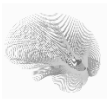
Neuropsychology of Colour Vision

Studies in patients with acquired brain damage, healthy participants, and cases with developmental disorders

Tanja Nijboer



Neuropsychology of Colour Vision

Studies in patients with acquired brain damage, healthy participants, and cases with developmental disorders

Studies bij patiënten met verworven hersenletsel, gezonde proefpersonen en cases met aangeboren stoornissen

(met een samenvatting in het Nederlands)

Proefschrift

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door

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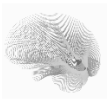
Contents

"You don't need eyes to see,
You need vision"

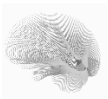


Voor mijn ouders

Chapter 1

General introduction

Visual perception in the human brain



In 1983, Sepp Zihl and his colleagues published an article about a 43-year old woman, LM, whose vision was intact apart from a complete inability to perceive movement. She had suffered a stroke that had damaged the posterior part of both the parietal lobes. Her condition, a selective deficit in the perception of movement, is now known as ´akinetopsia´ or 'motion blindness'. She reported that she perceived the world as a sequence of still images. Despite the fact that her vision was good otherwise, this disorder had serious implications for her daily life. Crossing the street, for example, had become very dangerous, because a car that she had last seen a good distance away might suddenly appear right in front of her. Pouring a glass of water was difficult, as she could not judge the speed with which the liquid level raised, was filling up. Even writing had become problematic as the stroboscopic movement of her own hand distracted her too much. These examples demonstrate that the visual system may become disrupted after focal lesions in the brain. These visual deficits can be very specific, affecting only a certain aspect of the visual world, such as motion. It is important to realise these highly selective visuo-sensory impairments can have serious repercussions for the patient in daily life. This thesis is not about motion, but about another normally obvious aspect of visual perception: colour. The studies reported here concern the way we process colour information, the problems people may encounter when colour perception is compromised, and the effect (loss of) colour perception has on our functioning in the real world.

Visual neuroscience

This work is conceptually embedded in the field of the cognitive neurosciences. This multi-facetted field pays allegiance to a number of different disciplines. Current knowledge of the structure of the brain comes from neuroanatomy and neurophysiology. Physiological studies in animals (e.g. single cell recordings) have delineated the response characteristics of individual or groups of neurons. Psychological models of mental processes have shaped the understanding of the brain at the functional level as delineated by neuropsychological and functional imaging (e.g. EEG, fMRI) studies. Vision is uniquely amenable for neuroscientific exploration as the neurophysiological structure of the primary visual system is highly comparable between different primates and because we are highly visual primates with about one third of the brain being dedicated to vision.

Functional specialisation of the visual cortex: anatomy and physiology

Most of the visual cortex is situated in the occipital lobe, but areas outside this region have been found to have functions related to vision as well. For example, the frontal eye fields in the frontal lobes are prominently involved in controlling eye movements and several distinct areas in the parietal and temporal lobes have been found to be involved in visual processing; lesions of the inferior temporal lobe, for instance, have been found to disrupt discriminations between objects, whereas lesions of the posterior parietal cortex have been found to disrupt discrimination in spatial arrangements (Mishkin, 1966; Mishkin, Ungerleider, Macko, 1983).

The occipital lobe encloses the major cortical visual area and can be subdivided into two parts, based on anatomical grounds. The largest subdivision is area V1, which has very distinctive cytoarchitecture and is therefore commonly referred to as the striate cortex. It differs sharply in its cytoarchitecture from the area surrounding it, the extra-striate cortex. The extrastriate cortex contains many visual areas (V2, V3, V4, V5), whereas the striate cortex is co-extensive with a single visual area, area V1 (see Figure 1.1).

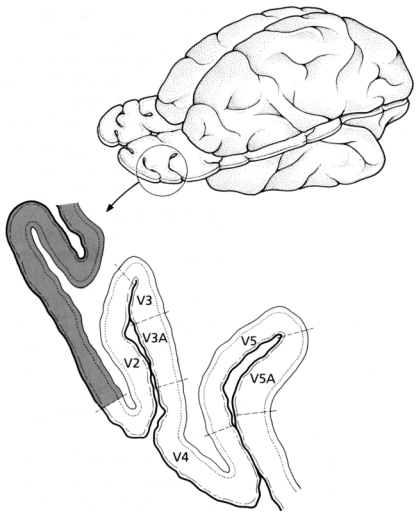


Figure 1.1. The visual cortex is subdivided in two parts: the striate (shown in grey) and the extrastriate cortex. The extrastriate cortex is further divided into distinct visual areas with functionally distinct groups of neurons (Adapted from Zeki, 1993).

These distinct areas in the visual cortex have been identified on the basis of specific patterns of connections, the presence of a retinotopic mapping of the contralateral half-field, receptive field characteristics and characteristic architecture as revealed by histochemical techniques.

Many areas in the visual cortex are not functionally homogeneous, but contain functionally distinct groups of neurons (Hubel, Wiesel, 1968; Hubel, Wiesel, 1977; deYoe, van Essen, 1985). Whereas both areas V1 and V2 have a very complete, well-defined retinotopic map of the spatial information in the visual field and contain functional groupings of cells, e.g. for orientation, spatial frequency, colour, and moderately complex patterns (Hubel, Wiesel, 1968; Hubel, Wiesel, 1977), areas V4 and V5 have a more specialised function. For example, most cells in area V4 are wavelength selective, even though many cells are also orientation selective (Zeki, 1977, Zeki, 1983; Desimone, Schein, 1987). Cells in area V5 are sensitive to motion and over 90% is even directionally selective (Zeki, 1974).

Differences in functional specificity have been found to originate in the retina and continue as partly separate processing streams to the lateral geniculate nucleus (LGN) of the thalamus and the striate and extrastriate cortex (see Figure 1.2). In the retina, three types of cones with different spectral sensitivities (i.e. short, medium, and long wavelengths) are responsible for photopic vision. The signals of the different cones are grouped together in two different groups of ganglion cells: midget ganglion cells (with small receptive fields, slow responses, and sensitivity to colour contrast) and parasol ganglion cells (with larger receptive fields, fast responses, and no sensitivity to colour contrast). Midget ganglion cells project to the parvocellular cells of the lateral geniculate nucleus (LGN), which further project to layer 4Cβ of V1 and then to the blobs and interblobs in layer 2 and 3 of area V1. The thin stripes and interstripes in area V2 receive input from the blobs and interblobs respectively and in turn project to area V4 (Kandel, Schwartz, Jessell, 2000). This constitutes the parvocellular pathway. The parvocellular pathway consists of two arms, one of which is selective for wavelength, but not orientation (parvocellular blob pathway), whereas the other is selective for orientation, but not wavelength (parvocellular interblob pathway), and both project to the inferotemporal lobe

(occipito-temporal route or WHAT-pathway (see Figure 1.2 and 1.3; Mishkin, Ungerleider, Macko, 1983)).

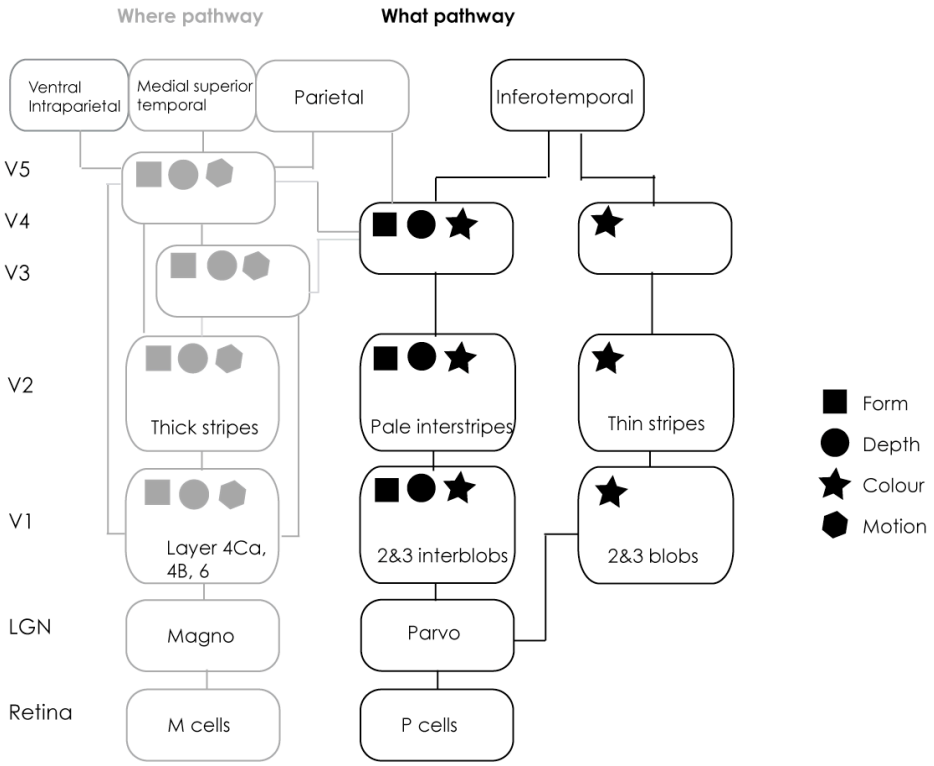


Figure 1.2. Schematic overview of the three major parallel visual pathways in the visual system. The WHAT pathway emanates from parvocellular interblobs and runs from V1 directly to V4 as well as through V2 up to V4 to the inferior temporal cortex, the 'highest-order area for the visual perception of objects' (Mishkin, Ungerleider, Macko, 1983), whereas the WHERE pathway emanates from magnocellular thick stripes and runs through V1 directly to V5 as well as through V2 up to V5 to the parietal cortex. (Adapted from DeYoe and Van Essen, 1988).

The magnocellular pathway arises from the parasol ganglion cells and projects to the magnocellular cells of the LGN, which then project to layer 4Cα of V1 via layer 4B in V1 to the thick stripes in area V2. The thick stripes in area V2 in turn project to area V3 and V5 (Kandel, Schwartz, Jessell, 2000). The orientation direction selectivity of cells in the magnocellular pathway together with high sensitivity for luminance contrast, in the absence of wavelength selectivity, have lead to a proposed role in

processing motion (and to a lesser extent form) information to areas in the parietal lobes (occipito-parietal route or WHERE-pathway (see Figure 1.2 and 1.3; Mishkin, Ungerleider, Macko, 1983)).

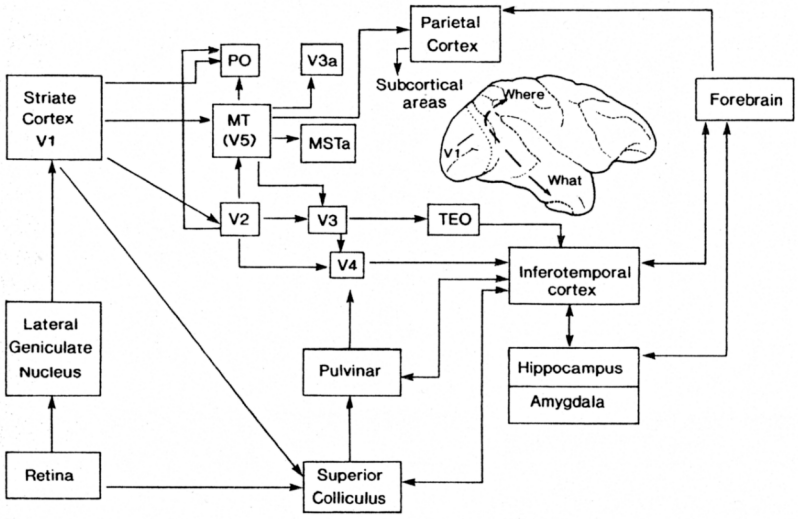


Figure 1.3. Schematic overview of the visual cortical areas, the major connections between them and the specialised pathways (Adapted from Davidoff, 1991)

In sum, specificity in the visual brain has been found at different levels: single cells with specific response patterns, clusters of cells with common specificities within as well as between areas, and connections between clusters of cells, resulting in functionally specialised pathways.

Neuropsychology of vision

The list of disorders resulting in poor vision is huge. Disturbances of vision can result from diseases of for example the cornea, iris, lens, retina, and choroid, or from damage to the structures comprising the visual pathway from the retina to the visual cortex. Various forms of retinopathy (e.g. macular degeneration, diabetic retinopathy) lead to loss of the ability to see fine detail or even blindness in the visual field of the affected eye. Damage to the visual pathway between the retina to the optic chiasm also leads to blindness in the visual field of the affected optic nerve (Figure 1.4a). Damage to the visual pathway beyond the optic chiasm leads to

impairments in the contralateral visual field (Figure 1.4c-g). Post-chiasmatic damage results in corresponding homonymous visual field defects (i.e. cortical blindness). Damage to the primary visual cortex can cause a variety of disorders, ranging from cortical blindness to much more complex deficits, such as visual agnosia (Girkin, Miller, 2001). The most common unilateral visual field defects are homonymous hemianopia (Figure 1.4d+g), quadranopia (Figure 1.4e+f), and paracentral scotoma. After partial *bilateral* damage to the striate cortex, incomplete bilateral hemianopia (i.e. tunnel vision), bilateral quadranopia, and bilateral paracentral scotoma can be observed.

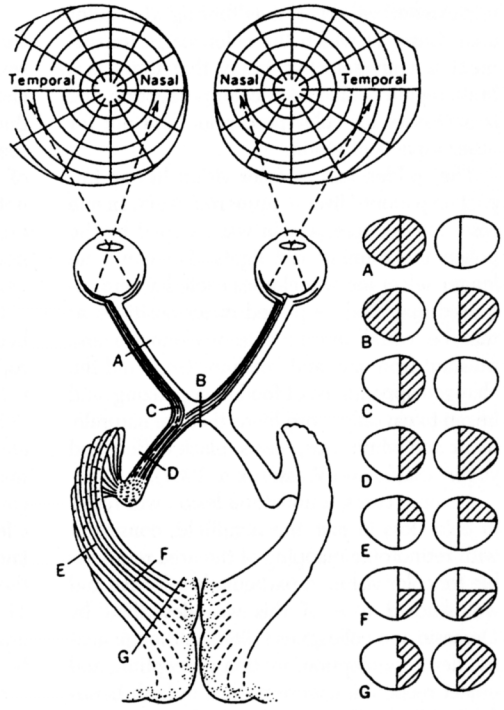


Figure 1.4. Schematic overview of the visual system, from the eyes via the lateral geniculate nucleus to the primary visual cortex. The figure shows how the right visual field (light grey) is processed in the left visual cortex, and vice versa. Damage before the optic chiasm leads to visual field defects in the ipsilateral visual field, whereas damage after the optic chiasm leads to visual field defects in the contralateral visual field (Adapted from Heilman, Valenstein,2003) .

Focal damage to areas in the extrastriate cortex can lead to selective impairment of specific visual functions. For example, impairments in colour vision (i.e. achromatopsia) have been found after (bilateral) damage to the ventromedial occipital cortex (occipito-temporal gyrus, and the lingual and fusiform gyri (human V4) (see Figure 1.5a; McKeefry, Zeki, 1997) and loss of the ability to see motion (i.e. akinetopsia) has been reported after damage to the middle temporal gyrus and the adjacent portion of the occipital gyri (human V5/MT) (see Figure 1.5b; Zihl, von Cramon, Mai, 1983; Zihl, von Cramon, Mai, Schmid, 1991).

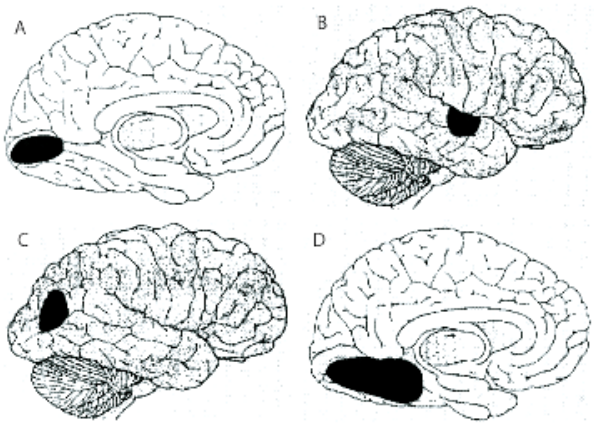


Figure 1.5. a) Location of the lesion in achromatopsia; b) location of the lesion in akinetopsia; c) location of the lesion in impairments in visual localisation; d) location of the lesion in visual agnosia (object agnosia, prosopagnosia, pure alexia)

Patients with damage to the occipito-parietal route (WHERE pathway) show a variety of visual deficits, which can be summarised as 'visuo-spatial' disorders and range from impairments in visual localisation of objects up to spatial cognition disorders (see Figure 1.5c; Grusser, Landis, 1991; Benton, Tranel, 1993). Typical signs of impairments in visual localisation are inaccuracy in fixation and reaching and grasping for objects. These impairments are usually worse after bilateral damage. A higher-order form of visual spatial disorientation is topographical agnosia (i.e. impairment of knowledge of geographic orientation in the real world), in which patients have problems orienting themselves in familiar surroundings or finding the

way using a map. Two disorders of visual attention, visual neglect and Balint-Holmes syndrome, are also associated with damage to the occipito-parietal route. Patients with visual neglect are not aware of their visual surroundings in the contralateral (usually left) hemisphere, do not perceive and respond to stimuli, and cannot shift attention towards this side of space. Bilateral visual inattention is the most prominent symptom in patients with Balint-Holmes syndrome, and might therefore be the severest form of 'dorsal simultanagnosia'; stimuli outside the central visual field go undetected and within this central visual field only a single stimulus can be seen at a time. Moreover, patients are unable to shift their eyes voluntarily or on command.

Damage to the occipito-temporal route (WHAT pathway) can affect discrimination, selection, and recognition of visual stimulus characteristics, and, at a higher-level of processing, of objects, faces, scenes, and letters (i.e. visual agnosia; see Figure 1.5d). Visual object agnosia refers to the inability to visually identify familiar objects (Davidoff, Warrington, 1999; Farah, 2004; Humphreys, 1999). A special type of visual agnosia is prosopagnosia, which refers to the inability to recognise familiar faces visually (Grusser, Landis, 1991; de Haan, 1999). Agnosia for letters represents a selective impairment in the recognition of letters and words at the semantic level of processing and is often referred to as pure alexia. Patients with simultanagnosia have problems with seeing more than one object at a time, which can result from a narrowed field of visual processing (dorsal simultanagnosia) or from integrating several parts of an object (ventral simultanagnosia) (Farah, 2004). Another high level impairment is the inability to recognise colours despite intact colour discrimination (i.e. colour agnosia). Patients with colour agnosia typically have difficulties with naming colours, associating colours with objects (e.g. red with tomato), colouring known objects, and verifying object colour. A related disorder is colour anomia, in which patients cannot name a colour on presentation, despite intact colour perception and good retrieval of object colour. These specific impairments of colour processing will be discussed in more detail below.

Colour vision

What is the function of colour vision? Colour greatly enriches our visual experience, but more importantly, it plays an important role in pattern detection and object

recognition, as colour is a very prominent property of certain objects and scenes. Knowledge of colours of familiar objects or scenes may help in recognition, but there is some disagreement whether colour actually facilitates object recognition. For example, coloured images of objects are recognised faster than achromatic images of the same objects (Ostergaard, Davidoff, 1985), but this only holds for certain types of objects and scenes, namely those high in colour diagnosticity, which are usually natural objects and scenes (e.g. bananas, tomatoes, forests, and deserts; Humphreys, Goodale, Jakobson, Servos, 1994; Tanaka, Presnell, 1999). Moreover, neuropsychological studies with patients have shown that impaired object recognition can be improved with coloured objects and scenes rather than with achromatic objects (Humphreys, Goodale, Jakobson, Servos, 1994: Steeves, Humphreys, Culham, Menon, Milner, Goodale, 2004).

Colour as a surface property actually does not exist in the real world, i.e. there is no pre-specified wavelength composition uniquely linked to the surface of objects. In other words, there is no 'red' in the real world, and as a result the brain has to construct the colour of a surface, such as the skin of tomato. The basis for colour vision lies in the different spectral sensitivities of the three cone receptors in the retina (trichromatic colour vision): each cone receptor (S, M. L cones) is sensitive to a different part of the visual spectrum (short, middle, and long wavelengths), and colours are discriminated through relative activation of each of the three cone receptors.

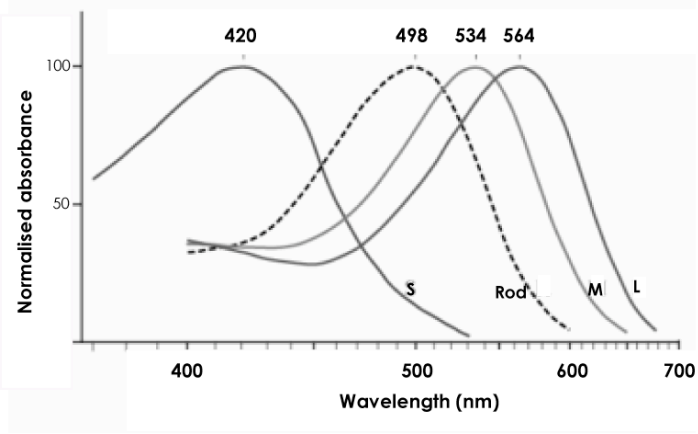


Figure 1.6. Normalised absorption spectra of human rod and cone (S, M., L) cells. Note that the wavelength scale is not represented linearly (Adapted from Dartnall, Bowmaker, and Mollon, 1983).

Together, the cones are sensitive to the whole range of the human visual spectrum, but they have their maximum sensitivity at different wavelengths: S receptor at 420 nm, M receptor at 534 nm, and L receptor at 564 nm (see Figure 1.6). Differences between cone responses are the basis for colour perception. However, the sensitivities of cone receptors fail to explain three important aspects of colour perception: first, colour opponency (i.e. certain colours are never perceived in combination, e.g. reddish green or bluish yellow); second, simultaneous colour contrast (i.e. opponent colours enhance each other, e.g. green stands out more on a red than a blue background); and third, colour constancy (i.e. colours of objects are perceived as being relatively constant despite enormous changes in the spectral composition of surrounding light). The opponent colour theory states that the human visual system interprets information about colour by processing signals from cones in an antagonistic manner: red versus green, blue versus yellow, and black versus white (achromatic, detection of luminance contrast). Information from the three types of cones, S, M, and L, is passed to bipolar cells in the retina, which may be the cells in the opponent process that transform the information from the cones (Kandel, Schwartz, Jessell, 2000). The transformation is then passed on to the ganglion cells of which the parvocellular cells process information about colour. Colour selective neurons have been found in areas V1 (~40%), V2 (~25%), and V4 (~55%) in non-human primates (Heywood, Cowey, 1999). Moreover, the left occipito-temporal area has been found to be involved in object-colour associations and retrieval of object-colour (Davidoff, 1991; Goldenberg, Podreka, Steiner, Willmes, Suess, Deecke, 1989; Goldenberg, Artner, 1991).

Neuropsychology of colour vision

"*… as soon as he entered, he found his entire studio, which was hung with brilliantly coloured paintings, now utterly grey and void of colour. His canvases, the abstract colour paintings he was known for, were now greyish or black-and-white. His paintings – once rich with associations, feelings, and meanings – now looked unfamiliar and meaningless to him. At this point the magnitude of his loss overwhelmed him. …*"

Adapted from: Oliver Sacks, The Case of the Colorblind Painter, 1995, In: An Anthropologist on Mars

The above described case of the colour-blind painter is an example of an acquired colour vision deficiency. Colour vision can be impaired due to retinal or cortical diseases. The most common form of colour blindness is hereditary retinal red-green blindness (~7%), caused by genetic mutations of the X chromosome. In the general population, about 1.3% of the men and 0.02% of the women have a L-cone defect (i.e. protanomaly, 'red blind') and 5% of the men and 0.35% of the women have a M-cone defect (i.e. deuteranomaly, 'green blind'). S-cone defects (i.e. tritanomaly, 'blue blindness') are very rare, and are not sex-linked with a prevalence of 0.0001% in both men and women. It is also possible to acquire colour blindness through damage to the retina, the optic nerve, or higher brain areas. The cortical processing of colour fractionates into a number of specific sub-processes, each with their own neuro-anatomical substrates. Humans have the ability to perceive, match, classify, name, memorise, and imagine colour and each of these abilities can be selectively lost as a result of brain damage. The occurrence and the co-occurrence of deficits suggest that each may be functionally independent. Neuropsychological studies have demonstrated selective colour impairments, which are, in semi-hierarchical order, selective impairments in colour perception (achromatopsia), selective impairments in colour naming (colour anomia), and selective impairments in colour recognition (colour agnosia).

Generally, patients with achromatopsia report that the world appears as if it has been drained of colour and even bright, saturated colours look pale. Patients cannot perceive, name and/or sort any colour, although they are still able to sort shades of gray and have intact motion and form vision (for review, see Zeki, 1990; Heywood, Cowey, 1999; Zeki, 1993). (Hemi-) achromatopsia is a relatively rare visual field disorder, that is associated with lesions in the territory of the posterior cerebral arteries, the occipito-temporal portion of the brain, often involving regions at or near the occipital pole: the lingual and fusiform gyri (human V4) (e.g. Damasio, McKee, Damasio 1980; Lueck, Zeki, Friston, Deiber, Cope, Cunningham, Kennard, Frackowiak, 1989; Meadows, 1974; Scotti, Spinnler, 1970; Zeki, 1990;). These (bilateral) lesions need to be symmetric and circumscribed, as more extensive lesions will result in hemianopia, if the optic radiations and the calcarine region are included (Rizzo, Smith, Pokorny, Damasio, 1993), or visual agnosia, if the gyrus temporalis inferior, fasciculus longitudinalis inferior and corpus callosum are included (e.g. Damasio,

Yamada, Damasio, Corbett, McKee, 1980; Meadows, 1974; Rizzo, Smith, Pokorny, Damasio, 1993). Because of preserved wavelength selective cells in V1 and V2, some achromatopsic patients still retain the ability to distinguish borders of coloured patches (Cowey, Heywood, 1995; Heywood, Cowey, 1999) or perform well on pseudoisochromatic plates (Meadows, 1974).

Significantly less is known about a more higher order colour disorder: colour anomia. Patients with colour anomia are able to point to the correct colour when a name is given, but cannot name a colour on presentation. Moreover, they seem to have good retrieval of object colour knowledge from achromatic pictures of objects (Beauvois, Saillant, 1985; Fukuzawa, Itoh, Sasanuma, Suzuki, Fukusako, 1988; Geschwind, Fusillo, 1966; Gil, Pluchen, Toullat, Miehenau, Rogez, Levevre, 1985; Larrabee, Lervin, Huff, Kay, Guinto, 1985). Usually, the semantic recall of colour is intact. Moreover, in most cases of colour anomia, pure alexia and right hemianopia coexists (Geschwind, Fusillo, 1966). Such a specific impairment for colour naming is very rare (Goodlglass, Klein, Carey, James, 1966), as no other language impairments should be present. Colour anomia is associated with lesions in the distribution of the left posterior cerebral artery; occipital and temporal cortex, corpus callosum with extensions to the thalamus, radiatio optica, fornix and gyrus cinguli, sometimes involving the calcarine cortex and the splenium (Damasio, Damasio, 1983; Damasio, McKee, Damasio, 1979; de Renzi, Zambolink, Crisi, 1987; Geschwind, Fusillo, 1966). It is related to abnormalities affecting the posterior language area.

A second higher order colour disorder is colour agnosia. Patients with colour agnosia have an impaired ability to recognize colours or to learn new colour terms and are usually not able to associate colours with objects and verify coloured objects, despite sufficiently intact colour discrimination and sometimes colour categorisation (Beauvois, Saillant, 1985; Davidoff, Fodor, 1989; Luzzatti, Davidoff, 1994; Micelli, Fouch, Capasso, Shelton, Tomaiuolo, Caramazza, 2001; Woodward, Dixon, Mullen, Christensen, Bub, 1999). Colour agnosia is often accompanied with occipital alexia and homonymous hemianopia (Beauvois, Saillant, 1985; Woodward, Dixon, Mullen, Christensen, Bub, 1999). Impairment of object-colour retrieval is associated with lesions in the left hemisphere (Luzzatti, Davidoff, 1994), usually involving the left temporal (Dumont, Griggio, Dupont, Jacquy, 1981) and occipital

cortices (de Vreese, 1991), the left visual sensory pathways (producing the right visual field defect) and the splenium of the corpus callosum or tracts from the splenium to left hemisphere white matter (Geschwind, Fusillo, 1996).

This thesis

The research described in this thesis will focus on visual perception in general and specifically on colour perception. Especially the learned associations of colour with certain objects, a unique feature of colour processing, is studied. The studies we describe are diverse: from the relationship between low-level perception deficits and higher-order recognition disorders in patients who suffered strokes (Chapter 2) to object-colour associations in healthy participants (Chapters 3 and 4), and from the development of colour terms and colour knowledge in children (Chapter 5) to the abilities and inabilities of a man with developmental colour agnosia (Chapters 6-10).

Thesis outline

Group study: threshold measurements of several visual primitives.

Our first aim is to address processing of different visual primitives (shape, luminance, colour, motion). Selective impairments in low-level perception after a stroke were investigated as well as the absence of impairments in low-level perception in higher-order gnostic disorders (*Chapter 2*). As mentioned above, functional specificity of the visual cortex has been found at different levels (cells, areas, connections, and pathways) and several selective disorders have been found after focal brain damage to the visual cortex. A newly devised method was used to investigate hemifield impairments on the discrimination of five visual primitives (shape, luminance, hue [red-green and blue-yellow], coherent motion, and shape-from-motion) after stroke. We found that all visual primitives may become selectively distorted and that these isolated (hemifield) impairments may have unexpected effects on higher-order processing (e.g. metamorphopsia) in some patients. The reverse was also found, impairments in higher-order processing (e.g. brightness agnosia) in absence of low-level discrimination impairments.

Healthy participants: knowledge of colour and its associations

Second, we report on the way colour is represented in the brains of healthy participants (*Chapters 3-5*). In *Chapter 3*, we report on the beneficial effects of both physical colour and colour names in recognition of words associated with a specific colour. In a priming experiment with a lexical decision response, we found that when an object word was preceded by either a physical colour or a colour name, both associated with that object, participants were faster to respond. Apparently, verbal and pictorial object-colour associations have a comparable facilitating effect. *Chapter 4* focuses on the influence of colour on memory for images of scenes. We show that even though colour can have facilitating effects on the recognition or identification of scenes, this effect is probably due to enhancement of the gist of the scene. In a delayed-match-to-sample experiment, we found that coloured images resulted in more 'false memory' for these images. In *Chapter 5*, we describe the development of colour terms and colour knowledge in children, aged between 3 and 7 years. In other studies, it has been found that children develop colour terms and object-colour associations relatively late. We investigated whether distinct developmental trajectories could be obtained and found that object-colour associations are primarily stored in a verbal fashion, even when adequate usage of colour terms and recognition of incorrectly coloured objects is not yet present. These results show a striking similarity with our results of MAH, a man with developmental colour agnosia.

Case studies: developmental colour agnosia.

In addition to studying impairments of vision after a stroke, we also examined a man with developmental colour agnosia (*Chapter 6-10*). In *Chapter* 6, we describe the first case of developmental colour agnosia, MAH. In *Chapter 7*, we report on a familial factor in colour agnosia, as both the mother and the eldest daughter of MAH show similar problems with naming colours and recognising correctly coloured objects, though to a lesser extent. In *Chapter 8*, we examined whether MAH, despite his explicit deficit in naming and recognising colour, would show implicit processing of colour. The results show that he is faster in verifying correctly written objects words when these are preceded by a physical colour that is associated with these objects.

Moreover, he shows a reversed Stroop interference effect when reading words that are printed in an incongruent colour. *Chapter* 9 describes the impairment of mental colour imagery in colour agnosia. It was shown that MAH was selectively unable to mentally compare colours of objects, despite his intact ability to perceptually compare colours. In *Chapter 10*, we focus on colour diagnosticity. According to the colour diagnosticity hypothesis, recognition of objects high in colour diagnosticity (usually natural objects) is more affected by colour manipulations (e.g. inversely coloured images) than recognition of objects low in colour diagnosticity (usually non-natural, man-made objects). With MAH, we had the unique opportunity to investigate low-level sensory colour processing versus higher cognitive level of colour processing. MAH did not show an effect of colour manipulations for the natural scenes, but was overall much slower in recognising these scenes. We ascribed this effect to the fact that he never learned the associations between objects or scenes and certain colours and therefore solely has to rely on shape and texture cues, which are not as informative for natural scenes.

A brief summary of the results and concluding remarks are provided in Chapter 11.

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Chapter 2

Group study: threshold measurements of five different visual features
Selective visuo-sensory deficits: an explorative study in stroke patients

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Submitted

Abstract

Studies with patients with circumscribed lesions in the posterior part of the brain have gained insight in the functional specificity of the visual cortical areas, as different aspects of the visual world (e.g. shape, colour, or motion) may become selectively disrupted after focal damage. Impairments in visual processing can be divided into two broad classes; first, cortical blindness; and second, impairments affecting specific visual functions (e.g. shape, luminance, hue, motion) in absence of cortical blindness. The aim of this study was twofold: first, the effect of posterior brain damage on visual hemifield processing of shape, luminance, hue, and motion was investigated using a new method for hemifield presentation of stimuli, exploring the proficiency in the perception of the main primary visual primitives; second, we were interested in the possible effect these visuo-sensory deficits might exert on higher-order processing. Therefore, we carefully explored the visual complaints of patients in terms of recognition deficits and/or experienced distortions of the outside world. Overall, our findings suggest the following: first, after unilateral damage in the visual cortex selective impairments in low-level visual processing may be observed in the contralateral hemifield, even without awareness (or conscious insight) of the patient; second, in some patients these low-level deficits appear to result in higher-order processing impairments; third, a low-level impairment of a single visual primitive will not necessarily have a subsequent higher-order effect; and fourth, higher-order recognition deficits can occur in absence of low-level perception deficits. The final conclusion must be that the different conditions under which these outcomes emerge can only be understood by in-depth studies using fine-grained assessment procedures for the different 'levels' of visual processing.

Keywords: visual perception, unilateral brain damage, threshold measurements

Introduction

Knowledge about visual processing has increased dramatically during the past decades, as new techniques and methodologies have been developed for studying the brain. Physiological research has delineated the functional role of neurons and their interconnections in nonhuman primates and humans. The selective visuo-perceptual deficits in neurological patients have informed us at the functional level, and these observations have been confirmed and extended by functional neuro-imaging.

