LEARNING PARTIAL GRAPHEME SYNAESTHESIA

by

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ABSTRACT

LEARNING PARTIAL GRAPHEME SYNAESTHESIA

Synaesthesia is a variation of normal human perception. A grapheme synaesthete, for example, can experience extra sensations, such as colours when seeing letters and/or numbers. Synaesthetic ability is commonly developed at an early age, and is linked to a genetic pre-disposition; however, there is a learnt component, as one must also learn to read and write to develop grapheme synaesthesia. To explore the extent to which synaesthesia can be learnt, a training method was employed, which was first used by Colizoli, Murre and Rouw (2012). In order to learn their own coloured letters a group of non-synaesthetic individuals read colour books, which are free eBooks reproduced to have four letters consistently appear in colour. Before and after reading, the participants completed a modified Stroop-design based on Mills (1999), which was used to measure if they had learnt the two key characteristics of synaesthesia, namely an involuntary and automatic reaction to letters. Both the colour reading (n=15) and control (n=6) groups did not have a significant involuntary reaction to letters. However, it was found that the participants had significantly more automatic reactions to letters. This included the control group, who did not read in colour, which suggests that merely completing the modified Stroop test is enough to learn the automatic characteristic of grapheme synaesthesia.

KEYWORDS:
Synaesthesia; synesthesia; grapheme; Stroop; perception; colour-reading; automaticity; pseudo-synaesthesia; trained synaesthesia; partial synaesthesia

DECLARATION

Student number: **43199372**

I declare that "***Learning partial grapheme synaesthesia***" is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

SIGNATURE DATE

Nicholas Brian Forssman

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ANOVA	Analysis of variance
AIT	Anterior infero-temporal
DTI	Diffusion tensor imaging
DCM	Dynamic causal modelling
ERP	Event-related potentials
fMRI	Functional magnetic resonance imaging
IPC	Inferior parietal cortex
LGN	Lateral geniculate nucleus
MEG	Magnetoencephalography
MST	Medial Superior Temporal
ms	Milliseconds
n	Number of people
PIT	Posterior infero-temporal
PET	Positron emission topography
RT	Reaction time
RGB	Red, green and blue
ROI	Regions of interest
SD	Standard deviation
TLE	Temporal lobe epilepsy
TMS	Transcranial magnetic stimulation

CHAPTER 1: INTRODUCTION

1.1. INTRODUCTION

This chapter introduces the perceptual phenomenon of synaesthesia. The focus of this dissertation is grapheme synaesthesia, which describes the involuntarily experience of perceiving letters or numbers in colour, alternatively called letter/number colour synaesthesia. Synaesthesia is considered a hereditable ability, which means a person has to have a genetic predisposition to develop the ability. However, recently a study sought to answer the question as to whether it is possible for non-synaesthetic individuals to learn grapheme synaesthesia. The research presented in this dissertation replicated the training technique used by Colizoli, Murre and Rouw (2012) to examine whether or not it is possible to learn a pseudo-synaesthesia.

1.2. WHAT IS SYNAESTHESIA?

When growing up, we are taught the various names associated with colours, sounds, smells, tastes and textures. When thinking about colours or sounds, we tend to characterise them as separate from one another. The last statement may seem obvious, and most people would assume that this is how the world is perceived by everyone, but there are some individuals who cannot separate their sensed world. Cytowic and Eagleman (2009) use the term “compartmentalized” [sic] to describe our senses as having boundaries between them. Synaesthesia is a contradiction of this compartmentalisation of perception, the peculiar ability to experience two senses simultaneously. For example, seeing music in colour, and tasting sounds. The word synaesthesia is a combination of the Ancient Greek ‘syn’ – which means ‘together’ – and ‘aisthēsis’, meaning ‘sensation’.

Synaesthetes describe their synaesthetic experiences as real, and as part of their reality. The physicist Richard Feynman describes his synaesthesia as follows: ”when I see equations, I see the letters in colors – I don't know why" (Feynman, 2007, p. 59).

Descriptions such as these are common for grapheme synaesthetes, where they experience extra perceptual feedback - which are typically colours - when seeing specific inducers such as letters and numbers (see Figure 1.1). Synaesthetic experience is not random. The "inducer" is a trigger for specific synaesthetic feedback called the "concurrent" (Grossenbacher & Lovelace, 2001). Richard Feynman's described his n's as appearing "slightly violet-bluish" to him (Feynman, 2007, p. 59).

Figure 1.1: Grapheme synaesthesia colours. (www.deviantart.com/art/Synaesthesia-Alphabet-FINALLY-200199534)

Synaesthesia and art have a history. The French poet Arthur Rimbaud wrote this poem about synaesthesia (Rimbaud, 1872).

Vowels

A black, E white, I red, U green, O blue: vowels,
I shall tell, one day, of your mysterious origins:
A, black velvety jacket of brilliant flies
which buzz around cruel smells,

Gulfs of shadow; E, whiteness of vapours and of tents,
lances of proud glaciers, white kings, shivers of cow-parsley;
I, purples, spat blood, smile of beautiful lips
in anger or in the raptures of penitence;
U, waves, divine shudderings of viridian seas,
the peace of pastures dotted with animals, the peace of the furrows
which alchemy prints on broad studious foreheads;
O, sublime Trumpet full of strange piercing sounds,
silences crossed by [Worlds and by Angels]:
-O the Omega! the violet ray of [His] Eyes!

Rimbaud describes the vowel as having not only chromatic associations, but as being associated with smell, emotions, and sounds as well. It is also possible for synaesthetes to have more than one form of synaesthesia. For example, it is common for personalities and/or gender to be associated with letters and numbers, which is called grapheme personification synaesthesia (Simner & Holenstein, 2007). It is not certain whether Rimbaud indeed had synaesthesia, but if he did, he probably had multiple forms. Synaesthesia does appear to have a determinable link to the arts. Rothen and Meier (2010) found a high prevalence of synaesthesia (7%) among art students (n=99), which does not sound high, but the control group of 96 was found to only have 2% presenting with synaesthesia. Ward, Thompson-Lake, Ely and Kaminski (2008) also found that synaesthetes (n=82) like spending time on creative endeavours, and that their form of synaesthesia is aligned with their creative pursuit, e.g. music-colour synaesthetes tend to enjoy playing music.

One of the main methods of determining whether someone has synaesthesia is the consistency measure, which shows synaesthesia is not a memory trick. Asking participants to write down their inducer/concurrent pairings and retesting them after an unspecified period of time shows close to 90% accuracy in reproducing the same pairs (Asher, Aitken, Farooqi, Kurmani, & Baron-Cohen, 2006; Rich, Bradshaw, & Mattingley, 2005; Simner et al., 2006; Simner, Harrold, Creed, Monro, & Foulkes, 2009). This means that Richard Feynman would more than likely consistently describe his n's as slightly violet-bluish. Non-synaesthetes reproduce the same letter colour pair with around 30% to 40% accuracy.

A person who develops synaesthesia will do so from an early age, and may not realise that they perceive the world differently from others (Cytowic & Eagleman, 2009). It is not until someone accidentally mentions to another person their letters have colour, that they may discover that not everybody experiences the world in the same way as they do. One reason why this may also go unnoticed by synaesthetes themselves is that synaesthesia is not out of place in everyday life. Synaesthetic phrases are common in the English language. It is not uncommon for people to combine colour and emotion, for example a familiar phrase "I'm having a blue Monday" (Ramachandran & Hubbard, 2001b). We can interpret this as a metaphorical statement, but surprisingly, the most common form of synaesthesia, according to Simner et al. (2006), is days of the week-colour synaesthesia (the association of a colour with each day of the week). Anecdotally, upon searching for participants in the case of this study, I happened to learn that two people within my extended family have days of the week-colour synaesthesia. My uncle related that "[he] associate[s] colours with days of the week since [he] was little, e.g. Saturday [is] red, Sunday [is] black, and so on".

Today synaesthesia is more widely accepted as an extant phenomenon, because more empirical methods have been developed to verify that it exists. However, over an extended period of time between approximately 1920 to 1980, synaesthesia research saw a marked decline, and according to Cytowic and Eagleman (2009) this was due to the behaviourist paradigm. The behaviourist perspective on human behaviour did not place an emphasis on subjective experience. Prior to the paradigm shift, there were numerous publications about synaesthesia. In 1880, Francis Galton reported on a number form synaesthesia, now called spatial sequence synaesthesia (Galton, 1880). However, these publications are based on people sharing subjective experiences, and not on observable behaviour. The difficulty with objectively verifying synaesthesia is that this made it incompatible with the behaviourist paradigm, and this is perhaps why interest dropped off (Cytowic & Eagleman, 2009; Ramachandran & Hubbard, 2001b).

Times have changed, and through advances in technology, new techniques and open-minded individuals, synaesthesia has received renewed interest in academia as well as in popular culture. For example, Ward (2013a) reports that an article pertaining to the structural differences in the brains of synaesthetes by Banissy et al. (2012) has been downloaded 398 times. In mainstream media, an exaggerated version of synaesthesia has been portrayed on popular television in shows such as Alphas and Heroes (Lafferty, 2011; Kring, 2006). The character Rachel in Alphas can see smells as colour, and in Heroes, a deaf musician has the ability to see music in colours.

Although occasionally portrayed erroneously in the media, the ability to associate sight and sound is not as far-fetched as it may appear. For Elisabeth Sulser, everyday life sounds such as cars, ringing phones or birds singing are all experienced as colourful strips that float in front of her (Bicknell, 2007). For Sulser, one form of sensory stimulation automatically stimulates another sense perception. Earlier synaesthesia was introduced as *two* sense perceptions experienced as one, but it is obvious that letters and numbers are not entirely sensory based where they additionally carry semantic meaning. The majority of the forms of synaesthetic inducers are transferred through culture, e.g. reading and writing, days of the week, music and numbers. For example, Sulser has another form of synaesthesia in which she can taste musical intervals. In music theory, a musical interval is the difference between two pitches, and it needs to be formally taught. Therefore, synaesthesia can be more than a union between two uncommonly paired senses; it can also include semantic meaning.

1.2.1. Forms of Synaesthesia

There are two categories of synaesthesia: sensory and cognitive. Different authors use different names to describe similar categories. Day (2005) distinguishes a cognitive category, which is when the inducer is meaning-based or symbolic, such as in the case of grapheme synaesthesia or days of the week synaesthesia. A second category called synaesthesia “proper” is closer to a typical definition of synaesthesia, where one sense modality is concurrently activated with a second sense, e.g. smell-sound or touch-sound. Marks and Odgaard (2005) categorise forms of synaesthesia based on whether the inducer and concurrent are in the same or a different sense modality, namely intramodal and intermodal. Intramodal (or cross-dimensional) refers to synaesthesia that has the inducer and concurrent in the same sensory modality, but in different dimensions, for example grapheme-colour are both in the modality of vision. Intermodal (or cross-modal) describes a case when the inducer and concurrent are not in the same sense modality, such as sound-taste synaesthesia, where sound modality crosses with taste. Hochel and Milán (2008) argue that these categories have some overlap, for example phoneme-colour synaesthesia (phonemes are distinct sounds in language), which is something learnt, so it is cognitive, but there are two different modalities (sound and vision), so it is also intermodal. The authors refer to the synaesthete R (see Hochel et al., 2007), who sees colour when looking at the sky with clouds, this could be intramodal, because vision is common in both, but it could also be synaesthesia "proper", because it does not include any cognitive components. Hochel and Milán (2008) recommend using the inter and intra modal categories, but also taking into account the cognitive/sensory aspect of the synaesthesia.

There are many different forms of synaesthesia, and many of them are empirically studied. New forms of synaesthesia are also documented frequently, expanding the number of known forms of synaesthesia. Rothen et al. (2013) reported on a swimming styles-colour synaesthesia and Ammari (2010) reported on a case of prayer-shape synaesthesia. Sean Day maintains an often updated list of about 60 types of synaesthesia (Day, 2013). The list is for informal use, and is not based on consistent sampling techniques (it is generated through correspondence with a community of synaesthetes), but is nevertheless a useful resource by means of which it is possible to gain a sense of the variety of synaesthesias that can be experienced. Some forms have also been removed from the list, due to a lack of sufficient data; mirror touch, non-graphemic ordinal personification, spatial sequence (number form) and ticker-tape, are all now excluded. The data (n=931) is represented in Table 1.1.

At first glance, it appears as though just about every conceivable combination seems capable of synaesthetic connection. The personality form has been mentioned already, and there is also an emotion-colour form. Combinations of complex emotions and personality in synaesthesia further suggests that it encompasses much more than the five senses. Grapheme synaesthesia appears at the top of the list as the most prevalent. Days of the week-colour synaesthesia appears second highest on the list, but as already mentioned, according to a random sampling study, days of the week synaesthesia is actually the most prevalent form (Simner et al., 2006).

Forms of synaesthesia involving just sense modalities do not have high representation, such as smell-colour (6.66%) and vision-sound (2.47%), but there appears to have been a large variety of sensory synaesthesias (37 sensory and 19 cognitive).

Table 1.1: Summary of different types of synaesthesia.

no.	Type	Inducer	Concurrent	Percentage %
1	Cognitive	Grapheme	Colour	62.51%
2		Time unit (e.g. day of the week)	Colour	21.91%
3		Musical sound	Colour	19.23%
4		Phoneme	Colour	8.92%
5		Musical note	Colour	8.70%
6		Personality	Colour (aura)	5.26%
7		Grapheme	Personification	2.69%
8		Emotion	Colour	1.93%
9		Lexeme	Taste	1.07%
10		Lexeme	Touch	0.43%
11		Personality	Smell	0.43%
12		Musical note	Taste	0.32%
13		Object	Personification	0.32%
14		Lexeme	Smell	0.21%

15		Grapheme	Touch	0.11%
16		Musical sound	Spatial Coordinate	0.11%
17		Personality	Taste	0.11%
18		Personality	Touch	0.11%
19		Time unit	Sound	0.11%
1	Sensory	General sound	Colour	14.72%
2		Smell	Colour	6.66%
3		Flavours	Colour	6.23%
4		Sound	Taste	5.91%
5		Pain	Colour	5.26%
6		Touch	Colour	4.08%
7		Sound	Touch	3.87%
8		Vision	Taste	3.11%
9		Vision	Sound	2.47%
10		Temperature	Colour	2.26%
11		Orgasm	Colour	2.15%
12		Vision	Touch	1.93%
13		Sound	Smell	1.50%
14		Kinetic	Sound	1.07%
15		Touch	Taste	1.07%
16		Vision	Smell	0.97%
17		Sound	Kinetic	0.86%
18		Flavour	Touch	0.54%
19		Smell	Sound	0.54%
20		Smell	Touch	0.54%
21		Sound	Temperature	0.54%
22		Touch	Smell	0.43%
23		Flavours	Sound	0.32%
24		Touch	Sound	0.32%

25		Vision	Temperature	0.32%
26		Emotion	Smell	0.21%
27		Kinetics	Colour	0.21%
28		Emotion	Taste	0.11%
29		Emotion	Sound	0.11%
30		Flavour	Temperature	0.11%
31		Kinetic	Personality	0.11%
32		Orgasm	Taste	0.11%
33		Smells	Taste	0.11%
34		Smells	Temperature	0.11%
35		Temperature	Sound	0.11%
36		Touch	Temperature	0.11%
37		Vision	Kinetic	0.11%

Looking at the top five inducers in Table 1.1, it is interesting to note that four of them they are culturally transferred (cognitive skills), i.e. graphemes (numbers, letters and words), verbal knowledge (phonemes), musical notes and time units. The reason for this is not clear, but it probably has to do with development of synaesthesia coinciding with critical periods of development e.g. primary education, and this may be why there are more reports of cognitive forms of synaesthesia (Hochel & Milán, 2008).

Looking at the concurrent column in Table 1.1, the most common ‘concurrent’ experiences are colours (also called photisms).The reason for this is again not clear, but in some forms, such as grapheme synaesthesia, the colour region of the brain is adjacent to the grapheme recognition region (Ramachandran & Hubbard, 2001b). If there were cross connections between these areas, they could be the cause of grapheme synaesthesia. This, however, does not explain all other forms of colour synaesthesia, because the colour regions are not always in close proximity to the appropriate region responsible for processing the inducer. For example, taste-colour synaesthesia involves the taste regions of the brain located in the parietal lobe, with the colour region located in the occipital lobe.

Additionally, there are phenomenological differences between synaesthetes pertaining to how the inducer is triggered (higher and lower synaesthetes) and how the concurrent is experienced (projectors and associators synaesthetes) (Dixon, Smilek, & Merikle, 2004; Ramachandran & Hubbard, 2001b). This will be discussed in detail in Chapter Two.

1.2.2. Prevalence and genetics

The widely reported study by Baron-Cohen, Burt, Smith-Laittan, Harrison and Bolton (1996) estimated a prevalence of one in 2000 (0.05%) synaesthetes, and a female bias, where a higher proportion (approximately 6:1) of females exhibit synaesthesia. Rich et al. (2005) reported a similar bias of 6 females to one male. However, these gender ratios and prevalence estimations have been criticised by Cytowic and Eagleman (2009); Hochel and Milán (2008); Ward (2013b) for using inadequate sampling methods. The authors used advertisements and based their estimates on the overall circulation of newspapers, which means that the reported synaesthesias were not objectively verified by current techniques.

Simner et al. (2006) address the issue in their study by objectively verifying their participants' synaesthesia with the “test of consistency”. As briefly mentioned earlier, synaesthetes have shown to be consistent when reporting the colours they experience, and test retest accuracy is high (close to 90%), with gaps between tests well over one year (Baron-Cohen et al., 1996). Consistency is explored further in Chapter Two. Simner et al. (2006) used retesting to identify genuine synaesthetes, and did not find a skewed gender ratio (1:1).They also found that the prevalence of synaesthesia was 88 times higher than previous reports indicated (4.4%).

It is widely agreed among authors that synaesthesia runs in the family, as synaesthetes are likely to report family members also having a form of synaesthesia (Rich et al., 2005; Barnett et al., 2008; Baron-Cohen et al., 1996). Although a genetic disposition is probably involved, the particular form of synaesthesia is not predicted by inheritance and different kinds of synaesthesia can develop among family members (Barnett et al., 2008). It is not known exactly how the genes are expressed in the brain to create abnormal bindings, or how they develop (Cytowic & Eagleman, 2009).

Synaesthesia cannot be entirely attributed to a purely genetic disposition. For example, there are two documented cases where one monozygotic twin developed synaesthesia, where the other did not (Smilek et al., 2002; Smilek, Dixon, & Merikle, 2005). Why would only one twin in a pair develop synaesthesia? The answer may be an environmental factor, such as learning a language, during early development.

