/Compumedics, Inc.) at a digitizing rate of 1,000 Hz. A physical band-pass filter was applied to online recording (0.10 – 100 Hz). EEG was recorded from 39 electrode sites: FP1, FPz, FP2, AF3, AF4, F7, F3, Fz, F4, F8,

FC3, FCz, FC4, T7, C3, Cz, C4, T8, CP3, CPz, CP4, P7, P5, P3, P1, Pz, P2, P4, P6, P8, PO7, PO3, POz, PO4, PO8, O1, Oz, O2, and the observer's right mastoid using Ag-AgCl electrodes physically referenced to the left mastoid. The EEG activities at the mastoids were averaged off-line and used as the reference. Eye blinks and eye movements were monitored via one bi-polar horizontal electro-oculogram (HEOG) channel located laterally of the canthi and one vertical electro-oculogram (VEOG) channel located above the observer's left eye. Impedance of each channel was reduced below 5kΩ prior to data collection. Following EEG recording, a zero phase-shift low-pass filter with amplitude cut-off frequency of 30 Hz and 24dB/oct roll-off was applied to the data. EEG and HEOG were epoched off-line with a window extending 600 ms after stimulus onset, relative to a 100 ms pre-stimulus baseline. Artifact rejection criteria comprised trials with a voltage exceeding ±60 µV at any electrode site. ERPs were generated by averaging EEG activities over trials time-locked to stimulus onsets.

5.3.4.4 Statistics and data analysis

For each component, peak latencies were calculated by taking the mean latency across those electrodes where activity was maximal. For each observer, electrodes were included in the calculation of peak latency providing an unambiguous peak was available for all eight hues. This guaranteed that for each observer the same electrodes were included for all hues. P1 had a maximal distribution over occipital and parieto-occipital sites (O1, Oz, O2, PO3, POz, & PO4) around 130 ms after stimulus onset. The anterior N1 was maximal around 136 ms after stimulus onset over frontal and fronto-central sites (AF3, AF4, F3, Fz, F4, FC3, FCz, & FC4). The posterior P2 was maximally distributed over occipital, parieto-occipital, and parietal sites around 230 ms after stimulus onset (O1, Oz, O2, PO3, POz, PO4, P1, Pz, & P2). Observers were excluded from the analysis if peak latency could not be reliable ascertained (N=1 for P1; N=3 for anterior N1; N=2 for posterior P2). For each observer, mean amplitude was calculated using a moving window approach, whereby their peak latency data directs the location of the middle of the window and amplitudes are averaged over a period of time before and after this peak. For each component, mean amplitudes were averaged and analyzed over a total window of 30 ms for those electrode locations specified above.

5.4 Results

Figure 5.1a is a polar histogram of unique and intermediate hue settings for all observers. Each observer's unique and intermediate hue settings were used to define the stimuli presented in the ERP task: Figure 5.1b plots the mean stimulus position of each hue across all observers in CIELUV colour space as well as the range of hue settings. For the ERP results we analyzed the peak latencies (ms) and mean amplitudes (µV) of each of the eight hues in three visual ERP components (P1, anterior N1, and posterior P2) – these are presented in Table 1. A sample of representative ERP waveforms which illustrate these components is given in Figure 5.3 in Supplementary 1.

Table 5.1. Mean peak latencies and amplitudes for the three ERP components for the four unique hues (white background) and four intermediate hues (grey background). Unique: Mean scores averaged for the four unique hues. Inter: Mean scores averaged for the four intermediate hues.

	P1		Anterior N1		Posterior P2	
	Latency (ms) ± SEM	Amplitude (µV) ± SEM	Latency (ms) ± SEM	Amplitude (µV) ± SEM	Latency (ms) ± SEM	Amplitude (µV) ± SEM
Red	130.86 ± 3.76	5.11 ± 0.73	137.36 ± 5.01	-3.08 ± 0.45	229.64 ± 3.91	4.73 ± 0.49
Orange	130.57 ± 3.51	5.24 ± 0.67	138.41 ± 4.96	-3.13 ± 0.46	233.81 ± 4.20	5.24 ± 0.37
Yellow	128.67 ± 4.13	5.09 ± 0.76	135.24 ± 4.53	-3.08 ± 0.46	232.09 ± 4.28	4.61 ± 0.44
Lime	130.89 ± 3.51	4.90 ±0.71	136.26 ± 4.92	-3.05 ± 0.41	234.40 ± 4.24	4.83 ± 0.41
Green	129.58 ± 3.94	4.83 ±0.71	134.48 ± 4.98	-2.92 ± 0.37	233.10 ± 4.98	5.05 ± 0.54
Teal	129.69 ± 4.33	5.26 ± 0.75	136.35 ± 4.85	-2.52 ± 0.46	234.77 ± 3.90	5.20 ± 0.46
Blue	130.35 ± 3.98	4.76 ± 0.78	138.81 ± 4.86	-2.74 ± 0.52	233.68 ± 4.81	4.61 ± 0.48
Purple	132.69 ± 3.30	5.09 ± 0.75	133.51 ± 4.26	-2.33 ± 0.38	234.38 ± 4.17	4.42 ± 0.47
Unique	129.86 ± 3.87	4.95 ± 0.75	136.47 ± 4.64	-2.96 ± 0.41	232.13 ± 4.28	4.75 ± 0.43
Inter	130.96 ± 3.41	5.12 ± 0.71	136.07 ± 4.45	-2.76 ± 0.38	234.34 ± 4.02	4.93 ± 0.39