Visual processing can be divided into several stages, ranging from low-level visuo-sensory processes to higher-level, cognitive processes: sensation, perception, association, and recognition (Benson, 1989). These separate stages are not hierarchically organised, but form a complex with parallel as well as serial connections and bottom-up as well as top-down processing. The visual cortex entails a number of different retinotopic areas, each with distinct functional properties, anatomical connections, and microstructure (e.g. Zeki, 1993). The functional role of these visual cortical areas has been explored in physiological studies using single cell recordings, and in a more limited fashion, in patients with circumscribed lesions in the posterior brain. Different aspects of the visual world (e.g. colour, motion or shape) may become selectively disrupted, which suggests that visual processing is highly fractionated.

Impairments in visual processing can be divided into two broad classes of visual impairments; first, complete loss of vision (i.e. cortical blindness); second, impairments affecting specific visual functions without cortical blindness. Lesions beyond the optic chiasm will lead to visual impairment in the contralesional regions of the left or right hemifield of both eyes (i.e. homonymous visual field defects). The most frequently reported post-chiasmatic visual impairments are those involving complete loss of vision in one hemifield (77%), or one quadrant of the visual field (upper quadrant: 10%, lower quadrant: 9%) or blind spots (paracentral scotoma: 4%). Bilateral damage resulting in full-field defects are even less frequently reported (6%) and involve hemianopia with macular sparing, tunnel vision, bilateral inferior hemianopia, or central scotoma (see, Zihl, 1989). Impairments affecting specific visual functions, while others may remain relatively spared (e.g. (hemi-

)achromatopsia), rather than complete loss of vision, are less often reported. Hemi-amblyopia and hemi-achromatopsia are the most well known impairments. Hemi-amblyopia is a homonymous depression of all visual functions within one hemifield. Perception appears to depend on the saliency of the stimuli, such as size, lightness, and movement of the stimuli. About 20% of patients show cerebral amblyopia after brain damage (Zihl, 1989). Hemi-achromatopsia is a comparatively rare visual field disorder: 6% of patients suffering from unilateral postchiasmatic brain damage report selective problems with perceiving colour in the contralateral hemifield and preserved form and lightness perception (Albert, Reches, Silverberg, 1975; Damasio, McKee, Damasio, 1980; Zeki, 1993). Achromatopsia extending throughout the visual field is even less common and occurs only after bilateral brain damage (Zeki, 1993). Other disorders have only been reported after bilateral damage and not as a unilateral deficit, such as akinetopsia (Zihl, von Cramon, Mai, 1983; Zilh, von Cramon, Mai, Schmid, 1991). It is as yet unknown whether bilateral lesions are necessary for selective impairments of other visual functions, or whether they go undetected as a result of head and eye movements of the patient.

The fact that the incidence of partial hemifield disorders is not well documented might also result from relatively easy compensation by the patients by moving their eyes and/or head. Given the fact that many hemianopic patients may in due course fail to notice their complete field defect, it is not hypothetical that patients may not spontaneously complain about partial impairments of specific visual functions. It is, therefore, perhaps not surprising that there is only limited insight into incidence and the nature of these hemifield defects. Detailed investigation of visuo-sensory abilities after unilateral damage to the posterior brain is needed to characterise these visual impairments as well as to assess the influence of these disorders on higher visual abilities, such as visual gnosis. Higher-level, gnostic deficits appear to result from more substantial lesions, where one hemisphere often appears to be dominant. For example, reading disorders are associated with left hemisphere damage, while face recognition impairments are more often reported after right hemisphere lesions (e.g. de Haan, 1999). The interplay between these levels of processing, that is the possible effects of sensory disorders on higher-order functions and the top-down influences on the processing of primary visual cues has been a controversial subject since Bay (1953) introduced the concept of 'Funktionswandel'

(i.e. "on its way to perception, the peripheral stimulus undergoes (…) an enlarged and instable transformation, disturbing the constancy of visual objects"). In Bay's view (see also Campion, Latto, 1985), stimulus-specific recognition disorders (e.g. object agnosia, prosopagnosia) resulted from low-level visual impairments. This suggestion has been refuted by Ettlinger, Warrington, and Zandwill (1957) and by De Haan, Heywood, Young, Edelstyn, and Newcombe (1995). Although patients with a recognition deficit may have sensory impairments, other patients who do not experience recognition problems can show equal or worse sensory impairments. Therefore sensory status alone could not explain the presence or absence of recognition disorders.

In the current study, we use a newly devised method to investigate hemifield impairments after a stroke. In this explorative study, we will focus on the discrimination of six visual primitives: shape, luminance, hue [red-green and blue-yellow], coherent motion, and shape-from-motion. First, we investigate the thresholds at which healthy participants are just able to discriminate between the stimuli within one visual primitive and second, we compare the performance of the patients to the thresholds of the healthy participants. Moreover, we will compare the discrimination thresholds of the stimuli presented in the contralateral hemifield to the stimuli presented in the ipsilateral.

Method

Participants

For this study, 27 healthy control participants (mean age: 34.6, SD: 11.3; 15 women, 12 men) with no history of psychiatric or neurological disorders, drugs or alcohol abuses, and normal or corrected-to-normal acuity were tested. In addition, 8 patients participated in this study and inclusion was as follows. All but one (Case 5, see below) patients with a suspected CVA admitted to the UMC Utrecht during the period from January 2004 until January 2007 were considered. Exclusion criteria were: older than 80 years of age, a history of psychiatric disorders, alcohol or drug abuses, and/or a ranking score of less than 4. If there was an indication for a lesion in the posterior part of the brain or if the patient complained subjectively about visual

problems, he or she was screened with short neuropsychological battery. If either the MRI data confirmed a lesion in the posterior areas of the brain or this screening confirmed a disorder in visual perception, patients were tested on the Utrecht Hemifield Battery (UHB). In Table 2.1, an overview of the patients' details is given.

Table 2.1. Overview of the patients (age, gender [M=male, F=Female], time post-stroke, stroke [vert. art. occ. = vertebral artery occlusion; haem. inf. = haemorrhagic infarction; migr. inf. = migraine infarction; SAH = subarachnoid haemorrhage , lesion location [Bilat. = Bilateral; L = Left; R = Right; Occ. = Occipital; Temp. = Temporal; Par. = Parietaland the field defects.

Case	Age	Gender	Time post-stroke	Stroke	Lesion location	Field defects
1	40	M	3 months	Vert. art. occ.	PICA	-
2	65	M	6 months	Haem. inf.	Bilat. Occ.	Tunnel vision
3	60	F	5 days	Haem. inf.	L Temp. Occ.	-
4	51	F	1 month	Migr. inf.	R Temp. Occ.	L Quadr.
5	66	F	5 years	SAH	R Par. Temp. Occ.	L neglect
6	76	F	4 days/2 weeks	Haem. inf	L Occ.	R Quadr.
7	75	M	6 months	Isch. stroke	Bilat. Occ. Cerebellum	L Hem R Quadr
8	54	M	10 days	Haem. inf	L Par.	-
9	63	M	8 days	Haem. inf	L Par.	-

Neuropsychological screening

Patients were screened with a short neuropsychological battery tapping the major cognitive domains: executive functioning (mental flexibility; Brixton), language (Boston Naming test, Verbal Fluency, Token test), verbal memory (Rey Auditory Verbal Learning test, Digit Span of WAIS III), visual memory (Rey Figure delay), visual perception (Benton Line Orientation, Benton Face Recognition, Ishihara test for Colour Blindness, Colour Arrays (see Heywood, Cowey, 1999, p. 26-27), visuo-construction (Rey Figure copy), and hemi-spatial neglect (Star Cancellation).

Apparatus

Data collection and stimulus presentation were controlled by a PC and two 17-inch monitors; one for presenting the stimuli to the participants (1024 x 768, 75 Hz) and the

other one for the experimenter. A chin and forehead rest fixed the distance between the monitor and the eyes. Fixation was controlled with an eye-tracking system (iView X, SMI) that was interfaced with the experimental setup. The delay between an eye movement and the stimuli disappearing from the screen was 1 frame. The experiment was programmed using Visual Basic 6.

Design and Procedure

For the left- and right-sided presentation, a 9-point calibration procedure was used to calibrate the iView X system per participant. In the calibration procedure, a fixation cross appeared on the screen and participants were asked to fixate the cross until it moved to another location. The 9 locations were the following: center of the monitor, left upper corner, right upper corner, left lower corner, right lower corner, central left, central right, upper central, and lower central.

After the calibration procedure, participants were instructed to fixate on the fixation cross throughout the experiment. Whenever they made an eye movement towards the stimuli, the stimuli disappeared and only when they were fixating again, the stimuli re-appeared on the screen. For the central presentation, no fixation control was performed and participants' eye movements were not recorded. The chin and forehead rest of the iView X system was used to control the distance between the eyes and the monitor.

There were six different discrimination tasks in the UHB: discrimination of shape, luminance, hue [red-green, blue-yellow], motion, and shape-from-motion (see Figure 1 for examples of the stimuli in the different tasks). In all tasks, three stimuli were presented either centrally or 3° visual angle to the left or right of the fixation cross (see Bourne, 2006). Participants were instructed to indicate which of the three stimuli was different (odd-one-out task) in the relevant dimension. Before the start of each task, participants were told which visual primitive to discriminate. Responses were given by pressing a specific button on a response box: when it was the upper stimulus that was different, participants were told to press the upper button, when it was the lower stimulus, they should press the lower button, and when it was the stimulus in the middle, the button in the middle should be pressed. There were 45 trials per task and after three correct responses the differences between stimuli

became 50% smaller, making the judgments more difficult (continuation). After each incorrect response the differences between stimuli became 50% larger, making the judgements easier (reversal). In this manner, a threshold per task could be obtained, based on the mean of the last six reversals.

Stimuli

For hemifield presentation, stimuli were presented on one side of the monitor, while participants were fixating on the other side (for examples of the stimuli at start, see Figure 2.1). For central presentation, stimuli were presented at the center midline of the monitor.

Stimuli for the shape discrimination task (see Figure 2.1a) were two squares (3.2° x 3.2° of visual angle) and one rectangle (6.4° x 1.6° of visual angle, at start), resulting in different shapes with the same surface area (10.24 cm2). After three correct responses, the differences between the squares and rectangle became smaller.

Figure 2.1. Examples of the stimuli in the UHB: shape (a), luminance (b), colour (c), and motion (d) discrimination tasks. In this example, fixation is on the left and stimuli are presented in the right visual field. Note that the distance between the fixation cross and the stimuli in these examples is bigger for illustrative purposes than in the UHB.

Stimuli for the luminance discrimination task (see Figure 2.1b) were three squares of the same size (3.2° x 3.2° of visual angle), one of which differed in brightness. At start, two of the stimuli were black (xyY = .304, .319, .480) and one was white (xyY = .318, .330, 105.33), or vice versa. After three correct responses, the Michelson contrast between the stimuli became smaller, resulting in more greyish stimuli. It is important to note that the odd stimulus could either be a darker or a lighter square.

Stimuli for the colour discrimination task (see Figure 2.1c) were three squares of the same size (3.2° x 3.2° of visual angle), one of which differed in colour. The two stimuli with the same colour differed in luminance, to rule out the possibility that the

task could be done based on luminance differences between the two different colours alone. There were two versions of this task: first, a red-green colour discrimination task, in which two of the stimuli were green (xyY coordinates = .287, .585, randomly varied) and one was red (xyY coordinates = .622, .339, randomly varied), or vice versa; second, a blue-yellow colour discrimination task, in which two of the stimuli were blue (xyY coordinates = .145, .065, randomly varied) and one was yellow (xyY coordinates = .420, .490, randomly varied), or vice versa (see Addendum 2.1, for xyY coordinates of colour steps, as measured with a colorimeter). After three correct responses, the colour contrast between the stimuli became smaller, resulting in more yellowish stimuli in the red-green discrimination task and in more greyish stimuli in the blue-yellow discrimination task. It is important to note that the odd stimulus could either be a more reddish or a greenish square (or more bluish or yellowish in the blue-yellow discrimination task).

Stimuli for the motion discrimination task (see Figure 2.1d) were three squares of the same size (3.2° x 3.2°), through which a more or less coherent field of moving dots could be perceived. The size of the dots was .078° (~4.5 minutes of arc) and each square contained 234 moving dots. At start, 100% of the dots in two of the stimuli were moving in one direction (left or right) and in the third, dots were moving in the opposite direction. After three correct responses, motion coherence was reduced by 50%. (i.e. 50% of the dots were coherently moving in one direction and the rest was randomly moving throughout the stimulus square). The speed of all moving dots was 1.32° per second, regardless of the direction of motion. It is important to note that the dots in the odd stimulus could either be moving leftwards or rightwards.

Stimuli for the shape-from-motion discrimination task were two squares (3.2° x 3.2°) and one rectangle (6.4° x 1.6°, at start), consisting of coherently moving dots on a background of randomly moving dots. After three correct responses, the shape of the rectangle changed in such a way that it resembled the squares more while the surface area remained 10.24 cm2.

Data analysis

For all participants, mean thresholds were calculated based on the last six reversals for the left-sided, right-sided, and central presentations separately. The least amount of obtained reversals was 9. Thresholds were always in between 1 (easiest presentation, biggest difference between the stimuli) and 0 (most difficult presentation, smallest possible difference between the stimuli, as calculated by the pc). In other words, a higher threshold value means that a relative big difference (e.g. high contrast) between the stimuli must be presented in order for the participant to see which one of the 3 stimuli is the odd-one-out. Differences between the thresholds for the visual primitives and sides of presentation for the healthy control participants were analysed with a Repeated Measures Analysis of Variance. The thresholds of the patients were compared to these of the healthy participants using Crawford and Howell's significance test on differences between an individual's score and a control sample (1998).

Results and Discussion

Healthy participants

First, we calculated and analysed the thresholds for the hemifield presentation as well as for the central presentations. In Figure 2.2, the thresholds per visual primitive are shown for the three presentation conditions (left, right, central).

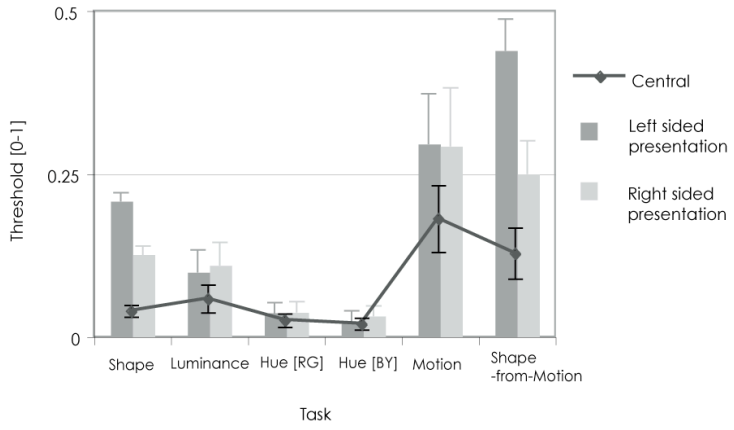

Figure 2.2. Mean thresholds of the healthy participants per visual primitive, split by side of presentation (Central, Left hemifield [right hemisphere], or Right hemifield [left hemisphere]. Thresholds are always between 1 (easiest presentation, biggest difference between the stimuli) and 0 (most difficult presentation, smallest possible difference between the stimuli).

There was a significant difference between the thresholds of the visual primitives ($F(5,130) = 85.854$, $p < .001$) and a significant effect of side of presentation ($F(1,26) = 15.059$, $p < .005$), with overall lower thresholds for right-sided presentations compared to left sided presentation. There was a significant interaction between visual primitive and side of presentation ($F(5,130) = 13.795$, $p < .001$): the thresholds for the shape and shape-from-motion discrimination tasks were lower for the right sided presentations, whereas there was no difference between left sided and right sided presentations for the luminance, hue, and motion discrimination tasks. Apparently, in healthy participants, shape discrimination in this experimental setup was better when presented in the right visual field/left hemisphere. In Table 2.1, an overview is given of the thresholds per visual primitive along with the size and contrast values or percentages coherently moving dots.

For central presentations, there was a significant difference between the visual primitives ($F(5,130) = 29,461$, $p < .001$). When comparing the thresholds for central and hemifield presentations, it is clear that the discrimination task with central presentation is easier than with hemifield presentation, resulting in lower thresholds. This is not the case, however, for either hue discrimination tasks, as the thresholds for central, left sided, and right-sided presentations are similar (see Table 2.2). This is no sign of a ceiling effect though, as all the observed thresholds for both discrimination tasks above the threshold one would obtain with only correct responses: .000061. Apparently, there is no difference in difficulty of discrimination for colour opponent stimuli when presented at 3° of visual angle.

Patients

We calculated and analysed the thresholds per task of each patient individually. It was not always possible to test patients on all tasks. This could be due to fatigue, difficulties with fixation, or the fact that some of the patients suffered from visual field defects (e.g. hemianopia, quadranopia, or tunnel vision) that interfered with the perception of the stimuli in the contralesional hemifield. The thresholds that could be reliably assessed are summarised in Table 2.3.

Table 2.2. Mean thresholds of the control participants per primitive per side of presentation and their meaning

Visual primitive	Threshold value [left / right / central]	Observable difference [left / right/ central]
Shape	.208 / .126 / .047	.67 x .55° / .4 x .39° / .15 x .14°
Luminance	.099 / .110 / .066	.216 / .230 / .147 [Michelson contrast]
Hue [red-green]	.037 / .038 / .035	xy red: .428 .480 / .428 .480 / .427 .482 xy green: .400 .502 / .400 .502 / .401 .502
Hue [blue-yellow]	.024 / .032 / .028	xy blue: .310 .321 / .304 .313 / .305 .319 xy yellow: .312 .329 / .318 .335 / .313 .330
Motion	.296 / .293 / .188	29.6% / 29.3% / 18.8% coherent motion
Shape-from-motion	.439 / .250 / .135	.14 x .98° / .8 x .64° / .15 x .14°

Case descriptions, neuropsychological examination, and visual impairments

Case 1 (PR) suffered an occlusion of the right vertebral artery, which resulted in a posterior cerebellar artery syndrome (see Appendix 2.2). PR was seen 3 months post-stroke for both the neuropsychological examination and the UHB. The neuropsychological screening indicated that his language and memory functions were normal. He did not show any signs of neglect, visual field defects, or colour blindness, nor impairments with visuo-construction. On the UHB, a significant isolated elevated threshold for shape discrimination in the left visual field was found ($t(26) = 3.073$; $p < .005$; estimated percentage of normal population falling below individual's score = 99.75%). The difference between the squares and the rectangles should be minimally 1.54 x 1.04°, in order for PR to detect the odd stimulus (for the minimal difference of the control participants, see Table 2.2). All other thresholds in both left and right visual field were within normal range, yet on the shape-from-motion task, PR was unable to see the stimuli.

Case 2 (HA) suffered a (bilateral) infarction in the posterior cerebral artery (see Appendix 2.2) resulting in tunnel vision. He reported that he did not have any residual problems besides tunnel vision. HA participated in this study 6 months post-stroke. The neuropsychological screening indicated that his language and memory functions were normal and he did not show any signs of neglect. He failed the Ishihara test, however, and was unable to indicate which of the two arrays, separated by thin bars, was sorted with respect to colour. He stated that he had not

suffered from congenital colour blindness prior to his infarction. HA's performance on the UHB revealed a significantly elevated threshold on the hue [red-green] discrimination solely ($t(26) = 10.42$; $p < .001$; estimated percentage of normal population falling below individual's score = 100%). In order for HA to detect the odd stimulus, the difference in xy-values for the red and green squares should be |.32 .56| for red and |.55 .39| for green (for the minimal difference of the control participants, see Table 2.2). The threshold for the blue-yellow discrimination was within normal range.

Case 3 (MZ) incurred a haemorrhagic venous infarction in the left temporo-occipital cortex with sub-cortical extension (see Appendix 2.2) after embolisation of a dural arteriovenous fistula. MZ participated in this study 5 days post-stroke. Neuropsychological examination revealed mild problems in verbal memory. There were no signs of neglect, and orientation in time and place was normal. MZ complained about parts of faces in her right visual field appearing to become smaller and bulge, which were interpreted as signs of metamorphopsia (Nijboer, Ruis, van der Worp, de Haan, submitted). Despite these distortions, recognition and matching of faces was normal. On the discrimination tasks, there was a significantly elevated threshold for shape discrimination with right-sided presentations ($t(26) = 7.531$; $p < .001$; estimated percentage of normal population falling below individual's score = 100%). The difference between the squares and the rectangles should be minimally 1.89 x 1.19°, in order for MZ to detect the odd stimulus (for the minimal difference of the control participants, see Table 2.2). Unfortunately, the motion and shape-from-motion tasks could not be finished, as the moving dots made MZ nauseas.

Case 4 (DR) suffered a migraine infarction in the right medial occipital and temporal cortex. She had a left upper quadranopia and complained about seeing lights and colours around the quadrant. Moreover, she reported that buildings, roads and rooms looked distorted: in rooms, objects seemed to overlap and integrate, and roads and buildings seemed to bulge. She had problems recognising familiar roads and buildings, although she knew where she was. She did not experience the same kind of distortions with objects or faces. DR was seen 1 month post-stroke for both the neuropsychological examination and the UHB.

Neuropsychological examination revealed problems in the perception and recognition of objects, faces and environments. There were no signs of neglect or impairments in visuo-construction. She was orientated in time and place and there were no language problems. Her verbal memory was impaired. On the UHB, she demonstrated significant elevated threshold on the motion discrimination task ($t(26) = 2.079$; $p < .050$; estimated percentage of normal population falling below individual's score = 96.26%), whereas the other thresholds were within normal range. The percentage coherently moving dots should be minimally 40,7% in order for DR to detect the odd stimulus (for the minimal difference of the control participants, see Table 2.2).

Case 5 I (LZ) incurred substantial bilateral damage in 2001 due to an acute subarachnoid haemorrhage in the right hemisphere (see Appendix 2.2) followed by surgical complications. Retrospection of early neuropsychological reports suggested severe left-sided neglect and left-sided hemiparesis. Neuropsychological examination 5 years post-stroke revealed moderate left-sided neglect and problems with face recognition and matching. There were no indications for language or memory impairments. In addition, she suffered from 'brightness agnosia' (for more details see: Nijboer, Nys, van der Smagt, de Haan, submitted), an impairment in the appreciation of brightness. Due to the left-sided neglect, LZ was unable to be tested per hemifield. With central presentation, she did not show any elevated thresholds on any of the discrimination tasks.

Case 6 (CH) suffered a haemorrhagic venous infarction in the left occipital cortex (see Appendix 2.2). Neuropsychological examination 4 days post-stroke revealed mild problems with recognising and naming objects and more severe problems with visuo-perception and -construction. The Hooper test suggested a reduced ability to organise and integrate visual information. There were no indications for memory problems, no signs of neglect, and no impairments in recognising faces. She had quadranopia in the upper right corner of her visual field with flashes of light and colours at its borders. CH participated in the discrimination examination 2 weeks post-stroke. The threshold of the shape-from-motion discrimination task was elevated ($t(26) = 1.958$; $p < .050$; estimated percentage of normal population falling below individual's score = 96.95%), but there were no further signs of low-level perception deficits. In order for PR to detect the odd

stimulus, the difference between the squares and the rectangles should be minimally .92 x .73 mm (for the minimal difference of the control participants, see Table 2.2).

Case 7 (MO) suffered a haemorrhagic infarction in the left parietal lobe (see Appendix 2.2). Neuropsychological examination 10 days post-stroke revealed an intact language and memory function. There were no indications of neglect or of problems with visual perception or construction. On the UHB, there were no further signs of low-level perception deficits.

Case 8 (MB) suffered a haemorrhagic infarction in the left parietal lobe (see Appendix 2.2). Neuropsychological examination 8 days post-stroke revealed an intact language and memory function. There were no indications of neglect or of problems with visual perception or construction. On the UHB, there were no further signs of low-level perception deficits.

Table 2.3. Overview of the patients' thresholds per visual primitive, split by side of presentation (C=central presentation, L=left sided presentation [right hemisphere], R=right sided presentation [left hemisphere]).

Case	Side of presentation	Shape	Luminance	Hue [red-green]	Hue [blue-yellow]	Motion	Shape-from-motion
1	L	**.481**	.066	.021	.019	.319	-
	R	.066	.016	.015	.017	.204	-
2	C	.106	.094	**.348**	**.031**	.045	.064
3	L	.239	.085	.032	-	-	-
	R	**.589**	.068	.049	-	-	-
4	C	.099	.061	.015	.017	**.407**	.017
5	C	.076	.066	.026	-	.218	-
6	C	.071	.054	.017	-	.043	**.286**
7	L	.138	.079	.201	-	.092	.243
	R	.019	.069	.019	-	.068	.175
8	L	.085	.089	.024	-	.205	.301
	R	.044	.040	.020	-	.101	.199

General Discussion

The aim of this study was twofold. First, we investigated the effect of posterior brain damage on visual hemifield processing; that is, the characterisation of the status of

the visual hemifields in terms of shape, luminance, hue and motion discrimination. To this end, we developed a new method for hemifield presentation of stimuli, exploring proficiency in the perception of the main primary visual primitives. Second, we were interested in the possible effect these visuo-sensory deficits might exert on higher-order processing. Therefore, we carefully explored the visual complaints of patients in terms of recognition deficits and/or experienced distortions of the outside world.

The first, perhaps not very surprising, finding is that posterior brain lesions may lead to a variety of visual field deficits. Half of the patients reported here suffered from some form of visual field cuts, ranging from tunnel vision to quadranopia. Although it is a theoretical possibility to observe islands of preserved processing within these visual field deficits (e.g. a spared ability to perceive motion in an otherwise blind part of the visual field), we did not observe such phenomena. One of the patients suffered from hemi-spatial neglect and the resulting problems with fixation control meant that we could only complete the central presentation condition. Finally, the UHB is a strenuous, time-consuming test battery and patients in the semi acute phase might find it difficult to complete all the subtests. Nonetheless, this study demonstrates that the UHB can be used to record reliable data. All healthy control subjects were able to complete the whole battery and all patients were able to finish, at least, an important subset of the tests. The control data provides us with reliable age-matched norms. For this first part of the study, it was the control data that yielded unexpected results. Thresholds for both the shape and shape-from-motion conditions differed between hemifield presentations; the thresholds for left hemifield presentations were significantly higher than for right hemifield presentation. We can only speculate as to the origin of this difference. If specific spatial cues would underlie this difference, one would expect the inverse pattern, as the right hemisphere is known to show enhanced spatial processing capabilities compared to the left hemisphere. Another possibility might be that shape and shape-from-motion need more attentional resources (are more difficult). A related result, recently presented, has shown that attentional effects can be lateralised to a large degree (Feeney, Dobkins, 2006). Again, this explanation is not satisfactory, since the above mentioned study showed differential effects of attention per hemifield on a motion discrimination task, a task which did not yield differential

thresholds in the present study. Moreover, the shape condition in the present study resulted in relatively low thresholds, and thus could presumably be performed without the allocation of many attentional resources. Another possibility is that the shape discrimination task is more related to object recognition than the other discrimination tasks. A relationship has been found between left hemisphere damage and the recognition of animals and tools (e.g. Tranel, Damasio, Damasio, 1997). Speculatively, it might be that, at a perception level, discrimination of shapes is also somewhat better in the left hemisphere.

The strict inclusion criteria provided us with a relatively small sample of patients. However, the individual performances of the patients in this sample on the UHB clearly demonstrated isolated impairments in visual primitives with either central, left, or right-sided hemifield presentation. In the 8 patients who were tested with the UHB, 5 demonstrated an elevated threshold of only one visual primitive. Interestingly, all visual primitives may become selectively distorted; thresholds on the shape discrimination task were elevated in two patients (Case 1 (PR) and Case 3 (MZ)), on the hue discrimination task in one patient (Case 2 (HA)), on the motion discrimination task in one patient (Case 4 (DR)), and on the shape-from-motion discrimination task in one patient (Case 6 (CH)). This selectivity of distortion was even found within one visual primitive, namely hue, as Case 2 (HA) only had an elevated threshold for the red-green discrimination task. When quizzed about his impaired performance on the Ishihara Test for Colour Blindness (1979) as well as on the Colour Arrays (Heywood, Cowey, 1999), he said that he used to paint and that, although he did not notice to have any problems with visual perception, his children said his paintings were different since his infarction: less coloured, less bright. He said he had not suffered from retinal colour blindness before his infarction. This shows that the selectivity of colour perception deficits can even occur within one type of colour-opponency.

These isolated (hemifield) impairments may have unexpected effects on higher-order processing. Case 3 (MZ) complained that her perception of faces was distorted in such a way that half of the face was perceived as being different in size (smaller), distorted (stretched, flattened, vaulted), or that specific features are not on their appropriate location (e.g. eyes, mouth, nose). Metamorphopsia usually lasts

for minutes up to hours, and is only rarely observed as a stable phenomenon lasting days or weeks. MZ showed an elevated threshold on the shape discrimination task, which could explain the experience of distorted face perception as well as the unique duration of the distortions, namely 6 weeks (see also Nijboer, Ruis, van der Worp, de Haan, submitted). The finding that MZ's metamorphopsia may be caused by low-level impairments in shape processing supports Bay's proposal (1953) in the sense that low-level impairments in shape processing found in MZ might have caused the metamorphopsia. Case 4 (DR) showed an elevated motion threshold and complained about distortions in the perception of buildings and roads. At first glance, it seems strange that an elevated motion discrimination threshold could result in the perception of distorted buildings and roads and not, for example, objects or faces. the latter is perhaps even more surprising as faces are hardly ever static. Buildings and roads, in contrast, do not move. However, there are now several strands of evidence suggesting that there are (at least) two largely independent motion processing channels, one tuned to lower and one to higher speeds (e.g. van der Smagt Verstraten, van de Grind, 1999). Van de Grind, van Hof, van der Smagt, Verstraten (2001) have suggested a functional division between these two channels: Whereas the 'low speed channel' is optimized for relative, object based motion, (3D) form-from-motion and smooth pursuit eye-movements, the much broader tuned 'high speed channel' is especially suited for navigational purposes (ego motion). Since the motion discrimination task here employed a relatively low speed, it is tempting to suggest that the low speed channel is selectively affected. Yet, based on van de Grind et al. (2001), one would expect DR's performance on the shape-from-motion task to be affected as well. In addition, she reported, that she perceived these distortions of roads and buildings, when she was driving her car, i.e. when navigating. We thus suggest that even though with the relatively low speed used in the present study, it is the fast motion channel that evokes these distortions when she was driving past buildings or watching the road in front of her. It would be interesting to test this patient further on specific navigational tasks including optic flow fields and heading stimuli. Case 6 (CH) showed a severe impairment in the ability to organise and integrate visual information on the neuropsychological screening, which was interpreted as a sign of integrative agnosia. The elevated threshold on the shape-from-motion discrimination task is consistent with the findings

on the neuropsychological screening. She did not show any further signs of low-level perception deficits.

The fine-grained analyses of visuo-sensory processing also allows us to investigate the reversed pattern, that is, the possibility of higher-order perceptual deficits in the absence of subtle problems in the processing of visual primitives in either hemifield. We observed impairments in higher-order processing while no visua-sensory deficits (no elevated thresholds) were found. Case 5 (LZ) reported problems with recognising whether lights in a room are on or off. Her normal thresholds for luminance as well as other primitives indicate adequate functioning at the perceptual level, yet she appears to have problems with comparing a normal percept to semantic knowledge about brightness or darkness in memory. The brightness recognition problems in LZ appear to result from problems with associating a (normal) percept with a visual representation stored in memory

Taken together, the present findings suggest the following: first, after unilateral damage in the visual cortex selective impairments in low-level visual processing may be observed in the contralateral hemifield, even without awareness (or conscious insight) of the patient (e.g. Case 2); second, in some patients, these low-level deficits appear to result in higher-order processing impairments (Cases 3 and 4); third, a low-level impairment of a single visual primitive does not necessarily result in a (subsequent) higher-order impairment: an elevated threshold for shape discrimination can, but by no means necessarily will, lead to higher-order processing deficits (Case 1 versus Case 4); fourth, higher-order recognition deficits do not have to result from low-level perceptual deficits (Cases 5 and 6).

This complex interaction between levels of visual processing has led to different views on visual perception deficits. According to Bay (1953), the constancies of visual objects are the first to be affected when transformations are disturbed, and this "Funktionswandel" affects certain recognition skills more than others. This suggestion has been refuted by Ettlinger, Warrington, and Zandwill (1957) and by De Haan, Heywood, Young, Edelstyn, and Newcombe (1995): even though patients with a recognition deficit may have sensory impairments, other patients who do not experience recognition problems can show equal or worse sensory impairments. Therefore sensory status alone cannot explain the presence or

absence of recognition disorders. The main point here is that, although sensory processing levels could not explain recognition deficits in some patients, it is still a viable explanation for impairments in other patients.