Synaesthetes have personalised concurrents, which means that no two synaesthetes have the same colours, or rather, not entirely, because there are reported similarities. For example, Baron-Cohen, Harrison, Goldstein and Wyke (1993) found among nine different colour-hearing synaesthetes that eight shared 88.9% of their colour pairings for three vowels: u was in the range between yellow and brown, 'o' was white, and 'i' between white and pale-grey. Day (2005) found similar commonalities among 123 Synaesthetes, 53% of whom associate 'o' with the colour white. Common synaesthetic colours could be learnt from common cultural influences, for example, Witthoft and Winawer (2006) found Synaesthete AED learned her synaesthetic colours from refrigerator magnets when growing up. What if another synaesthete had the same fridge magnets? If synaesthetes can share colour associations, it means that their early social and cultural environment could have an effect on personal synaesthetic colour preferences, which highlights the importance of environmental factors. However, currently not enough is known about how nature and nurture interact in developing synaesthesia.

1.3. GRAPHEME SYNAESTHESIA

Grapheme synaesthesia can refer to a person who is synaesthetically sensitive to both letters and numbers or just one of the two. The development of grapheme synaesthesia follows the same path as early skills acquisition (i.e. primary education) and people report their synaesthesia to start around the same time they started learning how to read and write (Cytowic, 2002; Cytowic & Eagleman, 2009). It was mentioned that there is a high consistency between inducers and concurrents, but that this is not so during childhood. Simner et al. (2009) found that children beginning to develop synaesthesia have colour pairings that either fluctuate or are not yet formed, but slowly become more stable until adulthood.

The idea or concept of a letter is the source of synaesthetic induction, which means that even if a letter's shape is changed (for example by capitalising it, converting it to lowercase, rotating it 180 degrees or printing it in a unique font), it will always elicit the same synaesthetic colour (Cytowic & Eagleman, 2009). Another example of this is when synaesthetes begin to learn a new language - after only a few minutes of learning the new letter they will start seeing colours (Cytowic, 2002; Cytowic & Eagleman, 2009). Mroczko, Metzinger, Singer and Nikolić (2009) measured that it takes 10 minutes for a synaesthete to learn a new grapheme, at which point it can induce a colour. In the experiment, three Glagolitic letters (a Slavic writing system dating from the 9th century) are equated to the corresponding letter in the English alphabet. Once learned, the synaesthete began experiencing the same colours for the new letter as for the English counterpart. Newly-learned graphemes can be influenced by other languages the synaesthete already knows, which means letters in the foreign language will naturally become associated with the letter most similar in shape or pronunciation to a language already known (Cytowic & Eagleman, 2009). Separately graphemes have colours, but this is not the case for words made up of letters. First-hand accounts vary between people: some say the first letter has the largest effect on the overall word; others say the letter colours merge or mix together, whereas vowels are generally dominated by surrounding consonants (Cytowic & Eagleman, 2009).

1.4. NEUROCOGNITIVE MODELS OF SYNAESTHESIA

There are currently two main neurocognitive models describing the neural mechanisms behind synaesthesia. The first is the cross-activation hypothesis, which is based on the concept of extra-structural connections between brain regions. Contrastingly, the disinhibition masking hypothesis proposes that there are no abnormal structural connections; instead, there are functional differences in the brain of a synaesthete.

The cross-activation hypothesis proposes that cross-modal connectivity is facilitated by extra-neural connections between contributing cortical regions in the brain. These extra connections are hypothesised to be early developmental connections left unpruned due to a genetic mutation. It is a common opinion that through a normal developmental process called ‘neural pruning’, the brain begins to remove unneeded connections during early childhood, and through gene expression, some synapses remain unremoved, thereby maintaining some connection between brain regions, and causing synaesthesia (Ramachandran & Hubbard, 2001b).

Discordantly, the disinhibition hypothesis describes fundamental functional differences in a synaesthete's brain. For example, neural pathways in the brain, processing sound and vision, cross over already in parts of the brain called nexi. The sound and vision connection do not feedback into each other, because the brain normally inhibits cross-talk. For this reason, it has been proposed that synaesthesia is due to a lack of inhibition between channels (Grossenbacher & Lovelace, 2001). Instead, the underlying mechanism may be a disinhibition between neural channels, where synaesthetic induction relies on already present neural networks found in normal adult brains.

The underlying assumptions of each hypothesis have unique implications for the interpretation of the brain's potential for learning synaesthesia. It is still not clear whether synaesthetic connections between parts of the brain that recognises letters, and the colour recognition region are maintained from childhood, or rerouted through normal brain networks. It is possible that it may be a combination of both. The neurocognitive theories will be explored further in Chapter Two.

1.5. PURPOSE OF THIS STUDY

The neurocognitive models can be interpreted as follows. If the cross-activation hypothesis is accurate, then it may not be possible to learn synaesthesia. If new structural connections are required, then non-synaesthetes may not be able to learn synaesthesia. Alternatively, the disinhibition hypothesis posits that normal neural connections are responsible for synaesthesia; however, they are normally inhibited. If these connections are already present, it may be possible to learn to disinhibit those channels through training and learn something similar to grapheme synaesthesia.

A recent study by Colizoli et al. (2012) provides a means of testing the idea that non-synaesthetes may be able to form similar connections and exhibit similar behaviour to genuine grapheme synaesthetes after going through training. Colizoli et al. (2012) employed a novel training technique by producing books printed with four letters, each of which always appears in a particular colour. Participants read these books in order to learn the letter-colour associations. The aim of this study is to replicate the training technique and test if non-synaesthetes can learn grapheme synaesthesia.

1.5.1. Objectives

The main objective of this study is to replicate and implement the training technique described by Colizoli et al. (2012) and to improve on their findings. The participants in this study will read colour-altered books. Colour-altered books are normal books, but with the exception that specific letters appear in colour consistently throughout the book. Part of this training included a second type of training, similar to the colour books, but instead, used an internet web-browser as a training medium. A Google Chrome Extension™ called *Synesthetize* changes the colours of letters on the web pages in a similar way to the colour altered book, although not in a static environment, such is the case when reading a novel. A single participant used the web colour changer for one month and has been included in the final analysis.

The secondary objective of this study is to test if the participants learnt grapheme synaesthesia in a systematic manner. There are two primary characteristics for synaesthesia, which show synaesthetic activation as being 'involuntary' and 'automatic'. In the current study, a modified Stroop Test was used to test for the involuntary and automaticity characteristics. Further details are presented in Chapters Two and Three.

1.6. CHAPTER SUMMARY

Although the development of synaesthesia is linked to a genetic disposition there is evidence of discordant development between monozygotic twins which suggests other factors are involved in its development, such as culture, education and personal experiences. In order to investigate how synaesthesia is developed, adult non-synaesthetes are given coloured books to determine whether or not they can learn their own letter-colour associations.

CHAPTER 2: LITERATURE REVIEW

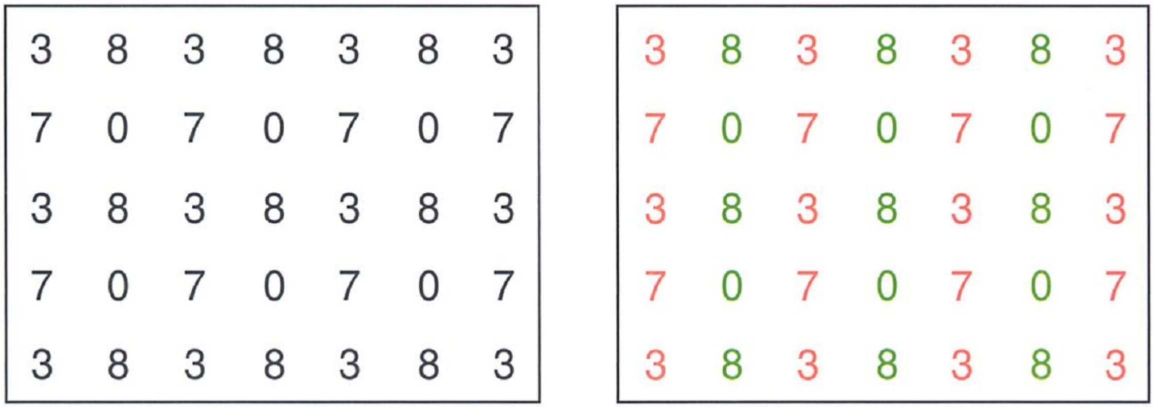
2.1 INTRODUCTION

Synaesthesia may seem abstract in some sense when you first encounter it, which is why the majority of this review centres on the defining characteristics of synaesthesia, highlighting some of the behavioural experiments used to verify the claims of synaesthetes. Thereafter, the current theoretical models for grapheme synaesthesia are reviewed, where each model has different implications for the possibility of learning synaesthesia. The remaining sections of the review examine forms of 'learnt' synaesthesias, or more precisely, the cross-modal experiences that appear similar to synaesthesia. These cross-modal experiences and synaesthesia are compared in relation to their behavioural, cognitive and neurological differences in order to try answer the question as to whether one can indeed learn synaesthesia.

2.2 DEFINING SYNAESTHESIA

Defining synaesthesia is difficult, because it is fundamentally a subjective experience. The expression “beauty is in the eye of the beholder” conveys the idea that reality is perceived differently by individuals, where I am incapable of seeing the world through someone else’s eyes. As individuals, we cannot truly know how others perceive reality. This is why earlier inquiries tended to begin with verifying whether the synaesthesia was genuinely a *perceptual* experience or not. In normal perception, similar visual features such as colour can aid perceptual grouping. Perceptual grouping occurs when items (e.g. stimuli such as letters, shapes or lines) in close proximity are grouped together based on similar visual features such as orientation, shape and colour (Treisman & Gelade, 1980). Figure 2.1 (right panel) shows a grid of coloured numbers; because the colours are prominent, they assist in visually grouping the numbers vertically. Alternatively, looking at the left panel with the same numbers, except in normal black, the numbers tend to group horizontally, because of their shape. The 3s and 8s more are similar in shape, biasing the grouping horizontally. Ramachandran and Hubbard

(2001a) demonstrated the way in which synaesthetic colours can affect perceptual grouping with two grapheme synaesthetes and 20 controls. They were shown different arrays of numbers in black (similar to Figure 2.1 left panel) for one second, and asked to state whether the numbers were grouped horizontally or vertically. The arrays were biased, so that the synaesthetes would group according to the colours elicited by the graphemes (vertical grouping). This was possible because the synaesthetes shared a similar colour for two different graphemes. The controls were biased by the shapes of the graphemes (horizontal grouping). It was found that the two synaesthetes did group according to their synaesthetic colours in the majority of trials (90.97%), whereas the controls grouped according to the visual form of the numbers (86.75%).



3	8	3	8	3	8	3
7	0	7	0	7	0	7
3	8	3	8	3	8	3
7	0	7	0	7	0	7
3	8	3	8	3	8	3

3	8	3	8	3	8	3
7	0	7	0	7	0	7
3	8	3	8	3	8	3
7	0	7	0	7	0	7
3	8	3	8	3	8	3

Figure 2.1: Left panel black number and right panel synaesthetic colours. (Ramachandran & Hubbard, 2001a)

The experiment above begins to show that synaesthesia is a genuine perceptual experience, because it has an effect on early visual processes, such as perceptual grouping (Ramachandran & Hubbard, 2001a, 2001b). However, the effect could not be found consistently in similar experiments (Ramachandran & Hubbard, 2001a). The experiment above provided valuable insight into how synaesthesia is perceptual, but in order to verify synaesthesia, it is important to have a standard agreement to define it, which can be supported with empirical evidence.

2.3 CHARACTERISTICS OF SYNAESTHESIA

Synaesthesia is not something that can be diagnosed, because this would imply that it is a disorder, or a condition with symptoms. In this dissertation, synaesthesia is rather viewed as an *ability*, with defining characteristics. Cytowic (2002) provided a list of characteristics for synaesthesia, in order to differentiate it from other types of cross-modal experiences that could be confused as being similar, e.g. use of psychedelic drugs. The characteristics are as follows: automatic and involuntary; consistent and generic; spatially extended; memorable; affect-laden; and form constant (Cytowic & Eagleman, 2009). The first two characteristics have the most empirical support.

2.3.1 Involuntary and automatic

A key characteristic of synaesthesia is the way in which synaesthetes describe their experiences as involuntary. They feel involuntary because synaesthesia is an early perceptual process. As seen in the section above, it can affect perceptual grouping. Ramachandran and Hubbard (2001b) used another early perceptual process known as the 'crowding effect' to study the early involuntary nature of synaesthesia. A participant is asked to focus on a single point at the centre of a screen, and then to identify a target stimulus located on the periphery (left or right) of the centre target, without adjusting their foveal vision, i.e. not looking directly at the peripheral target. If the peripheral target is isolated, it can be easily identified using peripheral vision. However when the peripheral target is surrounded by distracters or “crowded”, identification of the target becomes difficult (Bouma, 1970; Hochel & Milán, 2008; Strasburger, 2005). This is illustrated in Figure 2.2. The crowding effect can be attributed to lower resolution in the peripheral vision and attention overload (Hochel & Milán, 2008; Whitney & Levi, 2011).

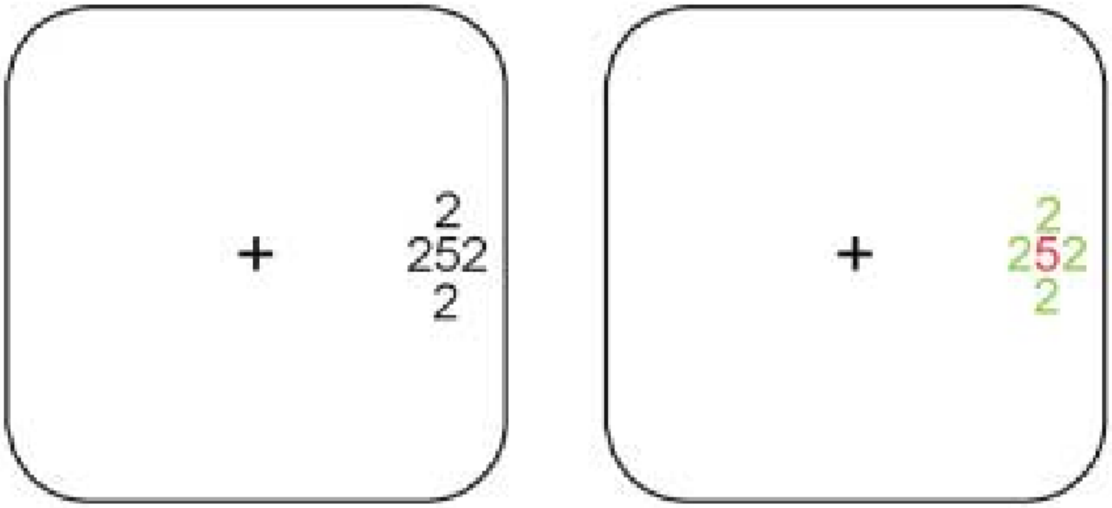


Figure 2.2: Crowding task: left panel 5 is the target, 2s are distractors, right panel colour is segregation.

(Ramachandran & Hubbard, 2001b)

It was discovered that if the target stimuli and the distractors were dissimilar from each other, the crowding effect lessened. For example, if the target appears in colour, the crowding effect would diminish and identification accuracy improved, even when surrounded by distractors (Kooi, Toet, Tripathy, & Levi, 1994; Põder, 2007; Whitney & Levi, 2011). If real colour can reduce the crowding effect, perhaps grapheme synaesthesia may have the same effect? Ramachandran and Hubbard (2001b) used the same basis as the crowding experiment above with grapheme synaesthetes, and found that two participant synaesthetes could identify a crowded target grapheme. The synaesthetes reported that they did not see the target, but could guess its identity from the colour they saw. These results varied depending on individual differences. Hubbard, Arman, Ramachandran and Boynton (2005) repeated the crowding test on a larger group of synaesthetes (n=6) and controls (n=6), and found the synaesthetes as a group were only slightly better than control subjects and improvements were not statistically significant; only three of the six synaesthetes were better at identification. The differences between participants could be due to individual differences between synaesthetes. The results suggest that synaesthesia can help overcome the crowding effect, but only for some synaesthetes. The finding that some synaesthetes have an advantage in the crowding test suggests that synaesthesia may be an early involuntary perceptual process.

Synaesthesia also extends into later processing, which involves higher-order cognitive processes. There is an automatic relationship or automaticity between an inducer letter and concurrent colours. Automaticity can be shown by creating interference between the triggering inducer letter and the synaesthetic colour response in a similar way to the classic 1935 paper by John Ridley Stroop. The original Stroop (1935) experiment illustrated the interfering effects that two simultaneously presented but incongruent stimuli can have on participant response times. In the experiment, the participants were asked to read a colour word or to name the colour in which a colour word was printed. Two main conditions are tested: incongruent and congruent conditions. The congruent condition matches the colour word to its print colour (semantic meaning aligns with print colour) and the opposite for the incongruent condition, e.g. the colour word ‘green’ is printed in the colour ‘blue’. Refer to Table 2.1.

Table 2.1: Stroop interference.

Congruent Condition	**Incongruent Condition**
Red	**Red**
Green	**Green**
Blue	**Blue**
Orange	**Orange**

Stroop found that participants are slower when naming the colour of colour word stimuli when they were incongruently matched (i.e. the colour word ‘red’ printed in the colour blue) than when naming the colour of congruently matched words. Stroop concluded that the interference experienced when attempting to name the colour of the incongruent colour word stimulus, is caused by normal reading response or typical vocalisation response. Seeing a word evokes a well-practised verbalisation, which appears to be associatively stronger than naming the colour of the word. Reading becomes second nature, and when seeing an incongruent colour word, the automatic reflex of reading the word interferes with the task of colour-naming. The interference can be mitigated with practice, but the experiment highlights the concept of *automaticity*.

Mills (1999) demonstrated automaticity between synaesthetic inducers and concurrents in much the same way as Stroop had done (1935), using conflicting stimuli. Instead of colour words, Mills created test stimuli based on the digit synaesthete's colour experiences of digits. Digits that looked the same as her synaesthetic digits were the congruent conditions, and incongruent conditions were incorrectly coloured digits, i.e. other than how she normally experiences the digit’s colour. Participants were asked to name the colour of the digit presented. It was found that colour-naming of incongruently coloured digits caused a significant delay in her reaction times. The slower naming times demonstrated the automatic nature of synaesthesia. When she saw the grapheme, it automatically elicited her unique colour for that grapheme. When it was shown to her in the wrong colour – incongruent to her synaesthetic perception – her normal synaesthetic colour response conflicted with the real colour of the digit. The control subjects did not show significant slowing for incongruently coloured digits.

In the same experiment, Mills (1999) also tested the involuntary characteristic of synaesthesia. If the synaesthete does have an involuntary/perceptual colour experience when seeing numbers, it should be similar to a genuine perceptual process, such as seeing a real coloured number. Mills (1999) also asked the synaesthete to name the synaesthetic colour of black digits so as to get a baseline for the onset speed of her synaesthetic colours, and to compare them to the congruent condition. It was found that the congruent condition and the black condition were quite similar (46ms difference). The small difference highlights the involuntary characteristic of synaesthesia, because when the participant sees and names a synaesthetic colour, this happens almost as fast as seeing and naming a real colour.