Our stimuli fall along a circle in CIELUV colour space. However, we observed that the peak latencies and mean amplitudes for individual observers were non-randomly distributed across regions of colour space. For example, Figures 5.2a and 5.2b shows the mean peak latency of the posterior P2 component as a function of hue angle in CIELUV space for two observers. The data points in each panel form elongated distributions with greater peak latencies usually along a roughly purple-lime axis. To account for this individual variability, for each ERP component we fit ellipses to each observer's peak latency (*r*) and mean amplitude (*r*) as functions of hue angle (*θ*). Ellipses for the two observers shown in Figures 5.2a and 5.2b are indicated by the dashed lines.
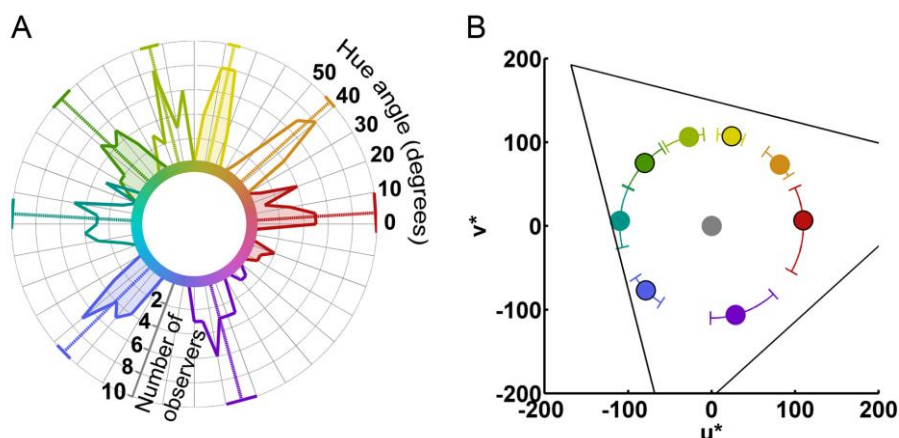

Figure 5.1. Hue selection data from the first task. (**A**) Polar histogram plotting median hue selections for each observer for the four unique hues (shaded) and four intermediate hues (not shaded). Hue angle is in CIELUV. Colored radial lines represent the mean of these median selections with corresponding 95% confidence intervals as solid lines on the circumference of the plot. (**B**) Cartesian plot in CIELUV of mean hue selections for each of the four unique hues (with black border) and the four intermediate hues (without border). The circumferential error bars denote the range of median hue selections across observers. The solid black triangle defines the monitor gamut. The gray circle indicates the white point (metameric with CIE Illuminant D65).

We found the residuals for each data point to the best-fitting ellipse, which is equivalent to the difference in the peak latency or mean amplitude for a particular hue compared to the peak latency or mean amplitude expected from that hue's position in colour space. The sign of each residual (i.e., positive or negative) indicates whether the peak latency or mean amplitude for each hue is smaller or larger than expected for its position in colour space, e.g. negative residuals fall inside the ellipse and indicate an earlier peak latency or smaller mean amplitude than expected. This method of fitting ellipses to account for the non-uniform effect of position in colour space on a behavioral measure follows that used by Witzel and Gegenfurtner (2013) and Bosten and Lawrance-Owen (2014).