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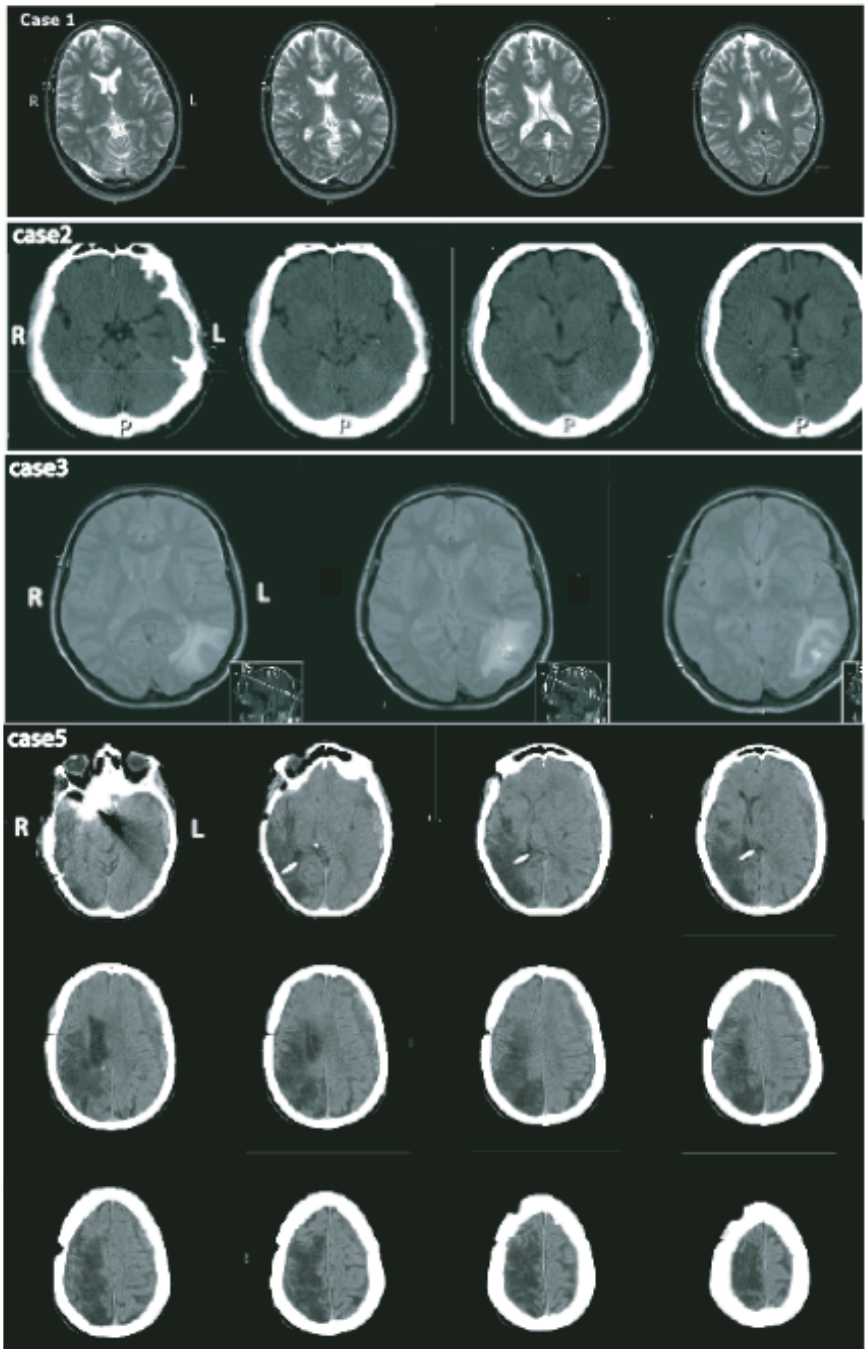
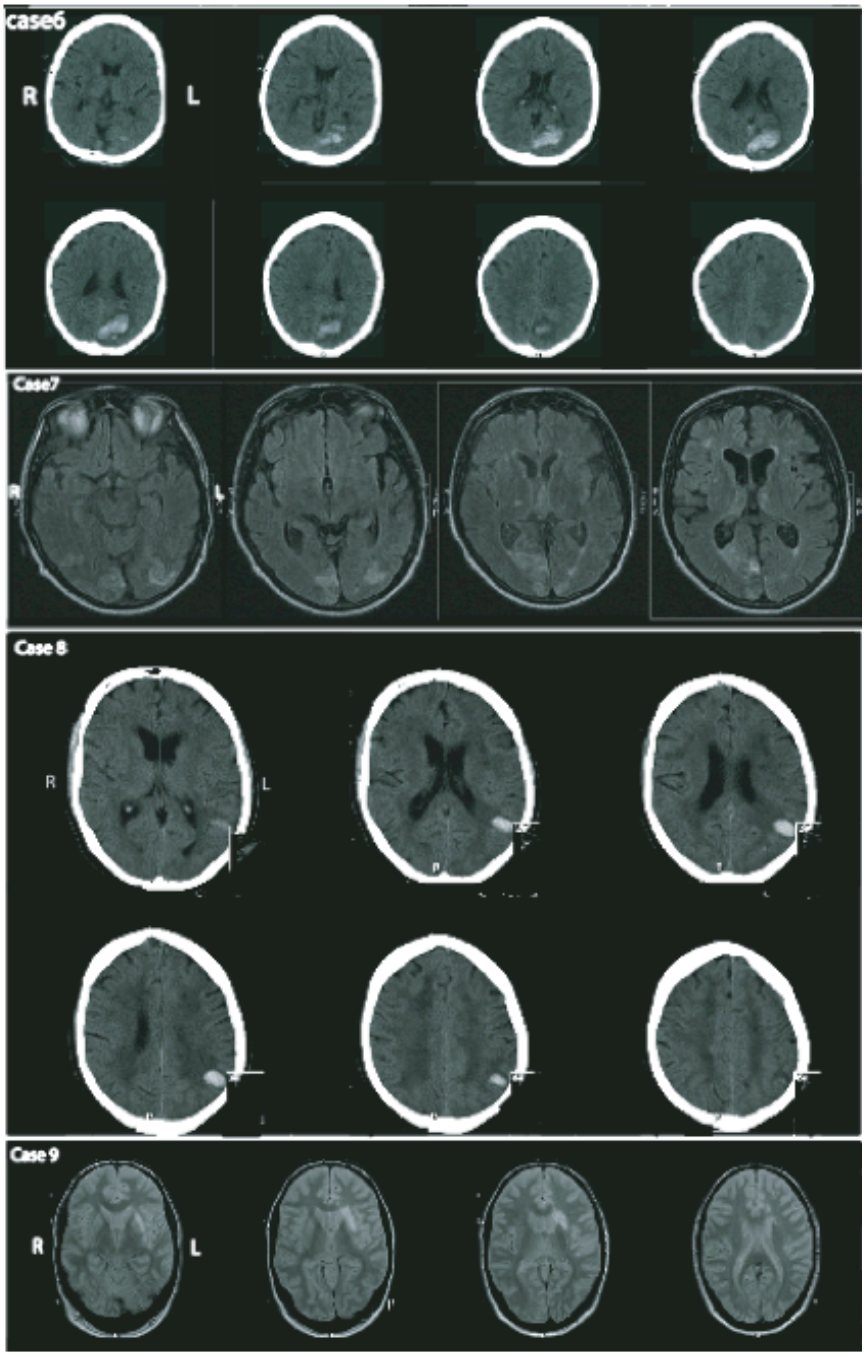
Addendum 2.1. Median xy coordinates per threshold, as measured with a colorimeter. Medians are calculated over 5 measurements per presented square per location (upper, middle, or lower square), resulting in 15 measurements per threshold in total. Luminance values (Y coordinates) are not presented, as these differed per colour per presentation, due to random differences in opacity of the coloured squares. The range of luminance differences is, as a direct result, very wide.

Threshold	Red		Green		Blue		Yellow	
	x	y	x	y	x	y	x	y
1	.622	.338	.287	.586	.144	.060	.419	.489
.75	.615	.343	.292	.585	.150	.069	.417	.487
.5	.575	.369	.305	.572	.176	.109	.404	.470
.375	.553	.396	.320	.560	.203	.151	.392	.450
.25	.507	.424	.344	.546	.237	.205	.370	.418
.185	.490	.438	.358	.532	.254	.232	.359	.400
.125	.464	.455	.372	.522	.272	.262	.345	.378
.094	.455	.466	.381	.513	.286	.282	.336	.364
.063	.440	.474	.392	.507	.294	.296	.329	.354
.047	.435	.441	.400	.505	.298	.303	.325	.345
.031	.427	.428	.404	.500	304	.313	.318	.335

Addendum 2. MRI-scans of he patients




case6
R
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Case7
Case 8
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Case 9
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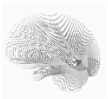

Chapter 3

Healthy participants: knowledge of colour and its associations

Seeing red primes tomato: evidence for comparable priming from colour and colour name primes to semantically related word targets

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Abstract

There is ample evidence that an independent processing stream exists that sub serves the perception and appreciation of colour. Neurophysiological research has identified separate brain mechanisms for the processing of wavelength and colour, and neuropsychological studies have revealed selective colour disorders, such as achromatopsia, colour agnosia, and colour anomia. The aim of the present study is to investigate whether the perception of colour may, despite its independent processing, influence other cognitive functions. Specifically, we investigate the possibility that the perception of colour influences higher-order processes such as the activation of semantically related concepts. We designed an associative priming task involving a colour prime (e.g. a red patch or the word RED) and a lexical decision response to a semantically related ('tomato' versus 'timato') or unrelated ('grass' versus 'griss') word target. The results of this experiment indicate that there is comparable facilitation of accessing colour-related semantics through the perception of a colour or the reading of a colour name. This suggests that colour has a direct effect on higher-order level, cognitive processing. These results are discussed in terms of current models of colour processing.

Keywords: colour processing, semantic system, lexicon, priming

Introduction

A central component of human vision is the perception of colour. Colour has been shown to facilitate object recognition, to enhance visual memory and to be very important as an aesthetic factor in visual experiences (Davidoff, 1991). Colour has a long history of research, and it still remains a dynamic area within the cognitive neurosciences (Bartels, Zeki, 2000; Zeki, 2003). Physiological studies have delineated pathways and brain structures that are involved in the processing of colour, using single-cell recordings (Van Essen, Zeki, 1978). Frequency-sensitive information is transferred from the retinal cone system, via the parvocellular pathway and the primary visual cortex to relatively dedicated visual areas involved in colour perception (e.g. V4). Lesion studies in humans and primates (Heywood, Gadotti, and Cowey, 1992; Heywood, Gaffan, and Cowey, 1995) and neuro-imaging (Beauchamp, Haxby, Jennings, and DeYoe, 1999; Beauchamp, Haxby, Rosen, and DeYoe, 2000; Tootell, Hadjikhani, 2001) have corroborated and extended these findings. It seems likely that there is not a single area for colour processing, but that perception of colour emerges through combined activity in different areas.

The neuropsychological literature supports the view that different areas of the brain are involved in different aspects of colour processing. The classical syndromes are – in a semi-hierarchical order – central achromatopsia (e.g. Meadows, 1974; Zeki, 1990), colour anomia (e.g. Davidoff, Ostergaard, 1984; Powell, Davidoff, 1995), and colour agnosia (e.g. Davidoff, 1996). The most striking is that these neuropsychological deficits in colour processing may occur in isolation.

Taken together, these different strands of evidence suggest a separate processing stream for colour perception involving independent processing modules: colour detection, colour matching, colour identification, and colour naming. As mentioned above, colour information, however, appears to sub serve object recognition and enhance visual memory. In order to be used in object recognition and visual memory, these independent processing mechanisms need to come together (Davidoff, 1991) and this implies strong connectivity between them. In this study, we want to investigate the possibility and nature of the link (Grossberg, 1987) between colour processing and the semantic system using a priming paradigm.

Priming is one of the most frequently used paradigms for studying human information processing. The characteristic of a priming study is the effect of the first stimulus (prime) on the response to the second stimulus (target). When the target stimulus is preceded by a prime stimulus that shares common characteristics, such as its spatial localisation (Posner, 1980), or semantic associations (Neely, 1976), it is processed more quickly. In the account of Posner and Snyder (1975) it is stated that semantic priming is produced by two mechanisms. One is a fast-acting, automatic, inhibition-free spreading of activation process that facilitates the recognition of words semantically related to the prime. The other is a slower-acting, strategy-dependent expectancy mechanism that facilitates and inhibits the recognition of words that are related or unrelated, respectively, with the prime.

Only a few studies have looked at priming effects of colour. These studies showed that the presentation of a colour may increase the performance on a subsequent colour discrimination (Simon, 1988; Marangolo, 1993) or same-different task (Rosch, 1975; Solso, Short, 1979). Marangolo (1993) used a repetition priming task to show that colour can facilitate the recognition of coloured targets. Rosch (1975) showed that priming with the prototypical name of basic colour categories (e.g. the words RED, BLUE, and GREEN) facilitates responses to good examples but inhibits responses to poorer examples of that category (e.g. different shades of the colour red, blue, and green). Solso and Short (1979) investigated the effect of the different mode(s) in which colour can be represented, e.g. physical representation (colour red), name representation (word RED) or conceptual representation (word BLOOD) in a same-different matching task. Colour patches were presented simultaneously, or 500 or 1500 ms before the presentation of a colour, a colour name or a semantic associate. They found that physical-physical matches are faster than physical-name matches, which both in turn are faster than physical-semantic associate matches. On the basis of these data, they suggest that colour information is processed in a sequential manner. Overall, these experiments support the idea of low-level repetition priming effects on colour perception. The study by Solso and Short (1979) also suggest a higher-order effect of semantic associates on colour recognition, but this effect was based on just four items.

A few studies exploring the so called 'reversed' Stroop interference effect have suggested that physical colour can influence the reading of colour words. In

his classic study, Stroop (1935; see Macleod (1991), for review) not only found that an incongruent colour name affects naming of physical colour, but also that an incongruent physical colour may affect the reading of colour names after extensive training. We demonstrated a reversed Stroop effect using degraded coloured words. Equiluminant and low-pass filtered presentations of coloured words resulted in significantly slower reading times for the incongruent coloured words (Nijboer, van Zandvoort and de Haan, 2006; Nijboer, te Pas, van Zandvoort, de Haan and de Weert, submitted). These findings suggest that a physical colour can activate colour names and subsequently compete for response selection.

These data have led to contrasting theoretical propositions. Glaser and Glaser (1982, 1989) postulated that physical colours have direct access to the semantic system, whereas colour names have only access to the semantic system through the lexical system. On the contrary, De Houwer, Fias and d'Ydewalle (1994) stated that colour does not have access to semantic information at all, as they found that Stroop interference effects were only observed with images (e.g. flower for spring) and not with colours (e.g. green for spring). The aim of the present study is to investigate whether the coding of colours can activate higher-order cognitive processes, e.g. the activation of concepts that are strongly associated with the colour, such as tomato with the physical colour red (colour patch) as well as with the colour name RED (word).

Methods

Participants

Fifteen participants who did not participate in the priming study were asked to rate the strength of the associations between objects and colours on a seven-point scale. Twenty right-handed participants (6 male, 14 female; age between 22-28 years) with Dutch as their first language participated in this study. All had normal or corrected-to-normal vision and reported no colour blindness, which was confirmed by a normal performance on the Ishihara test (1992). Each student participated in a single session lasting approximately 30 minutes.

Apparatus and Stimuli

We designed an associative priming task consisting of two blocks with two different primes (physical colour prime and colour name prime). In both conditions, seven prototypical colours were used: red, blue, green, yellow, pink, orange and brown. The primes could be congruent (red - TOMATO), incongruent (blue - TOMATO) or neutral (multicoloured patch - TOMATO) with respect to the meaning of the target word. There were eight target words for each colour. 168 Neutral words, that do not have an association with a specific colour, were used with all seven colour primes (e.g. red – BIKE).

Frequent words with a length of three to fourteen letters were selected (van Loon-Vervoorn, 1991) and used in both congruent and incongruent conditions. Pseudo-words were constructed by changing one syllable from an existing Dutch word. This change could be in the beginning, the centre, or the end of the word. The location of the change was equally distributed across words. Four semi-random lists were made to balance sequence effects, and the factors animacy and frequency were controlled for. Each participant was presented with one of the four lists of 672 stimulus pairs with a physical colour as the prime and one of the four lists of 672 stimulus pairs with a colour name as the prime.

Data collection and stimulus presentation were controlled by a PC. The experiment was programmed using E-prime 1.1. Stimuli were presented on a 22-inch 75 Hz flicker free colour monitor. The viewing distance was controlled for by a chinrest and set at 50 cm. The participants were tested individually in a quiet, darkened room. A trial started with a fixation cross (500 ms), followed by a prime presented centrally on a grey background for 100 ms. The physical colour prime stimulus measured 4 x 0.5 cm in width and height subtending approximately 4.5 x 0.5 ° of visual angle. The word prime stimulus measured 3 to 5 cm in width and 0.5 cm in height subtending respectively approximately 3.5 x 0.5 ° of visual angle and 5.5 x 0.5 ° of visual angle. After the prime there was a blank grey screen for 100 ms and subsequently, the target word appeared centrally on the same background. The target remained on the screen until the participant responded, with a maximum duration of 1500 ms. After that, participants had another 1500 ms to respond, without the target on the

screen. The length of the target words varied from 2 to 7 cm and the height measured about 0.5 cm subtending respectively approximately 2 x 0.5 ° of visual angle and 8 x 0.5 ° of visual angle.

Procedure

Participants were instructed to decide, as quickly and accurately as possible, whether the target word was an existing Dutch word by pressing the 'g' key for an existing word and the 'f' key for a non-existing, pseudo-word on the computer keyboard with respectively the index or middle finger of the dominant hand. After responding to the target, the participants had to press the space bar to start the next trial. The participants' responses and reaction times were recorded.

Results

Mean scores of this seven-point scale were calculated for both the associated and the not associated object-colour pairs and are shown in Table 3.1.

Table 3.1. Mean rating and standard errors of the mean of the typicality for congruent and incongruent object-colour pairs.

	Congruent	Incongruent
Mean rating of typicality (SEM)	6.30 (.20)	1.59 (.20)

As can be seen in Table 3.1, object-colour pairs that were chosen to be associated with one another, received a high score on the typicality rating, whereas object-colour pairs that were chosen to be non-associated with one another, received a low score on the typicality rating.

Participants made few errors and the number of incorrect responses was comparable across the three experimental conditions (congruent, incongruent, and neutral colour-word pairs) for both the physical colour primes (overall 4%) and the colour name primes (overall 3.8%). There was no indication for a speed-accuracy trade-off and the error data were not analysed further.

Median reaction times per participant were calculated for both correctly written and pseudo-words, but only responses to the correctly written words were included in the further analyses.

Table 3.2. Mean of the median reaction times (ms) and standard errors of the mean for colour patch and colour name primes in the congruent, incongruent and neutral condition, and for pseudo-words.

	Congruent	Neutral	Incongruent	Pseudo-words
Colour	531 (SEM 12)	562 (SEM 14)	572 (SEM 13)	583 (SEM 12)
Word	556 (SEM 14)	578 (SEM 17)	586 (SEM 15)	590 (SEM 11)

The means of the median reaction times of the correct responses were analysed with a two-way ANOVA with prime-type (colour versus name) and congruency (congruent, neutral, incongruent) as within-subject factors (see Table 3.2). The main effect of congruency was significant ($F_{2,38} = 48.41$; $p < 0.001$). There was no significant main effect for prime-type ($F_{1,19} = 1.84$; $p > 0.100$) and the interaction also failed to approach significance ($F_{2,38} = 1.19$; $p > 0.300$). The significant main effect for congruency was further analysed with planned comparisons with Bonferroni correction. The differences between congruent and neutral ($t19 = -7.26$; $p < 0.001$) and between congruent and incongruent ($t19 = -8.76$; $p < 0.001$) were significant. The difference between incongruent and neutral was not significant ($t19 = 1.90$; $p > 0.05$).

To establish that the significant priming effect was not due to specific colours used, we carried out an additional two-way ANOVA with colour (red, blue, green, yellow, pink, orange, and brown) and congruency (congruent, neutral, incongruent) as within-subject factors. The main effect of congruency was significant ($F_{2, 38} = 5.50$; $p < 0.02$). There was no significant main effect for colour ($F_{6, 114} = 0.105$; $p > 0.90$) and the interaction also failed to approach significance ($F_{12, 228} = 0.14$; $p > 0.90$). All colours added equally to the congruency effect (see Figure 3.1).

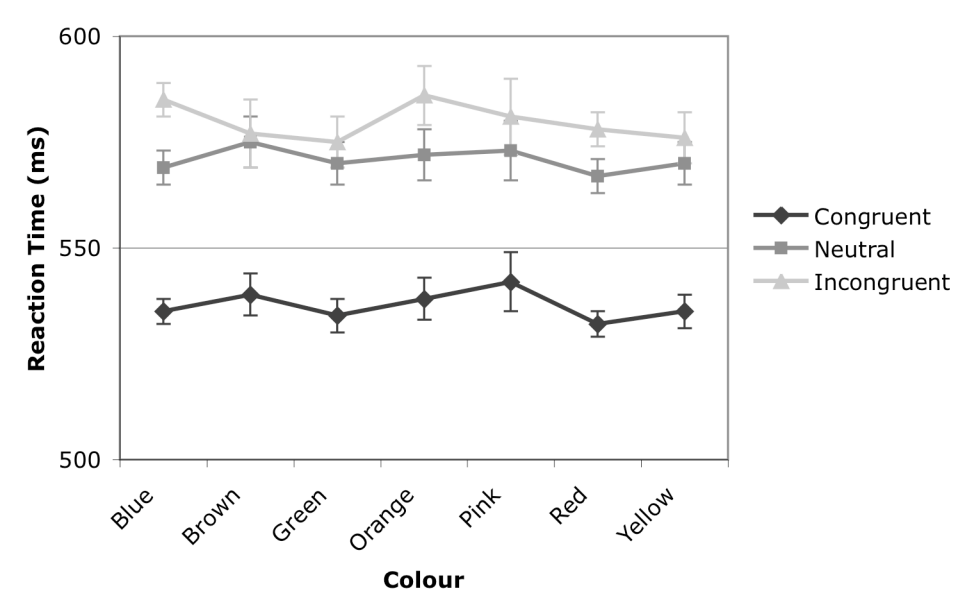


Figure 3.1: Mean of the median reaction times (ms) and standard errors of the mean for each colour separately in the congruent, neutral and incongruent conditions.

Discussion

The aim of this study was to investigate whether colour information can influence higher-order cognitive processes. Specifically, we looked at the effect of seeing a primary colour on the processing of the name of an item that is semantically associated with that colour. Moreover, we wanted to find out if there are differences between the codes in which colours can be represented by comparing physical colours (hue) and colour names. We observed comparable priming effects (facilitation without inhibition) from coloured patches and colour names. These results suggest that colour information activates concepts in the semantic system that are associated with that colour, and that it does not matter whether this information is conveyed in terms of physical colour or a colour name.

It had already been demonstrated that colour has an effect on low-level processes, using repetition priming (e.g. Marangolo, 1993), and Solso and Short (1979) had suggested that colour may have an effect on higher-level, cognitive

processes. Our results confirm and extend these observations. Even though the absence of a main effect of prime-type or an interaction with prime-type presents only indirect evidence, we would argue that our data show that (1) the perception of colour activates semantic concepts that are strongly associated with that colour, and (2) that the same colour concept conveyed by either a coloured patch or a colour name has a comparable effect.

These data appear to be in disagreement with Davidoff (1991) and the model proposed by De Houwer et al. (1994) who argued that colour information does not directly access the semantic system, but via the lexicon. It is still possible to speculate that both physical colour and colour names are accessed via the lexical system and one would then expect that processing of colour (hue) is slower than the processing of words. This is, however, not supported by our findings.

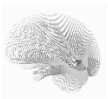
Our observations are partly in agreement with the suggestions put forward by Glaser and Glaser (1989), who postulated that physical colours have direct access to the semantic system, whereas colour names have only access to the semantic system through the lexical system. The fact that we found no main effect of, or interaction with, prime-type indicates that both types of input have similar access to the semantic system.

Overall, our findings are most in agreement with Rosch (1975) who suggested that the colour names affect perception at the level of meaning, as her results showed that priming with the prototypical name of a basic colour facilitates only good examples of that colour. Both her (repetition priming) and our experiment (semantic priming) show that the prime and the target stimulus need not be of the same form, e.g. words may prime colour perception and colour may prime word processing.

The present results can be explained by assuming that the perception and recognition of a colour and the reading and understanding of a colour word have comparable access to the semantic system. This seems to be true, at least, for those semantic concepts that are strongly associated with a particular colour. We can only speculate about the nature of this access to the semantic system. The observation that there is facilitation without inhibition suggests that the effect is automatic. The fact that the priming occurs with a relatively short SOA (200 ms)

supports this suggestion (Neely, 1976), although further experimentation is needed to substantiate this idea. An alternative explanation is that participants named the colour as soon as they saw it, thereby accessing the lexical systems and indirectly entering the semantic system. However, because naming the colour results in an extra processing stage, one might expect the reaction times with the colour primes to be somewhat longer than reaction times with the colour name primes. This is not the trend that we found.

In sum, we showed that physical colours and colour names prime the processing (lexical decision) of concepts that are strongly associated with that colour. These findings are interpreted as evidence for the idea that the recognition of a colour and the understanding of a colour name activate the same node in the semantic network and subsequently exert the same influence on further semantic processing.



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Chapter 4

Healthy participants: knowledge of colour and its associations

Recognising the forest but not the trees: the influence of colour on scene perception and memory

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Submitted

Abstract

Colour has been shown to facilitate the recognition of scene-images, but only when these images contain natural scenes, for which colour is 'diagnostic'. Here we investigate whether colour can also facilitate memory for scene images, and whether this would hold for natural scenes in particular. In the first experiment participants first studied a set of colour and greyscale natural and man-made scene images. Next, the same images were presented, randomly mixed with a different set. Participants were asked to indicate whether they had seen the images during the study phase. Surprisingly, performance was better for greyscale than for coloured images, and this difference could be attributed entirely to the higher false alarm rate for both natural and man-made coloured scenes. We hypothesized that this increase in false alarm rate was due to a shift from scrutinizing details of the image to recognition of the gist of the (coloured) image. A second experiment, utilizing images without a nameable gist, confirmed this hypothesis as participants now performed equally on greyscale and coloured images. In the final experiment we specifically targeted the more detail-based perception and recognition for greyscale images versus the more gist-based perception and recognition for coloured images with a change detection paradigm. The results show that (rather obvious) changes to images are detected sooner when image-pairs were present in greyscale than when presented in colour. This counterintuitive result held for both natural and man-made scenes and corroborates the shift from more detailed processing of images in greyscale to more gist-based processing of coloured images.

Keywords: colour, memory, gist, details, colour diagnosticity, change detection

Introduction

Humans are generally very good at visual recognition. A number of studies have documented our ability to identify hundreds of familiar objects and faces in a crowd of thousands of unfamiliar counterparts. In addition, Shepard (1967) and Standing (1973) have demonstrated that we have an enormous capacity for remembering and recognising pictures. From a more ecological point of view, it is surprising that memory for scene images has not attracted more scientific scrutiny. A scene is usually defined as a semantically coherent, nameable view of an environment, composed of multiple discrete objects. The studies that have looked at scene recognition often report that human visual memory may be limited in capacity and detail. For example, replacements of objects within a scene – between encoding and recognition - frequently go undetected (Friedman, 1979).

One explanation for these diverse observations is that visual information may be stored in more than one manner. It has been suggested that the image of a familiar scene can be stored in visual memory while the concept (or 'gist') may be encoded simultaneously in semantic memory. The term 'gist' generally refers to an interpretation of a story or an image on the basis of existing knowledge (Luck, Vogel, 1997; Treisman, 1986; Friedman, 1979). Depending on the conditions, the gist of an image may be remembered better than the visual details (Friedman, 1979; Miller, Gazzaniga, 1998; Rensink, 2000b) or vice versa.

The proficiency of visual memory depends on the time allowed to scrutinize details and the extent to which details are recognisable entities. Gist perception is considered to be fast (Biederman, 1981; Intraub, 1980; Oliva, 2005: Oliva, Schyns, 1997; Potter, 1975, 1976). For example, Potter (1975, 1976) demonstrated that less than 125 ms is needed for the meaning of an image to be understood. An interaction between visual scrutiny and gist recognition is suggested by the observation that expected or scene-consistent objects have been found to receive less attention, and subsequently, are encoded, stored, and retained in memory in a less detailed fashion than unexpected or inconsistent objects (Friedman, 1979; Hollingworth, Henderson, 2002).

An important visual cue that may affect both visual memory and gist recognition is colour. Only a few studies have specifically investigated the role of colour in memory for scene images. Homa and Viera (1988) found an advantage of coloured over black-and-white images across different retention intervals, ranging from immediate recall to a 12-week delay. They concluded that information about surface characteristics, such as colour, enhances memory. The effect of colour is modulated by the type of scene. In natural scenes (e.g. coasts, deserts, forests), there is a more consistent colour pattern that serves as a recognition cue compared to man-made scenes (e.g. cities, markets, rooms). In man-made objects and scenes, object-colour relationships are essentially random. Natural scenes, with a more consistent colour pattern, are also known as scenes high in 'colour diagnosticity' and have been found to be more (negatively) influenced by colour manipulations (e.g. inverted colour, greyscale) than scenes low in colour diagnosticity in recognition and naming studies (Nijboer, van der Smagt, van Zandvoort, de Haan, 2007; Oliva, Schyns, 1997; Tanaka, Presnell, 1999). It has been suggested that the effect of colour takes place at the level at which knowledge of object properties is stored (Humphrey, Goodale, Jakobson, Servos, 1994; Nijboer, van der Smagt, van Zandvoort, de Haan, 2007). In other words, colour helps us to recognise natural scenes, because it facilitates the identification of the gist of colour diagnostic images.

More recently, Wichmann, Sharpe and Gegenfurtner (2002) investigated the role of colour in recognition memory with carefully luminance matched colour and greyscale images. They used 4 categories of images: green landscapes, flowers, rock formations, and man-made objects. They found an overall 5-10% enhanced performance for the colour images compared to the greyscale images, irrespective of presentation duration. They concluded that colour as a surface property, at least for natural scenes, is stored in memory, but that sensory facilitation also played an important role, as colour recognition superiority was found independent of colour diagnosticity. Natural and man-made scenes, however, were not equally distributed in the study of Wichmann, Sharpe and Gegenfurtner (2002), with fewer images of man-made scenes. The present study, therefore, was aimed specifically at the role of colour in recognising natural and man/made scenes. A delayed-matching-to-sample method will be used to investigate whether colour information improves

scene memory for natural (colour diagnostic) scenes more than man-made scenes. In order to be able to compare our results directly, we designed a comparable experiment to the one used by Wichmann et al. (2002).

Experiment 1

The aim of this experiment was to investigate the effect colour on the recognition of scenes. We used a delayed matching-to-sample design with coloured and greyscale images of natural and man-made scenes. In order to make a direct comparison with the Wichman et al. study (2002), we also included a condition with inverted colour and presented images for a set of different durations.

Method Experiment 1

Participants

Twenty students (mean age 25.90, SD 3.05) participated in this study. All had normal or corrected-to-normal vision and reported no colour blindness, which was confirmed by the Ishihara test for colour blindness (1977).

Apparatus, Stimuli, and Procedure

The experiment was programmed using Matlab and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Stimuli were presented on a 21-inch monitor (80 Hz, 1024 x 768). Viewing distance was 57 centimetre, which was controlled for with a chin and forehead rest.

Images were chosen from different categories: coasts, forests and deserts for the natural scenes, and cities, markets and rooms for the man-made scenes. As Wichmann et al. (2002) found that recognition performance (HR and d') depends on image category, we used a comparable set of different scenes within each scene type (3 different natural scenes and 3 different man-made scenes).

All images were presented in colour, inverted colour and greyscale. Inverted colour images as well as greyscale images were manipulated in Adobe Photoshop from the original colour images. Images were first screened for category membership by 25 students, who did not participate in any of the experiments. Only images that were categorised consistently by all students were included. The mean

luminance was identical for all image formats. The size of the images was 256 x 256 pixels, subtending approximately 8o x 8o of visual angle.

The participants were tested individually in a quiet, darkened room. The experiment consisted of two phases: first, a study phase, in which the participants were sequentially shown a set of 96 images (32 in colour, 32 in inverted colour, 32 in greyscale), one at the time in a random order; second, a test phase, in which the participants' recognition memory for images was tested. In the study phase, participants only had to watch the images. Presentation durations of the images were varied from 50 ms up to 800 ms (50 ms, 200 ms, 400 ms, 800 ms) and images were randomly assigned to one of the four presentation durations. In the test phase, participants had to indicate whether the image shown was also presented in the study phase and respond by pressing a key on the keyboard.

The test phase started 3 minutes after the study phase had ended. The same 96 images were randomly mixed with 96 new images of the same scene categories.

Analysis

Repeated measures ANOVAs were performed on hit rate (HR), false alarm rate (FAR), discriminability (d'), criterion (c), and bias (β)[1]. Since no interactions between presentation durations and any measures were found (p's for all measures > .100) [2], the data were collapsed across duration. Hit rate, false alarm rate, d', criterion, and bias were calculated per scene type (natural versus man-made), per format (colour, inverted colour, greyscale) for each participant individually. For post-hoc testing, pair-wise comparisons with Bonferroni correction were used.

Results and Discussion Experiment 1

Table 4.1 shows the mean discriminability, criterion, and response bias for natural and man-made scenes, split by image format. As can be seen from Table 4.1, d' was influenced by the format of the presented images ($F(2,19) = 26.320$, $p < .001$), with the highest discriminability for the greyscale images for both the natural (p

[1] *d' = |z hit rate – z false alarm rate|; c = = -0.5 * |z hit rate + z false alarm rate|; β = 0.5 * d' * |z hit rate + z false alarm rate|*

[2] *Although there were no significant interaction, we did find a significant main effect of presentation duration; d', c, and β for images shown for only 50 ms differed from all other presentation durations (200 ms, 400 ms, 800 ms; p<.001), and d' for images shown for 200 ms differed from the images shown for 800 ms (p <.010)*

<.001; for greyscale images versus both colour and inverted colour images) and the man-made scenes (p <.001; for greyscale images versus both colour and inverted colour images). We also analysed the decision criterion and response bias (see Table 4.1). Decision criterion and bias shifted depending on the image format ($F(2,19) = 40.609$, $p < 0.001$), and ($F(2,19) = 46.336$; $p < 0.001$), respectively. These shifts in decision criteria and bias indicate that participants responded more conservatively to the greyscale images as compared to colour ($p < .001$) and inverted colour images ($p < .001$).

Table 4.1. D prime (a), criterion (b), and bias (c) per image format for recognition of different scene types.

	Natural			Man-made		
	Colour	Inverted colour	Greyscale	Colour	Inverted colour	Greyscale
d prime	1.020	0.767	1.547	1.052	0.961	1.844
criterion	-0.654	-0.690	-1.396	-0.809	-0.735	-1.613
bias	0.878	1.280	2.318	1.314	0.945	2.697

Figure 4.1 shows the mean hit rate and false alarm rate per scene type (natural and man-made), split by image format (colour, inverted colour, and greyscale). As can be seen from Figure 4.1 the influence of format on hit rate was different for natural and man-made scenes ($F(2,19) = 4.389$, $p < .020$. With natural scenes, colour images had a significantly higher hit rate than both inverted colour images ($p < .001$) and greyscale images (p <. 020). There is no difference between greyscale and inverted colour images. With man-made scenes, hit rate was not influenced by format. The influence of format on false alarm rate was the same for natural and man-made scenes. With both natural and man-made scenes, the false alarm rate for greyscale images was much lower than for both colour and inverted colour images ($p < .001$). In addition, with natural scenes, the false alarm rate for colour and inverted colour images differed significantly (p <.001).