Synaesthetic automaticity has been shown in various experiments using Stroop methodology by other authors (Dixon, Smilek, Cudahy, & Merikle, 2000; Mattingley, Rich, Yelland, & Bradshaw, 2001). Dixon et al., (2000) tested a digit synaesthete with a similar set-up, recording reaction times for congruent and incongruent digit conditions, and found a significant slowing in reaction times to incongruent digits. Mattingley et al. (2001) showed Stroop interference in a larger group of synaesthetes, with 15 synaesthetes and 15 non-synaesthetes, corroborating previous experiments. The Stroop effect can also be demonstrated in other forms of synaesthesia, such as music-colour synaesthesia (Ward, Tsakanikos, & Bray, 2006).

2.3.2 Consistency

Synaesthetic experiences are consistent and stable over time. For example, asking a grapheme synaesthete to record their colour experiences (e.g. ‘b’ is green), thereafter retesting them without warning (sometimes years later), they tend to select close to 100% of the same combinations. In contrast, non-synaesthetes are more random in their colour selections and do not consistently pick the same association in the retest (Simner et al., 2006). The consistency test is considered a ‘test of genuineness’ as it is the standard method for verifying many forms of synaesthesia (Asher, Aitken, Farooqi, Kurmani, & Baron-Cohen, 2006; Rich, Bradshaw, & Mattingley, 2005; Simner & Logie, 2008; Simner et al., 2006; Simner, Harrold, Creed, Monro, & Foulkes, 2009; Smilek et al., 2002). An online version of the test of genuineness is built into the synaesthesia battery (http://www.synesthete.org), which is a website capable of recording the participant's associations (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007). The online method works well for lexical-type synaesthesias (e.g. music, letters, and numbers), but obviously not for others, such as taste synaesthesias.

Synaesthesia is not always consistent in early development. Simner et al. (2009), in a prolonged study of children aged 6 to 8, presented their participants with consistency tests over a period of 12 months. The potential synaesthetes did not achieve the normal high consistency, but subsequent tests showed a gradual increase in 1) the number of associations and 2) improvements in accurately choosing the same colours. The study highlights that synaesthesia has a developmental process, and takes time for the associations to consolidate.

Synaesthetic associations are not complex, but consist of basic precepts, e.g. taste synaesthesia may have basic sweet and salty flavours (Cytowic, 2002). They are not pictorial or complicated (differentiated from imagination or imagery). In this regard, synaesthetic precepts are also specific, which means that they are unique to the triggering stimulus. Given a computer colour palette, graphemes synaesthetes will take care to find the best matching colour for their letters or numbers (e.g. the correct hue and brightness). Synaesthetes also use more words (e.g. lime green, moss green, forest green) to describe their colour precepts, than controls (Cytowic & Eagleman, 2009; Simner et al., 2005).

The modified Stroop experiment mentioned above, and variations on it, are used often by researchers to ‘authenticate’ synaesthesia. This it is commonly referred to as the 'congruency effect'. The congruency effect is dependent on the consistency between inducers and concurrents. For example, a grapheme synaesthete's ‘a’ may appear to them as red, and if we want to make the stimulus letter ‘a’ look red, how do we ensure that the experimental stimulus looks the same as the red that the synaesthete sees? Herein lies a problem, because it is sometimes easier to replicate the inducer - i.e. letters, music, numbers, words etc. - than to make the inducer look like the associated concurrent. Taking an example from the above Stroop experiment, Mills (1999) used coloured numbers as stimuli. The only way to ensure that the colour for the number is correct is if the synaesthete is allowed to select the colour herself. In this way, the colours are accurate, because the synaesthete's judgment is the best gauge, but it does not solve the problem, because there are still some inducers that cannot be accurately matched to real world colours. Mills used the numbers one to nine as stimuli, but had to exclude the number four, because the colour could not be correctly matched by the synaesthete.

One limitation of synaesthesia research is the difficulty of replicating inducers and concurrents fully, due to technical as well as ethical concerns. There are forms of synaesthesia where pain is the inducer (refer to Table 1.1), and it would of course be unethical to try to replicate pain for experimental ends (Simner et al., 2006). In the prevalence study mentioned in Chapter One, Simner et al. (2006) were obliged to exclude some participants because their synaesthesia was induced by pain. Other forms of synaesthesia pose challenges due to the form the inducers may take, e.g. flavours, smells and emotions, which are difficult to replicate. This introduces a limitation to the Stroop and consistency designs.

2.3.2 Form Constant

Form constant was added later to the list of characteristics to describe the relationship between the forms of synaesthetic concurrents and visual hallucinations (Cytowic & Eagleman, 2009). After giving his participants the drug mescaline, Klüver (1966) trained them to describe and report their visual hallucinations while on the drug. He found that there were congruencies between the descriptions of the hallucinations provided by different subjects (Cytowic & Eagleman, 2009). He suggested that there are a limited number of visual frameworks that the brain processes (called the form constants), which are the most basic and fundamental frameworks (i.e. spirals, tunnels and cones, central radiations, grating/honeycombs). These form constants can also be found in synaesthetes' descriptions of their concurrents, usually describing simple lines and spirals. If form constants are evident in synaesthetic perception, this highlights the similarity between normal perceptions and synaesthetic perception.

2.3.3 Spatially extended

A synaesthete's experiences are spatially orientated. Some may feel them external to their body (usually within arm's reach), describing the colours as if in front of them, or appearing on a small screen close to the face. In Chapter One, the synaesthete Sulser was quoted as describing her music-colours as colourful dancing ribbons, which she was able to see in front of her. Researchers often refer to the case of Michael Watson to highlight this feature of synaesthesia (Cytowic & Eagleman, 2009; Hochel & Milán, 2008). He would describe his taste-shapes by extending his arm and as if he were touching the shape in front of him (Cytowic, 2003).

Although 'spatially extended' is a characteristic, it is not a clear feature in all synaesthetes, where an associator synaesthete (discussed below) who experiences their precepts in their ‘mind’s eye’, does not fit this description, because the experiences are internalised (Hochel & Milán, 2008). An associator may feel a sense of direction when experiencing the synaesthesia, where it is simply not placed outside of one’s body.

2.3.4 Memorable and affect-laden

Many people report that their synaesthesia helps them to remember, because of the unique memorable combinations that may occur (Cytowic & Eagleman, 2009). A grapheme synaesthete may remember a person's name by the unique combination of colours that the letters illicit. For example, some names or words can be more appealing to an individual than others, which may make them more memorable. In the same regard, looking at incorrectly coloured letter graphemes, synaesthetes may feel uncomfortable (Ramachandran & Hubbard, 2001b). This implies that synaesthesia can influence emotions. For example, one music synaesthete avoided going to church, because the music was terrible for her to 'look at' (Cytowic & Eagleman, 2009). This indicates that synaesthetes may change their preference for music or social context based on their synaesthetic experiences. There are also forms of synaesthesia that directly trigger emotion, such as touch-emotion synaesthesia, wherein emotion is directly evoked through touching certain textures (Ramachandran & Brang, 2008). In a case described by Ramachandran and Brang (2008) synaesthete AW's preference for particular fabrics depended on the emotion they evoked, where for example, because denim elicits unpleasant emotions for her, such as disgust, she avoids wearing or touching denim garments.

2.4 INDIVIDUAL DIFFERENCES IN SYNAESTHETIC PERCEPTION

2.4.1 Perception of concurrents: Projector and associator synaesthetes

There are phenomenological differences in synaesthetic experience. At first, these subtypes were only distinguishable by subjective reports, but their difference has been shown objectively. Some grapheme synaesthetes called 'projectors' may perceive their colours or photisms (photisms are concurrent colour experiences) as externally projected onto the grapheme, while others who may perceive the photism in their 'mind’s eye' (internally experienced), are called 'associators'. Cytowic and Eagleman (2009) have expressed a preference for the terms ‘localizer’ (projector) and ‘non-localizer’ (associator).

Smilek, Dixon, Cudahy and Merikle (2001) used two object identification tasks to show that there was a significant difference in visual perception between a single synaesthete (known as ‘C’) and non-synaesthetes (n=7). There were two tasks: number masking and a visual search task. The masking task required the participants to identify a briefly shown digit at the centre of a screen on a varying coloured background (coloured either congruent or incongruent to ‘C's’ synaesthetic colours). The visual search task displayed digits on an unseen grid, also overlaid on a varying coloured background (congruent or incongruent). The objective was to locate either a ‘2’ or a ‘4’ amongst a varied number of distracter digits. Whenever C was required to locate or identify the target digit, her accuracy and reaction time significantly decreased when the background colour of the screen was congruent to her synaesthetic colour for that particular digit as compared to the control group, whose results were found to be similar across incongruent and congruent coloured backgrounds. The results support the projected photism claim, because it is possible that the synaesthetic colour and background blended together, making it more challenging for the synaesthete to locate or identify (Smilek et al., 2001).

Dixon, Smilek and Merikle (2004) divided a group of grapheme synaesthetes into associators (n=7) and projectors (n=5), based on their subjective reports of how they experienced their photisms, and then compared them on a variation of the Stroop test, with the normal colour-naming task and a photism-naming task. In the colour-naming task the objective was the same as normal Stroop designs (i.e. name the physical colour of the grapheme displayed on the screen as fast as possible), whereas in the photism-naming task, the synaesthetes were required to name the photism elicited by the displayed grapheme. The results were similar to the typical findings of the Stroop interference experiments discussed thus far (Dixon et al., 2000; Mills, 1999). The incongruent conditions caused a delay in naming times in both tasks and subtypes. However, there were significant differences between synaesthetic subtypes in the tasks. In the colour-naming task, the projectors were significantly slower when naming the real colour of graphemes as compared to the associators, who were faster. The reverse was found to be the case for the photism-naming task, wherein the projectors named the elicited photism faster than the associators.

Dixon and colleagues suggest the reason for the difference may be an attentional effect - in the colour-naming task the projectors were slower at naming colours, because the grapheme and their photism occupy the same visual frame, which causes more interference. For associators, their photisms are internal, and because external graphemes and internal photisms do not share the same attentional space, it may make it easier to ignore their photisms. In the photism-naming task, the projectors were faster, because it did not require them to shift their attention from the grapheme to the photism (the grapheme and colour are in the same space); whereas the associators were required to shift their attention internally to name the elicited photism. The authors concluded that each subtype of synaesthete experienced a different degree of Stroop interference, and that it is important to consider the subtype of synaesthete when interpreting results and drawing conclusion about grapheme synaesthesia.

Ward, Li, Salih and Sagiv (2007) confirmed these results in a replication of the experiment with seven projectors and seven associators. However, in their experiment, there were two synaesthetes who saw their photisms externally, but who were not bound directly to the graphemes, as is the case with a typical projector. Their photisms were projected onto a ‘screen’, which floated in their field of view. The authors therefore propose separating the projector subtype even further. This screen variation could be called 'space-projector', because photisms are externalised, but only near the inducer, whereas the familiar photism experienced on top of the grapheme could be called a 'surface-projector'. Despite this difference in qualitative experience within the projector subtype, the experiments by Ward et al. (2007) were not consistently able to discern the space-projectors from the associator subtype. Although space-projectors photisms are external, their reactions are not exactly the same as those of the surface-projectors. Their reactions in the colour-naming task are more similar to associators, because the photism and grapheme do not share the exact same spatial frame, and it may therefore be easier to suppress the automatic colour response. Currently there is no empirical method of discerning these two subtypes (space and surface projectors), and they can only be identified through self-report. Ward et al. (2007) also suggest that the associator subtype ought to be broken down further into 'see-associator' for those who see their colours internally, and 'know-associator', for those who know the colour of the grapheme. Currently, there are no measures that can confirm these two types of associators.

More recently, Rich and Karstoft (2013) found that the congruency tests described above are more appropriate for identifying projector synaesthetes. Testing 8 synaesthetes and matched controls, they found that the photism naming tasks were reliable for distinguishing two of the synaesthetes as projectors, and only one as an associator. The remaining five were not significantly different between the photism naming tasks and colour naming tasks, and could not be definitively defined as either associators or projectors; therefore (Rich & Karstoft, 2013) classify them simply as non-projectors.

2.4.2 Perception of inducers: Higher and lower synaesthetes

Ramachandran and Hubbard (2001b, 2003) identified higher and lower synaesthetes. The higher and lower synaesthetes differ according to the form an inducer must take in order to trigger synaesthetic induction. For higher synaesthetes, concurrents are triggered by the concept of the trigger, e.g. for a number-colour synaesthete, it is the numerical magnitude of a number that triggers the specific colour, and it would not make a difference if numbers were roman numerals, dice patterns or arabic numerals. If instead, the number-colour synaesthete is a lower synaesthete, it is the shape or form of the numbers which cause synaesthetic induction, which means they must look at the numbers directly, and are affected by the physical form of the inducer (Ramachandran & Hubbard, 2001a).

In some sense, all synaesthetes are higher synaesthetes. For example, as mentioned in Chapter One, grapheme synaesthetes experience the same colours for letters and numbers, regardless of font style. One problem with dividing synaesthetes into subtypes is that it creates a false dichotomy, where one synaesthete could perhaps have both higher and lower features mixed together. Ward and Sagiv (2010) present the case of the synaesthete "TD", who experiences synaesthetic colours from numbers, regardless of how they are represented. For example, TD describes his apprehension of the digit ‘5’ as having a “cardboard box-like brown colour” (Ward & Sagiv, 2010, p. 87), where the colour is projected onto the inducer itself, whether this be text, dice patterns or fingering-counting patterns (i.e. surface-projector). It seems that it is the concept of a number that evokes colour, but according to TD, when looking at finger-counting patterns, he will only experience colour when looking at a left hand, where the counting pattern must conform to his preferred pattern of fingers used. For example TD prefers the number three to be represented with the thumb, index and middle fingers. By all accounts, TD is a higher synaesthete, because number colours are the same for dice and finger counting patterns etc., but this is not entirely consistent with his description. Why might it be the case that synaesthetic induction is dependent on a specific hand, and preferred style for representing numbers with his hands? It may be reasonable to suggest that TD is also a lower synaesthete, because it seems to be the way the hand looks that elicits colour.

Ward and Sagiv (2010) used a priming and interference (i.e. Stroop) experiment to examine whether it is the numerosity, or the form of the finger counting pattern, that elicits TD's synaesthetic colours. In the experiment, TD had to name the colour of a neutral non-synaesthetic target (i.e. ####), which was preceded by a priming target. The prime was a picture of a normally coloured hand, displaying his style of finger counting pattern (numbers 1, 2, 3 and 5) for 400ms. The synaesthetic colours that the priming hand patterns evoked were either congruent or incongruent to the real colour of the following neutral stimulus. If the prime target evokes a colour experience, it may affect the participant's response to the following neutral target, and indicate automaticity between the hand pattern and evoked colour (Dixon et al., 2000; Mills, 1999). The results showed that TD was significantly faster in naming colours if the priming hand pattern was congruent to the colour of the neutral target. The results can be interpreted to mean that hand counting patterns are indeed synaesthetic inducers for TD, but this does not indicate what caused the induction i.e. whether it was the specific hand patterns or numerical number represented by the hand pattern. Ward and Sagiv (2010) tested the different hand patterns shown in three different configurations: 1) a right hand, which was the left hand image is reversed; 2) presenting the hand on either the left or right side of the screen; 3) the orientation of the hand (a hand upside down or right side up). A significant main effect was found between the hand pattern configurations (i.e. handedness, orientation and visual field), and colour congruency but not on any specific hand pattern configurations. It did not seem to matter if the hand pattern was shown on a right hand, even though the synaesthete stated that only the left hand elicited colours. Ward and Sagiv (2010) suggest that the numerosity of the hand pattern evokes synaesthetic colours, but that the hand configurations modulated the size of the congruency effect, wherein more familiar images, such as a left hand, have a larger effect than hand configurations in unfamiliar orientations.

Continuing in a second Stroop experiment, dice patterns and (as controls) random arrays of dots, were compared, to test whether it is the numerical magnitude, or the way the dice patterns looked, which induced colour. The participant had to name the real colour of the stimulus (dice patterns or random arrays of dots) that were either congruently or incongruently coloured, according to TD's synaesthetic colours. A colour congruency effect was found, but it was only significant for the dice patterns, which is peculiar, because it implies that TD's synaesthetic colours are depended on the dice patterns (physical forms of the patterns), and not the numerical magnitude, otherwise the dots would have elicited colours. For one type of inducer, TD responds like a lower synaesthete (dice patterns), but with other inducers, he responds more like a higher synaesthete (hand-counting patterns).

2.4.3 Comparison between subtypes

The two subtype groups were once suggested to be one and the same (Hubbard et al., 2005). For example, the lower is related to the projector, because they are both involved in the way in which the synaesthesia is externally triggered and perceived. In the case of associators, the concurrent is internally experienced, which is similar to a higher synaesthete, due to the fact that the concept of the inducer can trigger synaesthesia, and both are experienced internally. According to Ward et al. (2007) the two groups are independent of one another. They report on cases of synaesthetes having both higher and projector characteristics, and synaesthetes with both lower and associator characteristics mixed together. For example, the synaesthete TD was a surface projector, and exhibited higher and lower inducers. Instead of a dichotomy, the subtypes could be seen as lying on a continuum, with varying degrees of associators and projectors, and varying degrees of higher and lower synaesthetes (Ward et al., 2007). The subtypes highlight the importance of individual differences between synaesthetes, and that they cannot be regarded as a homogenous group. It is for this reason that Smilek and Dixon (2002) recommend single case designs to avoid making unwarranted conclusions and generalisations.

2.5 SYNAESTHESIA AND ATTENTION

At the beginning of this chapter, some experiments were discussed that investigated whether or not synaesthesia is truly perceptual. Perceptual processing such as vision is an early process and occurs before attentional awareness. This brings about the question of whether attention is necessary for synaesthetic induction. If we look at letters, a certain level of perceptual processing needs to be undertaken before we can consciously recognise them. If, for example, the letter inducer is synaesthetically bound to a colour concurrent, then at some point during the processing of the letter, it can be assumed that it triggers the concurrent. However, it is still a question as to what point during this processing the cross-activation occurs. It could occur later, after considerable processing, or earlier, when the inducer occurs only on a subconscious level. Attention is considered a higher level process, occurring towards the end of perpetual processing. First-person accounts from synaesthetes describe their synaesthesia as automatic, but it would seem that synaesthetes need to be aware of the inducer first, before induction. The section below reviews some of the experiments designed to test whether or not attention is a prerequisite for synaesthetic induction.

Ramachandran and Hubbard (2001a) embedded shapes made of graphemes, which formed a particular shape (e.g. triangle, square, rectangle or diamond, see Figure 2.3 below) into a display of distracting graphemes. It was hypothesised that synaesthetes would find the shapes faster than non-synaesthetes. It is suggested that if the graphemes making up the hidden shape elicit synaesthetic colour, this is different from the distracter graphemes, and the shape will stand or 'pop’ out, making it easier to identify. Two synaesthetes and 40 controls were shown different grapheme matrices for one second, and asked to identify the hidden embedded shape as quickly as possible. The synaesthetes were better at identifying the shapes in 81.25% of trials, while the controls had a lower score of 56.4% correct. The authors argue that texture segregation is an early process of perception, and if synaesthetic colours help to segregate the hidden shapes of graphemes, it can be assumed that synaesthetic induction is also taking place early in perceptual processing, before overt attention (Ramachandran & Hubbard, 2001a). This is however not enough evidence to support the pre-attentive proposition of synaesthesia, because the sample was small and the trials were not timed.