For peak latency and mean amplitude of each component, this analysis produced eight residuals for each observer, one for each hue. Friedman tests found no significant main effect of Hue on mean amplitude for any component (Figure 5.4a–c in Supplementary 2). There was a significant main effect of Hue on peak latency on P1, however when we grouped the four unique hues together and compared this to the four grouped intermediate hues, a Wilcoxon test found no significant difference in peak latency between these two groups ($Z = -1.35$, $p = .18$; Figure 5.2D). There was no main effect of Hue on anterior N1 peak latency (Figure 5.4e in supplementary). For the latency of the posterior P2 component, however, a Friedman test found a significant main effect of Hue (χ^2 (7) = 27.5, $p = .00027$), which was specifically associated with a difference between the grouped unique compared to the grouped intermediate hues. This can be seen in Figure 5.2c, which displays mean peak latency, across observers, as a function of hue angle, as well as in Figure 5.2d, which presents the group mean residuals of the positions of each hue from the best fitting ellipse. The residuals for all four unique hues are negative (meaning the posterior P2 occurs earlier than expected), while the residuals for all four intermediate hues are positive. A Wilcoxon test confirmed that the unique hues as a group had significantly earlier posterior P2 peak latency than the intermediate hues ($Z = -2.9$, $p = .004$, $r = .45$). This difference in peak latency in the ERP waveforms is presented in Figure 5.2e.
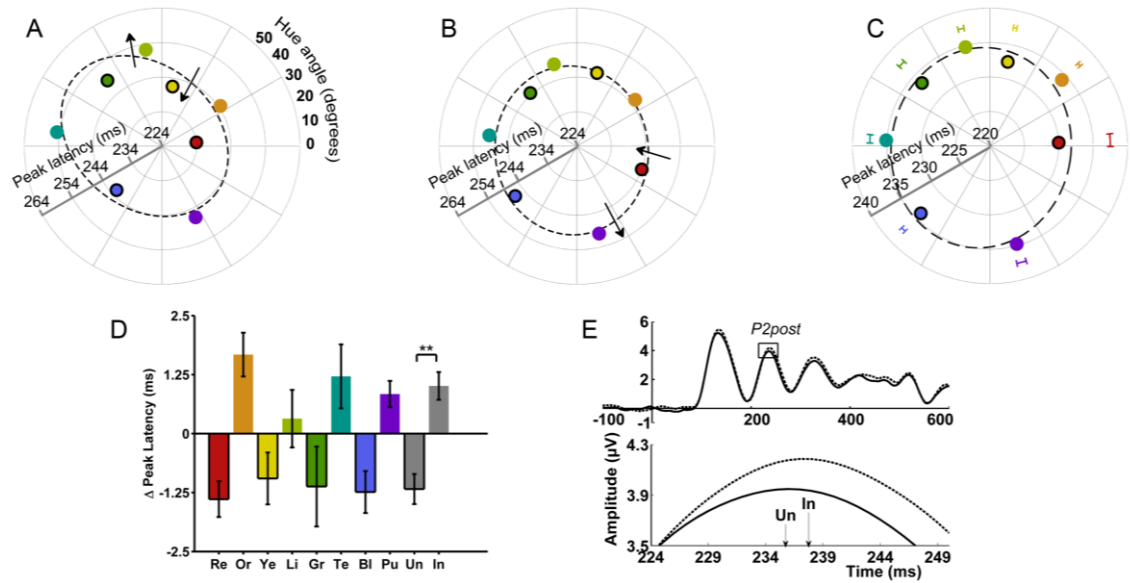
Figure 5.2. Results for posterior P2 peak latency. The four unique hues of red (Re), yellow (Ye), green (Gr) and blue (Bl) are denoted with solid black borders. The four intermediate hues of orange (Or), lime (Li), teal (Te) and purple (Pu) do not have borders. (**A**) and (**B**) Data from single observers depicted as polar plots showing peak latency (*r*) as a function of the observer's median hue selection (θ), i.e., hue angle in CIELUV. For each observer the unique hues all fall inside a best-fitting ellipse applied to the data (dotted black line) showing that they all peaked earlier than would be expected for their location in chromaticity space. Plots have been rescaled for graphical purposes so that the earliest latency depicted (224 ms) falls in the centre of each plot. Arrows highlight the trend for unique hues to fall inside the ellipse and intermediate hues to fall outside the ellipse. (**C**) Data averaged across all observers for whom peak latency could be ascertained (N = 21) and depicted as a polar plot in the same fashion as panels **A** and **B.** Here rho represents the mean of the median hue selections across observers. The error bars located towards the edge of the plot represent ± 1 SEM of the variation in median hue selections across observers. (**D**) Group mean residuals of the positions of each hue from the best fitting ellipse for posterior P2 peak latency (Bars for unique hues have black borders). The combined mean Unique (Un) and Intermediate (In) are shown in grey. Error bars are ± 1 SEM. (**E**) Representative ERP waveforms from electrode Oz (N = 21) for the averaged unique hues (solid line) and the intermediate hues (dotted line). The top panel

depicts the mean amplitude across observers from -100 to 600 ms stimulus onset. The posterior P2 component is surrounded by a box.