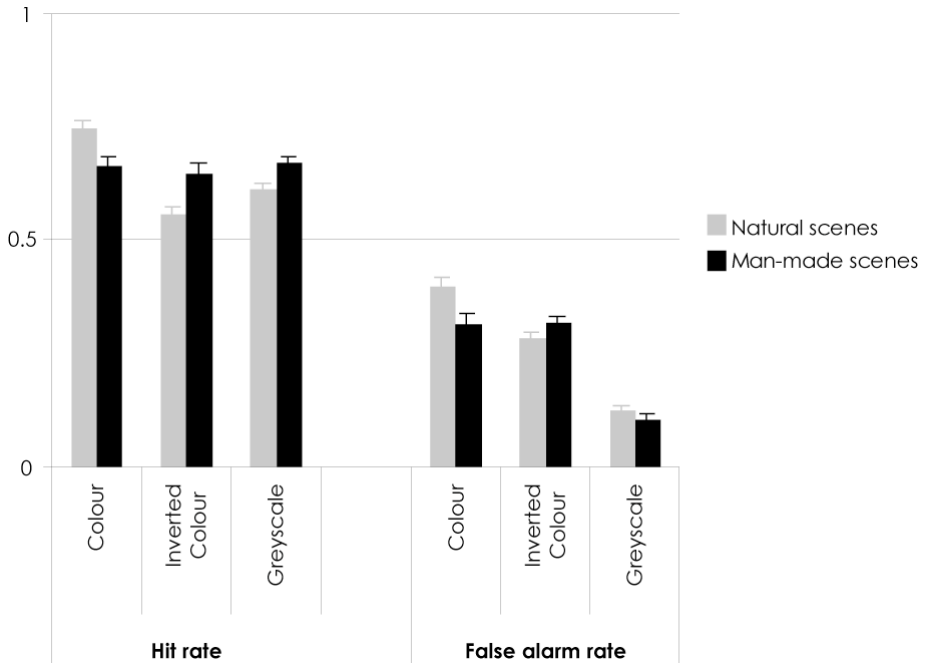

Figure 4.1. Effect (hit rate and false alarm rate; SEM) of image format on recognition of different scene types.

Taken together, recognition memory in terms of d' is best for greyscale images. This difference in performance is largely due to a significantly lower false alarm rate for the greyscale images than for the colour images. There was no difference in hit rate between coloured and greyscale man-made scenes, whereas hit rate was larger for coloured than greyscale images with natural scenes. These findings contradict the results reported by Wichmann et al. (2002) in two ways. First, they observed a better overall performance with coloured images and second, they did not find a difference in false alarm rate between coloured natural and man-made images. We suggest that the better performance with greyscale images was due to the fact that coloured images lead to faster identification of the gist of the scene, which in turn might have resulted in a less thorough scrutiny of the visual details of the to be remembered image. The reason this effect was not present in the Wichmann et al. (2002) experiment might be the longer intervals between images during the study phase. In other words, high false alarm rates for colour images might be obtained

only when the test phase requires subjects to distinguish between visually similar targets and distracters. This explanation is reminiscent of the experimental work on 'false memories'. This concerns the effect of expectation on memory for gist. Subjects are more likely to 'remember' objects that were not present in the original stimulus when they are semantically associated with the gist of the image (Brewer, Treyans, 1981; Loftus, 2003). Potter, Staub, and O'Connor (2004) demonstrated that false recognition of an image occurred more frequently when images with a conceptually similar gist were shown during the study phase, suggesting that stored semantic knowledge can interfere with detailed visual memory.

A test of our hypothesis that it is the fast identification of the gist that is responsible for the higher false alarm rate in coloured images, is the use of images that do not contain a readily nameable gist. For this second experiment, we used close-up images of tree bark or pebbles instead of pictures of scenes.

Experiment 2

This experiment investigates the effect of coloured and greyscale images of different textures on recognition memory. We did not use inverted coloured images as there was no a-priori correct colour-texture relationship for these stimuli.

Methods Experiment 2

Participants

Sixteen students (mean age 27.20, SD 3.85) participated in this study. All had normal or corrected-to-normal vision and reported no colour blindness, which was confirmed by the Ishihara test for colour blindness (1977).

Apparatus, Procedure, and Stimuli

Apparatus and procedure were identical to Experiment 1. Images were selected that do not contain a specific nameable gist. We chose close up images of tree bark or pebbles. All 72 images were presented in colour and greyscale (36 colour, 36 greyscale) in the study phase and were interleaved with 72 distracter images during the test phase. The size of the images was 256 x 256 pixels, subtending approximately 8° x 8° of visual angle. Viewing distance was 57 cm.

Analysis

Repeated Measures Analyses on hit rate (HR) and false alarm rate (FAR) were used. All were calculated per format for each participant individually.

Results and Discussion

As can be seen in Figure 4.2, there was no difference in hit rate ($F(1,15) = 2.98$, $p > .05$) nor false alarm rate ($F(1,15) = .456$, $p > .5$) between coloured and greyscale images, These results show that when images are presented without a nameable gist, recognition memory is comparable for coloured and greyscale images. This finding suggests that colour information per se is not sufficient for the increase in false alarm rate observed in Experiment 1 with coloured images.

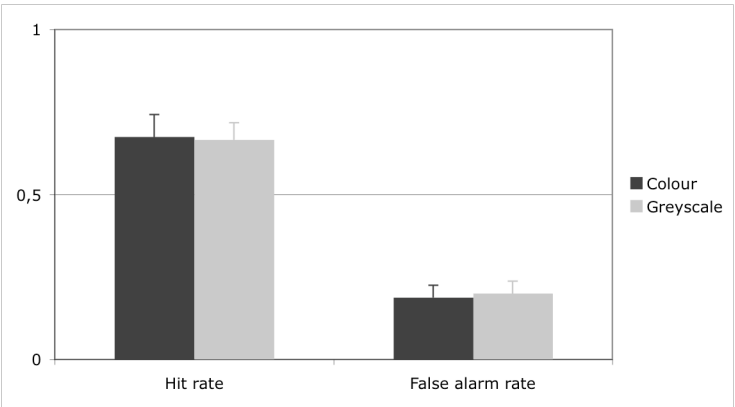

Figure 4.2. Effect (hit rate and false alarm rate; error bars depict ± 1 SEM) of image format on recognition of images with no specific nameable content.

The observed increase in false recognition for coloured images in Experiment 1 could have two (not mutually exclusive) origins. First, when a coloured image of a natural scene is presented for later recognition (study phase), the fast recognition of the gist could lead to less detailed encoding of the image. This is an explanation at the pictorial level. Second, when these images are presented in the test phase, the relatively fast gist recognition might induce a situation where the participant relies more on gist than on details, when comparing these images to images stored in memory. In such a situation, it might be more difficult to discard an image with the same gist than other (different) images that were presented during the study phase.

This account places the effect at the semantic stage of memory processing. From the work of Loftus (2003) and Potter et al. (2004), it is likely that semantic confusion plays a role. The extent to which such confusions will occur depends on the semantic content and number of the other images to be remembered, and the number and content of the distracters at the test phase. The first possible explanation appears less likely but has not been investigated before. Therefore, in order to investigate the possibility that differential visual scrutiny may play a role, we designed a change detection task with both coloured and greyscale images.

Experiment 3

In this experiment, we test whether the detection of change, an index of the proficiency of visual analysis, is the critical factor for the difference between coloured and greyscale images. If recognition of greyscale images is indeed based on details rather than gist, change detection performance should be faster for greyscale images than for colour images. This hypothesis is based upon existing explanations of change detection phenomena (Rensink, 2002). It has been shown that obvious changes to images can be hard to detect unless these changing (aspects of) objects are essential to the gist of the image (or denoted as "of central interest" to the image; see Rensink et al. 1997). For example, the disappearance of an engine from the picture of an aeroplane is difficult to detect, because an aeroplane without an engine is still recognised as an aeroplane. In contrast, it is easier to detect the disappearance of a wing, because wings are an essential feature of an aeroplane. In this study, we included coloured and greyscale images of natural and man-made scenes.

Method Experiment 3

Participants

This experiment was set up with a between subject design, since participants in this experiment could only be shown half of the image-pairs (see below). 32 Participants (mean age 33.4, SD 2.7) were included in this study. All had normal or corrected-to-normal vision and reported no colour blindness, which was confirmed by the Ishihara test for colour blindness (1971).

Stimuli and Procedure

Scene image pairs were chosen from different categories: coasts, forests and deserts for the natural scenes, and cities, markets and rooms for the man-made scenes. All images were not used in any of the other experiments. The mean luminance was identical for all image formats. The size of the images was 256 x 256 pixels, subtending approximately 8° x 8° of visual angle. The change between the first and the second image concerned details, such as replacements or deletions of whole objects, or changes in position of objects. Changes were equally distributed across the images (left, right, upper part, lower part).

Each image pair was presented both in colour and in greyscale, but participants never viewed the same scene twice. The experiment entailed 24 scene image pairs, presented in an alternating fashion with 200 ms presentation duration for each image of the pair, interleaved by a 200 ms blank interval. The sequence was repeated until the participant indicated (by pressing the space bar) that he/she had noticed the difference between the first and the second image of the image pair. Subsequently, they had to verbally describe the change they detected. Image pairs were shown until response or 2 minutes at most.

Two sets of image-pairs were used. The first set contained 12 scenes of the 24 total in greyscale and the other 12 in colour. The second set contained the same scenes, but image format was reversed. Half of the participants viewed one set; the other participants viewed the other set. All scenes were thus viewed 16 times in both formats.

Analysis

The time from stimulus-onset to the participant's key press (reaction time, RT) was recorded. Across participants, this resulted in RT-distributions for the different image-formats (colour and greyscale) and scene-types (natural and man-made scenes). Cases where participants did not describe the change correctly or failed to detect the change (RT > 2 minutes) where excluded from the distributions. Since RT-distributions are notoriously skewed, the resulting distributions were subsequently compared using the Kolmogorov-Smirnov (K-S) test. In addition, cumulative distributions were plotted (fraction of changes detected as a function of RT) and psychometric functions (Weibull-variant) were fitted through the data. 95%

Confidence intervals for the fit-parameters (notably shape and scale parameters) were calculated and compared.

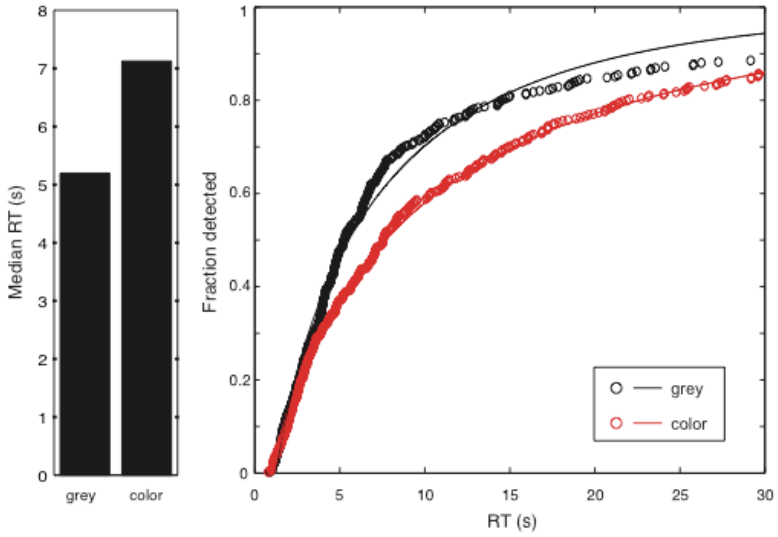

Figure 4.3. Median reaction times and cumulative distribution of reaction times, split by image format.

Results and Discussion

In more than 90 % of the trials the change was detected within 30 seconds presentation duration. Figure 4.3 shows the median RT (left panel) for both image formats. The overall finding is that changes in greyscale images were detected faster than in coloured images (K-S Z = 2.225, $p<0.001$). The right panel shows the cumulative distribution plots (circles are individual trials, the line depicts the fitted psychometric function). Both psychometric functions were excellent fits ($R2 > 0.99$). The 95% confidence intervals of the scale parameter of both functions did not overlap (greyscale: 4.17-4.94, colour: 7.25-7.71), indicating again a different underlying change-detection RT distribution for greyscale and colour image formats. These results corroborate our hypothesis that in coloured images the encoding emphasis is shifted towards encoding of gist compared to greyscale images, where more details are encoded.

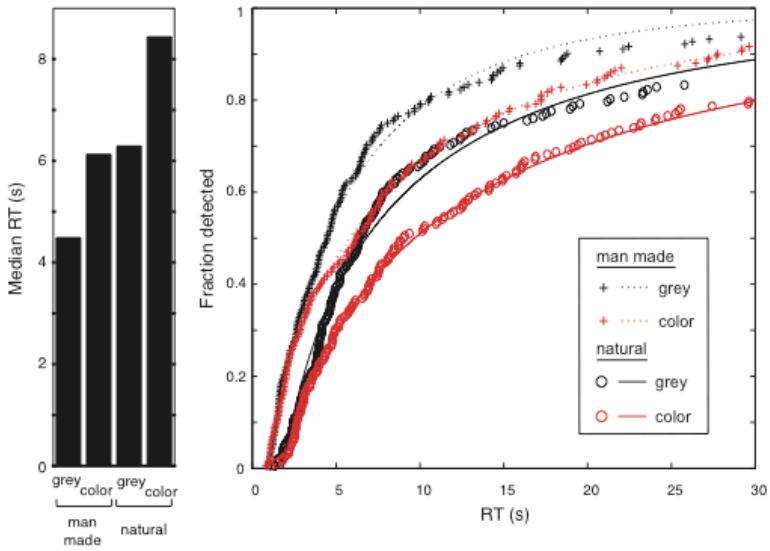

Figure 4.4. Median reaction times and cumulative distribution of reaction times, split by scene type and image format.

The images used in this experiment included man-made as well as natural scene categories. Thus the RT-distributions were also compared separately for both scene types. The results are shown in Figure 4.4. Again, the left panel shows the median RT for greyscale and colour images, for man-made as well as natural scenes. It is immediately clear that for both types of scene the changes in greyscale were detected faster than changes in colour (man-made: K-S Z =1.59, p = 0.013; natural: K-S Z = 1.64, p = 0.009). The right panel again shows the cumulative distribution plots with fitted psychometric functions ('+' and dotted lines show data and fits for man made scenes, circles and continuous lines show the data and fits for natural scenes). All psychometric functions were excellent fits (R2 > 0.98). The 95% confidence intervals of the scale parameter overlapped within scene category, but did not overlap between image formats (man-made greyscale: 3.43-4.00, man-made colour: 5.27-5.84; natural greyscale: 1.84-3.67, natural colour 5.70-7.03). In addition the 'shape' parameter differed between formats for the man-made scenes and between scene types (95% CI: man-made greyscale 0.64-0.71, man-made colour 0.57-0.61; natural greyscale 0.41-0.51, natural colour 0.47-0.51).

These analyses show that for both natural and man-made scenes changes in greyscale images are generally detected faster than changes in coloured images. In addition, they seem to indicate that changes in man-made scenes are detected sooner than changes in natural scenes. However, the latter result might easily be attributed to the differences in complexity between images from the two categories. Moreover, in this comparison only 12 man-made and 12 natural scenes were included, which were arbitrarily chosen. These images cannot readily be compared. However, this does not influence our main result (greyscale images versus coloured images), since this comparison deals with the same scenes, presented either in greyscale or in colour.

General Discussion

In the current study, we investigated memory for scene images. Our main research question concerned the interaction between the effect of identification of the scene (gist extraction) and the effect of coloured versus greyscale images (colour diagnosticity). In contrast to previous reports, we found that greyscale images were remembered better than coloured ones. More detailed analysis showed, as expected, that the hit rate was higher for coloured than for greyscale images of natural scenes. With man-made scenes, the hit rate was not influenced by format. More surprisingly, however, we found that false alarm rate was substantially higher with coloured images for both scene types. This means that recognition memory is worse for coloured images because subjects are prone to accept distracters more easily.

The discrepancy between our findings and those of Wichmann et al. (2002) might be the result of differences in inter-stimulus interval (ISI): our inter-stimulus interval (ISI) was 50 ms, whereas in the experiment of Wichmann et al. (2002) the ISI was 7000 ms. This is a crucial difference, as participants in the study of Wichmann et al. (2002) had more time in between successive images to consolidate more image details. It appears then, that consolidation of image details results in fewer false alarms, which will affect performance with the coloured images more than with greyscale images. In other studies, it has been found that scene memory builds up across separate glances and over a period of minutes (Hollingworth, 2004, 2005;

Melcher, 2001, 2006; see also the results of our Experiment 3). Therefore, it might have been more difficult for participants in the present study to remember the details of individual images, which could have resulted in differences in false recognition. Thus, we suggest that our observation that colour hampers recognition memory for scenes arises in experimental conditions in which encoding is restricted by time constraints. Other differences between our study and Wichmann et al. (2002) are the number of categories (six categories (three natural, three man-made) versus four categories (three natural, one man-made), respectively) and the number of images used (96 versus 48, respectively), Each of these differences might have contributed to the differences between our study and Wichmann et al. (2002).

In Experiment 2, we addressed the question whether identification of the scene is a necessary condition for the paradoxical colour effect to appear. To that end, we used images that did not contain a specific nameable content (i.e. gist). Under these conditions there were no differences in memory performance between coloured and greyscale formats (equal hit rate and false alarm rate). This finding strongly suggests that the increase in false alarms as found in Experiment 1 is contingent on the identification of the scene, and not on colour per se.

Potter et al (2002, 2004) suggested that there are two components of visual memory, a pictorial and a conceptual store, with a faster decay rate for the former compared to the latter. This idea for a multiple component memory system account is further supported by Cooper and Schacter (1992) who suggest that achromatic, detailed structural descriptions and more general, internalised gist-based descriptions in which colour information is also stored can be distinguished. On the basis of our findings in Experiment 1 and 2, we argue that – under time restrictions - colour information modulates the balance to which these two memory components are engaged. In Experiment 3, we tested the counterintuitive hypothesis that colour deteriorates the visual exploration of natural and man-made scenes. The results showed that changes are detected faster in greyscale compared to coloured images. This finding is in accordance with the results from Experiment 1, where the false alarm rate was overall higher for coloured images in both natural and man-made scene types.

In sum, we have shown that recognition memory for scenes is influenced by identification or gist extraction. In terms of a two-component model of visual memory, entailing a pictorial and a gist-based code, colour modulates the degree to which these two codes are employed. This effect is more pronounced under time restrictions. In our view, coloured images, and especially coloured images of natural scenes, lead to faster gist identification and to less detailed visual scrutiny. The latter effect becomes apparent when subjects are required to detect changes as fast as possible. Detection speed is significantly delayed when images are presented in colour.

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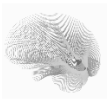

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Chapter 5

Healthy participants: knowledge of colour and its associations

Distinct trajectories for acquisition of colour terms and object-colour associations

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Submitted

Abstract

Children seem to acquire colour terms relatively late (3-5 years of age), while colour perception and colour discrimination is present at 3-4 months. In the current study, we investigate the development of colour term acquisition and its relation to object colour knowledge in children in a much broader age range than most research so far: 3-7 years of age. As different areas in the brain are involved in various stages of colour processing and several isolated colour processing disorders have been described, we investigate the relative developmental trajectories of these separate colour processing stages: colour naming, verbal object-colour associations and pictorial object-colour associations. We show that children aged between 3 and 4 years of age do not know all colour terms and do not apply all colour terms correctly, especially the terms for secondary colours. In addition, in 3 and 4 year old children verbal object-colour knowledge is much better than pictorial object-colour knowledge. We suggest that, initially, object-colour knowledge appears to be stored primarily as a verbal association, and this knowledge is available even before colour terms can be used adequately. Apparently, it is not necessary to have access to colour names prior to verbal object-colour associations. This pattern is strikingly similar to reported findings in a man with developmental colour agnosia, who has some verbal object-colour knowledge in absence of the ability to adequately name colour or to indicate correct pictorial object-colour.

Keywords: developmental trajectories, colour terms, colour associations, colour agnosia

Introduction

It is commonly observed that young children find it difficult to learn colour terms. Several studies report that children acquire colour terms relatively late in linguistic development (Soja, 1994; Pitchford, Mullen, 2001; Pitchford, 2006) or that children make many errors acquiring colour terms. Both findings are based on investigations that compare the acquisition of colour terms to that of other terms, such as objects or shapes (Davidoff, Mitchell, 1993; Rice, 1980; Pitchford, 2006). The difficulty in acquiring colour terms arises with mapping the exact colour terms onto the colours correctly. Children often use colour terms incorrectly (Pitchford, 2006).

The relative delay with which colour terms are acquired might be related to slow(er) development of several underlying mechanisms. Perceptual (e.g. categorical learning), attentional (e.g. colour preferences), and linguistic (e.g. frequency of usage of colour names) factors might all play a role. The underlying functional structure of colour processing might complicate acquisition of colour terms; even though the colour spectrum is continuous in physical terms, colour perception has been found to be categorical. Discrimination *between* colour categories (e.g. between red and yellow) has been shown to be better than discrimination *within* a single colour category (e.g. between two shades of red), even when the pairs' perceptual distances are identical (Bornstein, Kessen, Weiskopf, 1976; Franklin, Davies, 2004). Categorical perception of colour is probably 'hardwired' into the visual system, since even pre-linguistic children (3-4 months of age) show this phenomenon. Moreover, by 4 to 5 months of age, children regard a particular colour as the same, even under different lighting conditions (Dannemiller, 1989), which indicates that some degree of colour constancy is present at an early age.

Acquiring colour terms as well as the ability to verbally label the colour categories correctly have been found to appear much later than colour perception and discrimination, and even relatively late in linguistic development (3-4 years of age) (Pitchford, 2006). It has been suggested that the speed with which colour terms are acquired is related to the development of colour concepts or to "fixing of references" for colour terms (Franklin, 2006). Whereas colour conceptualisation encompasses knowledge that colour is not dependent on the function of the object

that has that particular colour (e.g. a tomato and a fire truck are both red, but obviously do not have the same function), fixing references means indicating 'boundaries' of each colour category. In other words, the former stresses the strong associative link between colour and objects, while the latter emphasises categorical perception.

Successful retrieval of object-colour knowledge (e.g. storage of colour information specific to certain objects) has been found to appear between 3 and 5 years of age (Perlmutter, 1980). Children preferred coloured images to greyscale images when objects high in colour diagnosticity (strong association with a specific colour , e.g. banana, strawberry) were shown, whereas this difference was not present with images of objects low in colour diagnosticity (weak or no association with a specific colour, e.g. bike, scissors). In addition, Davidoff and Mitchell (1993) found that the limited object-colour associations that children between the age of 3 and 4 have, are stored primarily as verbal associations. The finding that object-colour knowledge is retrieved either visually or verbally seems to be in line with results of neuropsychological studies with patients with selective impairments in one of both types of associations (Beauvois, Saillant, 1985; de Vreese, 1991). In our view, it is important to make distinctions between naming colours, reporting objects colours, and verifying correct object colours, since neuropsychological studies have shown that colour processing can be selectively distorted in disorders such as achromatopsia, colour constancy deficits, colour anomia, and colour agnosia. These findings suggest that perceiving colours, naming colours, reporting and verifying correct object colours are processed separately, in different cortical areas of the brain[3]. As these different colour processes have been associated with different brain areas, it might be likely that development of these processes can also be separated in time. Thus far, the developmental trajectories of these separate colour-processing stages have not been properly investigated. A direct comparison

[3] *Zeki and Marini (1998) have discerned three broad cortical stages in colour processing: first, occipital retinotopic maps in V1 and V2 are concerned with registering the presence and intensity of wavelength in the visual spectrum; second, V4 is mainly concerned with automatic colour constancy operations; and third, inferior temporal cortex, anterior parts of the fusiform gyrus, hippocampus, and ventrolateral frontal cortex are concerned with colour-colour relations and object-colour associations.*

of the relative developmental trajectories of these separate colour-processing stages will give insight in the interdependence of the different aspects of colour recognition.

In the current study, we investigate the development of colour term acquisition and its relation to object colour knowledge, with three different tasks tapping various stages of colour processing: *colour naming, verbal object-colour association,* and *pictorial object-colour association* (correctly and incorrectly coloured objects). Moreover, we will investigate colour term acquisition in a broader age range (between 3 and 7 years).

Methods

Participants

Sixty children participated in this study and were recruited from day care and primary school. They were assigned to one of five groups, according to their age (15 children of 3 years of age, 10 children of4 years of age, 15 children of 5 years of age, 9 children of 6 years of age, and 11 children of 7 years of age). All had normal or corrected-to-normal vision. Parental consent was given before the children participated in the experiment.

Stimuli and procedure

Stimulus presentation and data collection were controlled by a PC. The experiments were programmed using E-prime 1.1. Stimuli were presented on a 15-inch monitor with a vertical refresh rate of 60 Hz. The viewing distance was set at approximately 50 cm.

Stimuli for the *colour naming tasks* were 14 coloured squares (2 x 2 cm) in 7 different colours (red, blue, green, yellow, pink, and brown). In Table 1, an overview of the xyY coordinates for the colour used is given. All squares were presented sequentially, in a random order, for 500 ms. Children were asked to name the colours of the squares as accurately as possible. No reaction times were recorded, as a voice key cannot be reliably used with young children. The verbal responses of the children were written down by the experimenter.

For the *verbal object-colour association task*, children were asked to answer questions about the colour of objects, such as "What colour is a banana?". Again, no reaction times were recorded and verbal responses were written down by the experimenter. An overview of the questions is given in Table 1.

The *pictorial object-colour association task* was an object-colour recognition test and consisted of 40 coloured line drawings of objects that are highly associated with a certain colour. Object drawings were presented both in the appropriate and in an inappropriate colour (e.g. a red strawberry versus a blue strawberry). The line drawings remained visible until a response was given. The children were asked to indicate whether the line drawings were depicted in a correct colour ('g' key press) or not ('f' key press). They were explicitly told that there was no time limit and that it was more important to give the correct answer than to be fast. Table 5.1 gives an overview of the object-colour combinations used.

Analyses

We calculated percentages correct responses for the colour naming test, the verbal object-colour knowledge test, and the pictorial object-colour association test, for all groups of children separately. Non-parametric analyses were performed on these percentages per test per age group. Additionally, for the pictorial object-colour association test, we calculated hit rates ('g' key pressed when the line drawing was correctly coloured; HR) and false alarm rates ('g' key pressed when the line drawing was *not* correctly coloured; FAR).

Table 5.1.Overview of the stimuli used in the three different tasks.

Colour naming	xyY values		
Blue	.1546	.0765	9.50
Brown	.4878	.4145	13.72
Green	.3002	.5963	31.91
Orange	.5125	.3874	38.16
Pink	.3475	.2467	45.29
Red	.6264	.3299	21.98
Yellow	.4193	.5053	92.78

Verbal knowledge	object-colour	What is the colour of a…?	Banana
			Strawberry
			Cheese
			Pig
			Wasp
			Leaf
			Deer
			Chicken
			Lion
			Carrot

Pictorial object-colour association object-colour knowledge task

	Correct colour (2x)	Incorrect colour
Banana	Yellow	Red/Blue
Strawberry	Red	Blue/Yellow
Cheese	Yellow	Pink/Blue
Pig	Pink	Green/Blue
Wasp	Yellow	Red/Green
Leaf	Green	Blue/Pink
Deer	Brown	Blue/Red
Chicken	Yellow	Pink/Green
Lion	Orange	Blue/Pink
Carrot	Orange	Purple/Green

Results and discussion

Colour naming test

When percentages correct were split by age group, it is clear that the best performance was found in the groups with the older children: the youngest children (3 years of age) gave the correct colour name in 56% of the trials and the children

of 4 years of age gave the correct colour name in 65% of the trials. The 5-, 6-, and 7-year-old children performed at 95%, 98%, and 98% correct, respectively. A Kruskal-Wallis test with number of correct responses as dependent variable and age as a grouping variable revealed a significant difference in number of correct responses (Chi-square with 4 degrees of freedom = 41.6, $p < .001$) (see also Figure 1). A Mann-Whitney test with Bonferroni correction for multiple comparisons showed that the performance of 5, 6, and 7-year-olds was significantly better than the performance of the 3 and 4-year-olds (for all comparisons, $z > 3.5$, $p < .001$). The performance of the children of 3 and 4 years of age was comparable ($z = 1.3$, $p = .163$) as well as the performance of the children of 5, 6, and 7 years of age (for all comparisons, $z < .5$, $p > .5$). The bigger standard deviation at age 4 also indicates that the turning point for adequate use of colour terms is at this age.

Subsequently, the percentages correct were analysed for the 7 different colours in order to investigate the possibility of a specific order in the emergence of colour terms. An overview per colour is given in Table 5.2.

As can be seen in Table 5.2, the 3- and 4-year-old children were better at naming primary colours (red, green, yellow and blue squares; 67% and 75%, respectively), when compared to secondary colours (orange, pink, and brown; 28% and 54%, respectively). The low overall performance of the youngest children thus appears to be caused mainly by the low performance on naming secondary colours. For example, the orange, pink, and brown squares were often named red and only a few children responded that they did not know the name of the colour (10% of the total amount of errors). The older children (5-7 years of age) did not show a difference between the primary and secondary colours.

Table 5.2. Overview of the percentages correct per age group on the verbal object-colour associations task, split by object.

Colour	3 years	4 years	5 years	6 years	7 years
Blue	65	75	96	98	99
Brown	20	36	95	97	96
Green	70	71	96	99	99
Orange	22	55	95	98	99
Pink	41	71	95	99	98
Red	69	73	96	99	99
Yellow	64	80	95	98	99
Primary colours	67 (SD: 2,5)	75 (SD: 3,3)	96 (SD: 0,4)	99 (SD: 0.5)	99 (SD: 0.1)
Secondary colours	28 (SD: 9,5)	54 (SD: 14,3)	95 (SD: 0.1)	98 (SD: 0.8)	98 (SD:1,1)

Verbal object-colour knowledge test

When percentages correct were split by group, it can be seen that best performance was found in the eldest group (100% correct). The 3 and 4-year-old children performed at 69% and 86% correct. Performance of the 5 - and 6-year-old children was 97% and 98% correct respectively. Table 5.3 shows the percentages correct per object. A Kruskal-Wallis test with number of correct responses as dependent variable and age as a grouping variable revealed a significant difference in number of errors (Chi-square with 4 degrees of freedom = 45.3, $p < .001$) (see also Figure 1). A Mann-Whitney test with Bonferroni correction for multiple comparisons showed that the performance of the children of 3 and 4 years of age differed from all other groups (for all comparisons, $z > 2.2$, $p < .02$). The performance of the children of 5, 6, and 7 years of age did not differ from one another (for all comparisons, $z < 1.6$, $p > .1$).

As can be seen in Table 5.3, the 3- and 4-year-old children made most errors when they were asked to name to colour of a pig, a deer, and a wasp. This could reflect a specific object-colour knowledge problem, maybe as a result of infrequent associative learning occasions. When images were shown of these animals in the pictorial object-colour association test, children did not fail to recognise these

animals. These data suggest that the strength of object-colour associations can vary, especially at young age.

Table 5.3. Overview of the percentages correct per age group on the verbal object-colour associations task, split by object.

Object-colour	3 years	4 years	5 years	6 years	7 years
Banana	91	99	99	100	100
Strawberry	80	99	100	100	100
Cheese	78	83	97	99	100
Pig	50	73	96	100	100
Wasp	51	71	96	95	100
Leaf	75	89	99	100	100
Deer	47	75	95	95	100
Chicken	60	85	97	99	100
Lion	81	83	95	96	100
Carrot	71	98	100	100	100

Pictorial object-colour association test

Again the best performance was found in the groups with the older children: mean percentage correct for 3 -year-old children was 52%, for 4-year-old children, it was 68%, for the 5-year-old children 93%, for the 6-year-old children 96%, and for the 7-year-old children 99% (see also Table 5.4). A Kruskal-Wallis test with number of correct responses as dependent variable and age as a grouping variable revealed a significant difference in number of errors (Chi-square with 4 degrees of freedom = 29.8, $p < .001$) (see also Figure 1). A Mann-Whitney test with Bonferroni correction for multiple comparisons showed that the performance of 3 and 4-year-olds was significantly worse than the performance of the 5-, 6-, and 7-year-old (for all comparisons, $z > 3.3$, $p < .001$). The performance of the children of 3 and 4 years of age was comparable ($z = 1.1$, $p = .286$). The performance of the children of 5, 6 and 7 years of age did also not differ ($z = -1.5$, $p = .143$).

Table 5.4. Overview of the results of the 2 AFC test (total number of errors, % correct, hit rate, false alarm rate) per group of children

	3 years	4 years	5 years	6 years	7 years
Total number of errors	290	128	41	13	3
% Correct	52	68	93	96	99
HR	.64	.67	.92	.93	.97
FAR	.70	.44	.15	.09	.08

In Figure 5.1, an overview of the mean performance per task is shown per age group.

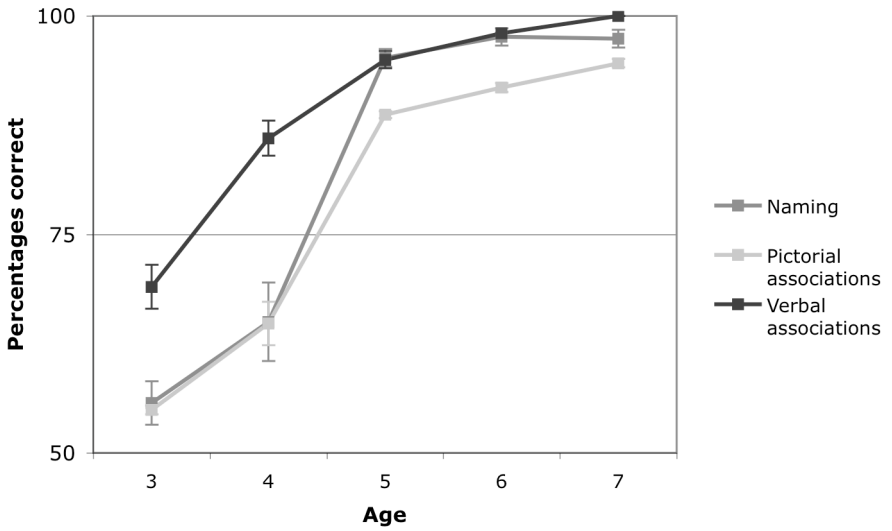

Figure 5.1. Overview of the mean performance (+SEM) per task per age group.

Additionally, we analysed hit rates (HR) and false alarm rates (FAR) to investigate the type of errors underlying the differences in performance between the groups of children. In Table 4, HR and FAR are given per group. A Kruskal-Wallis with HR as dependent variable and age as a grouping variable revealed a significant difference in number of errors (Chi-square with 4 degrees of freedom = 36.6, $p < .001$). A Mann-Whitney test with Bonferroni correction for multiple comparisons

showed that the performance of the children of 3 and 4 years of age was comparable (z = .587, p = .557) as well as that the performance of the children of 5, 6, and 7 years of age did not differ from one another (for all comparisons, z < 1.1, p > .07). The performance of 3- and 4-year olds was significantly different from the performance of the 5-, 6-, and 7-year-old (for all comparisons, z > 3.0, p < .001).