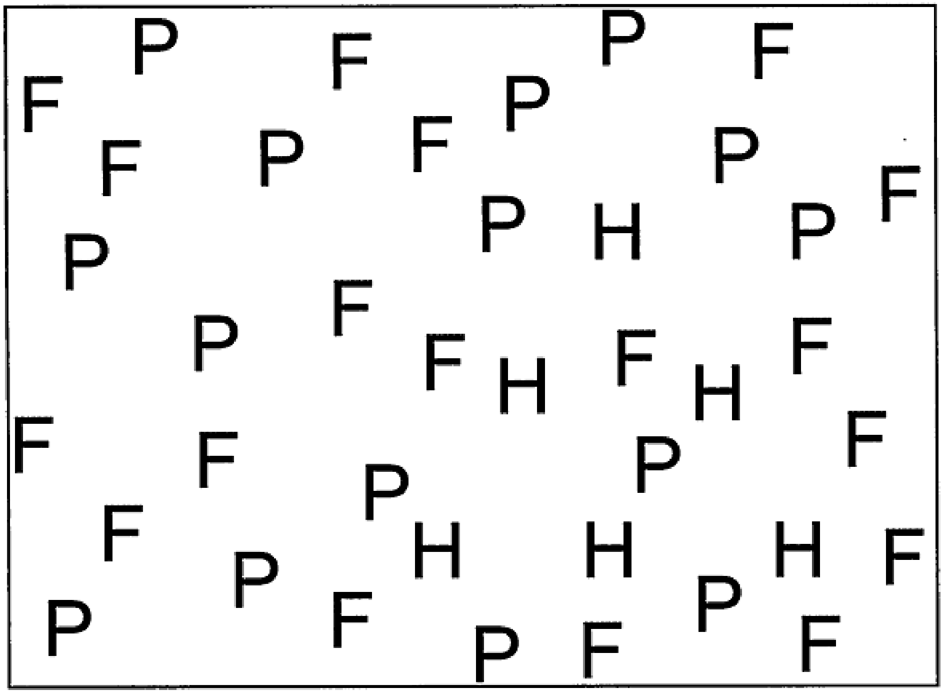


Figure 2.3: A triangle is formed by the Hs in the matrix. (Ramachandran & Hubbard, 2001a)

The same experiment was performed with six grapheme synaesthetes and 20 controls, and similar results were found, except that there were individual differences between synaesthetes; only five of the six synaesthetes performed better than the controls (Hubbard et al., 2005). A second control group was added to undertake the same type of task, except that the hidden geometrical shapes appeared in real colours. It was found that real colour provided a greater advantage to the control participants, which may be why they outperformed the synaesthetes (Hubbard et al., 2005).

Rich and Karstoft (2013) used a modified version of the embedded shape experiment to examine whether synaesthetes do experience a pop-out effect, but also took into account the individual difference between synaesthetes (e.g. projector and associator synaesthetes). The experiment was different in two ways, where the number of distracters was varied (see Figure 2.4 below) and only one shape was used (a triangle, either facing left or right). The participants were eight grapheme synaesthetes and eight matched controls, who were asked to decide which direction the triangle of Bs was facing, as quickly as they were able to. The synaesthetes were given a photism colour-naming test to discern their subtypes, and two were confirmed as projector and one as an associator. However, the rest could not be classified as either associator or projector, because they did not show the key difference in the photism colour-naming tasks, and therefore were classed non-projectors (see end of projector and associator section). If the pop-out advantage does exist, it would be evident in how quick and how accurate participants are in a search task such as the embedded figure task. The search slope should be relatively flat. The search slope is the ratio between the rate of time it takes to search for shapes by the accuracy. The data showed no significant differences in speed or efficiency of search between controls and synaesthetes; however, the synaesthetes were significantly more accurate at a set size of 64. Of the eight, only one synaesthete (one of the projectors) was more efficient than the matched control in searching. The authors argue that this could have been due to the control participant experiencing difficulty at larger set sizes. Overall, the synaesthetes did not show any difference in visual search from controls, and the study therefore does not support the claim of a pop-out advantage. Therefore, synaesthesia may not be pre-attentive.

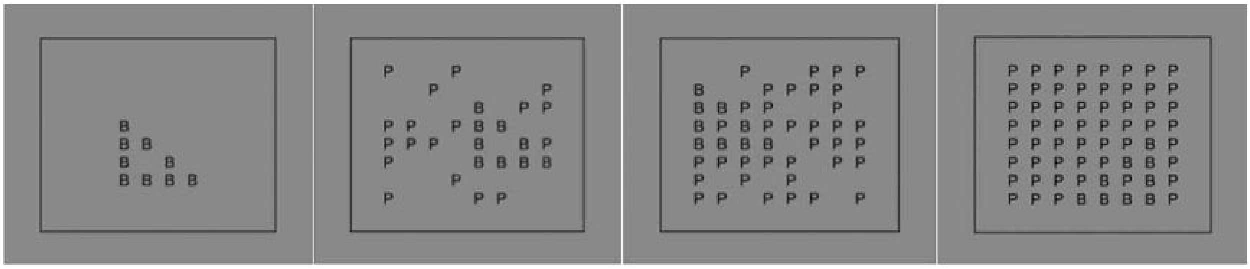


Figure 2.4: from left to right – set sizes of 9, 27, 45 and 64. Hidden triangle made of Bs which faces either left or right.

(Rich & Karstoft, 2013)

According to Mattingley et al. (2001) conscious awareness of the inducer is a requirement for synaesthetic induction. Fifteen synaesthetes and 15 controls were asked to name a colour patch. Before the colour-naming, participants were primed with a stimulus target that was also masked (i.e. a brief neutral target shown after the primer). The colour patch was either congruent, incongruent or neutrally coloured, according to the synaesthetic colours elicited by the primer. The results were significant for congruency effect and showed that synaesthetes were slower when the prime was incongruent to the colour patch. The authors then conducted the same experiment, except that the duration of the prime was shortened (26ms or 56ms), so that it was not consciously available to the participants. They did not find an effect on congruency when the prime was not consciously perceived, and the synaesthetes' results were similar to that of the control participants'. Their conclusion was that the inducer needs to be available to overt attention for synaesthetic induction to occur.

However, Johnson, Jepma and De Jong (2007) report on a study done with grapheme synaesthetes in which they made use of the concept of ‘attentional blink’, which refers to an effect wherein two target stimuli (both of which need to be identified by the participant), are shown in quick succession. Depending on the duration between the two stimuli targets (from 200ms to 500ms), participants have difficulty identifying the second target (Raymond, Shapiro, & Arnell, 1992). The utility of this impaired recognition was that it could be used to investigate dependence on attentional awareness. Adapting the concept to a synaesthete's inducer-concurrent preference, the researchers first asked 10 synaesthetes (nine associator and one projector) and matched controls to report the identity of the two targets, along with any synaesthetic colour that may have been elicited during the trial. The targets were embedded within distracter displays and matched according to personal inducer-concurrent colour profile. Each target consisted of a black letter and digit; the second target (inducer) was then blinked out of conscious awareness. What they found was that even though the synaesthetes were not able to report seeing the digit, they still experienced the synaesthetic colour associated with that particular ‘blinked’ inducer digit at a better-than-chance level. Mattingley et al. (2001) concluded that conscious awareness of the inducer is a requirement for synaesthetic induction, but that the conclusion may have been premature according to (Johnson et al., 2007). Johnson et al. (2007) concluded that even though the inducer digit was not consciously recognised, perhaps it was still processed up to a sufficient semantic level for concurrent activation. The variability of responses among participants should also be noted, where only half (5) of the participants reported seeing colours.

It appears that attentional awareness of the inducer is not needed for synaesthetic induction for some synaesthetes, where it is for others. This difference could be due to the phenomenological difference discussed above, i.e. between projector and associator synaesthetes. The question of attentional awareness and phenomenological difference will be returned to after a discussion of the visual system and neural correlates of synaesthesia.

2.6 NEURAL CORRELATES OF SYNAESTHESIA

When our eyes scan a line of text, or when we perceive ordinary household objects, our brain manages an extraordinarily complex process of encoding visible light frequencies into neural signals, which later give rise to qualia and experience. At the back of the eye, photoreceptor cells called rods and cones make up the retina. These cells are sensitive to light, and when a particular wavelength of light is detected, it is converted into neural signals, which are fed into the brain via the optic nerve (Bruce, Green, & Georgeson, 2003). The neural fibres leading away from each eye branch off into two bundles of axonal neural lines, and half of the axons move towards the opposite side of the brain, and weave through a convergence zone (see Figure 2.5). The convergence zone is called the optic chiasm, where no synaptic connections are formed between the interlaced axons coming from each eye (Kalat, 2004). Once the axons emerge on the opposite side, they join with the remaining axons that did not cross over to form the optic tract. The dorsal lateral geniculate nucleus is the endpoint for approximately 80 percent of the axons, and the remaining axons advance into subcortical areas, such as the superior colliculus and tectum (Wickens, 2005).

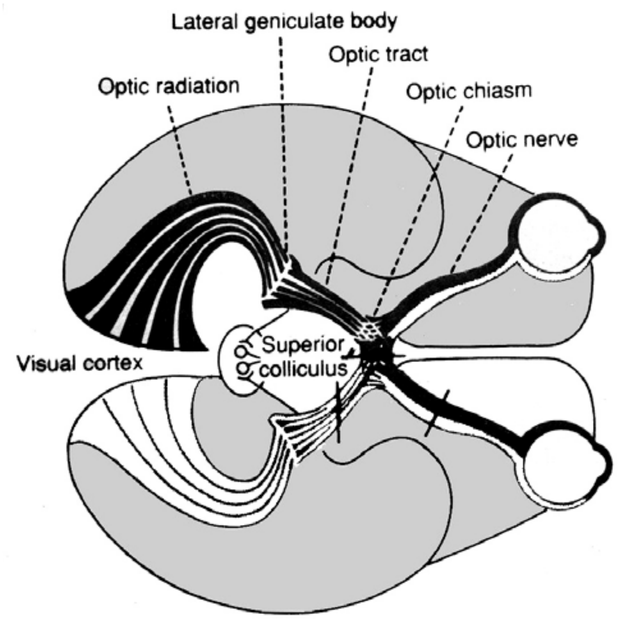


Figure 2.5: Visual pathway (www.vetmed.vt.edu/education/curriculum/vm8054/eye/cnsproc.htm)

The lateral geniculate nucleus (LGN) transmits the majority of neural signals between the eyes and visual cortex (Bruce et al., 2003). The axons then spread out from the LGN towards the back of the brain; these pathways are called optic radiations, and connect to the primary visual cortex in the occipital lobe (Wickens, 2005). The primary visual cortex V1 or striate cortex is the first area of visual processing (see Figure 2.7). Each hemisphere is responsible for analysing input from the opposite eye, e.g. the right visual cortex will process the left side of the visual scene (Kalat, 2004). The visual cortex is approximately 1.5 mm thick, arranged into six layers, and topographically mapped. Topographic layout, for example, means that if two adjacent photoreceptors on the retina are triggered, two adjacent areas in the visual cortex fire concurrently (Wickens, 2005).

2.6.1 Extrastriate cortex

Neural signals then project out from the V1 to the adjacent extrastriate cortical regions, beginning with V2. It is believed that the neural pathway diverges into 'two streams' following a dorsal (up) and ventral (down) route (see Figure 2.6); upwards towards the parietal lobe, and down to the temporal lobes (Baizer, Ungerleider, & Desimone, 1991).

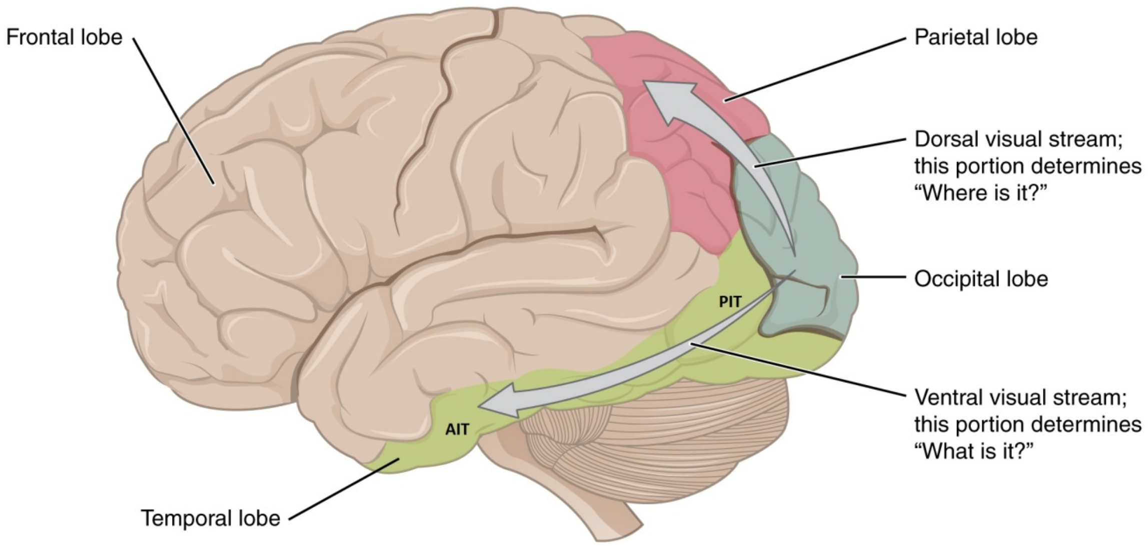


Figure 2.6: The two streams of visual processing: AIT - Anterior Inferior Temporal & PIT - Posterior inferior temporal gyri.

(cnx.org/content/m46557/latest/?collection=col11496/latest)

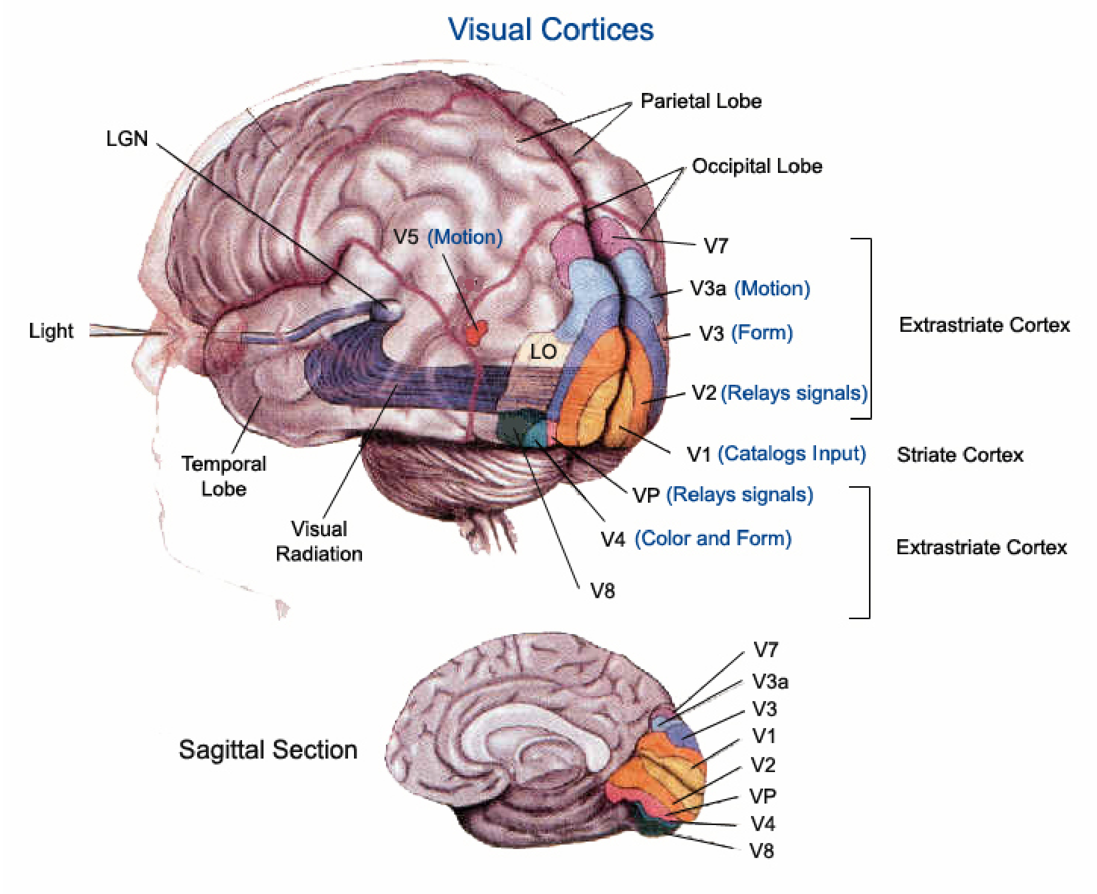


Figure 2.7: Extrastriate cortex (www.techcyn.com/feature.php?id=f2&issue=1)

The dorsal route is believed to be involved with 'where' visual information, such as movement and three-dimensional positions are; and the ventral route is believed to deal with the 'recognition' of objects, for example, form and colour (Figures 2.6 and 2.7). The dorsal and ventral routes fall on the following neurological sites: the dorsal route flows through the V3, VA3, medial temporal areas (MT or V5), Medial Superior Temporal areas (MST), and finally, the 7A; the ventral pathway goes down to the V4 followed by the posterior and anterior infero-temporal areas (PIT and AIT), located in the temporal lobe (Bruce et al., 2003).

The extrastriate cortical areas and their functions can be differentiated into a hierarchical system, with each stage of visual processing located further away from the

V1 (Maunsell & Newsome, 1987). There are at least 30 areas involved with later levels of processing, spanning the temporal, occipital and parietal cortex (Wickens, 2005). Each area cannot be definitively delineated; many overlap, and although commonly described as hierarchical, the connections between areas are not strictly linear, i.e. regions may project information to many areas not just the next in the hierarchy, and most of the connections are reciprocated (Bruce et al., 2003). De Haan and Cowey (2011) proposed a 'patchwork' or network model for the visual system, consisting of various cortical maps sensitive to particular forms of visual input (e.g. colour, form, movement). Activation of these cortical maps is on an 'as needed' basis, and depends on the type of visual input. The patchworks of cortical maps become more integrated and complex through use, e.g. a small child may not have the visual acuity of an adult, because they still need to see much more of the world. According to Hebbian learning theory, associative learning on a neuronal level is determined by the simultaneous firing of neurons, which can be summarised in the adage, 'cells that fire together, wire together' (Hebb, 1949). Each patchwork consists of cells; depending on need, they may activate at the same time as other patchworks. More simultaneous activation of each network increases the synaptic connections between networks, e.g. continuously practising a new skill. In this way, the brain can build itself according to experience.