5.5 Discussion

We report a neural signature of the unique hues that exists 230 ms after stimulus onset. The effect was strong: all four unique hues elicited an earlier posterior P2 peak latency than all four intermediate hues. We find no indication for a neural marker for the unique hues in earlier components (i.e., the P1 and anterior N1). Our results did not depend on our particular analysis using fitted ellipses: a significant main effect of hue was also present in the raw posterior P2 latencies, χ^2 (7) $= 14.2$, $p = .048$, with a significant difference between unique and intermediate hues, $Z = -2.8$, $p = .005$, $r = .44$. The P2 component is thought to reflect "post-perceptual" processes (Patel & Azzam, 2005), coming later than the P1 and early-phase N1 components, which are thought to reflect processes generated by the early visual system (Di Russo, Martínez, Sereno, Pitzalis, & Hillyard, 2002). The posterior P2 has been associated with a range of visual cognitive processes including attention (Anllo-Vento, Luck, & Hillyard, 1998), stimulus ambiguity (Latinus & Taylor, 2006), perceptual learning (Qu, Song, & Ding, 2010; Song et al., 2007), working memory (Lefebvre, Marchand, Eskes, & Connolly, 2005), stimulus detectability (Kotsoni, Csibra, Mareschal, & Johnson, 2007; Straube & Fahle, 2010), contour integration (Machilsen, Novitskiy, Vancleef, & Wagemans, 2011) and language processing (Kellenbach, Wijers, Hovius, Mulder, & Mulder, 2002). Though the findings on the posterior P2 are broad, many studies share task elements with our own. For example, (Anllo-Vento et al., 1998) found that the amplitude of the posterior P2 was smaller for attended than non-attended isoluminant colors. Analogously, unique hues may have recruited the attentional resources of our participants differently from intermediate hues. Song et al. (2007) found that the amplitude of the posterior P2 reduced as perceptual learning progressed for orientation discrimination of gratings. Perceptual learning during ontogenetic development may distinguish neural representations of the unique from those of the intermediate hues. In language processing, Kellenbach et al. (2002) found a lexical categorization effect for nouns

versus verbs in the amplitude of the posterior P2. Our findings could plausibly be related to lexical categorization differences for unique and intermediate hues.

Our results show different latencies of the posterior P2 for the unique and intermediate hues, and "uniqueness" is one defining characteristic of the distinction. However, there could an alternative scheme in which the hue categories that the unique hues belong to are advantaged. Hues from red, green, blue and yellow categories could achieve faster latencies because their representations are more accessible than those from other categories, independently of the uniqueness of the stimuli. Accessibility could be determined either linguistically (e.g. if red were faster to name than orange), or non-linguistically (e.g. the category green may have a stronger neural representation than the category teal if green objects occur more frequently than teal objects). We will raise each of these possibilities in turn.

Though our participants were not required to name the colors to do the task, language may have exerted an influence on our results if either an explicit or implicit linguistic strategy was adopted when memorizing and subsequently identifying the target. Red, green, blue and yellow hues are all named with basic colour terms, which are known to all speakers, are monolexemic, and are not subordinate to another colour term (Berlin & Kay, 1969). There is a known linguistic advantage (e.g. word frequency and response times) for basic over non-basic colour terms such as lime or teal (Davies & Corbett, 1997). However, two of our intermediate hues, purple and orange also have basic colour terms, and studies of colour naming show no response time advantage for naming red, yellow, green and blue over colors named with other basic terms (Boynton & Olson, 1987; 1990). Therefore, nameability by a basic colour term cannot necessarily account for our pattern of results where red, yellow, green and blue and peaked earlier than purple and orange as well as teal and lime.

If a non-linguistic category advantage for red, green, blue and yellow could account for our results, then there would have to be an ease of access advantage for these categories over other frequently used colour categories in a task that does not require colour naming. Though our participants were not asked to respond as quickly as possible on target trials, we collected behavioral response times to each hue target during the ERP recording session. We found no significant difference in mean response time for red, green, blue and yellow compared to the orange and purple hues, which are

also from basic colour categories (Z = -0.54, p = .59). Though to our knowledge a non-linguistic category advantage for red, green, blue and yellow has not previously been sought, in our data there is no evidence that red, green, blue and yellow have a stronger non-linguistic categorical representation than other frequently used colors. Therefore, a non-linguistic category advantage cannot obviously account for our results.