Next, a Kruskal-Wallis test with FAR as dependent variable revealed a significant difference between the groups (Chi-square with 4 degrees of freedom = 35.5, p < .001). A Mann-Whitney test with Bonferroni correction for multiple comparisons showed that the performance of the children of 3 and 4 years of age was only marginally significantly different (z = 2.0, p = .048) as well as that the performance of the children of 5, 6, and 7 years of age did not differ (for all comparisons, z < 1.8, p > .07). The performance of 3 and 4 year olds was significantly different from the performance of the 5- 6-, and 7-year-olds (for all comparisons, z > 3,1, p < .001)). In Figure 5.2, the HR and FAR are shown per age group.

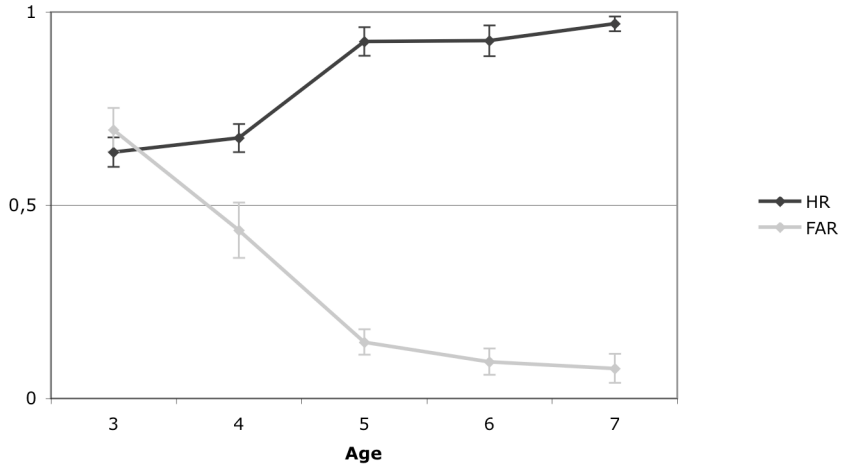

Figure 5.2. Overview of the mean HR and FAR (+SEM) per age group.

General Discussion

There is ample evidence that young children have considerable difficulty acquiring colour terms, resulting in a relative delay in adequately using the terms. Unfortunately, most of the research has either focussed on colour naming, or colour categorisation, and only a few studies have investigated object-colour associations.

In the current study, we investigated the development of colour term acquisition and its relation to object colour knowledge, with three different tasks: *a colour naming task, a verbal object-colour association task,* and *pictorial object-colour association task* with correctly and incorrectly coloured objects.

We found that in the colour naming task, children between 3 and 4 years of age did not know all colour terms and were not able to adequately apply all colour terms correctly yet. Interestingly, the children were better at naming red, green, yellow and blue squares, compared to orange, pink, and brown. This is partly in line with the basic colour categories of Kay and Berlin (1956). Children older than 5 years of age appeared to have learned all colour terms and are able to apply them adequately. The frequency with which colour names are used is, as mentioned in the Introduction, one of the linguistic factors that might be related to the slowness of acquiring colour terms. It appears that this frequency indeed has its influence; the primary colours red, green, yellow, and blue can be used adequately at a younger age than the secondary colours brown, orange, and pink.

In contrast to the performance on the colour naming task, on the verbal object-colour association task, even the youngest children were quite able to correctly answer simple questions about the colour of objects, such as "What colour is a banana?". The youngest children had some problems with giving the correct colour name for a pig, deer, and wasp. It might be due to differences in strength of associations, maybe as a result of infrequent occasions of associative learning. It is important to note that the children who did know the colour of a wasp, also knew that wasps actually have two colours, yellow and black, and also mentioned both colours.

Despite the adequate verbal knowledge of object-colour associations, it was found in the pictorial object-colour association task that the youngest children did not adequately recognise the correct colour of objects that were presented as simple line drawings. The combination of these two results indicates that children as young as 3 or 4 years of age do have semantic knowledge about the colour of objects, even though when confronted with an incorrectly coloured object, they do not appear to recognise this as odd. Apparently, children do not have to recognise yellow to still be able to semantically have learned that bananas are yellow. When

they are shown a physical colour or a line-drawing of an object, they have more problems with recognising the colour and relating it to the shown object. In other words, they have problems combining verbal and visual information. This is in line with earlier findings that object-colour knowledge is stored in both a verbal and a non-verbal manner (Beauvois, 1982; Davidoff, Mitchell, 1993; de Vreese, 1991; Paivio, 1971). It appears that children older than 5 years of age have learned the associations between colours and objects, not only verbally, but visually as well. An alternative explanation might be that children cannot reject incorrectly coloured objects, because in many books, pictures of objects are depicted in many different colours, even inappropriate ones. Their performance on the verbal associations task, however, implies that verbally the children do know which colour is associated with a certain object.

Interestingly, whereas the verbal object-colour associations appear to gradually develop with age (see Figure 5.1), acquiring colour terms as well as recognising correctly or incorrectly coloured objects appears to be less gradual, but more dichotomous: either one knows or one does not. Moreover, it appears that the early improvement of recognising correct object-colour is a result from an improvement of correctly rejecting incorrectly coloured objects. This might result from the improved ability to recognise and name colours correctly. It is possible that younger children start acquiring new colour terms by copying the terms they hear from others, without understanding exactly what is meant. Feedback from others on the appropriateness of the usage of the colour terms influences acquisition of these terms, their relations to colour categories, and object-colour associations. This feedback will be largely linguistic. Therefore, it might not be surprising that the verbal object-colour associations are formed earlier than the visual associations. In neuropsychological literature, different impairments of colour processing have been reported, such as achromatopsia, colour anomia, and colour agnosia. Our results with children aged between 3 and 4 show a striking similarity to the results of a man with developmental colour agnosia (van Zandvoort, Nijboer, de Haan, 2007) and two of his family members (Nijboer, van Zandvoort, de Haan, 2007). MAH is not able to neither name colours on presentation, nor indicate whether line drawings of objects are correctly coloured or not. On the contrary, MAH has access to basic

object-colour knowledge, as he can name prototypical colours of objects[4]. In other words, he has learned the verbal object-colour associations, but has never learned to recognise different hues as belonging to one colour term (i.e. "fixing references"; Franklin, 2006) or give the appropriate colour term on visual presentation. His mother and his eldest daughter have the same problems, though to a lesser extent.

To conclude, in the development of colour terms and colour knowledge, verbal object-colour associations appear to develop first, and colour as an object property only develops when the child learns that colour can be conceptualised as an object-function-independent surface property, before it can be used adequately as a colour term. It is important to note that there is a remarkable difference between the development of primary and secondary colour terms. Finally, as soon as the child realises that different shades or hues are part of a single category, recognition of (images of) correctly coloured objects is more or less present.

[4] *It is important to note that MAH only has verbal object-colour knowledge of objects that are frequently used in language or frequent associated with a specific colour. For example, he knows that bananas are usually yellow and strawberries are usually red, but he does not know that a billiard cloth is usually green or that a life jacket is usually orange. Also important to note is MAH's normal low-level colour vision (see van Zandvoort, Nijboer, de Haan, 2007).*

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Chapter 6

Case study: developmental colour agnosia

Developmental colour agnosia

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Cortex, 2007

Abstract

Colour agnosia concerns the inability to recognise colours despite intact colour perception, semantic memory for colour information, and colour naming. Patients with selective colour agnosia have been described and the deficit is associated with left hemisphere damage. Here we report a case study of a 43-year-old man who was referred to us with a stroke in his right cerebellar hemisphere. During the standard assessment it transpired that he was unable to name coloured patches. Detailed assessment of his colour processing showed that he suffers from a selective colour agnosia. As he claimed to have had this problem all his life, and the fact that the infratentorial infarct that he had incurred was in an area far away from the brain structures that are known to be involved in colour processing, we suggest that he is the first reported case of developmental colour agnosia.

Keywords: colour, agnosia, perception, developmental

Introduction

Colour agnosia is one of the classical neuropsychological syndromes. A striking clinical description of what is meant by colour agnosia was given by Kleist (1934) who stated that "a patient who has lost the general concept of colours behaves to colour stimuli as a normal subject behaves to certain odours. We can discriminate a large number of odours but we do not have general concepts for related types of smells and no names.." . The term refers to a selective impairment in the recognition of colour that cannot be explained by perceptual, memory, or language deficits due to an impairment in the internal colour space (Klein, 1953; Bruyer, 1977; Kinsbourne and Warrington, 1964; Beauvois and Saillant, 1985; Grüsser and Landis, 1991, Davidoff, 1996). It must thus be separated from cerebral achromatopsia, i.e. a selective colour perception disorder, and it can also be dissociated from colour anomia, which refers to a specific problem in naming colours as a result of a lexical impairment and must not be due to an impairment in the internal colour space (Roberson et al., 1999). In addition, general confusion or disorientation should be excluded as possible causes. Colour agnosia is selective in that it only affects colour, while the recognition of other primary visual cues, such as motion and shape, and higher-order visual categories, such as objects and faces, remain unaffected. It is associated with lesions in the left temporo-parietal region and is therefore often but not necessarily associated with aphasia (Stengel et al., 1948; Varney and Digre, 1983).

The first reports on colour agnosia date from the end of the nineteenth century. For instance, Lissauer described a patient with an intact ability to discriminate and perceive colours, but who made errors when asked to name colour patches or to name an object associated with a visual presented colour patch (Lissauer, 1890). This patient was also 'unable to point to the colour of a canary in the absence of colour vision impairments'. This observation was against the then dominant view that the inability to retrieve the colour of an object was a language disorder (Davidoff and Fodor, 1989). Although several cases of colour agnosia were subsequently reported in the literature, e.g. Kinsbourne and Warrington (1964), Hécaen et al., 1974, and Beauvois and Saillant (1985), the consensus on what constitutes colour agnosia appears to be based more on

clinical definition than on empirical testing or theoretical accounts (Beauvois and Saillant, 1985).

To dissociate colour agnosia from cerebral achromatopsia (Zeki and Marini, 1998; Bartels and Zeki, 2000), colour anomia (Beauvois and Saillant, 1985), or colour amnesia (Grüsser and Landis, 1991) performance on a variety of perceptual and neuropsychological tasks need to be taken into account. That is, visual sensory assessment of colour, but also of visual features such as shape and brightness should be normal to rule out explanation in terms of (isolated) perceptual impairments (Miceli et al., 2001). The general knowledge of colour (i.e. the definition of colour), and object-colour knowledge (i.e. the ability to name the prototypical colour of objects, such as a fire engine or a banana), should be intact to exclude colour amnesia (Goldenberg, 1992; Davidoff, 1991). Furthermore, the matching of isoluminant coloured patches (i.e. patches of different colour but comparable luminance) should be intact, in contrast to impairments in both naming and pointing to coloured patches on verbal command (Beauvois and Saillant, 1985). In addition, the ability to decide whether an object colour is veridical or not is impaired in cases of colour agnosia (Davidoff, 1991). Due to a loss of colour concepts and representation the categorization of colours is expected to be disturbed in colour agnosia, despite the ability to sort colour on the basis of individual matching (Roberson et al., 2000; Pilling et al., 2003). It is clear that a substantial analysis of the impaired and spared abilities is required before a convincing diagnosis of colour agnosia can be reached.

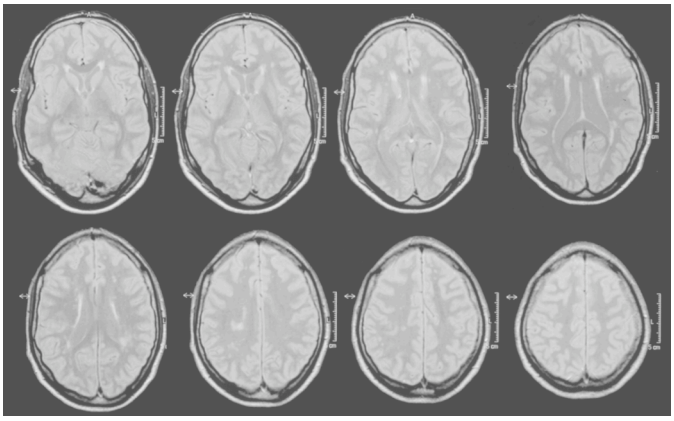
Until now, colour agnosia has only been described as a result of acquired damage. Other forms of higher-order recognition deficit, such as prosopagnosia (e.g. De Haan, 1999; Barton, et al., 2003) and alexia (Ley, 1938), have also been observed in healthy normal people without neurological or birth complications. These developmental cases shed light on the way in which function specialisation evolves in the brain. For instance, parallels between acquired adult-onset and developmental or childhood-onset prosopagnosia demonstrated comparable subtypes and revealed contributing perceptual encoding deficits in prosopagnosia suggestive for common functional mechanisms (Barton, et al., 2003). These parallels can only be discerned by comparison of acquired adult-onset and developmental cases, especially in the paucity of imaging evidence in developmental cases.

Acquisition of colour terms and colour-object knowledge in normal subjects have been studied extensively (e.g. Bornstein, 1985; Pitchford et al., 2002; Roberson et al., 2004), as well as the loss of colour names and knowledge in (semantic) dementia (e.g. Ukita, et al., 1999). Moreover, the way colour knowledge evolves and is represented in the brain appears to be basically understood. However, impairments in higher-order colour perception and its underlying mechanisms are not yet straightforward. Here, we report the first case of developmental colour agnosia. The diagnosis of colour agnosia is based on an extensive series of tests of colour processing.

Case History

In 1998, MAH was 39 years old when he suffered from a stroke in the right cerebellar hemisphere. He is a right-handed, academically educated man, who worked at a high professional level. He came to our attention during a neuropsychological screening study in which patients were included within the first 14 days after their stroke and re-examined after 24 months (van Zandvoort et al., 2004). Apart from residual dizziness and mild memory deficits, he had no complaints about his cognitive functioning, reported no changes with respect to his premorbid level of functioning and returned completely to his premorbid professional level. On MRI-imaging (TSE) an infarction in the right cerebellar hemisphere, predominantly the lower half and the vermis, consistent with the supply area of the posterior inferior cerebellar artery (PICA) was found. No additional brain abnormalities in the occipitotemporal cortices appeared to be present on MRI (see Figure 6.1).

Figure 6.1. No stroke lesion or brain abnormalities in the relevant cortical areas can be found on the MRI-slices (T2SE) of the occipito-temporal and (occipito-)parietal cortices of MAH at 14 days post-stroke.



His neuropsychological performance in the early stage and at 27 months post-stroke is summarized in Table 6.1. Taking his age and education into account he performed above average on all neuropsychological tasks tapping the major cognitive domains of reasoning, language, visual perception and construction, verbal memory, visual memory, executive functioning and neglect. The only task on which his performance was severely impaired during the second, more extensive examination was on the Token test (De Renzi, 1978). In this task subjects have to move tokens (circles and squares) in red, yellow, green, blue and white, on verbal command according to various syntactic variations (i.e. place the red circle next to the blue square). He was unwilling to perform this task, despite his cooperative test attitude during the rest of the testing session. When asked why, he declared to be 'colour blind or something like that' which had nothing to do with his stroke and had been part of his life for as long as he could remember. Nevertheless, his performance on the Ishihara Colour Plates was flawless and fast (Ishihara, 1971). When asked about the colour of a plastic bag in the testing room (bright green), he was insecure and after a while he said 'it is a bright colour; it might be either yellow or orange'. Then he stared out of the window for some time looked back at the bag and said 'no, it must be some kind of green because it looks like the grass outside'. He told us that he had this ´problem´ for all of his life.

*Table 6.1. Neuropsychological performance at 14 days post-stroke and after 27 months. WAIS: Wechsler Adult Intelligence Scale; RAVLT: Rey Auditory Verbal Learning Task; Rey-O: Rey-Osterrieth Complex Figure; n.a.: not administered *****.*

Neuropsychological Task		Early Examination	Second examination
Reasoning			
Raven APM		11/12	12/12
WAIS vocabulary		46/60	49/60
Language			
Boston Naming Task		172/180	180/180
Token Task		n.a.	0 / 21
Letter Fluency	-UNCA	n.a.	60
	- category	n.a.	39
Memory			
RAVLT	- immediate rc.	49/75	59/75
	- delayed rc.	8/15	14/15
	- recognition	29/30	29/30
Doors Task		19/24	21/24
Rey-O figure delayed rc.		14/36	35/36
WAIS - digit span		12	19
Location Learning Task	- displacement	n.a.	14
	- learning index		0.50
	- delayed recall		0
Wechsler Memory Scale: paired associated		n.a.	19/21
Corsi Block Span		7	6
Visual perception & Construction			
Judgement of Line Orientation		30/30	28/30
Face Recognition Task		47	45
Rey-O figure copy		36/36	36/36
Executive functioning			
Trailmaking	- A	36	33
	- B	81	52
Ishihara test for colour blindness		25/25	
Odd-one-out –shape		1.27 mm **	
-luminance		0.46 cdm^2	
-colour		2.16	
-motion		2.89% coherent motion	
Farnsworth-Munsell 100 hue		44 errors ***	

*******The first number is MAH's score on the test, the second number is the maximum score*

******** *Data of control participants on the Odd-one-out paradigm:*
Shape:1.03mm (SD:0,68) / Luminance:1.10cdm^2 (SD:0,30) / Colour:1.28 (SD: 0,78) / Motion: 2.33% coherent motion (SD:1.63)

********* *Normal range: 30-100 errors*

Subsequently, he was extensively interviewed regarding the nature of his colour recognition problem. He stated that as far as he knew there had been no birth complications, and that – until his stroke - he had never incurred a head injury or suffered from any neurological diseases. He claimed that he loved colour and surrounded himself both in the office and at home with colourful paintings, especially Fauvism. Nevertheless, he was unable to name the colour of his couch or curtains at home. Interestingly, he spontaneously suggested that his mother had reportedly complained about similar problems. Unfortunately, we were unable to test his mother. We examined MAH in the two following years during a number of occasions.

Methods and the performance of MAH

For the testing of the visual sensory assessment and the Farnsworth Munsell 100-hue test, including the standard and the (free)sorting procedure, we compared the performance of MAH to control data derived from a highly comparable comparison group consisting of four male subjects all with an academic degree and aged in the range of 38-48 years (mean 42 yrs). They all had normal or corrected-to-normal vision and reported no colour blindness, which was confirmed by a normal performance on the Ishihara test for colour blindness.

Visual sensory assessment

Assessment of the perception of primary visual sensory cues (brightness, shape, texture and colour) was carried out with an odd-one-out procedure (De Haan et al., 1995). On each trial three stimuli were presented in a vertical alignment. Two stimuli were identical and the third differed in the appropriate dimension. The odd-one-out had to be indicated via a touch sensitive screen. Each task consisted of 50 trials, and a titration procedure was designed to reach a reliable threshold with a minimum of trials. Three consecutive correct choices resulted in an increase in task difficulty and a single error resulted in an easier trial being presented. MAH encountered no problems on any of these tasks. He outperformed the healthy comparison subjects by reliably detecting a brightness difference of 0.46 cdm^2, which is more than 2 SDs beyond the sensitivity of the age-matched comparison

subjects (mean: 1.10 (SD: 0.30) cdm^2). Both his Just Noticeable Difference (JND) of shape and texture fell within the normal range with a shape discrimination of 1.27 mm (comparison mean: 1.03 mm (SD: 0.68)) and a texture discrimination of 2.89% difference (comparison mean: 2.33 % (SD: 1.63)). On the colour task his performance also fell within the normal range. He was able to discriminate between two adjacent colour steps (comparison mean: 1.28 (SD: 0.78)) that were created by constructing 80 isoluminant coloured patches that ranged, in roughly equal steps on the CIE chromaticity diagram between red and green (for details see de Haan et al, 1995). However, MAH was extraordinary slow, and made his decision after long and careful consideration.

Farnsworth-Munsell 100 hue test

The Farnsworth-Munsell 100 hue test (FH-100hue test) was administered according to the standard procedure in which the isoluminant coloured chips of the four boxes need to be sorted by hue (Farnsworth, 1975). Both the beginning and the end of each box are fixed and 21 coloured chips have to be put in between in the correct order. The Total Error Score (TES) of MAH was 44 which fell in the normal range of 30-100 TES, pointing out again that he was able to make subtle discriminations between isoluminant colours. The time he needed and the procedure he used to reach this performance, however, were anomalous. The sorting process took him about 15 minutes per box, whereas the mean sorting time for normal comparison subjects is 2.5 minutes for each box. In addition, he moved each chip along the line just as long as he found the most perfect match. Although he worked with the utmost precision he was never completely satisfied with the result.

Naming of and pointing to colours

For testing the ability of MAH to name colours and to point to colours we used standard coloured crayons as they represent the colours we learn early in life and on which broad consensus is reached and a 100% correct score is to be expected (see Table 6.2.). We repeatedly placed four crayons of different colour in front of him and asked to name the crayon we pointed out (Bruyer, 1977; Grüsser and Landis, 1991). For each trial the set of crayons was changed. MAH was given 8 trials and, as

shown in Table 6.2, he found it difficult to name the colours. Again he never felt confident in his response. He named 4 out of 8 colours correctly with a mean of 43.5 seconds to produce a colour name. He stated that he was incapable of doing it and there were no recognisable regularities to his mistakes. We asked him to verbalise the procedure he followed out loud. It turned out that he used a matching strategy, in which he compared the colours of the crayons to coloured objects in the environment of which he knew the colour based on semantic object-colour relations (e.g. plants in the room, the colour of the fire-escape sign etc.) to make his decisions. If the colour of the target crayon was not available, he tried to deduce the answer by elimination of the distracters. After colour naming we tested his ability to point to colours on verbal command using the same procedure of one target crayon between three distracters (see Table 2), and again his performance was severely impaired. He was correct on 3 out of the 8 trials with a mean response time of 32.6 (17.9) seconds. In sum, MAH was severely impaired in naming of and pointing to colours.

*Table 6.2. The time (seconds) needed to respond and the accuracy for the Pointing to and the Naming of colour pencils with representative everyday life colours. C: correct; IC: incorrect; * correct response*

	Pointing	**Naming**
trial 1	purple	purple
	red	red
	*orange	orange
	yellow	yellow
trial 2	red	red
	brown	brown
	yellow	yellow
	blue	blue
trial 3	yellow	yellow
	green	green
	red	red
	orange	orange
trial 4	*purple	purple
	green	green
	brown	brown
	black	*black
trial 5	brown	brown
	orange	orange
	blue	blue
	purple	purple
trial 6	red	*red
	green	green
	yellow	yellow
	*blue	blue
trial 7	yellow	yellow
	blue	*blue
	purple	purple
	green	green
trial 8	*black	black
	red	red
	green	green
	blue	blue
	Mean (sd): 43.5 (29.8)	Mean (sd): 32.6 (17.9)
	Accuracy: 4 /8	Accuracy: 3 / 8

Colour knowledge and Object-colour knowledge

First, we asked MAH to define "colour". He came up with an adequate account suggesting that colours are light of different wavelength resulting in colours that changed from infrared to ultraviolet and that this phenomenon can be observed in a rainbow. However, he was subsequently unable to name the colours of the rainbow in the correct order or to draw a rainbow with colour crayons. He knew that white contained all possible colours and that there were primitive colours i.e. red, green and blue which could be used to construct the total colour spectrum of, for instance, a colour television. With respect to blending colours, he stated that yellow and blue produce green, but that was the only mixture he could name. When asked to name the colour of common objects with a characteristic colour (e.g. banana, orange, traffic lights) from memory, he performed flawlessly and without any hesitation.

Table 6.3. True-False discrimination of living object in the category of animals, vegetables, and fruits in simple and double presentation. Stimulus presentation duration was 500 milliseconds in both tasks and conditions. naming of the object and the name of the prototypical colour of the object. # pictures based on the stimuli suggested by Davidoff and Kingsley.*

Task	**Accuracy**	**Percentage correct**
True-False drawings		
simple presentation	21/44	45%
double presentation	15/24	62%
achromatic naming*	44/44	100%
True-false pictures#		
simple presentation	27/40	67%
double presentation	22/24	92%
achromatic naming*	40/40	100%

When asked to colour in line drawings of common objects with crayons put in front of him, his performance was impaired (0 out of 6). For instance, he produced an

orange cherry with a purple stick to it and a blue meadow with pink daffodils, although he could name prototypical colour of the objects. Again, he was never completely satisfied with his performance and was not at ease while performing the tasks. In sum, he appears to have access to knowledge and the name of colour of common objects. He fails as soon as the task requires him to identify a perceived colour.

MAH was further tested on his object-colour knowledge by administering him two computer tasks in which he had to judge whether pictures of fruits, vegetables and animals were coloured in a veridical manner or not (see Table 6.3) (Ostergaard and Davidoff, 1985). Both computer tasks were piloted on a group of five students in the age range of 21-24 years. They all performed flawlessly and responded immediately after presentation of the stimuli on both tasks confirming that these tasks refer to readily available basic object-colour knowledge. In the first experiment, simple line drawings were presented either solidly filled in with the appropriate colour or with an inappropriate colour in a 50/50 proportion (see Table 3). Objects were presented individually for five seconds to allow him sufficient time to judge. He experienced great difficulties on this task and kept complaining that he needed more time. His performance did not exceed chance level with 19 out of 40 correct answer (47.5%). In a subsequent version of this task, a correctly and a incorrectly coloured object were presented simultaneously and MAH had to decide whether the right or the left object was correctly coloured. This offered him the opportunity to compare two alternatives and this resulted in a slight improvement in his performance to 15 out of 24 correct responses (62%). Using achromatic stimuli, MAH was able to identify the objects by naming them perfectly and also demonstrated that he had access to stored object-colour knowledge by attributing the correct colour to the objects.

In the second experiment, we used more sophisticated stimuli of coloured pictures in which luminance, reflections, and texture changes were incorporated (see Table 3). The same procedure was used. First, we presented individual line drawings for a free recall identification response, followed by a double presentation for a forced choice reaction, and an achromatic condition in which he had to identify the object.

Stimulus duration was 2 seconds in all conditions. Again MAH was severely impaired on the individual conditions, although his performance was better compared to the solidly filled line drawings, with 27 out of 40 correct responses (67%). Nevertheless, he admitted that he had been guessing in the majority of the trials. In the double presentation condition, he surprisingly performed almost flawlessly, with 22 out of 24 correct responses (92%). After the first four trials he revealed his strategy, he could 'see from the strange luminance and brightness which of the two presented stimuli looked a bit more artificial than the other'. This indicates that based on the colour information alone he was unable to recognize a veridical coloured object from an abnormally coloured one. Again he underlined his intact object naming and semantic knowledge of object-colour relation with a faultless performance in the achromatic condition. His knowledge of object-colour relation, therefore, appeared to be 'learned' rather than 'experienced based'.

In sum, MAH has basic object-colour knowledge. Conversely, he was severely impaired in attributing this object-colour knowledge to visually presented objects. That is, he was at chance level in deciding whether an object was correctly or incorrectly coloured. Moreover, his decisions appeared to be based on luminance and texture.

Free Categorisation of coloured chips

To examine his conceptual knowledge of colour in more detail, we asked MAH to categorise the 84 isoluminant coloured chips of the FH 100-hue test. All chips were presented in a random arrangement on a large sheet of white paper and he was asked to form groups of chips that belonged together. He was not given any clue about the number or size of the subgroups, and it took him a while to make sense of this task and to get started. In roughly 25 minutes he ended up with 21 categories (Figure 6.2, left panel). The approach he used betrayed a loss of colour concepts. He sorted colours by perceptual similarity rather than by categorical identity. The membership of and boundaries between the various groups were completely arbitrary; he would split up a group because he found it was too big and subsequently put them back together only a few moments later. In the end, he decided that this was the best he could do but he was not satisfied with the result.

This procedure of free categorisation was repeated in a session six months after the first free categorisation. His strategy was identical, and this time he ended up with 19 categories.

Forced Categorisation of coloured chips

MAH was again confronted with the 84 isoluminant colour chips of the FH-100 hue test, but this time he was instructed to form exactly five groups. At first, he took one chip to start with and chose four additional chips that were as much dissimilar with each other as possible. Then, he followed the same strategy as used in the free categorisation and matched chips two by two. Once he had five groups he moved the last chips along all five categories to see were it belonged best. After 30 minutes he ended up with the following five groups consisting of 25 chips in a green category, 22 chips resembled purple, 17 chips made up the red category, 11 chips could be described as blue, and 9 chips in the orange category (Figure 6.2, right panel). He was unable to name the colour of the formed groups nor could he name an object in the colour of the group, and again he was very insecure and dissatisfied with the result. In sum, MAH was unable to categorise colour on the basis of hue.

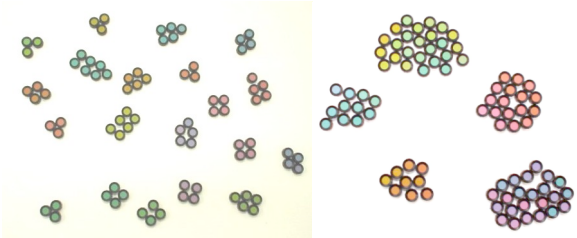


Figure 6.2a+b. Farnsworth-Munsell Free Categorisation (left panel) and Farnsworth-Munsell Forced Categorisation

Discussion

We set out to investigate the colour processing abilities in a man who had been referred to us after he had suffered a stroke in his right cerebellum. A lesion in the vermis in an otherwise normal brain was confirmed on MR. MAH had above average

intellectual capacities and performed within or above the normal range of performance, taken into account both age and education across the domains of language, visual and verbal memory, visual perception and construction, executive functioning and reasoning. His subjective problems with the perception of colours, which he claimed to have had for all of his life, pointed towards colour agnosia, which we defined as an impaired internal colour space. As he claimed to have had this problem all his life and the fact that the cerebellar infarct that he had incurred was in an area far away from the brain structures that are known to be involved in colour processing, we set out to test the hypothesis that he suffers from developmental colour agnosia. MAH was tested on several occasions with standard and experimental tasks to unravel his colour impairments. To start with, MAH is aware of the Newtonian explanation of colour and has a general appreciation of what colours are. Next, we employed a set of visual perception tasks to rule out an explanation in terms of (isolated) primary visual sensory impairments. He demonstrated a normal ability to discriminate between different shapes, texture, brightness, and colours. On the task for brightness perception, he significantly outperformed healthy age-matched comparison subjects. He was also flawless, though extraordinary slow, on colour discrimination as assessed by the FM-100 hue test. This slowness can be explained by an 'over-reliance' on perceptual similarity and the absence of concept-driven strategies in addition to a total lake of self-confidence when it came to a explicit judgement of coloured stimuli, even with simple matching as in the visual sensory assessment tasks. He figured out the odd-one-out, but then it took him a long time to convince himself that this should be the right choice to make and in the end he declared himself often insecure with his answer. Nevertheless, all this taken together show that his visual sensory processing of visual cues, including colour, was preserved. Therefore, MAH does not suffer from central achromatopsia.

Subsequently, we investigated his knowledge of prototypical object-colour relations. His adequate naming of object colours from memory is not characteristic for colour anomia. Problems arose as soon as he had to name colour patches or had to point to coloured patches that matched colour names that were presented to him auditorally. He was unable to do so, and only achieved correct responses via

abnormal, and sometimes very convoluted, idiosyncratic strategies. Moreover, he was unable to discriminate veridically coloured objects from incorrectly coloured objects, despite of his flawless performance in naming the prototypical colour of these same objects in the achromatic condition. He could not imagine colours of familiar objects nor match familiar objects based on colour (e.g. are your curtains at home the same or a different colour as your carpet?). The loss of the conceptual representation of colour was also confirmed by his inability to categorise isoluminant coloured chips. Especially this inability to categorise colours is indicative of an impaired internal colour space. His colour anomia appeared to be a consequence of an impaired internal colour space, and thus of colour agnosia in line with the description of Goldstein (1948 in Roberson et al., 1999). MAH's behaviour on the free categorisation task resembled LEW (Roberson et al., 1999), however, unlike LEW MAH's impairments were restricted to colour and he did show idiosyncratic behaviour. We conclude that the pattern of spared and impaired abilities argue strongly for a diagnosis of colour agnosia. In Table 6.4, MAH's performance is summarised along the dimensions of verbal, verbal-visual, visual-verbal and visual (Grüsser and Landis, 1991;Beauvois and Saillant, 1985). His test performance rules out central achromatopsia and colour anomia, and his inability to identify or categorise colours support the conclusion of colour agnosia (Davidoff, 2001; Roberson et al., 1999; Gerlach et al., 1999). Also impaired imagination of colours is consistent with colour agnosia (Goldenberg, 1992; Bartolomeo, 2002). The idiosyncratic strategies he used together with his extreme slowness on some of the colour perception tasks may result from the fact that – in contrast to patients with acquired colour agnosia – MAH has never been able to recognise and conceptualise colour in the way normal observers do.

The most striking aspect of this case of selective colour agnosia is the developmental nature of the deficit. MAH has had these problems for all of his life and there is no ground for a neurological explanation, either by medical history, birth complication, or imaging. He has learned a number of amazing strategies to compensate for his impairments, which confirm his report of 'having learned to live with it'. He used to draw on his semantic knowledge of the world which appeared to be learned and not so much experience-based when it comes to object-colour

relations, for instance, in the presence of an 'exit sign' in the room, he was able to name all greenish objects in the room simply by matching them to the colour of the sign and his semantic presumption that this should be green. Sometimes he would write down the colours of his clothing in order to use these as points of reference for matching so that he would be able to name colours in his environment when needed. These strategies are cumbersome, time consuming and still often ineffective.

In sum, this is the first report of a case of selective developmental colour agnosia. Obviously, more research is indicated to confirm this observation. It is important that future studies take into account the observation that the mother of MAH apparently experienced the same colour processing problems suggesting a familial basis. Moreover, future findings of additional cases of developmental colour agnosia and a possible familial basis might offer the opportunity to compare the developmental cases to the acquired adult-onset colour agnosia. Possible parallels between both forms of colour agnosia can contribute our understanding of the typical and atypical pathways involved in colour perception and colour representation and the acquisition of object-colour knowledge.