2.6.2 Neuronal correlates of linguistic colour Synaesthesia

If synaesthesia is a result of abnormal binding between cortical areas responsible for visual processing, there should be evidence of abnormal cortical activity in the extrastriate cortex. Modern technology provides a means of studying the neural correlates of synaesthesia with brain imaging, e.g. Positron Emission Topography (PET), Functional Magnetic Resonance Imaging (fMRI), Magnetoencephalography (MEG) and Diffusion Tensor Imaging (DTI). Functional MRI can measure increased blood flow in the brain at a high spatial and temporal resolution (Hugdahl, 1995). If more blood flows to a particular area of the brain, it indicates increased activity. A higher concentration of oxygenated blood can be detected by magnetic resonance, because more oxygen affects the magnetic properties of haemoglobin (Wickens, 2005). A three-dimensional image can be constructed to localise areas of higher activity/increased blood flow. Researchers can study brain function by asking participants to complete tasks (e.g. cognitive tasks) during which brain images are taken to find areas of higher activity. In this way, the various areas of the brain can be functionally described.

Using brain imagining, researchers have been able to investigate the difference between synaesthetic colour and real colour processing in the brain. Hubbard et al. (2005), using fMRI, found that six grapheme synaesthetes had higher activity in the V4 (see Figure 2.7) when viewing achromatic letters, as compared to the controls. The V4 is associated with colour processing, and has been found to have higher activity when viewing abstract colour displays (Zeki et al., 1991). The researchers also found that some synaesthetes showed higher activity in earlier regions of the visual cortex V1, V2 and V3, and that the strength of the activity in these areas correlated with better performance on two behavioural measures (embedded figures and crowding test - see above). Sperling, Prvulovic, Linden, Singer and Stirn (2006) tested four grapheme synaesthetes and found that only two had a significant level of activation in the V4 and V8 when viewing achromatic blocks of letters. The V8 (see Figure 2.7) is also involved with colour perception (Hadjikhani, Liu, Dale, Cavanagh, & Tootell, 1998). The authors noted that the two synaesthetes who showed significant activation in V4/V8 described their synaesthetic experience as if appearing on a flat screen in their mind's eye, and the remaining two, with no V4 activation, experienced a blurry version of the letter on a transparent screen, also as if in their mind's eye (Sperling et al., 2006).

In similar language forms of synaesthesia V4 activation is found. Nunn et al. (2002) found that colour-hearing synaesthetes (n=13) had increased activity in the extrastriate cortex when listening to words that induced colours, as opposed to pure tones, specifically the left V4/V8. Steven, Hansen and Blakemore (2006) also found that a blind colour-hearing synaesthete had significant V4/V8 activation when listening to inducer words.

These experiments suggest that the V4 is involved in grapheme synaesthetic perception; however, activity in the V4 is not always found in grapheme synaesthetes. It can also be found in other sensory regions in the extrastriate cortex. Paulesu et al.

(1995) conducted an early study into colour-hearing synaesthetes (n=6), done with PET. PET imaging is an older technique, but is based on similar principles, where a chemical tracer is injected into the bloodstream, which can be detected by sensors. A greater concentration of the tracer in areas of the brain indicates higher blood flow, and higher activity. Participants were blindfolded and listened to words and tones. Both synaesthetes and controls showed activity in language areas, but synaesthetes did not show activity in the V4. Rich et al. (2006) compared six grapheme synaesthetes and matched controls to study the difference between imaginary colour and synaesthetic colours. The imagery task involved participants making judgments about greyscale images of two objects, deciding which is darker in colour (e.g. a banana and a lemon). For this task, both synaesthetes and controls had higher activation in the V4. In the synaesthetic task, participants were presented with blocks of letters: chromatic letters, achromatic letters and a baseline condition. The synaesthetes showed greater activity in the left medial lingual gyrus (see Figure 2.8 below) when viewing achromatic letters, a region associated with colour knowledge (Chao & Martin, 1999; Martin, Haxby, Lalonde, Wiggs, & Ungerleider, 1995; Price, Moore, Humphreys, Frackowiak, & Friston, 1996).

Rouw, Scholte and Colizoli (2011) point out that although many studies seem to find activation in the V4, this may not always be consistent, because normal colour processing is supported by many cortical networks, and not just one region, e.g. the V8 (Hadjikhani et al., 1998). The authors highlight that the V4, besides being sensitive to colour (Zeki et al., 1991), also responds to shape (Desimone and Schein, 1987) and is also involved in attention (Chelazzi, Della Libera, Sani, & Santandrea, 2011). They explain that when delineating regions of interest (ROI) in the brain, such as colour processing regions, a difference in attentional load between baseline conditions and experimental conditions could cause erroneous activations in areas such as V4.

Individual differences between synaesthetes can also affect the findings, especially if there are a small number of participants in a given study. Rich et al. (2006) reported that the synaesthetes in their study describe their colours as appearing in the 'mind's eye' and two synaesthetes said their colours appeared on a dark screen, or on an overlay on top of letters. This could mean that the majority may have been associator synaesthetes, but at least two also had projector attributes. It has been suggested that projector/associator and higher/lower synaesthetes would have different neural correlates, which could explain some of difference between the studies (Ramachandran & Hubbard, 2001b).

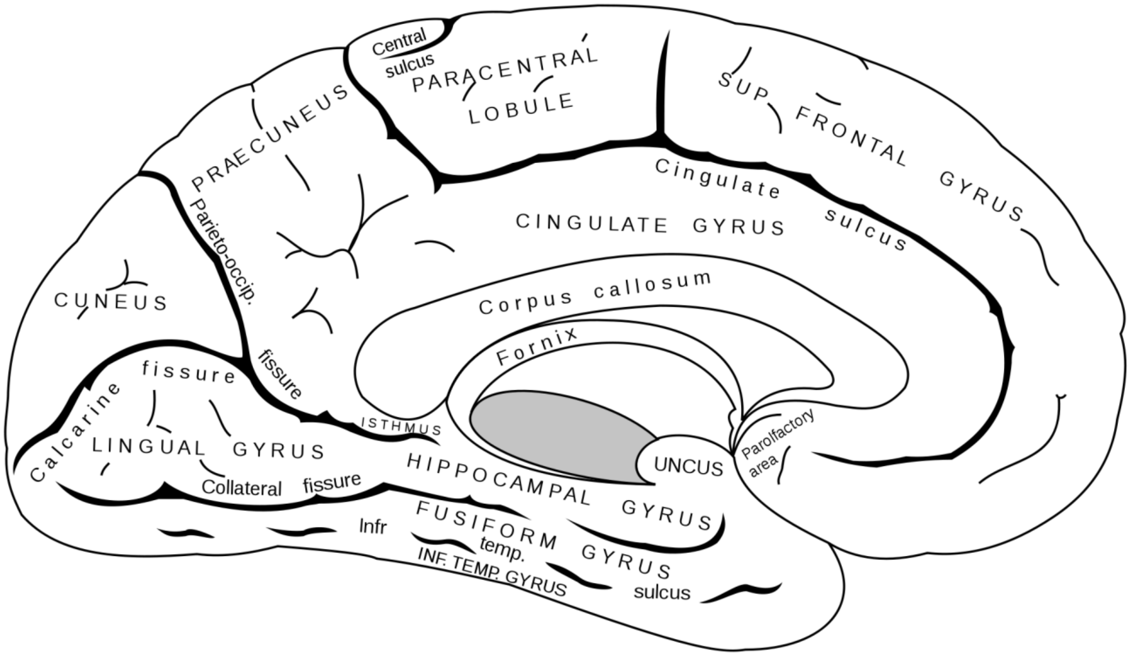


Figure 2.8: Lateral view of brain: fusiform gyrus. (commons.wikimedia.org/wiki/File:Gray727.svg)

Apart from functional differences in the brain, synaesthetes have structural differences from non-synaesthetes. Diffusion Tensor Imaging (DTI) measures what the process of diffusion does to the molecular directionality of water molecules in the neuronal tracts. The process of diffusion changes the water molecules differently in the grey matter and white matter in the brain. The directionality in grey matter is isotropic (unrestricted), whereas white matter is highly anisotropic (restricted) (Bargary & Mitchell, 2008). White matter, such as the optic radiations (see Figure 2.5), connects cortices in the brain, and by measuring anisotropic white matter, it is possible to infer connectivity in the brain, and roughly to determine the percentage of axons flowing in a unified direction, or the higher number of axonal tracts. Using DTI, Rouw and Scholte (2007) found that synaesthetes have greater connectivity to the inferior temporal cortex, close to the fusiform gyrus (see Figure 2.8), including greater connectivity to the parietal and frontal cortex. It was also found that projectors had greater connectivity in the inferior temporal cortex, close to fusiform gyrus than the associators. The different structural connectivity between subtypes may explain some of the inconsistencies in the studies mentioned so far. The V4/V8 is part of the fusiform gyrus, and greater connectivity to these areas could account for the externally localised photisms, which projectors describe. These structural differences may also account for the difference in attentional awareness of the inducer. Earlier regions such as the V4 may be needed for externally-projected synaesthetic colours. For projector synaesthetes, synaesthetic activation thus occurs early, before conscious awareness of the inducer. This may be why there were disparities in the experiments mentioned above, about whether conscious awareness of the inducer is a requirement for synaesthetic induction. There may have been different synaesthetes (associators) in each experiment, and projectors may have more pre-attentive synaesthetic colours than associators. Also, see Rouw and Scholte (2010) for an updated view of the neural differences between projectors and associators.

Synaesthetic induction is not isolated to the occipital-temporal regions. Weiss, Zilles and Fink (2005) tested nine grapheme synaesthetes and found these synaesthetes to have significant activity in the left intraparietal sulcus (see Figure 2.9), where additionally, synaesthetes viewing incongruent graphemes showed bilateral activity in the dorsolateral prefrontal cortex, which includes the dorsal (top) of the frontal cortex (Figure 2.9). Weiss et al. (2005) suggest this is due to the task involving conflicting stimuli.

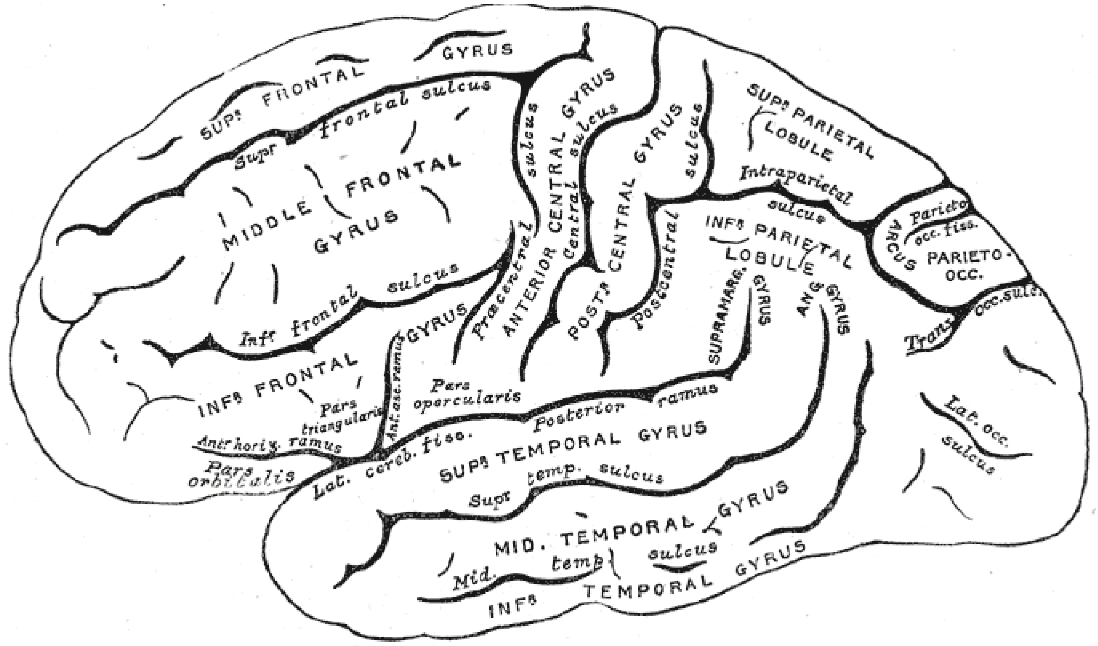


Figure 2.9: Brain regions (commons.wikimedia.org/wiki/File:Gray726.svg)

Rouw et al. (2011) compared the many brain imaging studies, including some mentioned above, and found a pattern of activation that emerged. This led them to suggest that synaesthetic perception relies on three hubs of cognitive functions: sensory processing (visual cortex), attentional and spatial binding (parietal cortex), and cognitive control (frontal cortex). The evidence reviewed above indicates that synaesthetic colours are also activated by the same sensory areas that process normal colour, e.g. V4 (Hubbard et al., 2005; Nunn et al., 2002; Steven et al., 2006). The next key process is the attentional binding of the inducer to the concurrent (or the 'where' stream of visual processing, see Figure 2.6), linked to activity in the parietal cortex. The parietal cortex is associated with visual feature binding; a network for spatial attention. For example, Nunn et al. (2002), Steven et al. (2006), and Weiss et al. (2005) found increased activity in the inferior parietal lobule (see Figure 2.9). Activity in the parietal cortex suggests attentional processes are important for synaesthetic perception. Also see Esterman, Verstynen, Ivry and Robertson's (2006) TMS study below in the disinhibition section, which suggests that the parietal regions are important for 'hyperbinding' inducers to concurrents. Finally, the cognitive control functions are supported by the frontal cortex (see Figure 2.9). Rouw et al. (2011) report that many studies find activation in the frontal cortex, e.g. frontal gyrus (Paulesu et al., 1995; Sperling et al., 2006; Weiss et al., 2005). The frontal regions are involved in consolidating conflicting sensory information, such as in the Stroop interference task, wherein synaesthetes respond to conflicting stimuli.

2.7 NEUROCOGNITIVE MODELS OF SYNAESTHESIA

2.7.1 Cross-activation

Ramachandran and Hubbard (2001a, 2001b) have proposed that within a synaesthete's brain, cross-activation occurs due to extra-structural connections between cortical maps. They likened ‘cross activation’ to a neural phenomenon known as 'phantom limb', wherein an arm amputee may begin to experience tactile sensations from the amputated appendage via direct tactile stimulation of either certain areas of their face or the surviving arm. The cortical areas of the hands and face are in close proximity in the parietal cortex, and once the brain does not receive input from the amputated arm, the surrounding cortical regions begin to remap onto the missing arm’s cortical network (Ramachandran, Rogers-Ramachandran, & Stewart, 1992). This remapping would account for the sensations from the phantom arm. The cerebral cortex is capable of accelerated remapping, which in one instance, required fewer than four weeks to rewire post amputation (Ramachandran, Rogers-Ramachandran, & Cobb, 1995).

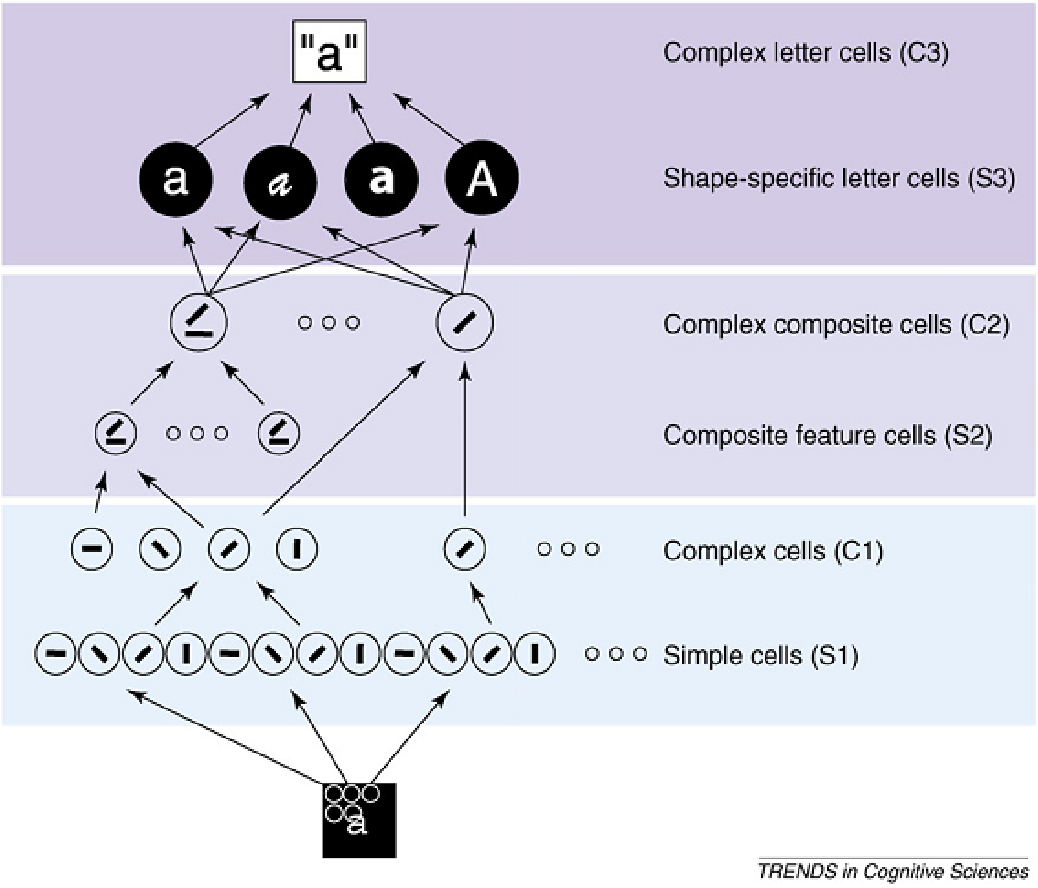
Similarly, in grapheme synaesthesia, two adjacent cortical regions may be structurally wired in this manner. Specifically, cross-activation between regions in the ventral pathway, the V4 colour centre and adjacent grapheme recognition areas, located in the fusiform gyrus.

As discussed in the neural correlates section above, there is much support in the literature to be found for this model of grapheme synaesthesia. Hubbard et al. (2005) tasked their participants to view black and white graphemes (either alphabetic or numeric) and a control stimulus of non-linguistic symbols, whilst monitoring neural activity. They found a significant difference in activation of the V4 in synaesthetes when viewing letters, as opposed to the case of the controls, who showed no significant activity. As mentioned above Nunn et al. (2002); Sperling et al. (2006); Steven et al. (2006) find similar activation in V4 during synaesthetic perception. Rouw and Scholte (2007) found that synaesthetes' brains are structurally different from those of non-synaesthetes’, in particular, greater connectivity in the temporal, parietal and frontal regions. Projector synaesthetes show greater connectivity to the right inferior temporal cortex, which is in close proximity to V4. In addition to V4 activation, a two stage model was introduced into the cross-activation model to account for parietal activity (Hubbard, 2007; Hubbard, Brang, & Ramachandran, 2011). For example, Nunn et al. (2002) and Steven et al. (2006) found increased activity in the inferior parietal lobules, and greater connectivity to the parietal areas (Rouw & Scholte, 2007). The first stage is the cross activation in the fusiform gyrus (Hubbard et al., 2005), and the second stage is the binding of the inducer to the concurrent in the parietal cortex (Esterman et al., 2006).