A potential advantage for colors from red, green, blue and yellow categories could be linguistic or non-linguistic, but both possibilities rely on our stimuli being close to focal examples of those categories. Focal colors are the best colour examples for each category, and are typically defined in a colour space that includes variation in luminance and saturation. For example, focal red is saturated and of a low luminance, while focal yellow is found at a higher luminance (Sturges & Whitfield, 1995). By contrast, unique hues are defined along loci in colour space that include a range of saturations and luminances – unique blue is a blue that is neither reddish or greenish but could be dark, light, or of high or low saturation. Our stimuli were defined around an isosaturated and isoluminant circle in the CIELUV colour diagram, chosen to ensure that we could isolate uniqueness independently of luminance and saturation. Our unique hues were therefore different to focal colors. For example, our unique red was less saturated than focal red, and might even be labeled pink if observers were forced to give it a name. Therefore, even if focal red, green, blue and yellow are at a linguistic or conceptual advantage, that advantage does not necessarily apply to our stimuli, which were defined according to their uniqueness.

The origin of the unique hues has been mysterious. They are not encoded at an early retino-geniculate level of visual processing, and here we find no evidence of a correlate in the early sensory ERP components P1 and early-phase N1. Our results are consistent with a later neural representation. But what could cause the unique hues to receive their uniqueness? The perceptual salience hypothesis has long proposed that the unique hues are hardwired and that confers the cross-cultural consensus in their positions (Kay & Regier, 2003; Kuehni, 2005). However, this framework has been undermined by the fact that unique hues do not show a privileged position in behavioral response times (Lindsey et al., 2010; Wool et al., 2015), discriminability (Witzel & Gegenfurtner, 2013), but see also Danilova and Mollon (2012), consistency (Bosten & Lawrance-Owen, 2014) and perceived saturation (Witzel & Franklin, 2014). Our finding of an effect of uniqueness in the P2 is neutral with respect to the perceptual

salience hypothesis (since the P2 is not a clear marker for perceptual salience), yet the effect does provide evidence that unique hues are not solely a linguistic construct, but that they are represented at some other level.

An alternative but not mutually exclusive account to the perceptual salience hypothesis favors an environmental origin of unique hues, which would become internalized either genetically or ontogenetically. Unique blue and yellow could arise from familiarity and normalization to the colour statistics of natural scenes, and particularly daylight illuminants (Mollon, 2006; Welbourne, Morland, & Wade, 2015), though there is currently not a good account in this framework for the origin of unique red and green (Broackes, 2011). O'Regan and colleagues have proposed that reflectance spectra corresponding to unique hues generate more reliable colour signals across changing illumination (Philipona & O'regan, 2006; Witzel, Cinotti, & O'Regan, 2015). Alternatively, the social rather than the physical environment may confer the unique hues' special status through linguistic and cultural consensus. To distinguish the contributions of neural hardwiring, language and environment to the unique hues, their measurement across cultures and in prelinguistic infants will be critical. Having now established a neural marker of the unique hues, such fundamental questions about the origins of unique hues can be addressed.

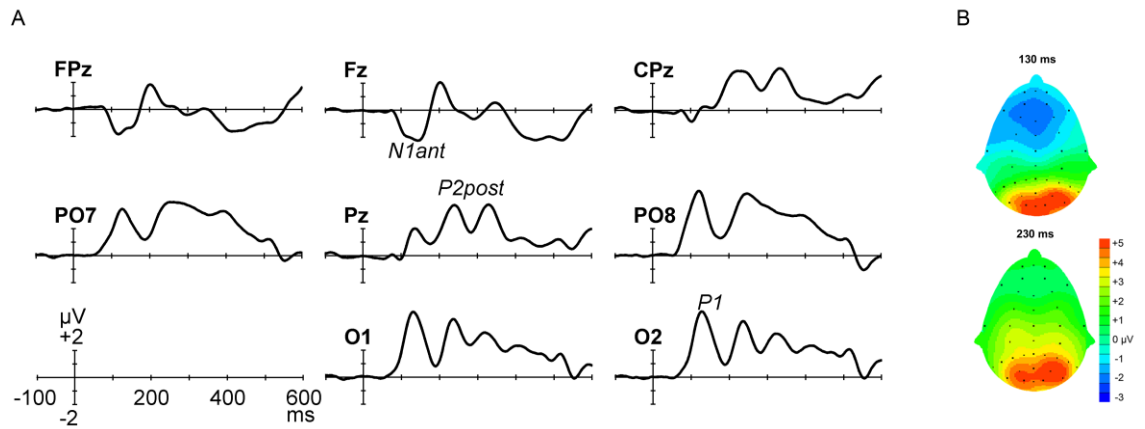5.6 Supplementary 1: Representative ERP waveforms and topographic maps