Table 6.4. MAH performance compared to expectations from colour anomia and colour agnosia.0 = flawless; 1 = mildly impaired; 2 = impaired

Tests	Performance MAH	Expectation from Colour agnosia	Colour anomia
Visual			
Ishihara colour plates	0	0	0
Farnsworth-Munsell 100 hue test	0	0	0
Colour matching	0	0	0
Colour Categorisation	2	2	0
Visual-Verbal			
Object: naming colour	2	2	2
Colour: object naming	2	2	1
Naming colour of colour tokens	2	2	2
Verbal-Visual			
Pointing to named colour tokens	2	2	1
Pointing to named objects	0	0	0
Token test	2	2	2
Verbal			
Naming colours from memory	0	0	1
Naming colour for named object	1	1	2
Naming object for named colour	1	1	2

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Chapter 7

Case study: developmental colour agnosia

Familial factor in developmental colour agnosia

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Abstract

An important aspect of research into the link between genes and behaviour concerns the identification of familial determination. There is evidence for familial factors in selective deficits, such as developmental dyslexia and developmental prosopagnosia. Colour agnosia concerns a selective neuropsychological condition in which colour perception is intact, while the identification and naming of colour is disrupted. We recently demonstrated that this deficit can occur as a developmental deficit. Here we show that there is a familial factor in the development of colour agnosia by reporting the colour processing abilities of the mother and the daughters of a man with developmental colour agnosia.

Keywords: colour agnosia, familial factor, colour perception, colour knowledge

Introduction

The last decade has seen a steady increase in the neuropsychological investigation of selective developmental disorders (e.g. de Haan & Tranel, in press). Observations of specific cognitive deficits have been interpreted as additional evidence for cognitive modularity (e.g., Fodor, 1983; Shallice, 1988; Baron-Cohen, 1998; Pinker, 1999), and they might provide the basis for an interface between cognitive function and neurogenetics. An important observation is that these developmental conditions tend to mirror the nature of conditions manifested in adult patients with acquired brain damage (e.g., Temple, 1997). Some notable examples are developmental prosopagnosia (e.g. McConachie, 1976; De Haan, Campbell, 1992; De Haan, 1999; Jones, Tranel, 2001; Kennerknecht, Grueter, Welling, Wentzek, Horst, Edwards, Grueter, 2006) and developmental dyslexia (Brambati, Termine, Ruffino, Danna, Lanzi, Stella, Cappa, 2006; McGrath, Smith and Pennington, 2006).

In this study, we are concerned with colour agnosia. Despite intact colour perception at a visuosensory level, i.e. intact matching of equiluminant colours and intact performance on colour perception tasks like the Farnsworth Munsell 100 hue test, colour agnosics are incapable of accessing colour knowledge. That is, they cannot name colours, match colour-names to colours, categorise hues into general clusters of colour (e.g. different shades of red into one cluster named 'red') or point to colours named by an examiner. It has been suggested that their problems result from an impairment in their internal colour space (Klein, 1953; Bruyer, 1977; Kinsbourne, Warrington, 1964; Beauvois, Saillant, 1985; Grusser, Landis, 1991, Davidoff, 1996). Colour agnosia can be separated from cerebral achromatopsia, a selective colour perception disorder. It can also be dissociated from colour anomia, which refers to a specific problem in naming colours as a result of a lexical impairment (Roberson et al., 1999). Patients with colour anomia are able to point to colours named by an examiner and associations between colours and specific objects are also intact in colour anomia, which is not the case in colour agnosia (Davidoff, 1996).

Although colour agnosia is clinically rare, it has attracted considerable scientific interest. Acquired colour agnosia is usually the result of bilateral occipito-temporal lesions (de Vreese, 1991), but is strongly associated with lesions in the left

temporo-parietal region and is therefore often, but not necessarily associated with aphasia (Stengel et al., 1948; Varney, Digre, 1983). In the first case of its kind to appear in the literature, we reported a man (MAH) with developmental colour agnosia (van Zandvoort, Nijboer and de Haan, in press).

MAH is an academically educated man, who reported severe difficulties in colour naming, despite normal colour perception. The diagnosis of colour agnosia was established on the basis of his inability to reliably name and categorise the hue of standard coloured tokens. Especially the latter finding suggested that MAH has an abnormal internal colour space. In a series of experiments (van Zandvoort, Nijboer, de Haan, 2007), we demonstrated that he could not imagine the colours of familiar objects (e.g. what colour is your car?), discriminate correctly coloured objects from incorrectly coloured objects, nor name or categorise colours. The selectivity of his colour recognition impairment became apparent when he showed no additional problems in the recognition of visual cues, such as shape, motion and position, or higher-order categories, such as objects, faces or text (van Zandvoort, Nijboer, de Haan, in press).

Subsequent studies with MAH have revealed that he continues to process colour information at an implicit level (Nijboer, van Zandvoort, de Haan, 2006); he showed a priming effect of a congruent colour prime on a lexical decision task (e.g. red square prior to tomato/timato). Moreover, in a reversed Stroop interference task (MAH cannot perform the usual Stroop test, as he cannot name colours), he showed normal interference from equiluminant, incongruent ink colour on reading colour names. There are some, not mutually exclusive, explanations. First, the continued implicit processing of colour is degraded to a degree that it can no longer evoke conscious colour awareness. Second, the underlying deficit in colour agnosia could be a failure of access instead of storage or knowledge defect. The precise nature of the colour processing deficit is as yet unclear.

MAH claims to have had these problems all his life and suggested that his mother and eldest daughter (daughter A in this study) experience similar difficulties. These observations argue strongly for a developmental form of colour agnosia. The aim of this study is to explore the possibility of a familial factor in the development of colour agnosia by testing the colour processing abilities of his family members.

Methods

Participants

We were able to interest four direct family members to participate in this study. Apart from MAH, we tested his mother (age 73), and both his daughters (daughter A: 8 years old and daughter B: 7 years old). In addition, we tested three groups of control participants, that were comparable in age to MAH (N = 6, mean age = 39.1 [SD = 2.6], to the mother (N = 6, mean age = 63.8 [SD = 4.8]) and to the daughters (N = 20, mean age = 8.9 [SD = 0.89]). All had normal or corrected-to-normal vision and reported no colour blindness. Reading ability, as measured with the score on the AVI-system (Dutch system of reading ability; score between 1-9) was above average for both daughters (6 for the youngest, and 9 for the eldest daughter).

Procedure and Stimuli

Two standard tests were chosen to measure colour perception: the Ishihara test for colour blindness (1971) and the Farnsworth-Munsell 100 hue (FM 100) test for colour matching (1957). In addition, two experimental tests were included to evaluate the more higher-order processing of colour: first, a colour-naming task and second, an object-colour recognition task. Stimulus presentation and data collection were controlled by a PC. The experiments were programmed using E-prime 1.1. Stimuli were presented on a 15-inch monitor with a vertical refresh rate of 60 Hz. The viewing distance was set at approximately 50 cm.

The colour-naming task consisted of 14 coloured squares (red, blue, green, yellow, orange, pink, brown) that were sequentially presented in a random order, both for 100 and 150 ms on a monitor (28 squares to be named in total). Participants were asked to name the presented colours as accurately and fast as possible. Presentation durations were chosen to prevent MAH, his mother and his eldest daughter from using matching strategies. We know, that in daily life MAH uses strategies to infer the colour of objects, for example comparing the surface properties of a presented object with that of an object he knows (e.g. his shirt). He is very proficient in judging brightness, and uses brightness cues to guess the colour. We first measured whether control participants were able to correctly name the colours presented on the monitor at these durations; with these presentation

durations all age-matched controls were able to perform flawlessly. Accuracy was measured as the dependent variable. As a voice key is not a reliable instrument with young children, no reaction time data were collected.

The second experimental task was an object-colour recognition test and employed 40 line drawings of objects presented in both an appropriate and an inappropriate colour (e.g. red strawberry versus blue strawberry). The line drawings remained on the monitor until a response was given. Participants were asked to indicate as accurately and fast as possible whether the line drawings were depicted in a correct colour or not. They were told to press the 'g' key when a line drawing was correctly coloured (e.g. red strawberry) and the 'f' key when a line drawing was incorrectly coloured (e.g. blue strawberry). They were explicitly told that it was more important to give the correct answer than to be fast.

Both accuracy and reaction times were the dependent variables.

Data analysis

For the FM100 test, total error scores (TES) were calculated. The TES of MAH, his mother, and his daughters were compared to the normal range as given in the manual of the FM100. We calculated percentages correct for the Ishihara test, the colour-naming test, and the object-colour recognition test. The percentages correct for MAH, his mother and daughter A and B were compared to those of the age-matched controls, using Crawford and Garthwaite's test for abnormality scores in single case studies (2002).

Additionally, we analysed the reaction time data of the object-colour recognition test, using again Crawford and Garthwaite's test for abnormality scores in single case studies (2002). One-tailed probabilities are reported.

Table 7.1. Overview of the results of MAH, both his daughters, his mother and the three groups of age-matched controls (AMC). Tests are split by perception (Ishihara, FM 100) and recognition (Naming, Indicating correct colour). Percentages correct are shown for Ishihara, colour naming and indicating correct colour. The total error score (TES) is shown for the Farnsworth-Munsell 100 hue test. Significant differences between MAH, daughter A, the mother and their age-matched controls are printed in bold type.*

	Perception		Recognition	
	Ishihara	FM 100*	Naming	Verification
MAH	100	44	43	45
6 AMC	100	-	100 (SD 0)	100 (SD 0)
Daughter A	100	84	78.6	71.5
Daughter B	100	84	100	100
20 AMC	100	-	97.9 (SD 3.2)	99.7 (SD .48)
Mother	100	44	78.6	79
6 AMC	100	-	100 (SD 0)	100 (SD 0)

Results

Accuracy

The results (see Table 7.1) are clear-cut. All members of the family performed flawlessly on the Ishihara test for colour blindness, as did both groups of age-matched controls. Moreover, performance on the FM 100 test was within normal range for all members of the family.

On the tasks measuring colour knowledge, impairments were apparent for MAH, daughter A and the mother. Their performance is significantly different from their age-matched controls. We found that on the colour naming task, MAH, daughter A and the mother made significantly more errors than their age-matched controls ($t(5) = -105.543$, $p < 0.0001$, $t(19) = -5{,}886$, $p < 0.0001$), and ($t(5) = -39{,}625$, $p < 0.0001$) respectively). The performance on the naming task of daughter B did not differ from the age-matched controls ($t(19) = 0.640$, $p = 0.265$). On the object-colour recognition task, we again found that MAH, daughter A and the mother made significantly more errors than their age-matched controls ($t(5) = -98{,}137$, $p < 0.0001$,

t(19) = -57,334, p < 0.0001), and (t(5) = -38,884, p < 0.0001) respectively), while the performance on the object-colour recognition task of daughter B did not differ from the age-matched controls (t(19) = 0.610, p = 0.275). There was no systematic pattern of errors within and across participants. The object colour recognition impairments of both daughter A and the mother appear to be of intermediate severity compared to MAH and the normal controls. Importantly, MAH as well as his mother and his daughter were perfectly able to name the line-drawings of the objects. Their impaired performance could therefore not have resulted from unfamiliarity with the objects.

Reaction times

Table 7.2 shows the mean reaction times of correct responses of the mother, daughter A and daughter B and their age-matched controls. The errors made by the mother and daughter A were equally distributed between the correctly and incorrectly coloured line drawings (see Table 7.2). As MAH was at chance level at this task, we could not reliably analyse his reaction time data.

We found that the reaction times on correctly and incorrectly coloured line drawings of the mother, daughter A and daughter B were within normal range of their age-matched controls. (p all > 0.192). This means that line drawings of correctly coloured objects were responded to faster than line drawings of incorrectly coloured objects. This suggests that despite the reduced access to colour knowledge, daughter A and MAH's mother still show the normal object-colour matching advantage for correctly coloured objects, but only when they do recognise the colours correctly.

Table 7.2. Overview of the hit rate (HR: respond with 'g' key to correctly coloured objects) and false alarm rate (FAR (respond with 'g' key to incorrectly coloured objects) and the mean reaction times of correct responses of the daughters, the mother and their two groups of age-matched controls.

				Mean Reaction Times (ms)	
	HR	FAR	D prime	Congruent colour	Incongruent colour
MAH	.476	.619	-0.256	n.a.	n.a.
Daughter A	.667	.285	0.707	1090	1295
Daughter B	1	0	2.549*	992	1235
20 AMC	.997	.004	3.818	933	1216
Mother	.809	.238	1.122	944	1098
6 AMC	1	0	2.549*	929	1102

**For HR=1 and FAR=0, a standard correction was used; correction for HR=1: (1 - 1/(2N)), with N=number of targets; FAR=0: (1/(2N)), with N=maximum number of false alarms.*

Discussion

In this study, we presented a family in which a man, his mother and his eldest daughter are poor at object-colour recognition and colour naming. These impairments are not due to visuo-sensory deficits, as they all perform normally on colour perception tasks. In terms of experience and learning, it is important to note that one of the daughters, the youngest, does not have any problems with colour recognition and associations, thereby ruling out the possibility that the daughters did not learn appropriate colour terms or object-colour associations, because their father was not able to teach them.

We have quizzed MAH and his mother regarding birth complications, or childhood trauma, of either of them or the two daughters and there is no suggestion that the colour recognition problems might in fact have been acquired at an early age. MAH and his mother both claim that they have always had these 'problems' with colours. These findings suggest to us that these different family members suffer from developmental colour agnosia. This is the first demonstration of a familial factor in the development of such a higher-order colour impairment.

The fact that three members of one family have the same problems with colour recognition and associations argues for a biologically determined ability for recognising colours. Exactly how colour recognition and associations could be biologically determined is as yet unknown. The suggestion for biological determined colour recognition is strengthened by two lines of evidence. The first is based on experimental studies on colour term acquisition in young children. Although accurate colour naming or successful retrieval of object-colour knowledge is achieved quite late around 3-4 years of age (Davidoff, Mitchell, 1993; Kowalski, Zimiles, 2006; Perlmutter, Myers, 1976), colour perception and discrimination is achieved in pre-linguistic children as young as 4 months of age (Bornstein, Kessen, Weisskopf, 1976; Franklin, Davies, 2004). For the former tasks, the development of the internal colour space with hierarchically clustered focal colours (primaries: red, green, blue, yellow; secondaries: brown, purple, pink, orange) has been found to be important (Davidoff, Mitchell, 1993; Rosch, 1975). Regarding the latter, categorical perception of colour has been found in pre-linguistic children who have not learned colour terms, yet show better discrimination between colour categories (e.g. red, yellow) than within one colour category (e.g. two shades of red), even when the perceptual distances were equal for the between and within categories (Bornstein, Kessen, Weisskopf, 1976; Franklin, Davies, 2004). In the family described here, MAH, the mother and the eldest daughter have some lexical knowledge, as they can come up with a list of colour names, but they have difficulties with choosing the correct colour from this 'list' when having to name a coloured patch. Moreover, they have problems with object-colour associations. These difficulties may result from a poorly developed internal colour space, hampering easy access to colour categories and colour knowledge.

The second line of possible explanations comes from patient studies. Brain lesions resulting in acquired colour agnosia are strongly associated with lesions in the left temporo-parietal region (Stengel et al., 1948; Varney, Digre, 1983). Zeki and Marini (1998) have discerned three broad cortical stages in colour processing: first, V1 and V2 are concerned with registering the presence and intensity of wavelength; second, V4 is concerned with automatic colour constancy operations; third, inferior temporal cortex, anterior parts of the fusiform gyrus, hippocampus, and ventrolateral frontal cortex are concerned with colour-colour relations and object-

colour associations. In support of these cortical stages, neuropsychological studies have indicated that colour processing can be selectively distorted, in disorders such as achromatopsia, colour constancy deficits, and colour agnosia.

Combining the findings of these two lines of possible explanations, it is tempting to suggest that developmental colour agnosia might be a result of impaired development of connections to or from the inferior temporal cortex. It is of obvious interest to further explore the possible genotypical underpinnings of colour agnosia. Yet, given the limited number of relatives, this is not a feasible endeavour at this time. Unfortunately, the family refused participating in further experiments, which leaves open the question of possible inherited defects. However, the results of this study clearly put forward a familial component in these cases of developmental colour agnosia.

In sum, here we report for the first time a familial factor in the development of colour agnosia by showing that the mother and a daughter of a developmental colour agnosic experience problems in the recognition of colours as well.

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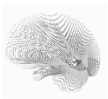

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Chapter 8

Case study: developmental colour agnosia

Implicit access to colour names in a case of colour agnosia

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Abstract

Patients with colour agnosia can perceive colours and are able to match coloured patches on hue, but are unable to identify or categorise colours. It is a rare condition and there is as yet no agreement on the clinical definition or a generally accepted explanation. In line with observations from object agnosia and prosopagnosia, we hypothesised that (some of) these patients might still be able to process colour information at an implicit level. In this study, we investigated this possibility of implicit access to colour semantics and colour names in a man (MAH) who suffers from developmental colour agnosia. We designed two experimental computer tasks: an associative colour priming task with a lexical decision response and a reversed Stroop task. The results of these experiments suggest that there is indeed automatic processing of colour, although MAH was unable to explicitly use colour information.

Keywords: implicit colour knowledge, colour priming, reversed Stroop interference

Introduction

Colour vision is a powerful aid for distinguishing and identifying objects. It enriches subjective visual experience and enables object- and pattern recognition, especially when the object possesses characteristic or 'diagnostic' colours.

The cortical processing of colour fractionates into a number of specific sub-processes, each with their own neuro-anatomical substrates. Humans have the ability to match, classify, name, memorise and imagine colour. Each of these abilities can be lost as a result of brain damage and the occurrence and the co-occurrence of deficits suggest that each may be functionally independent. Neuropsychological studies have demonstrated selective colour impairments, e.g. cerebral achromatopsia (selective impairment in colour perception; e.g. Heywood&Cowey, 1999; Meadows, 1974; for review, see Zeki, 1990), colour agnosia (selective impairment in colour recognition; e.g. Beauvois&Saillant, 1985; Davidoff, 1996), and colour anomia (selective impairment in colour naming; e.g. Davidoff&Ostergaard, 1984; Geschwind&Fusillo, 1966). In this paper we will focus on colour agnosia.

One of the first clinical descriptions of patients with a selective impairment in retrieving the colour of familiar objects was reported by Lewandowsky ((1908); for translation, see Davidoff et al, 1989). This patient could not name or indicate the colour of objects, even when presented with the object name or an uncoloured drawing. He also experienced problems in sorting colours, and naming or pointing to colours that were named by the examiner. Lewandowsky (1908) attributed the dissociation of colour and form to colour anomia, a view shared by Damasio, McKee and Damasio (1979). Colour agnosia is often accompanied by alexia and homonymous hemianopia (Beauvois&Saillant, 1985; Woodward, Dixon, Mullen&Christensen, Bub, 1999). However, others have suggested that colour agnosia can result from a disturbed access to the colour lexicon or to imagery disturbances (Beauvois&Saillant, 1985; de Vreese, 1991). Poor object-colour retrieval with good colour naming is very rare. Beauvois and Saillant (1985) studied two patients with visual, verbal and visuo-verbal tests and differentiated two syndromes: colour agnosia, (specific impairments on the visual tests) and optic aphasia for colours (specific impairments on the visuo-verbal tests). Further dissociations have

been found between poor object-colour retrieval with preserved ability to categorise colours and to name colours (e.g. Beauvois & Saillant, 1985) and without the ability to name colours (Levine, 1978). This shows that knowledge about colour is neither strictly verbal nor visual. The suggestion that colour agnosia may not be a unitary condition has been strengthened by the work of Luzzatti and Davidoff (1994). They reported two patients who could name colours, but could not associate a colour with an object. Moreover, they had no problem with naming fruits and vegetables. The authors argued that these patients suffered from selective impairments in object colour knowledge and that impairment in retrieving object colour knowledge did not necessarily impair naming performance for categories of living objects, such as fruits and vegetables. This latter view was put forward by Warrington and Shallice (1984). Miceli, Fouch and Capasso (2001) reported a patient who had a selective impairment in object colour knowledge, but was able to arrange, recognise and name coloured patches, and had intact knowledge about object form, size and function. These three examples indicate a functional independence between colour knowledge and object colour knowledge.

In summary, patients with colour agnosia can perceive colours and are able to match coloured patches on hue, but are unable to identify or categorise colours. Moreover, they often cannot name or indicate the colour of familiar objects. This inability is not caused by memory or language deficits and these patients have intact conceptual knowledge of objects (Davidoff, 1991). Overall, three conclusions can be drawn: first, colour agnosia is not a unitary disorder; second, there is no agreement on a proper clinical definition; third, there is no generally accepted explanation.

Although patients with colour agnosia do not have explicit access to colour knowledge, it is unclear whether there might be any implicit colour processing. In many neuropsychological disorders, it has become clear that despite the absence of 'acknowledged awareness' preserved information processing can be demonstrated (Schacter, McAndrews&Moscovitch, 1988). Implicit knowledge has been observed in patients with visual field defects ('blindsight': Weiskrantz, Warrington, Sanders&Marshall, 1974; Weiskrantz, Cowey&Barbur, 1999), object agnosia, a disorder in which patients have difficulty perceiving and recognising visual objects (Goodale, Milner, Jakobson&Carey, 1991) and prosopagnosia, the

impaired ability to recognise familiar faces (Bauer, 1984; De Haan, Young&Newcombe, 1991; De Haan, Bauer&Greve, 1992; Tranel, Damasio, 1985). The key element of the distinction between explicit and implicit cognitive processing is the presence or absence of awareness.

Analogous to observations in amnesia and prosopagnosia, we hypothesised that (some of) the colour agnosia patients might still be able to process colour information at an implicit level. In this study, we used two experimental tasks: an associative colour priming task with a lexical decision response and a reversed Stroop task. Priming paradigms are among the most frequently used methods for studying implicit information processing. Priming effects have been observed even in the total absence of recall or recognition. It has been suggested that repetition priming effects depend on changes in the perceptual representation systems that preserve information about the form and structure, but not the meaning and associative properties of words and objects. Associative priming on the other hand, is taken as an effect that is derived from the level of processing where meaning is accessed (e.g. Neely, 1971) This latter task is well suited for studying covert processing. Another useful experimental procedure for studying covert effects is an interference or 'Stroop' task. The classical Stroop effect is demonstrated by asking subjects to name the hue of colour words printed in incongruent ink colour. The Stroop interference effect is a very robust effect and replicable for a variety of stimulus materials and experimental tasks (see MacLeod, 1991, for a comprehensive overview). As patients with colour agnosia have difficulties naming colours, we needed to change the standard Stroop paradigm. In the standard Stroop interference task, hardly any interference is found when participants read a colour name printed in an incongruent colour, so we reduced readability by making the 'ink colour' equiluminant to the background. The observation of a reversed Stroop effect would indicate covert processing of colour not only at the level of access to semantics, as in the associative priming, but also at the level of colour words.

With these two tasks, we are able to test implicit processing at two different levels. The priming tasks measures access to object-colour associations, at the level of structural knowledge of objects and semantics, whereas the Stroop interference task measures access to colour-name associations, at the level of assigning correct

names to colours. It has been argued that category-specific problems may arise from damage to different components of the object recognition system. Some patients have problems accessing stored structural knowledge of objects (e.g. Sartori &Job, 1988), whereas others may have difficulty accessing semantic information about objects (e.g. Hillis &Caramazza, 1991) and still others are unable to access the correct name for objects (e.g. Farah&Wallace, 1992).

Case report

MAH is a 44 year-old male, who came to our attention when he was included in a longitudinal research project on the cognitive sequelea following a stroke. Patient MAH has been reported in detail elsewhere (van Zandvoort, Nijboer & de Haan, in press) and will be briefly summarised here. He had suffered a cerebellar infarct, and the neuropsychological assessment in the acute phase showed mild dizziness and subtle memory deficits. At follow-up, two years later, no cognitive consequences could be detected, and he did not have any residual complaints and fully returned to his pre-morbid occupational life. Overall, the neuropsychological assessment showed that MAH functions at a very high-level of general intelligence with above average performances on memory, language, attention and executive tasks.

However, during the initial neuropsychological assessment, while administrating the Token test for language comprehension, it became apparent that he could not name the coloured tokens. This observation was in stark contrast to his faultless performance on the Ishihara test for colour blindness (1971). His intact colour perception was subsequently confirmed on the Farnsworth-Munsell 100 hue test (1942). The diagnosis of colour agnosia was established on the basis of his inability to reliably name the hue of standard coloured tokens (pencils). In addition, he performed at chance-level on a task where he was required to indicate whether an object was depicted in the veridical or an incongruent colour. Finally, he performed in a very idiosyncratic manner on a task where he was asked to categorise the Farnsworth Munsell tokens (van Zandvoort, Nijboer, de Haan, in press). In stead of the five main categories (red, green, blue, yellow, and orange) that most observers use, he sorted the tokens in a large number of small groups consisting of 3 or 4 tokens. This suggests that MAH has an abnormal internal colour space. He claims that he has always had this problem. In daily life, he uses strategies

to infer the colour of objects, e.g. comparing the surface properties of a presented object, such as its luminance, with that of an object of which he knows the colour (e.g. his shirt). He is very proficient in judging brightness, and he uses brightness cues to guess the colour.

Experiment 1 Colour priming task

Participants

First, thirty students (21-32 years of age, mean age 25 (SD 2.87) were asked to participate in the student control study to demonstrate the expected priming effect. Then MAH and four male age- and level of education-matched subjects (38-48 years of age, mean age 42 (SD 3.74)) participated in this study. All had normal or corrected-to-normal vision and reported no colour blindness, which was confirmed by a normal performance on the Ishihara test for colour blindness.

Apparatus and materials

Data collection and stimulus presentation were controlled by a PC. The experiment was programmed using E-prime 1.1. Stimuli were presented on a 22-inch colour monitor with a vertical refresh rate of 75 Hz. The viewing distance was controlled for by a chin rest and set at 70 centimetres.

Design and Procedure

We designed a colour-word associative priming task with a lexical decision response. A target word could either be preceded by an associated prime (e.g. a red patch followed by tomato versus timato; congruent condition) or a non-associated word (e.g. a red patch followed by grass versus griss; incongruent condition). Only frequently used and concrete words (Loon-Vervoorn, 1991) were used in both the congruent and incongruent condition. Pseudo-words were constructed by changing one phoneme of the existing word. The location of the change was equally distributed across words. Each participant was presented with a list of 140 stimulus pairs (70 correctly written words, (35 congruent pairs, 35 incongruent pairs); 70 incorrectly written words/pseudo-words). Each target word was presented twice, with a congruent and an incongruent prime preceding it.

Therefore, possible priming effects cannot be attributed to stimulus characteristics.

The participants were tested individually in a quiet, darkened room. A trial started with a fixation cross (38 frames, resulting in 507 ms), followed by a prime, a coloured solid square (red, blue, green, yellow, pink, orange, or brown) presented centrally on a grey background for 38 frames, resulting in 507 ms. Subsequently, the target word appeared centrally on the same background. The target remained on the screen until the participant responded, with a maximum duration of 150 frames, resulting in 2000 ms.

Participants were instructed to decide, as quickly and accurately as possible, whether the target word was a Dutch word by pressing the 'g' key for an existing word and the 'f' key for a non-existing word on the computer keyboard with respectively the index or middle finger of the dominant hand. The task was self-paced and each word was presented until the participant gave a response. The participants' responses and reaction times were recorded. Only responses to the correctly written words were included in the analyses. Reaction times shorter than 150 ms were interpreted as anticipatory responses and were excluded per participant. Reaction times longer than two SD above mean per participant were also excluded, as they were interpreted as outliers.

Results

Overall, less than 2% of the data was excluded from the analyses, for either being an incorrect response or an outlier.

First, we performed a Repeated Measures Analysis on the reaction times of correct responses of the student controls. Significant effects of congruence were revealed for the student controls ($F(1,29) = 13.66$, $p < .001$); reaction times on the congruent colour-word pairs were significantly faster compared to the incongruent colour-word pairs. The experiment revealed a priming effect of 32 ms (see Figure 8.1a).

Second, we performed a Repeated Measures Analysis on the reaction times of correct responses of the age-matched controls and MAH. There was a significant main effect of congruence for both age-matched controls and MAH ($F(1,4) = 35.88$, $p <.005$): reaction times on the congruent colour-word pairs were significantly faster compared to the incongruent colour-word pairs. There was no difference between

the age-matched controls and MAH ($F(1,4) = .80$, $p > .400$). The experiment revealed a priming effect of 49 ms for the four age-matched controls and a priming effect of 52 ms for MAH (see Figure 8.1b). There was no significant interaction between congruence and group; the effect of congruence was the same for the age-matched controls and MAH.

Third, we compared the two control groups (students and age-matched controls). There was no difference between the two groups on the effect of congruence (Bonferroni correction, $p = .840$).

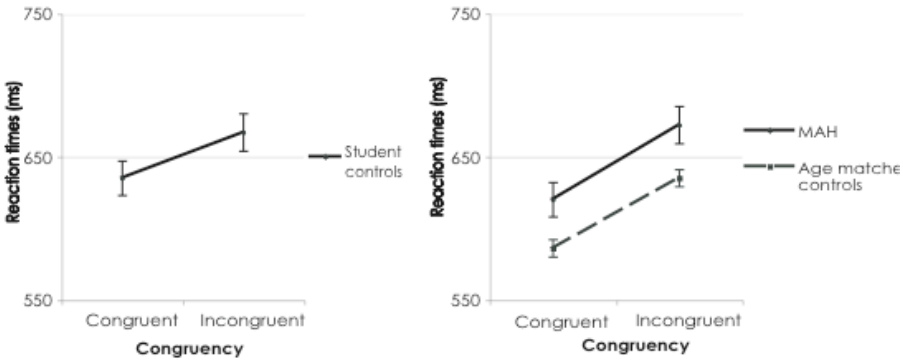

Figure 8.1a&b. The mean reaction times and standard errors of the mean for the congruent and incongruent condition, for both MAH and the control subjects.

Immediately after testing, MAH was again presented with the coloured squares used as primes. He was asked to name the colour of the squares and to come up with a few names of objects that had that specific colour. He was not able to name any of the colours of the squares, but he tried to match them to the colour of his clothes. After being told what specific colour the squares had, he was not able to name objects with that colour easily, even though he had just seen them in the experiment.

Experiment 2 Reversed Stroop colour-word task

We needed to change the standard Stroop interference task to be able to measure colour-word interference, as MAH is not able to name colours. In the standard Stroop interference task, hardly any interference is found when participants read a word printed in an incongruent colour. Apart from short-lived practising effects (Stroop, 1935), a small reversed Stroop interference effect has been observed by reducing the readability of the words by partial obliteration (Gumerik, Glass, 1970; Dyer, Severance, 1972). Making the 'ink' colour equiluminant to the background has two advantages. First, readability will decrease under equiluminance. The bulk of studies looking at the readability of text as a function of foreground-background colour combinations report that, regardless of the colour combinations used, higher-levels of luminance contrast appear to lead to better readability (Radl, 1980; Bruce, Foster, 1982; Small, 1982; Legge, Rubin, 1986). Second, this ascertains that there is only colour information in the stimuli presented. This is important, as MAH uses brightness cues to guess the colour, as he has learned that certain colours, such as yellow or pink are brighter than other colours, such as blue or red. He explicitly states, when asked to name the colour of a square: "It is bright, so probably will be a bright colour. Maybe it is yellow or very light green. I do not know. It is bright." To rule out the possibility, that he does use luminance to guess the ink colour, we made all ink colours equiluminant to the background.

Participants

Twelve students (24-30 years of age, mean age 26 (SD 1.92) and the same four age-matched control subjects were used in this experiment. Each participated in a single session lasting approximately 30 minutes. All had normal or corrected-to-normal vision and reported no colour blindness, which was confirmed by a normal performance on the Ishihara test for colour blindness.

Apparatus and materials

A flicker photometry procedure was programmed using Matlab 6.5 and the Psychophysics Toolbox for Windows (Brainard, 1997). This procedure was used to set red, green and blue equiluminant to the background for each participant. The Stroop experiment was programmed using E-prime 1.1. Stimuli were presented on

the same 22-inch colour monitor using a vertical refresh rate of 60 Hz. The viewing distance was 70 centimetres.

Each participant was presented with a list of 108 stimuli (36 congruent colour-words, in which the ink colour was congruent with the colour word, e.g. word 'red' printed in red; 36 incongruent colour-words, in which the ink colour was not congruent with the colour word, e.g. word 'red' printed in blue or green; 36 neutral colour-words, in which the ink colour was not related to the word, e.g. word 'rich' printed in red (12), green (12), or blue (12)). The neutral words ("rijk" (rich), "droog" (dry), "breed" (wide)) were chosen on the basis of the number of letters and word frequency in Dutch (Loon-Vervoorn, 1991), to match the colour words ("rood" (red), "groen" (green), "blauw' (blue)). Two lists, in which the order of the words was altered in a pseudo-random fashion, were made to balance sequence effects. There were two conditions: one in which the ink colour of the words was equiluminant to the background (equiluminant condition) and one in which the background was black (baseline condition). The ink colour of the words was the same in both conditions, so only the background changed.

Design and Procedure

First, participants had to carry out the flicker photometry procedure. They were allowed to practice until they were accustomed to changing the colours by moving the mouse from left to right or vice versa. This was done for all three colours, red, blue, and green.

Participants were asked to read the words presented on the screen as fast and accurately as possible. A trial started with a colour word appearing on the screen and was ended via a voice-key switch when the participant gave a verbal response. After a pause of 32 frames, resulting in 533 ms, the next word was presented on the screen. Half of the participants started with the equiluminant condition and the other half of the participants with the baseline condition.

The participants' responses and reaction times were recorded. Reaction times shorter than 150 ms were excluded for they were interpreted as anticipatory responses. All reaction times associated with incorrect responses were excluded from analyses. Any reaction time that was more than ± 2 standard deviations from

the subject's mean in any given condition was excluded, as they were considered outliers.

Results

For the baseline reading task, less than 1% of the data was excluded from the analyses, for being an incorrect response or an outlier. For the equiluminant reading task, 1.4% of the data was excluded from the analyses for being an incorrect response or an outlier.

First, we performed a Repeated Measures Analysis of Variance on the reaction times of correct responses of the student controls. A significant effect of condition was revealed for the student controls ($F(1,11) = 71.42$, $p<.001$), showing that reaction times were significantly faster for the baseline condition compared to the equiluminant condition. There was a significant effect of congruence ($F(2,22) = 42.57$, $P<.001$), showing that congruence influenced reaction times. Posthoc tests with Bonferroni correction revealed that congruent colour word-pairs were significantly faster than both the incongruent ($p<.001$) and neutral colour-word pairs ($p<.02$) and that the neutral colour-word pairs were significantly faster than the incongruent colour-word pairs ($p<.001$) (see Figure 8.2a) There was also a significant interaction ($F(2,22) = 19.52$, $p<.001$); the congruence effect was far more pronounced in the equiluminant condition than in the baseline condition.