A criticism of cross-activation theory is that fMRI studies cannot accurately determine when the V4 is active during synaesthetic perception. Cohen Kadosh, Cohen Kadosh and Henik (2007) have argued that fMRI has a temporal measurement limitation, which makes a determination of the order or sequence of activation difficult, meaning that although it may be that the V4 is active, it cannot be accurately determined 'when' exactly during the process of synaesthetic induction it is active. Certain neural activities may then be incorrectly attributed to synaesthetic induction. More recently, Brang, Hubbard, Coulson, Huang and Ramachandran (2010) used MEG to study four projector synaesthetes and matched controls. MEG can detect magnetic activity from neurons firing in the brain with a high temporal and spatial resolution. The authors showed the same activation in V4 when viewing achromatic letters. After stimulus presentation, the MEG recorded activation of the posterior temporal grapheme areas (PTGA) between 105ms and 109ms, and activity in the V4 at 110ms and 114ms in synaesthetes. Importantly, the findings indicate that activation of grapheme form areas and colour areas in the fusiform gyrus are nearly simultaneous, which is why it can be argued that cross-activation between those areas is mediated by structural connections.

2.7.1.1 Cascaded cross-tuning model for grapheme synaesthesia

In recent years, cross-activation theory has been updated by integrating a hierarchical feature analysis of letter processing (Brang et al., 2010). Letter recognition is based on the Pandemonium model, which is a hierarchical system of increasing levels of complexity, starting with basic components, and progressing to letter identification (Grainger, Rey, & Dufau, 2008; Selfridge, 1958). Each level consists of cells sensitive to specific features (basic, composite or shape), each preceding level cascades into the next, feeding forward until letter shape is identified (see Figure 2.10).



TRENDS in Cognitive Sciences

Figure 2.10: Hierarchical letter recognition model.
(Grainger et al., 2008)

Brang et al. (2010) propose that cross-activation occurs at the component level. Each basic feature, for example a perpendicular line, is the most basic component feature for the letters 'l' and 'L', the brain cells sensitive to those basic component features in the

PTGA cross-activate basic colour components in the V4. In a similar manner as for the way in which the basic features progress into each level, they also 'cross-tune' basic colour features, which eventually cascade into an identifiable shape and colour (see Figure 2.11).

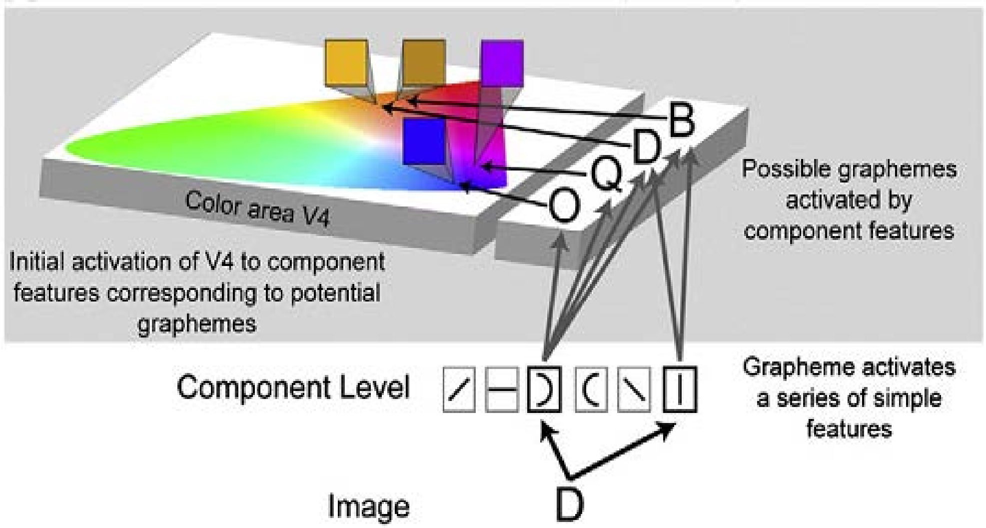


Figure 2.11: Cross-tune cascading model of Grapheme Synaesthesia.
(Brang et al., 2010)

Support for the pandemonium model comes from experiments designed to show that letters have visual similarities, i.e. that they share some basic features. Courrieu, Farioli and Grainger (2004) built a matrix using the time it took participants (n=42) to discriminate between pairs of letters, either identical or different (e.g. #b#p# or #b#d#). They were asked to respond when the pairs were different as quickly as possible. An inverse discrimination matrix was generated from the time taken to discriminate between different pairs of letters, and it was found that it takes longer to discriminate if letters are more visually similar. The authors calculated 14 dimensions or groups of letters with visual similarity and proximity in component shape, for example v-shaped letters, such as 'v','y'. There were also 11 dimensions, which the authors described as distinctive features. When the letters are closer in shape, they compete more in the lower levels of a hierarchical feature system; this is why it takes longer to discriminate between them. Brang, Rouw, Ramachandran and Coulson (2011) created colour component matrices for 16 projector and 36 associator grapheme synaesthetes. The authors found that synaesthetic colour components correlated to the letter shape similarity dimensions found by Courrieu et al. (2004). That is, letters that were similar in shape were also similar in synaesthetic colours; however, projectors showed a greater correlation to shape similarity than did associators.

2.7.1.2 Development

Ramachandran and Hubbard (2001b, 2003) suggest that extra-neural pathways are perhaps left behind from a defective neural pruning process, which takes place during early development. A developing brain has a greater number of connections between and within cortical regions, and through the process of axonal pruning some of these connections are removed. It has already been established that synaesthesia has a genetic component. Therefore, if a gene has affected the pruning process, extra-prenatal connections might remain. The untrimmed structural connections between cortical regions become the mode for cross-activation.

The cross-activation hypothesis was developed primarily with grapheme synaesthetes, but it could also explain the other various forms of synaesthesia (Hubbard et al., 2011; Ramachandran & Hubbard, 2001b). The genes affecting axonal pruning may manifest irregularly in the brain, leaving multiple areas with the potential for cross-activation. This irregularity could also explain why synaesthetes have a higher chance of developing more than one form of synaesthesia.

2.7.2 The Disinhibition Feedback hypothesis

The disinhibition feedback hypothesis proposed by Grossenbacher and Lovelace (2001) takes a different stance, suggesting that it may not be necessary to have extra connections between the brain regions to cause cross-modal activation. Synaesthetes may not have a different neuronal structure, but rather, abnormal inhibitory processes which facilitate synaesthesia. As explained earlier, the human visual processing system is hierarchically organised. Visual input goes through different levels of processing, each level involves processing different components, and each level increases in complexity. The authors explain the process of synaesthetic induction as involving two processing pathways: an inducer pathway, and a concurrent pathway. An underlying assumption of this model is that within each pathway, there is a complete 'representation' of the triggering inducer and concurrent percept. It is assumed that along the pathway the inducer representation triggers the corresponding concurrent representation. One possible route could be direct activation or 'cross-activation', as proposed by Ramachandran and Hubbard (2001a, 2001b). Grossenbacher and Lovelace (2001) have called these 'horizontal' connections between the inducer pathway and the concurrent pathway. Instead of horizontal connections, Grossenbacher and Lovelace (2001) propose that the inducer representation activates the concurrent representation via a multimodal convergence region in the brain. When the inducer representation travels through the successive stages of processing, it reaches – along with other processing pathways – a multimodal convergence area in the brain. In this convergence area, the inducer representation may feed down into the concurrent pathway, activating the concurrent representation (Figure 2.12). In normal brains, the two pathways are ordinarily inhibited, and are prevented from feeding back into other pathways.

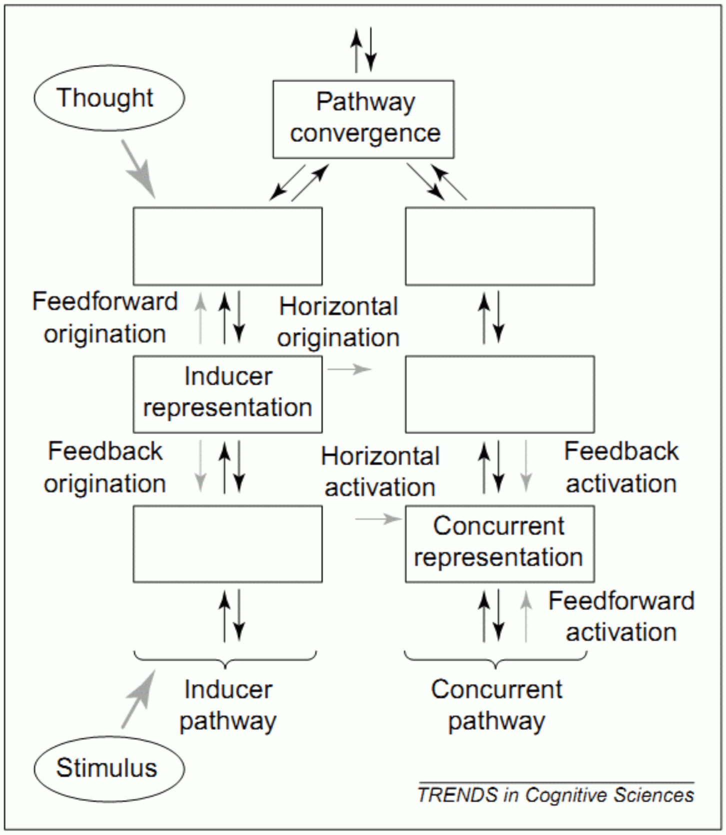


Figure 2.12: Disinhibition feedback model. (Grossenbacher & Lovelace, 2001)

The authors proposed the superior temporal sulcus as a possible candidate for the multimodal convergence area; however, there is currently no evidence to support this (Rouw et al., 2011). There is, however, support for alternative areas, such as the parietal cortex. For example, as mentioned in the neuronal correlates section above, Rouw and Scholte (2007) showed that synaesthetes had greater connectivity to the parietal cortex. According to Esterman et al. (2006), the use of transcranial magnetic stimulation (TMS) over the right posterior parietal lobe attenuates Stroop interference in projector synaesthetes (n=2). The authors reasoned the parietal regions are important for synaesthetic induction.

In order to understand the way in which the parietal regions are involved in synaesthesia, we must return to an early assumption about the direction of activation between inducers and concurrents. Synaesthesia is not strictly unidirectional, that is, graphemes giving rise to colours, but the reverse, i.e. colours evoking graphemes, is also possible. Reverse activation is called bi-directional synaesthesia, and has been observed in synaesthetes, but only on an unconscious level (see Johnson et al., 2007). In an earlier section, the synaesthete TD was shown to be a higher synaesthete, because the numerosity of the inducer elicited colours (Ward & Sagiv, 2010). To test whether colours can elicit numbers, the researchers showed TD pictures of finger-counting patterns that were Photoshopped in colours that were either coloured congruently or incongruently to the numerosity of the pattern. He was asked to name either the number of fingers or the colour of the hand. It was found that congruency had an effect in both tasks. Naming the number of fingers, TD was faster when they were congruent to the colour (e.g. the numbers of fingers and colour of the hand were the same) and when asked to name the colours of the hand, he was also faster when they were congruent (e.g. the colour of the fingers were the same as the number of fingers). Taken together, the congruency effect is found in both directions, and the fact that the colour of the hand can interfere with number naming suggests reciprocal activation, i.e. bidirectional activation between colour and numerosity.

Cohen Kadosh et al. (2007) used fMRI and event-related potentials (ERP), which is a method for determining the sequence of electrical activity over the cerebral cortex by placing electrodes on specific locations on the scalp. These techniques were used to compare comparatively similar Stroop tasks in a projector grapheme synaesthete and 6 matched controls. The synaesthete was unique in this instance, because he had conscious bi-directional synaesthesia. If one could test both directions of activation, it may be possible to find a common area involved. To test colour against numerosity activation in the first task, the participants compared the physical size of a pair of coloured triangles, which were different in size. Participants were required to indicate which coloured triangle was larger in size. Each coloured triangle corresponded to a number for the synaesthete. The researchers were testing whether congruency affected reaction times. For example, in the congruent condition, the larger triangle will appear as a synaesthetic colour associated with a larger number inducer and vice versa for the incongruent condition. In the second task, participants were required to compare a pair of numbers, and were asked to determine which had the largest numerical magnitude. Similarly, the numbers were coloured congruently or incongruently according to the synaesthete's colours. It was found in both tasks that the incongruent condition caused significantly slower reaction times for the synaesthete, but not for the controls. Importantly, the fMRI and ERP results indicate that even though both caused Stroop interference, each task depended on different areas of the brain being active and brain areas were active at different times during Stroop interference. In the triangle comparison task, fMRI showed significant activation for the synaesthete in the left fusiform gyrus for the incongruent condition, but controls did not show a significant difference. These findings were consistent with previous findings (Hubbard et al., 2005; Nunn et al., 2002; Sperling et al., 2006). In the ERP, the N170 component showed a higher voltage in the incongruent condition between 160ms and 200ms after the stimulus was presented. The N170 component refers to the average of electro-potentials over specific areas of the scalp at a specific point in time; it is suggested that the N170 component is related to early orthographic processing (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999). These findings are consistent with early visual sensory areas contributing to synaesthetic induction and cross-activation. In the numerical comparison task, the synaesthetes' reactions were also slower during incongruent trials, but this was not the case for controls. In ERP, the synaesthete showed activity over a different component, the P300 component, located over the parietal area (Linden, 2005) and purported to be associated with the categorisation of inputs (Kok, 2001). The fMRI results were consistent with the ERP results, and showed activity in the left intraparietal sulcus and left angular gyrus (Figure 2.9), similar to Esterman et al. 2006; Weiss et al. (2005), as discussed above. These results are consistent with later processes and support a disinhibition mechanism. Cohen Kadosh and colleagues add that inconsistent findings between researchers (e.g. fusiform or parietal activation) can be attributed to the different tasks used in different studies, as in this experiment, where the two tasks each modulated a different brain area.

Furthermore, in the triangle comparison task, bi-directional activation is shown to be genuine. Cohen Kadosh and colleagues propose that synaesthetes may all have these bi-directional connections, but that they are normally inhibited; in this particular case, the task creates an opportunity for these connections to be disinhibited (the authors use the term 'unmask' instead of disinhibition).

More recently Neufeld et al. (2012) analysed fMRI data with a functional connectivity method of analysis, comparing 14 colour-hearing associator synaesthetes to matched controls. Three predefined regions were selected: the left inferior parietal cortex IPC (Figure 2.9) and both sides of the auditory cortex (Figure 2.9) were analysed for functional connectivity during auditory perception. It was found that when listening to tones and chords, synaesthetes' left IPC had greater connectivity to the left auditory cortex and right visual cortex, but earlier than V4. Controls did not show any connectivity differences in these regions. The authors argue that evidence supports the disinhibition model, because cross-activation implies that instead, there would be significant connectivity between the auditory cortex and visual cortex, which was not in fact the case.

It should be noted that the modality of the inducer stimulus, that is whether the letters or words are heard or seen, may each rely on different neuronal mechanisms. Colour-hearing may rely on disinhibition in the parietal cortex, and coloured graphemes may rely on the earlier visual cortex, mediated by a cross-activation mechanism. One would need to test groups of grapheme synaesthetes and colour-hearing synaesthetes specifically to understand the relationship fully. This is why researchers ought to take care when reporting the underlying modalities of the inducer, because some synaesthetes can be induced by both verbal and visual inducers (Rouw et al., 2011).

2.7.3 The Reentrant Hypothesis

The reentrant hypothesis proposes that synaesthesia depends primarily on the perceived meaning of an inducer (Smilek et al., 2001). This implies a similar mechanism to disinhibition, wherein feedback signals from a convergence zone on a higher level of processing alter an earlier visual area through feedback signals. The authors suggest that once initial visual processing occurs in the early visual areas V1, V2 and V4, this is followed by the anterior regions PIT and AIT (see Figure 2.6), where meaning is processed. It is suggested that these anterior regions feed the 'reentrant' signals back to alter earlier colour processing areas V4.

Smilek et al. (2001) used number-masking tasks to show that the meaning of a number viewed against a coloured background can change the way in which earlier visual areas (e.g.V4) segregate it from the background. A projector synaesthete and seven controls were asked to identify a black digit flashing on a screen with a coloured background, followed by a masking symbol. The background colour of the screen was coloured either incongruently or congruently, according to the synaesthete’s number-colour associations. It was observed that the synaesthete was less accurate in identifying black numbers presented on coloured backgrounds congruently matched to her synaesthetic colour, whereas the controls did not show a congruency effect. What this means is that, for her for example, the number two has the colour red projected onto it; briefly showing the number two on a red background decreased her identification accuracy. According to Smilek et al. (2001) reentrant signals may be responsible for lower accuracy, because once the number is identified by meaning areas, reentrant signals project back to the V4 altering the way in which the number is segregated from the background. The number and background may have blended together, making it difficult to tell them apart.

The reentrant hypothesis is similar to disinhibition, but is, based on how an inducer is interpreted, or on its perceived meaning. Myles, Dixon, Smilek and Merikle (2003) showed that the context in which a grapheme is presented affects how it is interpreted, and subsequently, affects the synaesthetes' concurrent experience. The authors presented a number-colour synaesthete, JD, with grapheme inducers that were ambiguous e.g. Z, which is similar to the form of the digit ‘2’ and the letter ‘Z’. Each ambiguous grapheme was shown in a colour (either congruent or incongruent) and presented in two different contexts (either a string of letters, or of numbers), respectively. The participants had to name the colour of the ambiguous symbol in each context. The aim was to test whether the same ambiguous symbol elicited a different synaesthetic colour, depending on its context, and hence, the symbol would be either congruent or incongruent, depending on its context. The results showed that the synaesthete did indeed experience Stroop interference from the ambiguous symbol depending on how it was interpreted. For example, the synaesthete sees the digit ‘2’ in dark green, and the letter ‘Z’ in brown. If the ambiguous symbol Z is coloured dark green, and shown in a letter context it would be incongruent if interpreted as a letter and cause slower colour-naming. The same coloured symbol would be congruent if interpreted as a number, and would have no interference effects. In one context, the ambiguous symbol is congruent, and in another, it is incongruent. It should be noted that only three ambiguous graphemes were tested, and only two showed context-dependent congruency. However, in another study, Dixon, Smilek, Duffy, Zanna, and Merikle (2006) tested the same premise with a different synaesthete using five ambiguous graphemes and found similar results. The studies show that the context of the grapheme can change its meaning and subsequent concurrent experience.

The authors suggest that the results have implications for current synaesthesia models, because if synaesthetic induction is connected to the physical form of the grapheme, the 'cross-activation' would occur earlier in processing, before processing of semantic meaning. The colours experienced because of the ambiguous symbols show that the same form can elicit two different photisms, depending on its 'meaning'. This re-entrant signal from the meaning areas of the brain feed back to the colour processing areas to alter perception. Furthermore, subjective reports from synaesthetes (see Chapter One) state that the font type or size of graphemes do not affect the synaesthetic colour, where it is the meaning and not the physical form of the inducer that determines synaesthetic colour (Smilek et al., 2001).