Figure 5.3. Representative ERP waveforms and topographic maps. (**A**) Grand averaged ERP waveforms at eight electrode locations, averaged for all participants (N = 23). Due to the similarity in waveforms across the eight hues and for graphical purposes the waveforms have been averaged across the eight hues to produce a single plot for each electrode. The electrode location (e.g., FPz) is specified at the top of each plot above the *y*-axis. The three ERP components (e.g., P1) are each specified in italics on a single plot. *N1ant:* The anterior N1 component. *P2post:* The posterior P2 component. (**B**) Topographic maps depicting the location of maximum amplitude (µV) for the three ERP components. Top figure (130 ms): P1 and anterior N1; bottom figure (230 ms): Posterior P2.

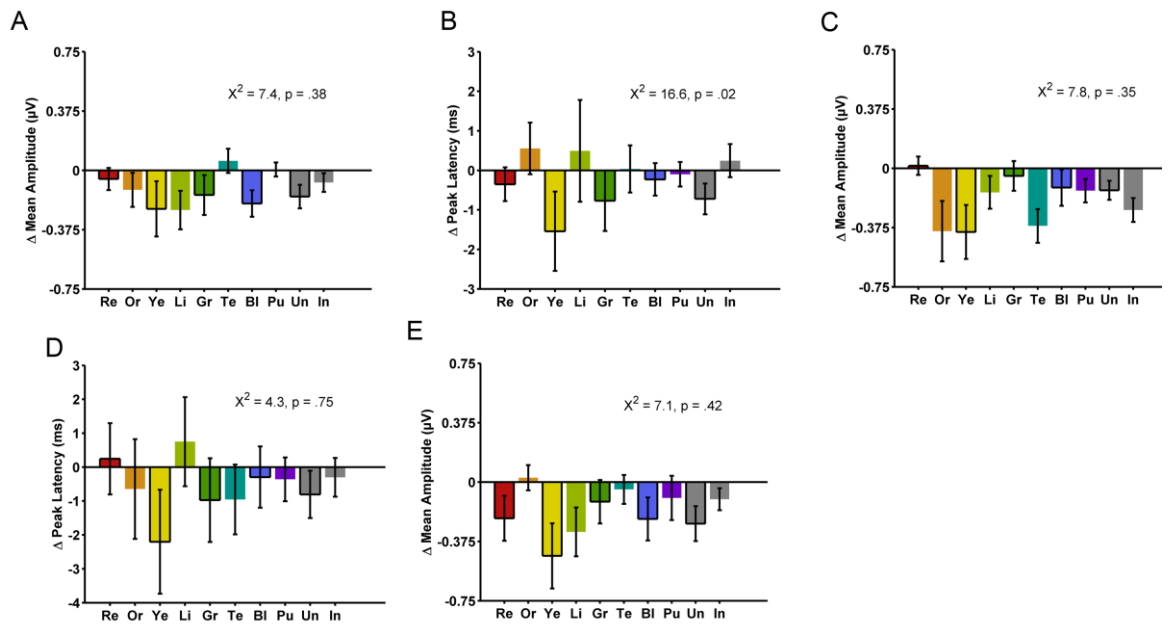5.7 Supplementary 2: Analysis of ERP components

Figure 5.4. Analysis of ERP components. Data corresponds to group mean residuals of the positions of each hue from the best fitting ellipse applied to each observer's data individually. The four unique hues of red (Re), yellow (Ye), green (Gr) and blue (Bl) are denoted with solid black borders. The four intermediate hues of orange (Or), lime (Li), teal (Te) and purple (Pu) do not have borders. The combined mean for each of these groups (Unique: Un; Intermediate: In) are likewise shown and in gray. (**A**) P1 mean amplitude. (**B**) P1 peak latency. (**C**) Anterior N1 mean amplitude. (**D**) Anterior N1 peak latency. (**E**) Posterior P2 mean amplitude. Error bars are ± 1 SEM.

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