Second, we performed a Repeated Measure Analysis of Variance on the reaction times of correct responses of the age-matched controls and MAH. There was no difference between the age-matched controls and MAH ($F(1,4) = 4.11$, $p > .100$). A significant effect of condition was revealed for both the age-matched controls and MAH ($F(1,4) = 90.14$, $p<.001$), showing that reaction times were significantly faster for the baseline condition compared to the equiluminant condition. There was no significant interaction between condition and group; the effect of condition was the same for the age-matched controls and MAH. There was a significant effect of congruence ($F(2,8) = 14.29$, $P<.005$), showing that congruency facilitated verbal responses. There was no significant interaction between congruence and group; the effect of congruence was the same for the age-matched controls and MAH. Posthoc tests with Bonferroni correction revealed that responses to congruent colour word-pairs were significantly faster than to the

incongruent (p<.050), but not to the neutral colour word pairs. Reaction times on the neutral colour word pairs were not different from the incongruent colour word pairs (see Figure 8.2b). There was also a significant interaction (F(2,8) = 5.65, p<.005); the congruence effect was far more pronounced in the equiluminant condition than in the baseline condition. There was no significant interaction between condition, congruence and group; the interaction between condition and congruence was the same for the age-matched controls and MAH.

Third, we compared the two control groups (students and age-matched controls). There was no significant difference between the baseline and the equiluminant condition in the two groups (Bonferroni correction, p = .117), and there was no significant difference between the two groups on the effect of congruency (Bonferroni correction, p = .200). There was also no significant interaction between condition and congruency and the two groups (Bonferroni correction, p = .697).

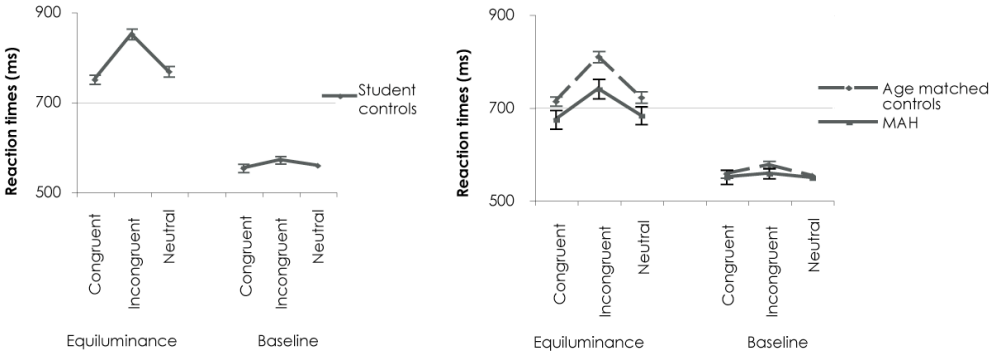

Figure 8.2a&b. The mean reaction times and standard errors of the mean for the congruent, incongruent, and neutral words per condition, for both MAH and the controls.

General discussion

Patients with colour agnosia suffer from an inability to recognise or categorise colours, while they can perceive colours and are able to match coloured patches on hue. All the affected functions are routinely evaluated with explicit tasks. We hypothesised that some colour agnosics might continue to process colour information implicitly, despite the absence of explicit recognition. We investigated whether MAH, who suffers from developmental colour agnosia, demonstrates signs

of implicit processing of colours. We assessed this with an associative priming task and a reversed Stroop interference task.

Results indicated that MAH shows facilitation from congruent colours in the priming task at about the same level as demonstrated in age-matched control subjects. It seems that there is indeed automatic processing of colour, although MAH was unable to explicitly use any colour information. This is a striking dissociation between his preserved ability to access information about colour associations in implicit tests and his severe problem in accessing such information in explicit tests. In an immediate post-test, he could not name any of the colour primes and he was unable to give any examples of objects with a particular colour, even though he had just been confronted with many names of objects with a specific diagnostic colour. In the reversed Stroop interference task, MAH showed an interference effect that was comparable to the interference effect of the age-matched controls. This suggests that he also has implicit access to colour-name associations. Together these findings suggest that although MAH is not able to use colour information in any explicit recognition or recall tasks, he has preserved covert access to both colour-names as well as semantic associations with colour.

It seems reasonable to suggest that the underlying problem in some cases of colour agnosia is a failure of access and not a storage or knowledge defect, as the information is demonstrably still there. MAH cannot identify or categorise colours explicitly, but he shows a normal pattern of performance in tasks that test recognition implicitly. Young, Hellawell and De Haan (1988) argued that in prosopagnosia the operation of intact face recognition mechanisms can become isolated from other parts of the cognitive system. They proposed a disconnection model describing the functional components involved in face and name recognition. Category-specific problems may arise from damage to different components of object recognition. In the case of colour agnosia, these problems may reflect impairments in accessing structural knowledge about colour. This refers to knowledge about colours in the real world, such as the way coloured surfaces change due to illuminant changes (as in colour constancy) or information about object-colour associations. With our experiment, we measured both levels and MAH seems to have implicit access to both levels, as he shows both a reversed Stroop interference effect and an associative priming effect.

Next to the disconnection model, there are at least two other models that could explain our results. First, there is the 'interactive activation and competition' (IAC) model proposed by Burton, Bruce and Johnston (1990). In the IAC model of face recognition, all links are equally strong and bi-directional with global decay to eliminate activation over time in absence of input. Covert recognition can be captured by the IAC model, in which the links between the 'object' recognition units and the identification nodes are attenuated, but not deleted. This attenuation means that presentation leads to activation in the identification nodes that are below recognition threshold, but enough to be passed on to associated semantic information units and recognition units and back, leading to priming. Because the activation in the identification nodes is below recognition threshold, there is no explicit knowledge available.

Second, there is the multiple memory system (MMS) approach that states that different brain systems support explicit and implicit memory, perhaps by providing two distinct storage locations or two distinct retrieval routes to a common storage location (e.g. Johnson, 1983; Tulving, 1972; Warrington&Weiskrantz 1982). The focus of dichotomous distinctions was between implicit and explicit (Graf&Schacter, 1985) or procedural and declarative memory (Squire&Knowlton, 1996). Dissociations between implicit and explicit memory systems have been found in healthy participants and patients, e.g. amnesic patients performing poorly on explicit tests of recall or recognition, but at normal levels on implicit partial information tests (Warrington&Weiskrantz, 1970). This suggests that explicit knowledge depends on memory mechanisms that are different and independent of the memory mechanisms for implicit knowledge. Moreover, it suggests that one of the memory systems can be selectively disrupted, resulting in very selective knowledge retrieval deficits.

All above-mentioned theories can explain the covert processing we found in colour agnosia in absence of any explicit knowledge. We feel that it is important to present our data within a more general theoretical context.

It seems that colour agnosia can be added to the list of neuropsychological disorders in which covert processing may be demonstrated. Preserved processing in the context of impaired explicit knowledge has also been found for other colour

deficits, such as achromatopsia (e.g. Rizzo, Smith, Pokorny&Damasio, 1993; (Heywood, Cowey&Newcombe, 1991; Cavanagh, Henaff, Michel&Landis, 1994). These results indicate that there is a wide range of implicit processing of chromatic information, from a low perceptual level to a high associations level. This study certainly adds to the growing evidence of multiple neural pathways and different neuro-anatomical areas involved in colour processing.

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Chapter 9

Case study: developmental colour agnosia

Mental colour imagery in colour agnosia

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Submitted

Abstract

Mental imagery abilities were investigated in MAH, a man with developmental colour agnosia. Judgements of similarity with respect to colour, shape, or weight were required for line drawings of objects as well as object names (words). Our results show that the performance of MAH on shape and weight perception and imagery is comparable to the performance of the control participants, both for accuracy and reaction times. The consistent pattern of results concerning spared (weight and shape) and impaired (colour) functioning in recognition as well as imagery suggests that his colour agnosia occurs at the level of stored colour representations. The observation that he demonstrates covert colour processing (Nijboer et al, 2006) indicates that the functional locus of his recognition deficits may be best conceptualised as an access problem to the internal colour space.

Keywords: colour agnosia, mental imagery, verbal object-colour knowledge

Introduction

Neuropsychological studies of colour processing have discerned several types of deficits. The most important deficits in this realm are achromatopsia (i.e. inability to see colour), colour agnosia (i.e. inability to recognise colour) and colour anomia (i.e. inability to name colours). This study deals with colour agnosia. Patients with colour agnosia are impaired in categorising and recognising colours despite intact colour perception (Davidoff, 1991; Lewandowsky, 1908; van Zandvoort, Nijboer, de Haan, 2007). Spared visuo-sensory processing may be demonstrated on colour tasks like the Ishihara test for colour blindness (1971) and the Farnsworth Munsell 100 hue test (1942). In contrast to achromatopsic patients, they report that they 'see' colours, but this subjective experience is clearly abnormal, as knowledge about colour categories and labels (names) is apparently unavailable (Beauvois, Sallaint, 1985; Davidoff, 1991). In addition, these patients suffer from an inability to retrieve object-colour relationships, other than those that are common semantic information (e.g. grass is green and bananas are yellow).

The functional locus of colour agnosia remains controversial. For instance, Davidoff (1991) has argued that colour recognition is dependent on retrieval of the appropriate visual semantics and the category label. Others, (e.g. Franklin, Davies, 2004; Franklin, Clifford, Williamson, Davies, 2005) suggested that colour categorisation precedes access to names. In related areas, such as face recognition, the evaluation of mental imagery has helped to delineate the functional locus of the recognition impairment. Young, Humphreys, Riddoch, Hellawell, de Haan (1994) showed that a prosopagnosic patient with a more perceptual deficit could still imagine familiar faces, while a patient with a higher-order impairment, probably involving the stored representations of familiar faces, could not.

Mental imagery is the process by which stored knowledge is used to create an internal temporary, percept-like image. Neuropsychological studies have shown both associations and dissociations between visual mental imagery and visual perception (Goldenberg, 1992). Specific deficits in visual perception are often accompanied by deficits in visual imagery, and as a result, it has long been thought that the processes underlying visual perception and visual imagery have a common

basis (e.g. Kosslyn, 1994; Farah, 1984). However, cases have also been described in which dissociations are found between visual perception and visual imagery. For example, Bartolomeo et al (1997, 1998) have reported a patient with impaired colour perception with intact colour imagery, whereas the opposite, impaired colour imagery with intact colour perception has also been described (Goldenberg, 1993). Bartolomeo et al (1997) suggested that colour perception and colour imagery take place in separate, but proximate cortical visual areas. In the case of acquired brain damage, it is likely that the lesion occupies both areas.

The aim of the current study was to investigate mental imagery for colours in a man with colour agnosia. This man suffers from developmental colour agnosia, and has been reported in detail elsewhere (Nijboer, van Zandvoort, de Haan, 2006; Nijboer, van der Smagt, van Zandvoort, de Haan, 2007; van Zandvoort, Nijboer, de Haan, 2007). Although the neuro-anatomical basis of his deficit cannot be traced, he is a particularly interesting case, given the relatively selective nature of his impairment.

Method

Participants

MAH, a man with developmental colour agnosia (44 years of age) and 24 control participants (mean age 33.5 years [SD 3.1]) participated in this study. All had normal or corrected to normal vision and reported no colour blindness, which was confirmed with the Ishihara test for colour blindness (1971). On neuropsychological screening, MAH performed at a very high-level of general intelligence with above average performances on memory, language, attention, and executive functions. He was, however, unable to name colour adequately, indicate whether objects were correctly coloured or categorise Farnsworth-Munsell tokens into five main categories. His colour perception, as measured with the Ishihara (1971) and Farnsworth-Munsell 100 hue test (1942) was intact.

Stimuli

Two tasks were designed to investigate imagery in colour agnosia; first, a 'mental hue comparison task' (de Vreese, 1991); and second, an 'odd-one-out task'. In the mental hue comparison task, the names of common objects that are associated

with a specific colour are presented verbally and participants were asked to indicate the one object with the most prototypical colour (e.g. mustard or a daffodil for 'yellow'). We made sure that none of the objects have either a different meaning in language (e.g. 'red' eyes) or are frequently used to indicate a specific hue (e.g. blood red). Moreover, none of these objects had a colour that was common verbal knowledge. MAH knows these frequently used associations, but the limit of his object colour knowledge is unknown.

In the odd-one-out task, 3 stimuli were presented, either object names or line drawings of objects. Stimuli were selected from the extensive set of Snodgrass and Vanderwart line drawings (1980) and presented on a grey background, using Eprime software. Three types of comparisons could be made: colour, shape, or weight. For the colour comparisons, two of the three line drawings were objects that normally have a comparable (diagnostic) colour, whereas the third has a different colour (e.g. lemon, banana, cucumber). The same holds for the shape comparisons (e.g. wheel, ball, ruler) and the weight comparisons (e.g. bed, couch, chair). All line drawings were presented in black-and-white. Per task, 16 stimulus sets were presented (with 4 practise trials before the start of each task).

Procedure

For the 'mental hue comparisons test', the experimenter read out loud the names of two objects. Subsequently, participants were instructed to choose from the two options the object that, in real life, has a colour that is closest to the prototypical hue within that colour category.

The method of presentation for odd-one-out task was as follows: three stimuli (images or words) were presented on a monitor (21 inch, 75 Hz, 1024x768) in a horizontal alignment. The participants were asked to indicate which of the three stimuli was the odd-one-out with respect to either the colour, shape, or weight of the presented set of stimuli, by visualising the objects in their appropriate colour, shape, or weight/size and compare which of the two were more similar. Stimuli were presented in blocks and participants were told in advance which comparisons were to be made (colour, shape, or weight). Line drawings or words remained on the

monitor, until a response was given. Responses were made manually by pressing one of three corresponding keys on the keyboard.
All blocks were randomised over the control participants to balance for sequence effects. Within the blocks, the stimulus sets and the order within the set of three stimuli (left, middle, right) were also randomised. The duration of the experiment was approximately 30 minutes per participant.

Data analyses
For the mental hue comparisons test, responses of MAH were compared to the mean percentages correct per comparison. For the odd-one-out task, accuracy and reaction times were recorded. Percentages correct and reaction times to correct responses were included in the data analyses. Median reaction times were calculated per participants and Repeated Measures Analysis of Variance was used for the analysis of the control participants. MAH's data were analysed using Crawford and Garthwaite's test for abnormality scores in single case studies (2002).

Results
MAH was unable to mentally compare the hues in the mental hue comparison test, as he did not know the colour of most of the objects. Table 1 gives an overview of the responses of MAH and the control participants. As can be seen in Table 9.1, the controls participants responded consistently on the mental comparisons. MAH, however, was unable to answer the questions, as he did not know the colour of the objects and as a result could not make the comparisons.

Table 9.1. Performance of MAH and the control participants on the mental hue comparison task.

Comparison	Control participants	MAH's response
pear-billiard	100% billiard	do not know the colour of billiard cloth
tennis court-life jacket	100% life jacket	do not know the colours
Nivea box-sky	92 % Nivea box	do not know the colour of a Nivea box
mustard-daffodil	96% daffodil	do not know the colour of mustard
poppy-cherry	92% poppy	do not know the colour of a poppy

The results of the odd-one-out task are also clear-cut (see Table 9.2). Overall, the control participants scored above 95.3% correct on all tasks. There was no

difference in accuracy scores of the control participants between the different tasks. MAH's accuracy score on the colour imagery tasks was 58.3%, whereas he was flawless on the shape and weight imagery tasks. When comparing the accuracy scores of MAH to those of the control participants, it is immediately clear that accuracy on the shape and weight comparisons, for both words and images, are within the range of the control participants. The accuracy of MAH on the colour comparisons, however, is significantly lower both for words and images compared to the control participants ((t(19) = -11.06, p < .001) and (t(19) = -41.96, p < .001) respectively).

Table 9.2. Performance of MAH and the control participants (accuracy and reaction times (ms)) for the different comparisons, split on presentation format.

		Colour words	Colour images	Shape words	Shape images	Weight words	Weight images
MAH	accuracy (%)	62.5*	56.3*	100	100	100	100
MAH	reaction times (ms)	7696	13359	3499	2166	2654	2001
Controls	accuracy (%)	96.9	99.7	99.7	100	95.3	95.3
Controls	reaction times (ms)	3250	2780	3320	2301	3005	2383

***** *Performance of MAH is significantly different from that of the control participants (p < .001).*

Control participants performed equally fast on the three tasks. There was, however, a significant difference of presentation format (F(1,19) = 26.166, p <. 05), with shorter reaction times for the images than for the words. There was also a significant interaction between task and format (F(2,38) = 21.50, p <.05), with significantly shorter reaction times for the shape and weight comparisons when stimuli were presented as images ((t(19) = 7.61, p <.05) and (t(19) = 4.59, p <.05), respectively), while there was no difference between formats for the colour comparisons.

For MAH, reaction times on the shape and weight comparisons, for both words and images, were within the range of the control participants. His reaction times on the colour comparisons, however, are much longer. Note, that the reaction times are the medians of only the correct responses, and thus only approximately half of the trials for MAH. As there was no difference in median reaction times between the correct and incorrect responses, the reaction times of the correct

responses were considered highly unreliable and were not statistically compared to those of the control participants.

Discussion

In this study, we investigated whether colour imagery is impaired in a man with developmental colour agnosia. His recognition impairment has been shown to be very selective and the processing of other visual cues is spared. We report the following findings.

First, mental hue comparisons were almost impossible for MAH, as he did not know the colour of many of the objects. The objects in this test were chosen in such a way that their colour was no common verbal knowledge. In earlier studies, we reported that MAH is able to give the colour of some objects, such as grass or a banana and we surmised that this knowledge is based on the frequency with which these colour-object relationships appear in spoken and written language.

Second, our results show that the performance of MAH on shape and weight imagery is comparable to the performance of the control participants, both for accuracy and reaction times. His performance on the colour comparisons, however, is clearly defective, both with respect to accuracy and reaction times.

Imagery impairments have also been found in visual agnosic patients, who generally do not have problems with perception, but are impaired in recognising for example objects or faces visually (Barton, Cherkasova, 2003; Mehta, Newcombe, de Haan, 1992). Imagery and recognition impairments may co-occur in a particular domain. Mehta and Newcombe (1996) pointed out that a patient with a higher-order reading disorder could not image words, but was able to image objects, while the reverse pattern of spared and impaired imaging abilities was observed in an object agnosic patient. This consistent specificity of impairment in imagery and perception is also apparent in MAH who was perfectly able to make mental comparisons on the shape and weight tasks, but was selectively impaired on the colour task. Thus, MAH is unable to recognise colours and cannot imagine colours. This strongly suggests that the functional deficit (i.e. colour agnosia) occurs at the level of stored representations (Young, Humphreys, Riddoch, Hellawell, de Haan, 1994). These imagery and recognition impairments might be the result of a problem in the 'internal colour space' (Davidoff, 1991), which is the 'memory palette' from

which colour categorisation proceeds. This internal colour space might be used for colour imagery as well as comparing and categorising 'real' colours.

The nature of the deficit of MAH may be qualified in terms of storage versus access problems. Young et al (1994) reported two patients with prosopagnosia, one patient (PH) with good perception and impaired imagery, who also showed covert recognition, and another patient (HJA) with impaired perception and good imagery, who did not show covert recognition. It is suggested (Shallice, 1988) that covert recognition is a marker for an access deficit, because covert ability implies that the patient still possess the information, be it at an implicit level. Our earlier results of covert access to colour names and colour associations in MAH (Nijboer, van Zandvoort, de Haan, 2006), combined with our present results of impaired imagery suggest that the functional locus of colour agnosia lies in the 'access to stored representation'.

In conclusion, we showed that a man with developmental colour agnosia was unable to carry out mental imagery tasks with colour. This deficit was selective for colour, as shape and weight imagery was preserved. The selective nature of his imagery deficit is mirrored by his recognition impairment, which was also restricted to colours. Based on our earlier observation of covert colour recognition, we postulate that he suffers from a selective access impairment to stored colour information.

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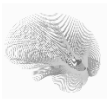

Chapter 10

Case study: developmental colour agnosia

Colour agnosia impairs the recognition of natural but not non-natural scenes

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Abstract

Scene recognition can be enhanced by appropriate colour information, yet the level of visual processing at which colour exerts its effects is still unclear. It has been suggested that colour supports low-level sensory processing, while others have claimed that colour information aids semantic categorisation and recognition of objects and scenes. We investigated the effect of colour on scene recognition in a case of colour agnosia, MAH. In a scene identification task, participants had to name images of natural or non-natural scenes in six different formats. Irrespective of scene format, MAH was much slower on the natural than on the non-natural scenes. As expected, neither MAH nor control participants showed any difference in performance for the non-natural scenes. However, for the natural scenes, appropriate colour facilitated scene recognition in control participants (i.e. shorter reaction times), whereas MAH's performance did not differ across formats. Our data thus support the hypothesis that the effect of colour occurs at the level of learned associations.

Keywords: colour knowledge, scene recognition, colour diagnosticity

Introduction

What is the function of colour vision? Subjectively, colour greatly enriches visual experience, but more importantly, colour plays an important role in pattern detection and object recognition, as colour is a very prominent property of objects. As a result, knowledge of object colour might help to recognise objects better, along with luminance boundaries, shading, texture and contours (e.g. Livingstone, Hubel, 1987).

Colour information has been shown to improve object recognition. Coloured images of objects are recognised faster than achromatic images of the same objects (Ostergaard, Davidoff, 1985; Biederman, Ju, 1988[5]), but this only holds for certain types of objects (Humphrey, Goodale, Jakobson, Servos, 1994; Tanaka, Presnell, 1999), namely objects that are usually strongly associated with a specific colour, i.e. for which the colour is 'diagnostic' (Tanaka, Presnell, 1999). Interestingly, colour has no influence on object verification (Biederman, Ju, 1988; Ostergaard, Davidoff, 1985). Apparently, appropriate colour facilitates finding the correct name of an object in memory, whereas it does not influence the comparison of a given name with a shown object. Ostergaard and Davidoff (1985) suggested that objects are listed in semantic representation as a collection of physical attributes. One of these attributes is specific colour information. They claim that colour, being an attribute in the lexicon, makes it possible to prime linked object names in the same lexicon. This explains why colour facilitates object naming, but not object verification.

Recognition of objects high in colour diagnosticity (usually natural objects) is more affected by colour manipulations (e.g. incongruently coloured images) than recognition of objects low in colour diagnosticity (usually non-natural, man-made objects) (Joseph, Proffitt, 1996; Price, Humphreys, 1989). When colour is not informative, object recognition appears to be based on other cues, such as shape and texture cues (Oliva, Schyns, 1997; Tanaka, Presnell, 1999).

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[5] Note however, that Biederman and Ju (1988) also showed that using a mask eliminated this facilitatory effect of colour.

Neuropsychological studies have shown that some brain-injured patients with impaired object recognition abilities demonstrate improved performance when identifying coloured images of objects compared to incongruently coloured or achromatic images (Humphrey et al., 1994; Mapelli, Behrmann, 1997). Humphrey et al. (1994) showed that colour facilitated object recognition in DF, a patient with visual form agnosia. This patient has a profound deficit in object recognition on the basis of shape, size and orientation, but a relatively spared ability to recognise objects on the basis of colour and texture (Milner, Perrett, Johnston, Benson, Jordan, Heeley, Bettuci, Mortara, Mutani, Terassi, Davidson, 1991; Milner, Heywood, 1989; Humphrey, Goodale, Jakobson, Servos, 1994). Colour specifically improved recognition of natural objects for both DF and control participants. From the studies mentioned above, it can be concluded that appropriate colour facilitates the recognition of the objects high in colour diagnosticity, whereas these objects are recognised more slowly and less accurately when inappropriately coloured.

Results found in object recognition studies can be extended to recognition of more complex stimuli, like scenes (Oliva, Schyns, 1997; Steeves, Humphrey, Culham, Menon, Milner, Goodale, 2004). A scene is usually defined as a semantically coherent, nameable view of an environment, composed of multiple discrete objects. In natural scenes (e.g. canyon, seashore, forest, desert), there is a more consistent colour pattern that serves as a recognition cue than in non-natural scenes (e.g. city, road, shop, room). Again, scenes high in colour diagnosticity (natural scenes) are more affected by colour manipulations than scenes low in colour diagnosticity (non-natural scenes; Oliva, Schyns, 1997; Steeves et al., 2004). Moreover, Steeves et al. (2004) showed that the form agnosic patient DF used colour information to categorise scenes.

It is still under debate at which level in the visual pathway the beneficial effects of colour for recognising natural scenes and objects occurs. Cases have been made for lower, sensory levels (e.g. Wurm et al., 1993) as well as for higher, cognitive processing stages (e.g. Humphrey et al., 1994). As mentioned above, Humphrey et al. (1994) concluded that colour facilitates naming of natural objects when they are presented in their diagnostic colour. Moreover, they concluded that this facilitation

occurs at a high (-er) level of visual analysis, where knowledge of object properties, such as colour, is stored.

In contrast, Wurm et al. (1993) concluded that for recognising objects, colour information plays a role at a sensory level. They investigated the role of colour in object recognition from the perspective that colour differences, like luminance differences, may provide reliable information for scene segmentation. For ecological reasons, they used images of food throughout their experiments. Their hypothesis was that colour may be particularly useful, when either the stimulus or the sensory processing is degraded, as in the case of low-pass filtered images, or low-vision, respectively. In their first two experiments, they showed that colour speeds up object recognition about equally for normal and degraded vision (for both low-pass filtered images and low-vision). To investigate the origin of the effect of colour, they carried out two more experiments. They presented participants with images of a same object from different perspectives, i.e. the prototypical view and three views that deviated systematically from the prototypical view. The results demonstrated that the effect of colour increases when images deviate more from the prototypical view. Wurm et al. (1993) suggested that non-prototypical views of objects are more difficult to recognise, and therefore benefit more from colour, because recognition is then "more dependent on surface characteristics". Their final experiment was directly aimed at the question whether explicit object-colour knowledge plays an additional role in the advantage of colour in object recognition. Wurm et al. (1993) used information theory to calculate the informational value of participants' colour knowledge for a fixed set of food items, based on ratings from the same participants to what degree colour would be helpful for recognition. The algorithm showed that the recognition of, for example, a lemon or a carrot, would benefit more from colour information, than, for example, an apple or a pepper. Subsequently, Wurm et al. (1993) observed that this object characteristic, which they termed "colour diagnosticity", did not correlate with the colour advantage found in the algorithm. They argued that explicit knowledge about food colour does not account for the advantage of colour in real-time object recognition. Their overall conclusion was that the primary role of colour in object recognition is sensory in nature.

In the present study, we have the unique opportunity to further investigate the suggested low-level sensory colour processing versus the higher cognitive level of colour processing by examining the role of colour information in scene recognition in a patient with colour agnosia. Patients with colour agnosia have intact colour perception, as demonstrated by normal performance on for instance hue-matching tasks, but have no explicit colour knowledge (e.g. Nijboer, van Zandvoort, de Haan, 2006). If scene recognition is improved by specific knowledge about which colours are appropriate for specific scenes, then we would expect to find a reduced effect of colour on scene recognition in patients with colour agnosia. If instead, the colour diagnosticity effect is derived from low-level processes, agnosic patients should, similarly to control participants, benefit from appropriate colour information. In other words, by using a scene recognition task with a colour agnosic patient, we can distinguish between the above mentioned higher and lower level explanations of the effect of colour in visual recognition.

Case study

MAH is a 44 year-old male, who came to our attention after an infarct in the right cerebellar hemisphere, as confirmed with an MRI-scan. A more detailed description is presented in van Zandvoort, Nijboer, de Haan (2007) and only a short summary will be given here. Neuropsychological assessment in the acute phase showed, apart from residual dizziness, some mild deficits in memory functioning. At follow-up, two years later, his performance on all neuropsychological tasks tapping the major cognitive domains of reasoning, language, visual perception and construction, verbal memory, visual memory, executive functioning and neglect was above average, taken into account his age and education.

Surprisingly, he showed an absolute inability to perform the Token test (de Renzi, 1978). He could not match the spoken colour name with coloured tokens and on subsequent testing he was unable to name the primary colours presented to him on a monitor. Additionally, his ability to perceive colours was evaluated on three different tests. His performance on the Ishihara test for colour blindness (1977) and the Farnsworth-Munsell 100 hue test (1957) was well in the normal range. In addition, an experimental task was used in which the threshold of the just-noticeable-difference was established for three primary visual sensory cues (shape, colour,

luminance, apparent motion; de Haan, Heywood, Young, Edelstyn, Newcombe, 1995). MAH was shown three simultaneously presented stimuli. Two stimuli in each test were identical and the third differed in either shape, colour, luminance, or apparent motion. Task difficulty changed in a 3-down-1-up manner. MAH encountered no problems in any of these tasks: he outperformed the control participants on the luminance test and he was within normal range on the shape, colour, and apparent motion tests.

Despite good colour perception, MAH turned out to be impaired in categorising and naming colour on the basis of hue. He performs at chance level on a task where he has to decide whether an object is depicted in the veridical colour or not (e.g. blue tomato). He claims that he has always had this problem. In daily life, he uses strategies to infer the colour of objects, e.g. comparing the surface properties of an object with that of an object with a known colour (e.g. his shirt or grass), or he uses brightness cues (he is very proficient in judging brightness) and light colours are often identified as yellow or pink and dark ones as red or blue.

Influence of Luminance and Colour Inversions in Scene Recognition

Our experiments were based on the experimental design of Steeves et al. (2004). The most important conditions in their experiment for examining colour diagnosticity were normally coloured and inversely coloured images. Intrinsic to this colour manipulation is the fact that luminance information is inverted as well. This luminance inversion might complicate the recognition of scenes, and might thus partly explain the poorer recognition of inversely coloured images. Since colour agnosic patients are perfectly able to use luminance information, it was essential to rule out this explanation beforehand. Therefore we tested sixteen control participants on the scene recognition task to which a new format was added, namely: inverted greyscale.

Methods

Participants

Sixteen control participants (twelve student controls and four age-matched controls; mean age = 29.9; SD = 8.1), and MAH (44) participated in the experiment. All

participants had normal or corrected-to-normal vision and reported that they were not colour blind, which was confirmed with the Ishihara test for colour vision (1977).

Apparatus and Stimuli

Images were generated by a PC and presented on a laCie Electron 22 inch blue IV display. Screen resolution was 1024 x 768 pixels, and the computer was running in 256-colour mode. The viewing distance was 80 centimetres.

The stimuli were adapted from Steeves et al. (2004) and the greyscale images were manipulated in order to produce the inverted greyscale images. Images were first screened for category membership by 25 students, who did not participate in the scene recognition experiment, and only images that were correctly categorised by all students, in all formats, were included. The size of the images was 256 x 256 pixels, subtending approximately 8.2˚ x 8.2˚ of visual angle. There were three categories of natural scenes (coast, forest, and desert) and three categories of non-natural scenes (room, city, and market). Six different formats were used: normal colour, inverted colour (each colour was replaced by the opponent colour in colour space, e.g. blue replaced by yellow, green replaced by red), greyscale, inverted greyscale, black-and-white (texture degraded), and spatially rotated (by 180° along the horizontal axes, or upside down). Black-and-white images and spatially rotated images were included for full comparison to the findings of Steeves et al. (2004). Here the focus was on the normally coloured images and these were compared to all other control formats: inverted colour, greyscale, inverted greyscale, black-and-white, and spatially rotated images.

Procedure and Design

The participants were tested individually in a quiet, darkened room. A trial started with a fixation dot for 500 ms, followed by a blank screen for 150 ms, which in turn was followed by an image. Each trial was ended via a voice-key switch when the participant gave a verbal response. After a 150 ms pause, the next trial started. Before the experiment started, participants were given the category names of the different scenes along with an example image. They were instructed to name the category to which the image belonged, as quickly and accurately as possible.

Verbal responses were recorded with a tape-recorder. No feedback was given during the experiment.

There were two within-subject manipulations: scene type (natural and non-natural) and format (normal colour, inverted colour, greyscale, inverted greyscale, black-and-white, and spatially rotated). Each participant was presented with 360 images (10 images per sub-scene, all in the 6 different formats: 10 images x 6 sub-scenes x 6 formats).

Data-analysis

The participants' responses and reaction times were recorded. All reaction times associated with incorrect responses (less than 2% per participant) were excluded from further analyses. From the overall reaction times for correct responses, trials with reaction times less than 150 ms were excluded, under the assumption that they were anticipatory responses and reaction times over 2500 ms were excluded, as they were interpreted as failures of the voice-key measurements. Any reaction times that were more than 2 standard deviations from the participant's mean were also excluded, as they were interpreted as outliers. Less than 1% of the responses in total were excluded.

The reaction time data of the control participants were subjected to a 2-way Repeated Measures Analysis of Variance. When Mauchly's Test of Sphericity was violated, the Greenhouse-Geisser correction was applied. For planned comparisons, paired samples t-tests with Bonferroni correction for multiple comparisons were used for comparing normally coloured images to all other control formats (inverted colour, greyscale, inverted greyscale, black-and-white, spatially rotated).

Results and Discussion

Figure 10.1 shows the mean reaction times of the control participants. We collapsed the data of the two control groups, resulting in one control group that is very comparable to the one used by Steeves et al. (2004). Moreover, it simplified the methodology to one experiment with one reliable control group

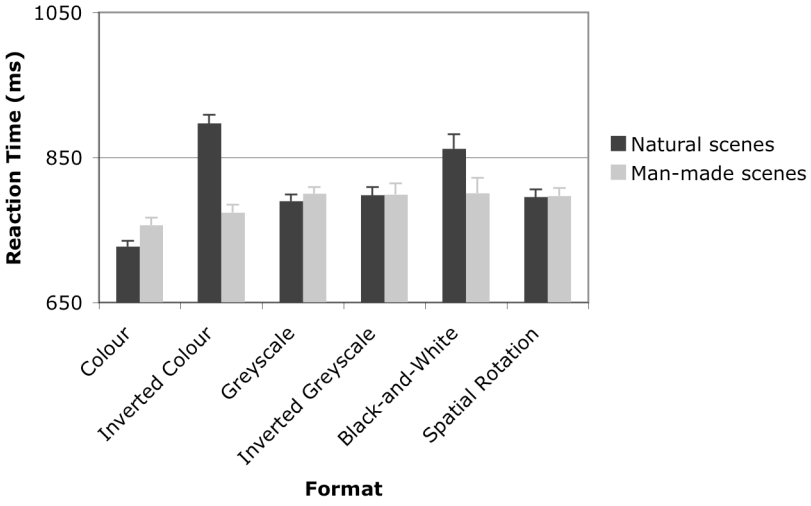

Figure 10.1. Mean verbal reaction times (ms) and standard errors of mean (derived from the within subjects mean square error term) of the control participants for natural and non-natural scenes in six different formats.