2.7.4 Summation of neurocognitive models

The above models for grapheme synaesthesia can be grouped into two types of connection mechanisms, namely structural local connectivity (cross-activation), or functional long distance connection (disinhibition and reentrant). Which mechanisms predominate may depend on the type of synaesthesia and phenomenology of the synaesthetic experience. In grapheme synaesthesia, the colour region and grapheme recognition areas are already close together in the fusiform gyrus, which is why cross-activation or local connectivity constitutes a reasonable argument for abnormal connectivity. However, if the form of synaesthesia involves other sensory areas that are not close together, such as colour-hearing, or if the synaesthesia is not externalised, then a long distance mechanism could be argued for, e.g. disinhibition or a reentrant mechanism. Therefore, both of these mechanisms can be valid, depending on the type of synaesthesia and the phenomenology of the experience. The cross-activation experiments predominantly test projector synaesthetes, which suggests that cross-activation can better describe the phenomenology of externalised colours. Local connectivity in the early visual areas could account for some synaesthetes seeing their photism externally. Van Leeuwen, Den Ouden and Hagoort (2011) found evidence for this when they compared a group of projectors (9 surface and 6 space) and associators (n=5) using a dynamic causal modelling (DCM) method. DCM is a hypothesis-driven method of data modelling. In this case, fMRI data was used to model the effective connectivity between brain areas and modulation of these connections. It was found that projectors' synaesthetic experiences are mediated by early visual areas, whereas associators' synaesthetic experiences are mediated by later processing areas, such as the parietal cortex. This is corroborated by much of the evidence described above for each mechanism, where evidence for the cross-activation experiments often uses projector synaesthetes, and this may be why earlier visual areas such as V4 are implicated. Associator synaesthetes instead may rely on later regions such as the parietal cortex, mediated by disinhibition.

In summary, synaesthesia begins to develop at an early stage of life around the start of primary education. Watson, Akins, Spiker, Crawford and Enns (2014) suggest that synaesthesia may develop because of a need; associating numbers or letters to colour could have helped overcome a learning obstacle. This is likely because of the high prevalence of linguistic types of synaesthesias (Day, 2013). It has been suggested that language and metaphors are related to synaesthesia, and that in fact, it could be argued that language is a form of synaesthesia (Ramachandran & Hubbard, 2001b). For example, when you read this sentence, the graphemes are automatically becoming sub-vocalisations in your mind. Each letter or word can be seen as inducers that involuntarily evoke phonemic concurrents. It might be suggested that reading could accurately be called ‘word-sound synaesthesia’. The developing brain is essentially adapting to its environment in early life, learning how to read and write requires years of study. Learning a new skill recruits specific task-related patch networks of neuronal cells in the brain, similar to the patchwork system for the visual system described by De Haan and Cowey (2011). Learning how to pronounce and visually recognise the shapes of letters activates the necessary areas in the brain, e.g. grapheme regions and auditory regions. Over time, through hebbian learning, these recruited networks begin to rewire synaptic connections together to better adapt to the particular task (Hebb, 1949).

As a child, a synaesthete may come to associate a letter with a particular colour, where at first these associations are weak (Simner et al., 2009). But as he/she gets older, the synaptic connections of the grapheme areas and colour areas become stronger, and with more use, more consistent associations form (Rich et al., 2005). The phenomenology of how the synaesthesia is experienced may determine the mechanism connecting each particular region. For example, projector synaesthetes have externalised colours, which rely on early regions of the visual system. Because the grapheme recognition region and colour region V4 are in close proximity in the fusiform gyrus, a cross-activation between these regions may be formed to externalise synaesthetic colours. On the other hand, associator synaesthetes may prefer internalised colours, which is why the parietal areas are more active and are connected to the early visual areas through a disinhibition mechanism, because they are not close together.

2.8 NON-CONGENTIAL SYNAESTHESIA

In the final section of this literature review, different types of cross-modal experiences similar to synaesthesia are described.

2.8.1 BRAIN TRAUMA

Brain injury has been known to cause acquired synaesthesias. Brain injuries naturally cause the brain to heal itself; however, the repairing process can leave behind aberrant connections. Beauchamp and Ro (2008) have reported on a case of acquired sound-touch synaesthesia as result of a stroke, where a few months after suffering a stroke, a woman reported being able to feel certain sounds in her body. If the damaged areas in the brain subsequently rewired some regions together abnormally, it is logical to argue that structural changes could be responsible, and also gives credence to the cross-activation hypothesis. In a case of sensory deafferentation (a technical term for the elimination of nerve fibres), a man with retinitis pigmentosa started losing his sight in childhood, subsequently becoming entirely blind by the age of forty. Peculiarly, he began experiencing a form of synaesthesia (Armel & Ramachandran, 1999), where tactile stimulation to his hand caused intense visual phosphenes. Ramachandran and Hubbard (2001b) suggest that it may have been the lack of activation in the visual areas which caused tactile pathways to activate them, assuming a similar mechanism to that of a phantom limb, as described earlier.

People who suffer from Temporal Lobe Epilepsy (TLE) may report experiences similar to synaesthesia (Cytowic & Eagleman, 2009). These seizures cause sudden electrical discharges in the brain that adversely affects the brains structure. Ramachandran and Hubbard (2001b) suggest that the cross-activation hypothesis could explain this intense ephemeral binding mediated in the temporal cortex, which causes a similar mixing of the senses. However, Cytowic and Eagleman (2009) argue that although there are overt similarities between TLE and synaesthesia, further research is needed to establish whether it is comparable to the neural architecture and consistency of naturally-developed synaesthesia.

2.8.2 INDUCED

2.8.2.1 Drug induced

There are pharmacological ways to induce cross-modal experiences without significant structural changes to the brain. Psychedelic experiences (e.g. LSD, mescaline) may resemble synaesthesia (Aghajanian & Marek, 1999). Grossenbacher and Lovelace (2001) suggest that the similar experiences of hallucinogenic drugs and synaesthesia support the disinhibition hypothesis, because this removes the need for abnormal structural changes in the brain. Hubbard et al. (2011) and Ramachandran and Hubbard (2001b) argue that the neural mechanism may not be the same as congenital synaesthesia, and that the similarities are superficial and temporary, including the fact that not all people may experience the same cross-modal experience under the influence of drugs. More recently, Sinke et al. (2012) compared congenital and acquired (e.g. brain damage) forms of synaesthesia to the drug-induced form, and found that they were largely discordant, where essentially drug-induced cross-modal experiences are not consistent nor automatic, and therefore not able to be considered genuine forms of synaesthesia.

2.8.2.2 Hypnotic Induction

Cohen Kadosh, Henik, Catena, Walsh and Fuentes (2009) found that post-hypnotic suggestion can induce grapheme synaesthesia in non-synaesthetic individuals. A group of highly suggestible individuals underwent hypnotic induction, where they were instilled with the suggestion to associate the digits ‘1’ through ‘6’ with specific colours. A digit detection task was used to determine if the post-hypnotic suggestion did indeed induce grapheme synaesthesia. The digit detection task is based on an experiment described earlier- (Smilek et al., 2001): the participants are required to name a number that appears on a screen with a coloured background, which is either congruently or incongruently coloured, to the hypnotically-suggested digit-colour pairs. The results indicate that the individuals (n=4) who were under post-hypnotic suggestion made significantly more errors when attempting to identify digits on congruently coloured backgrounds, in a way more similar to genuine synaesthetes (Smilek et al., 2001) than to the two control groups (naive (n=4) and hypnosis (n=4)). Cohen Kadosh et al. (2009) argue that it is highly unlikely that their participants suddenly ‘rewired’ cortical regions to exhibit synaesthetic ability. The cross-activation hypothesis cannot account for this case of hypnotically suggested synaesthesia. Cohen Kadosh et al. (2009) suggest this result shows a link between synaesthesia and normal brains. If synaesthetes’ neuronal wiring is so different from that of non-synaesthetes, why is hypnotic suggestion able to induce synaesthesia?

In a study in the same vein, Terhune, Cardeña and Lindgren (2010) examine the reverse possibility i.e. of using post-hypnotic suggestion to remove their participant’s genuine synaesthesia temporarily. The participant was a highly suggestible synaesthete who exhibited colour-face synaesthesia, where she consistently sees people's faces in particular colours in her mind’s eye. A Stroop design was adapted to show the synaesthete and eight controls coloured faces as a stimulus, and concurrently measure three ERP components: P1, N2 and N400. It is important to note that the focus was on the N400 component, which occurs 400ms to 600ms post-stimulus, and shows a greater negativity during conflicting stimulus tasks, such as Stroop interference (Hanslmayr et al., 2007). The participants were required to name the colours of each face presented, each coloured either congruently or incongruently, according to the synaesthete's colours. It was found that the synaesthete's responses were slower when presented with incongruently coloured faces before the hypnotic suggestion, and the ERP N400 showed a greater negative deflection. The controls did not show a significant difference between congruent and incongruent faces in either the behavioural measure, or the N400 component. Following hypnotic induction, and the suggested removal of her synaesthesia, the synaesthete's response times levelled out for congruently and incongruently coloured faces, where she showed similar reaction times and N400 negative deflection to the control group. Cancellation of the hypnotic suggestion brought her results back to a slower response time for incongruently coloured faces, and N400 component returned to baseline levels. Another important finding was that for the synaesthete, the P1 component associated with early visual processes (50ms to 150ms) was more positive in all conditions (i.e. baseline, post-hypnotic and cancelation). Early visual processes may therefore not be susceptible to top-down modulation (Terhune et al., 2010).

2.8.3 LEARNING

There have been comparisons between well-learned associations and grapheme synaesthesia. Nunn et al. (2002) trained non-synaesthetes (n=28) to associate words with colours, and compared their brain activity with that of a colour-hearing synaesthete (n=12). The synaesthete showed significant activity in the V4, but the trainees did not. Not finding activity in the V4 may indicate that trained synaesthesia will not use the same areas as developmental synaesthetes; however, the word-colour association training was neither extensive, nor done over a long time. Participants trained until they achieved a certain number of word-colour associations correct in a row. It is not clear, however, whether this training occurred on the day of testing or well before. Elias, Saucier, Hardie and Sarty (2003) compared the brain activity (fMRI) of a grapheme synaesthete to that of a non-synaesthetic individual, who, over a period of eight years, had come to associate numbers to colours in a consistent way as a method of assisting with cross-stitching patterns. Four controls were also included. Participants were tested with a modified Stroop design, and it was found that the 'trained' participant showed similar brain activity and behavioural performance to the grapheme synaesthete (i.e. slower responses to incongruent stimuli). Therefore, the authors suggest that Stroop interference is not unique to synaesthesia. However, the similarity between the well-trained non-synaesthete and the grapheme synaesthete can be interpreted differently, i.e. that it may be possible to learn automaticity. The non-synaesthete's eight years of associating numbers to colours is not arbitrary, and is more or less equivalent to how long it would take a child synaesthete to develop their cross-modal associations. Finding similar brain activity and performance indicates that the fundamental component of synaesthesia, automaticity, can be learnt, even though this may take some time.

Niccolai, Wascher and Stoerig (2012) used ERP to compare trained non-synaesthetes (n=7) to grapheme synaesthetes (n=7). The non-synaesthetes were trained on custom computer software to learn 30 colour grapheme pairs over six days for an average of 18 minutes per day. The training involved three variations of a similar exercise in which, a grapheme and its colour had to be matched correctly. The participants completed congruency-priming tasks consisting of a primer, which was followed by a target that was either coloured congruently or incongruently. Reaction times and ERP components were measured. For ERP the following components were measured: N170 (100ms to 200ms), N300 (200ms to 320ms), P300 (300ms to 340ms) and N400 (320ms and 420ms). Incongruent trials caused slower reaction times for the synaesthetes and the trained non-synaesthetes, and both had higher voltages for N300 and N400 component. N300 was related to the expectation of the target stimulus in priming tasks (Franklin, Dien, Neely, Huber, & Waterson 2007), and N400 mentioned above already is related to conflicting stimulus. Higher voltages in the P300 (i.e. categorisations mentioned above) component were unique to the trainees, and only the synaesthetes showed significant early activity in the N170 (orthographic processing) component. Similar N400 component activation for incongruent trials suggests that directed learning of grapheme colour pairs appears to have the same later activation as grapheme synaesthesia had done. Synaesthetes appear to be deviant very early in activation (i.e. N170), but not trainees.

Colizoli et al. (2012) gave coloured books that were printed with four letters appearing in colours to 15 volunteer non-synaesthetes. A crowding task and a Stroop task were used to measure any behavioural changes in the trainees. The Stroop task administered before and after the reading found that the trainees were indeed slower at naming incongruently coloured trained letters after having read the colour books. The Stroop test specifically tested whether there was a difference in the level of Stroop interference between uppercase and lowercase letters. The overall frequency of uppercase letters in an average book is much lower than lowercase letters, This was significant because it was found that uppercase letters did not have as strong an interference effect as did lowercase letters. The trainees were also tested on a crowding task. The crowding task was discussed at the beginning of this chapter. The results showed that there were no differences between trainees and controls (n=30) when attempting to locate crowded letters. Previous experiments with genuine synaesthetes showed that they had an advantage when locating the crowded target letter (Ramachandran & Hubbard, 2001b).

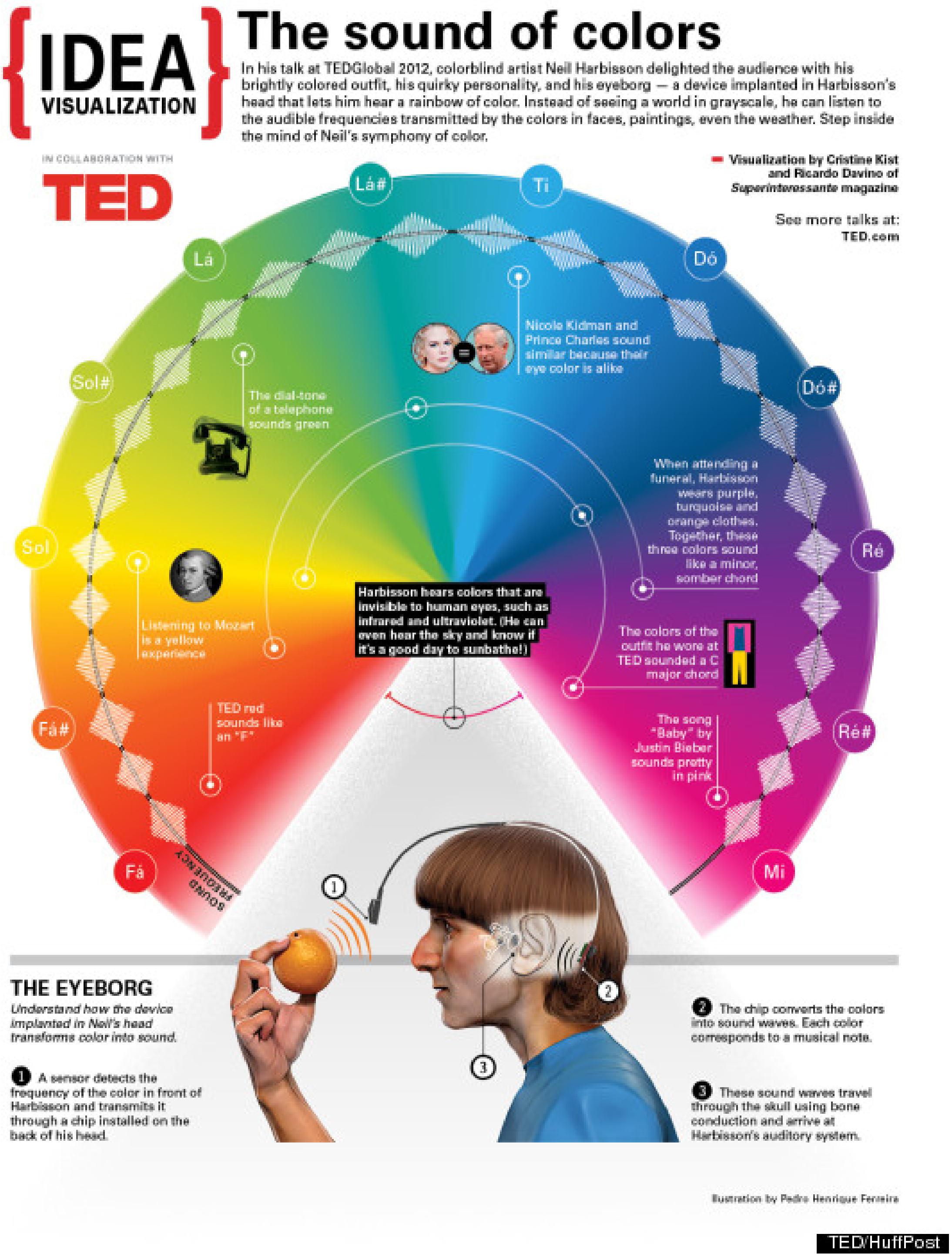
These studies yield two important findings. Firstly, they show that it is possible to learn the automatic component of synaesthetic associations with training. This is corroborated by the training implemented by Niccolai et al. (2012), who found a significant N400 component associated with conflicting stimuli. Secondly, there does appear to be a limitation to the training, where the early visual systems do not appear to be affected, because the trainees did not have an advantage in the crowding test, which relied on early perceptual processes. This finding is also corroborated by Niccolai et al. (2012), because only synaesthetes have significant early N170 potentials. However, Colizoli and colleagues comment that the crowding test was done using uppercase letters, which could have affected the test, because uppercase letters have been shown to have a lower Stroop interference level.

2.8.4 SENSORY SUBSTITUTION

There are experimental technologies that combine the senses in unique ways, called sensory substitution devices. One example of a unique device comes from a technology hacking competition, where talented individuals collaborate for 48 hours to create new and creative technology. One project called the “Syneseizure” (Figure 2.13 below) is an unusual-looking face mask, described as a “...full head mask that allows the wearer to feel images in real time” (Pescovitz, 2011). It works by turning a grid of 12 speakers positioned over the face on or off. A low resolution 12 pixel black and white camera acts as the 'inducer'; where each pixel corresponds to a speaker. If a pixel is black, the speaker turns off, if the pixel is white, the speaker turns on. The person who wears the mask would see by feeling. This is an example of technology creating bridges between senses that would otherwise not ordinarily combine. These technologies could also fill the void of a missing sense.

Figure 2.13: Syneseizure by - Science Hack SF. (boingboing.net/2011/11/23/syneseizure-isodrag-typeface.html)

A colour-blind artist, Neil Harbisson, uses a device called the Eyeborg to help him ‘hear’ colours. The device works with a head-mounted video camera that detects specific colour wavelengths, and then plays a unique sound, which corresponds to that particular colour (Figure 2.14). The device can be seen as simulating a form of synaesthesia. The cross-modal experience is mediated by artificial means, but it mimics synaesthesia in the sense that seeing a colour, it automatically ‘becomes’ sound. In the TED presentation entitled *I listen to color* (2012), Harbisson holds up a piece of green-coloured cloth to the camera on his head and the device responds with a few chirpy tones; upon hearing the sounds he says “this is the sound of... grass”.