As can be seen in Figure 10.1, there was a significant main effect of scene type, with shorter overall reaction times for the non-natural scenes than for the natural scenes ($F(1,15) = 6.808$, $p < .020$), which is in line with the data of Steeves et al. (2004). Moreover, there was a significant main effect of format, with the format of the scene image affecting reaction times across scene types ($F(5,75) = 29.827$, $p < .001$). Furthermore, there was a significant interaction between scene type and format ($F(5,75) = 24.584$, $p < .001$): colour inversion had a large effect on the reaction times of natural scenes, whereas it did not influence non-natural scenes. Reaction times were much longer on the colour inverted images when compared to normally coloured images for the natural scenes ($t(15) = -10.545$, $p < .001$), whereas reaction times on the colour inverted images did not differ from the normally coloured images for the non-natural scenes ($t(15) = -1.795$, $p > .05$). Appropriate colour facilitated recognition of natural scenes, as reaction times were shorter for normally coloured images when compared to all other control formats: black-and-white ($t(15) = -9.2164$, $p < .001$), greyscale ($t(15) = -5.293$, $p < .001$), inverted greyscale

images ($t(15) = -8.790$, $p < .001$), and spatially rotated images ($t(15) = -7.658$, $p < .001$). For non-natural scenes, reaction times were shorter for normally coloured images only when compared to black-and-white ($t(15) = -5.222$, $p < .001$), greyscale ($t(15) = -6.241$, $p < .001$), and inverted greyscale images ($t(15) = -5.196$, $p < .010$). This effect is also in accordance with Steeves et al. (2004). Importantly, for both natural and non-natural scenes, there was no difference in reaction times between greyscale and inverted greyscale images.

In short, colour manipulations had a large influence on scene recognition for natural images but not for non-natural images. This is in line with the colour diagnosticity hypothesis. Luminance inversion does not play a role in scene recognition.

Scene Recognition in Colour Agnosia

Having established that it is appropriate colour, not appropriate luminance that is crucial for rapid scene recognition, we examined MAH, a man with developmental colour agnosia. Less than 1% of the data of MAH was excluded due to incorrect responses.

The mean reaction times in the six formats per scene of MAH are presented in Figure 10.2. As can be seen, there was a significant main effect of scene type, with overall shorter reaction times for the non-natural scenes than for the natural scenes [$F(1,299) = 18.72$, $P<.001$]. There was no significant main effect of format, indicating that the format of the scene image did not affect reaction times irrespective of scene type. In addition, there was no significant interaction.

In order to directly compare the pattern of performance of a single case (MAH) on the normally coloured images versus the other control formats with that of the control participants, we used Crawford and Garthwaite's (2005) modified paired samples t-test. With this test, we compared the magnitude of the differences between reaction times for colour images and the other formats for MAH with the magnitude of differences between reaction times for colour images and all other formats for the control participants (i.e. comparing 'effect sizes'). The planned

comparisons using the Crawford and Garthwaite's statistics were done with a Bonferroni correction for multiple comparisons.

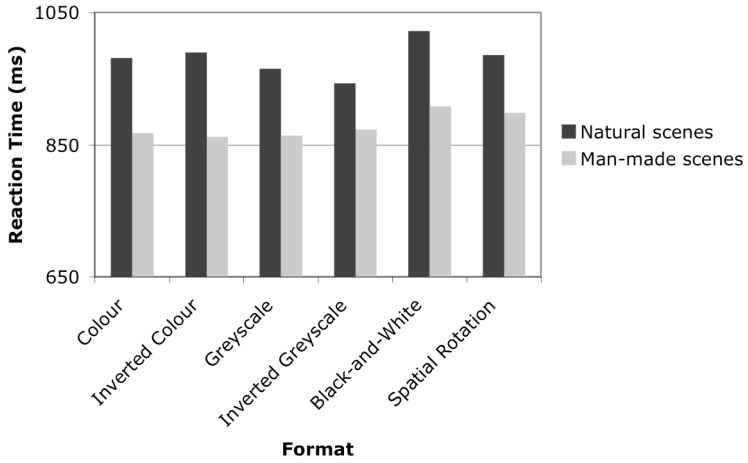

Figure 10.2. Mean verbal reaction times (ms) of MAH for natural and non-natural scenes in six different formats.

Overall, MAH's mean reaction times were longer compared to the control group, for both the non-natural ($t(15) = 3.395$, $p < .010$) and the natural scenes ($t(15) = 7.251$, $p < .001$).

In spite of his longer reaction times, MAH's pattern of performance on the non-natural scenes resembled the pattern of performance observed in students and age-matched control participants (see also Figure 10.2); the magnitude of the differences between normally coloured images and all other formats of MAH fell within the normal range of the control participants (for all comparisons between normally coloured and the other formats used, $p > .050$). This means that the effect of colour is not statistically different between MAH and controls.

MAH's pattern of performance on the natural scenes, however, differed from the control participants. As is apparent from Figure 10.2, the reaction times of control participants to the natural scenes presented in inverted colour were much longer compared to normally coloured images. For MAH, there was no difference in reaction times for images presented in inverted colour compared to normally

coloured images. This lack of an effect of colour manipulations for MAH is very different from the effect colour manipulations have on reaction times for the control participants (t (15) = 7,019, $p < .001$). In addition, the observed absence of a beneficial effect of colour over greyscale and inverted greyscale for MAH was different from the observed effect of the control participants (t (15) = 3.691, $p < .050$, and $t(15) = 3.269$, $p < .050$, respectively). In other words, the absence of differences between colour and inverted colour, greyscale, inverted greyscale, black-and-white, and spatially rotated images of MAH did not fall within the normal range of the control participants.

Note that the lack of an effect of colour for MAH on the natural scenes condition is not merely an overall inability to name scenes fast and accurate irrespective of format, i.e. a floor effect. This notion, tempting though it is, cannot explain his normal performance on the non-natural scenes. This suggests that MAH does not use colour information to assist him in scene recognition, irrespective of colour diagnosticity.

General Discussion

Colour is an important visual cue. It helps us to decide for instance whether fruit is ripe, and in a more general sense, it helps us to recognise our environment. Several studies have demonstrated that especially natural scenes and objects are recognised better when presented in a colour that is deemed diagnostic for these scenes and objects. Other features, such as contour and visual texture are especially informative for recognising non-natural scenes and objects (see below).

The purpose of the present experiments was to examine the role of colour information for scene recognition in colour agnosia. First, we established that the deterioration in scene recognition because of colour inversion found in other studies could not be attributed to the luminance inversion intrinsic to this manipulation. Second, we investigated the level of visual analysis at which colour influences scene recognition by testing a colour agnosic patient. Colour manipulations did not influence the recognition of natural scenes for MAH the same way they did for the control participants. Interestingly, MAH's performance on the natural scenes

compared to non-natural scenes was degraded independent of the scene format, as normally coloured, colour inverted as well as achromatic images were responded to with longer reaction times. This could not be attributed to additional processing deficits, such as form or texture (see also Table 1), or an overall inability to name scenes fast and appropriately, as his performance on the non-natural scenes was within the range of the control participants.

Which cues are informative for scene recognition?

Obviously, colour is but one of the features for recognising objects and scenes. Computational models that permit accurate scene classification without the prior recognition of individual objects (Oliva, Torralba, 2001; Vailaya, Jain, Jiang, Zhang, 1998) make use of properties such as the spatial complexity of the scene, visual texture and colour (Oliva, Schyns, 2000; Oliva, Torralba, 2001). Natural scenes are composed of undulating contours and complex textures, but have characteristic colours. For non-natural scenes, texture and contour cues are more informative, whereas colour cues are not so straightforward. In other words, colour is the key property for recognising natural scenes, whereas shape and texture are the key properties for recognising non-natural scenes (Tanaka, Presnell, 1999). Since colour can only become diagnostic when one learns that certain objects or scenes tend to have certain colours, MAH, who has developmental colour agnosia, never learned this diagnostic value and thus lacks the benefit of colour information for recognising natural scenes. His poorer internal representation of colour (e.g. impaired colour imagery, conceptualisation, and explicit associations; van Zandvoort et al., in press; Nijboer et al., 2006) due to his developmental colour agnosia together with only texture and contour cues available for recognising the scenes, resulted in his overall slower, but still very accurate recognition of natural scenes. In other words, it is the specific combination of an impaired association between natural scenes and specific colours and the spatial complexity (complex textures and contours) of these natural scenes that can explain his overall slowing in recognising the images.

Based on MAH's performance on the scene recognition task, one would expect a patient with visual form agnosia to show the inverse pattern, i.e. slower performance on the non-natural scenes. Interestingly, this is exactly what has been found in the study of Steeves et al. (2004; see their Figure 4), where DF was much

slower in identifying non-natural scenes than natural scenes. These findings are in line with the results of Tanaka and Presnell (1999) who found that when shape information is degraded, recognition of objects low in colour diagnosticity is more impaired than recognition of objects high in colour diagnosticity.

Levels of visual processing

An important reason for testing scene recognition in colour agnosia is that there still is considerable debate about the level of visual analysis at which colour influences recognition of objects and scenes. By testing a colour agnosic patient, we can distinguish between these levels of analysis. Colour associations and semantic representations are selectively impaired or lost, but low-level colour perception is not affected in colour agnosia (van Zandvoort, Nijboer, de Haan, in press). *Any* deviation in performance on the scene recognition task is therefore more likely to be attributable to a deficit in processing of colour information at a higher cognitive level than to a deficit at a sensory level. Wurm et al.'s (1993) conclusion of a sensory role for colour was based upon results from experiments in which all objects would, according to the definition used in our as well as Price and Humphrey's (1989) experiments, make up a colour diagnostic stimulus set. Apparently, the level of diagnosticity (high or low, e.g. carrot or apple, respectively) does not influence the beneficial effect of presenting objects in their diagnostic colour. Note, however, that our conclusion about MAH's performance does not depend upon either the definition of colour diagnosticity or the stimulus set used (see Introduction).

Therefore we can conclude, in line with Price and Humphreys (1989), that the *characteristic* colour of an object or scene is stored in the structural or semantic representation of that object or scene. Apparently, the surface property colour linked to specific (natural) objects or scenes is stored in memory. The beneficial effect of appropriate colour in recognising natural scenes occurs at a higher cognitive level, and is the result of internal colour representations, based on learned associations.

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Chapter 11

Summary and Conclusion

Concluding remarks

In this thesis, we studied the neuropsychology of low-level sensory and higher-order visual perception in healthy participants, patients with acquired deficits in visual perception, and a man with a selective developmental deficit in colour processing.
In neuropsychological literature, sensory disorders as well as higher-order recognition deficits have been reported after acquired brain damage. There is still considerable debate about the link between sensory disorders and higher-order, recognition deficits (i.e. agnosias). In this thesis, a relatively small group study is reported that investigated this link (Part I; Chapter 2). In the remainder of the thesis, colour vision is emphasised. In Part II, learned associations between colours and objects in healthy participants are dealt with (Chapters 3-5). Besides acquired impairments in visual perception, cases have been described with developmental deficits. The neuropsychology of colour vision, ranging from colour perception, discrimination, and categorisation to colour naming, object-colour knowledge and colour imagery, is extensively studied in a unique case of developmental colour agnosia (MAH) (Part III; Chapters 6-10). In this final chapter, a concise summary of the results from is presented along with the major conclusions and a discussion of methodological strengths and weaknesses of the experiments.

Part I. Selective visuo-sensory hemifield deficits: an explorative study in stroke patients

Studies with patients who have incurred circumscribed lesions in the posterior parts of the brain have increased our insight in the functional specificity of the visual cortical areas. It has been demonstrated that after brain damage, different aspects of the visual world (e.g. shape, colour, or motion) may become selectively disrupted. In Chapter 2, the effect of posterior brain damage on visual hemifield processing of shape, luminance, hue, and motion was investigated with a new method for gaze-controlled presentation of stimuli (Utrecht Hemifield Battery, UHB). This method allowed us to explore the proficiency in the perception of the main primary visual primitives (shape, luminance, hue, motion) as well as the possible knock-on effects that these visuo-sensory deficits might exert on higher-order processing. We found that all visual primitives may become selectively distorted after stroke, both in patients with and without visual field cuts (i.e. cortical blindness). It is important to note that the patients with visual field cuts could only be tested on

the UHB with central presentation of the stimuli and free viewing conditions. In our relatively small sample of patients, we found evidence for both low-level and high evel perceptual impairments and double dissociations between low-level (perception) and higher-level (recognition) impairments.

In almost half of the patients seen for both neuropsychological screening and the UHB, visual field cuts were found. This study demonstrated that the UHB can be used to record reliable data (with hemifield and central presentations) and find indications for (mild) impairments in the discrimination of visual stimuli, even when patients are not aware of these impairments. In other studies (e.g. Nys, van Zandvoort, de Kort, Jansen, de Haan, Kappelle, 2005), it has been found that impairments in visual perception are a reliable (negative) predictor for the long-term outcome after stroke. Therefore, careful investigation of (hemifield) impairments after stroke is clinically important. Given that the appropriate equipment to determine perceptual deficits is lacking in most clinical centres, the number of patients suffering from these impairments is probably higher than currently diagnosed.

Despite the promising results in a representative stroke patient population, the UHB is still in its infancy. It should be stressed that at this point visual field cuts or hemi-spatial neglect introduce logistical challenges for the practical execution of the UHB. In patients with large visual field cuts, fixation calibration becomes difficult and misperception of part of the stimulus display introduces task-unrelated problems for patients, when carrying out the tasks. In these patients, only central presentation with free viewing conditions can be used. Moreover, as the complete battery entails 6 subtests, patients in the semi-acute phase might find it difficult to complete the battery due to fatigue.

Part II: Healthy participants: knowledge of colour and its associations

Colour plays an important role in pattern detection and object recognition. Chapters 3 to 5 (and Experiment 1 of Chapter 9) focussed on learned object-colour associations. The particular function of colour vision was investigated using four different tasks (priming, delayed-match-to-sample, and colour naming and object-

colour verification), which measure the influence of colour information at different levels of processing (implicit as well as explicit).

The results of Chapter 3 showed that both physical colour and colour names can have a facilitating effect on the recognition of object words associated with a certain colour, when the appropriate colour precedes the object word. This suggests that object-colour associations are stored in a verbal as well as in a pictorial fashion.

Moreover, our results on colour diagnosticity and identification of scenes (Chapter 9; Experiment 1) as well as the comparable results of others (Steeves, Humphreys, Culham, Menon, Milner, Goodale, 2004; Humphreys, Goodale, Jakobson, Servos, 1994) show that natural objects and scenes are recognised faster when presented in colour compared to inverted colour or greyscale, and that this effect appears to result from stored semantic knowledge rather than from sensory processing.

The findings reported in Chapter 4 on the effect of colour on memory for images show that colour can also display a more 'negative' influence, as recognition memory for images of scenes was better with greyscale than coloured images.

The results reported in Chapter 4 (worse memory for coloured images) and Chapter 9 (faster identification for coloured images) might at first sight seem contradictory. This does not necessarily need to be a contradiction, however. Potter et al. (2002, 2004) suggested that there are two components of visual memory, a pictorial and a conceptual store, with a faster decay rate for the former compared to the latter. This idea for a multiple component memory system is further corroborated by Cooper and Schacter (1992), who suggested that achromatic, detailed structural descriptions and more general, internalised gist-based descriptions, in which colour information is also stored, can be distinguished. We argued that factors at the study phase, such as time restrictions and whether the images are coloured or not, modulate the balance to which these two memory components are engaged. Under certain conditions, too much reliance on gist encoding (at the cost of less detailed visual scrutiny) may lead to increased false alarm rates, while in other circumstances gist encoding will result in a better identification performance.

In Chapter 5, it was found that in the development of colour terms and colour knowledge, the verbal object-colour associations are learned first and adequate use of colour terms or pictorial object-colour associations develop around 4 years of age. Combined results of the studies reported in Chapters 3 and 5 suggest that recognition of object colour and retrieval of object colour partly make use of the same neural network. The difference in development of verbal and pictorial object colour knowledge does not mean that these different forms of associations are stored separately. However, the relatively spared verbal object colour knowledge compared to pictorial object colour knowledge in MAH, a man with developmental colour agnosia (Chapters 6-10) *does* seem to point in this direction. These data do imply that there are actually two ways to represent object-colour associations, of which the verbal object-colour associations are 'easiest'.

Part III: Case study: developmental colour agnosia

Chapters 6 to 10 deal with developmental colour agnosia. In an extensive set of experiments, the abilities and inabilities of MAH were investigated. MAH is a unique case of developmental colour agnosia. When we first neuropsychologically screened MAH, he displayed severe problems with a relatively simple test, the Token test (in which differently coloured tokens have to be moved on verbal command), despite normal performance on tests for colour perception (Ishihara and Farnsworth Munsell 100 hue test) and above average performance on all other neuropsychological tests. Interestingly, he told us that he had had these 'problems' with colour all his life.

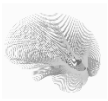
In contrast to most of the case studies reported in the literature (for overview, see Davidoff, 1991), we had the opportunity to investigate most levels of colour processing: colour discrimination, colour categorisation, object colour recognition, object colour recall, colour naming, pointing to named colours, and object-colour imagery. The studies reported in this part of the thesis have shown that even though colour discrimination is intact, MAH has severe problems with colour categorisation (Chapter 6), colour imagery (Chapter 9), object/scene colour recognition (Chapter 6 and 10), colour naming (Chapter 6), and pointing to named colours (Chapter 6). Despite this impairment in explicit colour knowledge, MAH was able to implicitly

access colour knowledge, both for colour names and for object-colour associations (Chapter 8). With respect to verbal object colour recall, MAH displayed some knowledge about the colour of certain objects, but depended strongly on the strength of the associations or the frequency with which the object colour associations are used. For example, MAH was able to correctly answer questions, such as 'What colour is a banana or grass?' but did not know the colour of the surface of a billiard table or a life jacket. The specificity of this impairment is shown in the reported experiments, as MAH did not show any signs of a recognition deficit with respect to shape, texture, or luminance.

Our studies suggest that something so 'basic' as categorising or naming colours can - selectively - fail to develop normally without any observable causes, such as birth complications. A familial basis even suggests that it might be a hereditary condition. The observation that several members of one family (but not all!) suffer from colour agnosia in varying grades of severity (*Chapter 7)* indicates a biological, if not genetically determined ability for recognising colours. But is it reasonable to suggest specific genes for colour knowledge? We do not know and, unfortunately, cannot investigate this possibility as yet, due to the limited number of relatives and the rarity of the disorder. And if genetically determined, at what level of colour processing would this genetic determination express itself? As mentioned in the Introduction, functional specificity has been found at different levels: single cells with specific response patterns, clusters of cells with common specificities within as well as between areas, and connections between clusters of cells, resulting in functionally specialised pathways. With respect to processing of colour information, several areas have been found to be involved (V1, V2, V4, infero-temporal cortex). One could speculate that the underlying impairment in (developmental) colour agnosia is a deficit in colour constancy. The phenomenon of colour constancy is thought to reflect the differences between frequency-dependent processing of visual information versus colour perception and is often associated with the fusiform gyrus (V4/V8; Bartels, Zeki, 2000; Tootell, Nelissen, Vanduffel, Orban, 2004). Colour constancy ensures that the perceived colour of objects remains relatively constant under varying illumination conditions. For example, a banana looks yellow to us at midday (under white light) as well as at sunset (under reddish light). Thus, colour constancy helps us to identify objects. A failure of colour constancy would then

prevent the development of boundaries of colour categories and the learning of associations between objects and colours. Preliminary data suggest that perceiving colour changes is indeed impaired in MAH, in such a way that he does not perceive colour changes across boundaries of colour categories.

Overall, these studies reaffirm the special role of colour in our visual system. It is clear that colour modulates the way visual material is inspected and it influences visual memory. The three cones provide the brain with relatively precise information regarding the spectral profile of light that reaches the retina. The subjective perception of colour is based on this input, but substantial additional processing is required before we can label a surface as, for example, 'red'. The cortical mechanisms that sub serve this processing appear to be dedicated and specialised. There are different patients in whom colour processing is disrupted at different stages of the system, and there are healthy people (at least one man, his mother and his eldest daughter) who have failed to develop some of the necessary processing components. Development of the ability of categorical perception (i.e. establishing the boundaries between different colour categories, and the experience of colour constancy within these categories) appears to be crucial Adequate recognition and labelling of colour is contingent on these two functions: colour categorisation and colour constancy. The qualia of colour depend on them. It is then, perhaps, not surprising that it is these two functions that are least understood. Luckily, there is still work to be done before we truly understand colour.



Chapter 12

Summary and Conclusion
Samenvatting in het Nederlands

In dit proefschrift worden de resultaten beschreven van onderzoek naar de neuropsychologie van zowel basale, sensorische perceptie als hogere orde visuele waarneming en herkenning in (a) patiënten met verworven visuele stoornissen als gevolg van een Cerebrovasculair Accident (CVA, ook wel beroerte genoemd), (b) in gezonde proefpersonen, en (c) een gevalstudie waarin een selectieve ontwikkelingsstoornis in de verwerking van kleurinformatie.

Visuele waarneming in patiënten met verworven visuele stoornissen

Verwerking van visuele informatie begint in de retina waar zich lichtgevoelige receptor cellen bevinden, te weten staafjes (voor achromatische verwerking) en kegeltjes (voor chromatische verwerking). De informatie vanuit deze lichtgevoelige cellen wordt geprojecteerd naar twee type ganglioncellen, grote 'parasol' cellen en kleinere 'midget' cellen. De ganglioncellen vormen samen de optische zenuw en vervoeren de informatie via het optisch chiasma naar de thalamus. In het optisch chiasma kruisen de zenuwbanen gedeeltelijk, waardoor het linker visuele veld van beide ogen via de rechter thalamus door de rechter hemisfeer wordt verwerkt en het rechter visuele veld van beide ogen via de linker thalamus door de linker hemisfeer. In de thalamus wordt informatie vanuit de 'midget' cellen in 'parvocellulaire' en vanuit de 'parasol' cellen in 'magnocellulaire' lagen apart verwerkt en doorgegeven naar de primaire visuele cortex, van waaruit de informatie naar verschillende gebieden in de visuele cortex wordt geprojecteerd. De functionele specificiteit die al bestaat in de retina (bijvoorbeeld cellen die voor achromatische en chromatische waarneming zorgen) blijft bestaan tot in de visuele cortex. Zo verzorgt het parvocellulaire systeem voornamelijk de waarneming van kleur en oriëntatie en het magnocellulaire pad voornamelijk de bewegingswaarneming. Ook in de visuele cortex blijft deze functionele specificiteit bestaan; zo zijn gebieden waar cellen voornamelijk gevoelig zijn voor kleurinformatie (V4) of bewegingsinformatie (V5). De oogzenuw, de geniculate kernene van de thalamus, de optische radiatie, en de corticale gebieden die betrokken zijn bij de visuele waarneming zijn zo gestructureerd dat de ruimtelijke structuur van de retina behouden blijft. Dat wil zeggen dat in de verschillende statia van het visuele systeem er steeds sprake is van een mate van retinotope representatie. Door de functionele en anatomische specificiteit kunnen na

hersenbeschadiging dan ook verschillende visuele stoornissen ontstaan, zoals achromatopsie (V4) en akinetopsie (V5) naast een algehele verstoring van de visuele waarneming (corticale blindheid (hemianopsie) of algehele vermindering van visuele functies (amblyopsie)). Alle bovengenoemde stoornissen kunnen voorkomen in het gehele visuele veld, maar ook alleen in het rechter of linker visuele veld, afhankelijk van de locatie van de beschadiging in de visuele cortex.

In eerder onderzoek van onze groep is aangetoond dat stoornissen in de visuele waarneming een betrouwbare, negatieve voorspeller zijn voor de lange termijn uitkomst na CVA (Nys, van Zandvoort, de Kort, Jansen, de Haan, Kappelle, 2005). Dus vanuit dit deels fundamenteel (taxonomisch) en deels klinisch wetenschappelijke oogpunt is het belangrijk dat er onderzoek wordt gedaan naar (selectieve) stoornissen in de visuele perceptie en de repercussies van dergelijke stoornissen op het cognitief functioneren en het gedrag. Daarbij het van belang is om ook onderscheid te maken tussen de verschillende visuele velden.

In het eerste deel van dit proefschrift is een exploratieve studie beschreven (Hoofdstuk 2) naar de verwerking van verschillende visuele kenmerken: vorm, helderheid, kleur, en beweging. Met behulp van een nieuwe methode, namelijk het onderzoeken van visuele informatieverwerking per visueel veld, is een groep gezonde proefpersonen en patiënten met beschadiging in de posterieure delen van de hersenen ten gevolge van een CVA onderzocht op het voorkomen van basale, sensorische stoornissen zowel als hogere orde, cognitieve stoornissen. In deze relatief kleine groep vonden we dat het vermogen om bovengenoemde visuele kenmerken adequaat te onderscheiden selectief gestoord kan raken, zowel in patiënten met (partiele) corticale blindheid als in patiënten zonder corticale blindheid, en dat basale, sensorische stoornissen in een aantal patiënten een effect kunnen hebben op hogere orde, cognitieve verwerking, maar dat patiënten met specifieke hogere orde stoornissen niet altijd basale, sensorische stoornissen hoeven te hebben.

Kennis van en associaties met kleur in gezonde proefpersonen

Naast een esthetische waarde heeft kleur een belangrijke invloed bij patroondetectie en objectherkenning. Kleur is een karakteristieke eigenschap van bepaalde objecten en scènes, zoals rood bij tomaten en groen bij bossen, die de herkenning van desbetreffend object vereenvoudigd. De objecten en scènes waarbij kleur een faciliterende rol speelt zijn vaak natuurlijke objecten en scènes, zoals fruit en bos. Kleur heeft minder invloed bij artificiële objecten (bijvoorbeeld gereedschap of auto's) en niet-natuurlijke scènes (steden, markten). Dit verschil wordt de diagnostische waarde van kleur genoemd. Deze aangeleerde object-kleur associaties hebben we onderzocht in het tweede deel van dit proefschrift in gezonde proefpersonen. In Hoofdstuk 3 hebben we met behulp van 'priming' gekeken naar de invloed van kleur op de herkenning van woorden, die al dan niet geassocieerd konden zijn met een specifieke kleur. We vonden dat als een woord, dat geassocieerd wordt met een specifieke kleur (kleurdiagnosticiteit), voorafgegaan werd door deze kleur (rood gevolgd door tomaat) dan de woordherkenning versneld werd, terwijl dit niet zo was bij een niet-passende kleur (blauw gevolgd door tomaat). Dit was niet het geval bij woorden die geen kleurdiagnostische waarde hadden.

In Hoofdstuk 4 hebben we een geheugenexperiment gebruikt om de associatie tussen kleur en scènes verder te onderzoeken. In een onderzoek deels beschreven in een later hoofdstuk (Hoofdstuk 9, Experiment 1) hebben we laten zien dat natuurlijke scènes sneller benoemd worden als ze aangeboden worden in de diagnostische kleur, terwijl dit effect niet werd gevonden bij niet-natuurlijke scènes. Deze kleurdiagnostische associaties moeten geleerd worden en in het geheugen opgeslagen. Dit vormde de reden voor het volgende experiment waarin we onderzoek wat de invloed van kleur is op het moeten onthouden van foto's van verschillende scènes. Uit dit onderzoek bleek dat kleur naast een faciliterende invloed ook een ook een meer negatieve rol kan spelen: geheugen voor gekleurde foto's bleek veel minder adequaat (door meer 'foutieve herkenning') dan voor foto's in grijstinten en dit effect was evidenter voor foto's van natuurlijke (diagnostische) scènes ten opzichte van niet-natuurlijke scènes. Deze beide effecten lijken in eerste instantie tegenstrijdig. In ander onderzoek (Potter et al, 2002, 2004) is gesuggereerd dat er twee componenten in visueel geheugen zijn, namelijk

een pictoriële en een conceptuele component, waarbij de eerste een gedetailleerde, structurele omschrijving is en de tweede een meer algemene, geïnternaliseerde omschrijving van de kern of betekenis van de afbeelding, de 'gist'. In de laatste component zitten ook de kleurkennis en kleurassociaties opgeslagen. Wanneer foto's van landschappen benoemd moeten wroden, kunnen deze associaties het benoemen versnellen, omdat kleur helpt bij de opbouw van de semantische omschrijving. Het onthouden van gekleurde foto's voor discriminatie met foto's die er erg op lijken wordt echter moeilijker, omdat de betere opslag in termen van semantische beschrijving (gist) leidt tot een slechtere opslag in termen van pictoriele informatie. Deze pictoriele informatie is juist nodig om de verschillen tussen de verschillende foto's (van bijvoorbeeld verschillende bossen) te kunnen herkenne.

In Hoofdstuk 5 werd onderzocht hoe de ontwikkeling van het aanleren van kleurnamen, kleurkennis en kleurassociaties verloopt. Kinderen van 3 tot 7 jaar kregen 3 taken: 1) gepresenteerde kleuren te benoemen, 2) verbale vragen te beantwoorden over de kleur van objecten en 3) goed of fout gekleurde plaatjes te herkennen. Uit de resultaten blijkt dat rond het vierde jaar kleurkennis en kleurassociaties ontstaan en dat de verbale kennis eerder ontwikkelt dan de pictoriele kennis (adequaat benoemen van kleuren en herkennen van goed of fout gekleurde objecten). Deze dissociatie tussen de ontwikkeling van verbale en pictoriele kennis over kleuren in jonge kinderen vertoont een sterke overeenkomst met de neuropsychologische stoornis 'kleuragnosie', waarbij de pictoriele gestoord en de verbale relatief intact is.

Aangeboren kleuragnosie

Kleuragnosie is een selectieve stoornis in de verwerking van kleurinformatie, waarbij mensen wel kleuren waarnemen en kunnen discrimineren, maar kleuren niet kunnen benoemen of herkennen en vaak ook geen objectkleurkennis hebben. Vaak ontstaat kleuragnosie na hersenletsel, bijvoorbeeld een CVA, maar in de man, MAH, die wij uitvoerig hebben onderzocht en beschreven is er sprake van een ontwikkelingsvariant. In Hoofdstuk 6-10 wordt een overzicht gegeven van de (medische) achtergrond van MAH en zijn selectieve problemen met kleur. MAH

heeft geen basale, sensorische stoornissen in de waarneming, maar kan gepresenteerde kleuren niet adequaat benoemen. Daarnaast heeft hij problemen met het herkennen van goed of fout gekleurde objecten, hoewel hij verbale vragen over objectkleurassociaties goed kan beantwoorden, mits de associaties frequent voorkomen in de talige communicatie. Zo weet hij dat bananen geel zijn en gras groen, maar niet dat een biljartlaken groen is en een reddingsvest oranje. Deze problemen spelen ook door in het maken van mentale (verbeelding-)vergelijkingen van kleuren en objectkleuren, dus zonder dat er kleuren of objectkleuren gepresenteerd worden. In een experiment naar kleurdiagnosticiteit en het benoemen van scènes liet MAH niet het normale patroon zien van de foto's van gekleurde natuurlijke scènes zien. De selectiviteit van zijn stoornis blijkt uit het feit dat hij geen problemen heeft bij taken waarin vorm, textuur, of helderheid gemanipuleerd wordt. Ondanks al deze expliciete problemen met kleur is gebleken dat MAH impliciet wel toegang heeft tot kleurinformatie. Zo is MAH ook sneller in het herkennen van woorden als deze voorafgegaan worden door een passende kleur (zie Hoofdstuk 3) en heeft hij last van een niet passende, equiluminant gemaakte inktkleur bij het moeten lezen van kleurwoorden.

Het interessantste van deze casus is dat MAH claimt dat hij deze problemen altijd al gehad heeft, zonder hersenletsel of complicaties bij geboorte. Er blijkt een familiaire component te zijn. Ook zijn moeder en één van zijn dochters vertonen vergelijkbare problemen, zij het is mindere mate. Het is in dit stadium (nog) niet mogelijk om een biologische of zelfs genetische component te onderzoeken, maar het voorkomen van eenzelfde probleem binnen één familie wijst wel in deze richting.

Tot slot...

Kleur heeft binnen de verwerking van visuele informatie een speciale rol. Kleurinformatie heeft op verschillende niveaus invloed op menselijk functioneren (waarnemen, herkennen, identificeren, geheugen etc) en kan, net als andere visuele kenmerken, selectief gestoord raken na hersenletsel. Ook de ontwikkeling van deze verwerking van kleurinformatie kan in verder normaal functionerende mensen falen. Dit leidt tot problemen bij processen die zo fundamenteel zijn voor ons dagelijks functioneren, dat we er in het dagelijks leven niet eens bij stil staan.

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Martine J.E. van Zandvoort, **Tanja C.W. Nijboer,** Edward H.F. de Haan (2007). Developmental colour agnosia. *Cortex*

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Liefs Tanja

Curriculum Vitae

Tanja Nijboer werd op 22 oktober 1978 geboren in Wijk bij Duurstede. In 1997 behaalde zij haar VWO diploma aan het Revius Lyceum te Doorn. In datzelfde jaar begon zij aan de HBO opleiding tot Fysiotherapeut, Hogeschool van Utrecht. Een jaar later werd begonnen met de studie Psychologie, Faculteit Sociale Wetenschappen, Universiteit Utrecht, waar zij in 2002 afstudeerde in de richting Neuropsychologie.

Tijdens deze studie deed ze haar afstudeeronderzoek aan Durham University (UK), onder begeleiding van Prof. Dr. David Milner en Dr. Robert McIntosh, met als onderwerp de invloed van prisma adaptatie op exogene en endogene aandacht in patienten met extinctie. Door dit onderzoek werd de basis gelegd voor de wetenschap.

Na een paar maanden als onderzoeksassistent te hebben gewerkt bij Dr. Chris Dijkerman aan de Universiteit Utrecht, kon zij aan de slag als AIO op het door NWO gefinancieerd project "de Neuropsychologie van de kleurwaarneming". Naast het onderzoek waar dit proefschrift het resultaat van is, was ze lid van het PhD council van de onderzoeksschool Helmholtz Instituut en zat ze in de redactie van het tijdschrift van de Nederlandse Vereniging voor Psychonomie (NVP), de Psychonoom.

In September 2007 zal zij als Postdoc aan de slag gaan bij Universiteit Utrecht, om het onderzoek naar visuele perceptie stoornissen na CVA uit te breiden. Daarnaast zal zij beginnen met de postdoctorale opleiding tot GZ-psycholoog.