In his talk at TEDGlobal 2012, colorblind artist Neil Harbisson delighted the audience with his brightly colored outfit, his quirky personality, and his eyeborg — a device implanted in Harbisson's head that lets him hear a rainbow of color. Instead of seeing a world in grayscale, he can listen to the audible frequencies transmitted by the colors in faces, paintings, even the weather. Step inside the mind of Neil's symphony of color.

Visualization by Cristine Kist and Ricardo Davino of *Superinteressante* magazine

See more talks at: TED.com

Nicole Kidman and Prince Charles sound similar because their eye color is alike

The dial-tone of a telephone sounds green

When attending a funeral, Harbisson wears purple, turquoise and orange clothes. Together, these three colors sound like a minor, somber chord

Listening to Mozart is a yellow experience

Harbisson hears colors that are invisible to human eyes, such as infrared and ultraviolet. (He can even hear the sky and know if it's a good day to sunbathe!)

The colors of the outfit he wore at TED sounded a C major chord

TED red sounds like an "F"

The song "Baby" by Justin Bieber sounds pretty in pink

Understand how the device implanted in Neil's head transforms color into sound.

❶ A sensor detects the frequency of the color in front of Harbisson and transmits it through a chip installed on the back of his head.

❷ The chip converts the colors into sound waves. Each color corresponds to a musical note.

❸ These sound waves travel through the skull using bone conduction and arrive at Harbisson's auditory system.

Illustration by Pedro Henrique Ferreira

Figure 2.14: TED Conference: The Sound of Colours. (ideas.ted.com/2013/07/11/the-sound-of-color-neil-harbissons-talk-visualized/)

He goes on to describe how at first, it was necessary for him to remember the names of each colour and corresponding tone, but that after longer use, it became part of his perception. He even claims that he now dreams in colours. One curious effect was that he began hearing normal sounds in colours as well, such as the sound of a ringing telephone. This is similar to the bi-directional synaesthesia described earlier. If Harbisson can dream in colour and hear in colour, then this implies that his brain has slowly rewired in a similar manner to the brains of synaesthetes. Harbisson has since extended the range of his colour vision to include infrared and ultraviolet light.

These sensory substitution technologies have been successfully used to help completely blind people to see shapes with sound. Striem-Amit and Amedi (2014) trained seven blind individuals to see with sound, using a sensory substitution device called vOICe. The software mediates visual information through sound with an algorithm that sweeps across an image from left to right where sounds are played for each pixel in the frame. The pitch of each sound is higher or lower, depending on how high each pixel is situated in the frame. For example, a small dot in the bottom left corner of a frame will sound like a low-pitched beep, where a dot in the top right corner will have a higher-pitched beep. Blind participants were trained to recognise the silhouettes of human body shapes using this device for ten hours. After enough training, the blind participants could identify body posture correctly. These participants were compared in brain activation to sighted controls (n=7), while looking at body shapes. Both sighted and blind participants had significant activation overlap in the right extrastriate cortex. The overlapping area is located at the posterior inferior temporal sulcus and middle temporal gyri called the extrastriate body area, and are sensitive to body shape information (see Figure 2.7) (Spiridon, Fischl, & Kanwisher, 2006). It is obvious that the blind participants have never been able to see, but why would they show similar activation in an area of the brain shown to be body-shape selective? The findings corroborate what De Haan and Cowey (2011) have proposed about how the visual system is organised. As mentioned earlier in this chapter, the visual system consists of a patchwork of networks, and each network is particularly sensitive to different types of visual information such as shapes, motion or colour. The type of visual information received determines which networks are activated. Even though the information about a visual scene is conveyed as sound, the visual cortex still contains the most appropriate networks for visual processing, which is why Striem-Amit and Amedi (2014) suggest that the blind participants had significant activity in the extrastriate cortex, similar to their sighted peers, when looking at body-shapes.

2.9 CONCLUSION: IS IT POSSIBLE TO LEARN SYNAESTHESIA?

At the beginning of this chapter, a set of characteristics was discussed in order to distinguish genuine synaesthesia from other cases such as the ones presented in this section. In order for any of the above cases to be considered genuine synaesthesia, they would need to satisfy all these characteristics, primarily the first three (automaticity, involuntary) and consistency (because they can be readily tested). The remaining criteria do not have as rigorous an empirical basis yet, and are not widely accepted by all researchers, i.e. spatially extended, memorable, affect–laden and forms constant (Hochel & Milán, 2008). Therefore, this comparison will focus on whether the cross-modal forms are automatic, involuntary and consistent.

In forms of acquired cross-modal interaction through brain trauma, it is not clear from the research whether the visual phosphenes are consistent, which is to say, whether there is a unique pairing between an inducer and a concurrent. The visual phosphenes are described as involuntary and automatic; however, these types of cross-modal experiences stemming from brain trauma cannot be considered synaesthesia, because the remapping of cortical networks is not done over a prolonged period of time and gradually developed. Although not mentioned as a characteristic, one could argue that synaesthesia should be found to have developed over a long period of time, as found by Simner et al. (2009). This does not necessarily require that it can only be developed at a young age, as is the case when it comes to normal synaesthesia, but only that there should be some time spent creating the cross-modal associations in a meaningful way.

In the hypnosis experiments, it was found that participants who were post-hypnotically suggested to associate numbers with colours, performed similarly to genuine synaesthetes in an object-detection task. The object-detection task is more effective on projector synaesthetes, which implies that the post-hypnotic suggestion was strong enough to modulate early perceptual processes. However, this was not the same for the genuine synaesthete; the post-hypnotic suggestion can temporarily remove automaticity (i.e. N400 component), but there was no effect on early perceptual processes (i.e. P1 component). In these experiments, the post-hypnotic suggestions were removed, so it remains to be seen if they would last a long time and remain consistent. More research is needed, because the sample sizes in these experiments were small, but they do show that it is possible for normal people to experience cross-modal interaction.

Training for synaesthesia is promising, but it does have its limitations. Colizoli et al. (2012) showed that participants who read coloured books did have Stroop interference for incongruent letters, which suggests that the automatic component was learned. However, the trainees failed to show any advantages in the crowding test, which indicated the involuntary activation was not learned. Furthermore, Colizoli et al. (2012) contacted the trainees six months after the experiments, and asked them what their colour-letter associations were, and the researchers found that most of them could not recall their colours for each letter. Therefore, the inducers and concurrents did not maintain their consistency over time. One important factor for learning is how long the training goes on for, e.g. a non-synaesthetic participant, who used the same number-colour association for practical application in cross-stitching patterns for eight years, had the same brain activation as a genuine synaesthete (Elias et al., 2003).

The sensory substitution devices seem to hold great promise for enabling the unsighted, but also have the potential for adaptation, to create new kinds of synaesthesias. The algorithm ensures a consistent image to sound conversion, and can be interpreted as satisfying the consistency characteristic. With longer use, the people using the devices more than likely developed automatic and involuntary responses to the inputs. The blind participants had similar brain activation in extrastriate body selective area, while perceiving soundscapes of silhouettes. The Eyeborg enabled Harbisson, a colour-blind artist, to perceive colours mediated by sound, which he claims even integrate into his dreams. One important aspect in these cases is the combination of sensory substitution with dormant cortical networks. It may be that these devices may be more effective in people who have unused cortical networks. Someone who can already see in colour may not have the same experience.

Overall, learning synaesthesia could be a combination of two key components 1) training method and 2) prolonged training. Furthermore, integration of sensory substitution technology might be able to accelerate the training of cross-modal associations.

CHAPTER 3: METHOD

3.1 INTRODUCTION

One of the key open questions in synaesthesia research is the extent to which it is actively developed, as well as the question of the possible inherited learning component, as one would first need to learn to read and write in order to have grapheme synaesthesia. Reading in colour is a relativity new idea, and provides an interesting way of examining the question of the extent to which synaesthesia is learnt. The research design described below implemented the training method of reading in colour first described by Colizoli et al. (2012). To test whether or not the non-synaesthetic participants acquired any synaesthetic ability, the modified Stroop tests used by Mills (1999) was adapted to measure two of the key characteristics for synaesthesia known as 'involuntary' and 'automaticity' activation between letters and colours.

3.2 RESEARCH DESIGN

The research design for this study is similar to, but not entirely a replication of, a study by Colizoli et al. (2012). I decided on this particular topic for this study, based on an article that reported on a conference abstract presented by Colizoli, Murre and Rouw (2010), regarding the reading of books in colour to learn synaesthesia. The final study had not been published when the methodology for this study was designed, and I based the research design on information contained in the conference abstract, a brief communication with the lead author, and an early literature review. This is why there are differences between this study and the published study. These differences are discussed below, and in subsequent chapters where relevant.

3.2.1 Colour-reading

Colizoli et al. (2012) tested whether reading books in colour was enough to learn colour-letter synaesthesia. The coloured books provide a simple method for presenting a letter and colour simultaneously, without directed training. The concept for training was that each participant would read the colour book to examine whether an associative relationship between the letter and colour could emerge, similar to that of grapheme synaesthesia. The participants were assessed with a modified Stroop test (previously discussed in Chapter Two) showing that, after the training, they were slower when naming the colour of incongruently-coloured letters. When genuine grapheme synaesthetes are shown incongruently-coloured letters, they are also slower at naming the colours. Due to the automaticity between the letters and colours, seeing letters in the wrong colours causes interference. If the trainees reading in colour were slower at colour-naming incongruent letters, it could be assumed that a strong enough association formed between the letter and colour to cause measureable interference, and therefore, that there is an automatic association between trained letters and colours.

The training methodology employed in this study is based on the same training approach implemented by Colizoli et al. (2012). The trainees were asked to read a reproduced book (colour-altered book), in which the prescribed stimulus letters were concordantly printed in colour. Trainees read a colour-altered book to learn their own colours in response to graphemes analogous to that of real grapheme synaesthetes. In addition to this *book-based training medium,* a second training method was employed, namely an experimental Google Chrome extension™.

The authors of the Chrome Extension™ were inspired by the research done by Colizoli et al. (2012). Synesthetize 1.11™ is a browser add-on that can implement colour-letters in real time by changing the colours of individual alphabetic characters displayed on typical webpages (see Chrome Webstore, (2012)). It can be installed onto any recent version of Google Chrome web browser. Colizoli et al. (2012) gave their participants a web applet to perform a similar function. It could also change letters on a webpage into colours, but it was reported that most participants did not use the web applet consistently.

Originally, three participants in the current study were using Synesthetize on their own personal computers. It was conceived that they could browse the internet as usual, but with the extension running all the time, changing the colours of the letters. The advantage was similar to reading books in colour, but this was more contextually based in an everyday activity. The concept was interesting; however, practical implementation proved difficult, because the extension was unable to change the letters consistently. Feedback from participants indicated that many of the websites they frequented would not convert to colours successfully, and often turned webpages into garbled code. Only one participant managed to use the extension for a period of one month, and her results are included in the analysis presented in Chapter Four.

3.2.2 Rationale for colour-reading

The Hebbian learning process of neuronal network organisation during associative learning can be described by the adage, 'cells that fire together, wire together' (Hebb, 1949). According to De Haan and Cowey (2011) the visual cortex is composed of patchworks of overlapping neural networks; each network of neuronal cells is sensitive to particular forms of visual information, e.g. motion, colour, shapes and so on. The kind of visual information the visual cortex receives determines which patchworks become active. For example, looking at a blue square activates the shape and colour networks. The more often these networks are turned on simultaneously, the greater the increase in synaptic strength between the networks. For example, learning how to read is difficult at first, because prolonged repetitive practice is needed to strengthen the associated synaptic networks in the regions of the brain necessary to perform coordinated pattern recognition. After enough practice, the networks become refined, and if mastery is achieved, the individual does not even need to think about what a word means, or how it is pronounced. The response is simply automatic.

In a similar way, repeatedly reading coloured text may require the colour and grapheme regions in the brain to activate simultaneously. After enough colour reading, it is assumed that the associated networks become better connected and automatic. A grapheme synaesthete has a high associative strength between inducers and concurrents - this is why viewing incongruently coloured letters causes slower colour naming times. If the non-synaesthete trainees read in colour long enough, the associative strength between the colours and letters may become strong enough to be tested with a modified Stroop test.

3.3 MODIFIED STROOP DESIGN

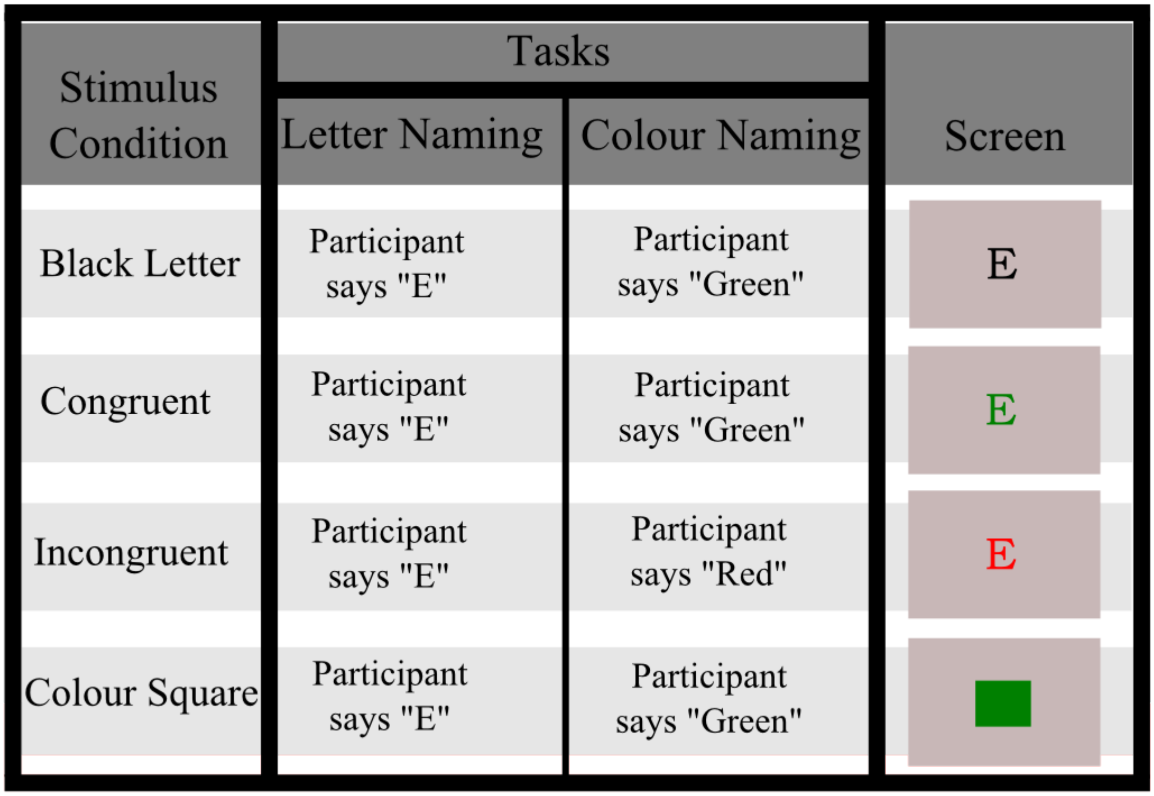
Stroop (1935) discovered that participants naming the visual colour of colour words experienced a delayed response when responding to stimuli that were incongruently matched. For example, if the colour word 'red' appears in the colour blue, it is incongruently matched. The conflict between the visual and conceptual colour of the word needs to be consolidated by higher order cognitive processing, which results in a measureable delay in reaction to naming the colour of the word. The Stroop test has been modified to test the colour automaticity between letter/number inducers and synaesthetic colours for grapheme synaesthetes (Dixon et al., 2000; Mattingley et al., 2001; Mills, 1999). Grapheme synaesthetes are slower at naming the colour of incongruently coloured graphemes. For example, if a digit synaesthete sees the digit ‘5’ in blue and is asked to name the colour of the number ‘5’, showing it in red will cause a slower naming time. By the same reasoning, the modified Stroop test can also be used to measure the automaticity learnt from reading in colour. A modified Stroop test was adapted from Mills (1999) to assess the automaticity of the trainees’ learnt colour-letter associations. It is hypothesised that trainees will have a similar result of slower colour-naming response to incongruently coloured letters after having read coloured books.

3.3.1 Tasks: Colour-naming and letter-naming

Mills (1999) originally tested a digit synaesthete to determine if her synaesthesia was automatic. The test consisted of two tasks: digit-naming and colour-naming. Depending on the task, the objective was either to name the colour or name the digit presented as quickly and accurately as possible. The two tasks for this study were adapted from the Mills (1999) study, except that instead of digits, the stimuli were letters. There were four stimuli conditions; each condition is described below.

3.3.2 Stimuli conditions

In each task four conditions are presented; letters may appear in one of these four stimulus conditions: black letter, congruent colour, incongruent colour and colour squares (Dixon et al., 2000; Mattingley et al., 2001; Mills, 1999). See Figure 3.1 for a summary.



Stimulus Condition	Tasks		Screen
	Letter Naming	Colour Naming	
Black Letter	Participant says "E"	Participant says "Green"	E
Congruent	Participant says "E"	Participant says "Green"	E
Incongruent	Participant says "E"	Participant says "Red"	E
Colour Square	Participant says "E"	Participant says "Green"	🟩

Figure 3.1: Summary of Modified Stroop Test

3.3.2.1 Black letters

Colour-naming task: The participant was shown a black letter and was required to name the colour they associated with it, that is, the congruent colour for that particular letter (e.g. participants were required to say "green" when presented with a black letter ‘e’).

Letter-naming task: The participant was shown a black letter and was required to name the letter they saw (e.g., Participant says "e" when presented with a black ‘e’).

In the study by Mills (1999), the grapheme synaesthete had a similar response time for colour-naming of black letters and congruently coloured graphemes. In the current study, the trainees do not have synaesthesia, and relied upon memory to name the colour correctly. The inclusion of the black letter condition ensures that participants do not have synaesthesia and tests memory. For example, if they did have synaesthesia, their reaction times for the congruent and black letters would have been roughly the same during the pre-test (see Chapter Two - section 2.3.1). The same comparison will be used for first hypothesis test (see below).

Furthermore, the control participants were under the impression that the test – in particular the black letter condition – was their primary synaesthesia training. Since they were not presented with any colour books, the black letter condition made it appear to them as though they were practising memorising the colour of letters.

3.3.2.2 Congruent letters

The congruent condition is a stimulus letter that appears in the colour chosen by the participants.

Colour-naming task: Participants are required to name the colour in which the letter appears (e.g. Participants say ‘green’ when presented with a green ‘e’).

Letter-naming task: Participants are required to name the letter they see (e.g. participants had to say ‘e’ when presented with a green ‘e’).

3.3.2.3 Incongruent letters

Subjects are shown a letter in a colour that is different from the colour they associated with the letter.

Colour-naming task: The participant is required to name the colour he/she sees (e.g., the participant says ‘red’ when presented with a red ‘t’).

Letter-naming task: The participant is required to name the letter he/she sees (e.g., the participant has to say ‘e’ when presented with a red ‘e’).

Additionally, each incongruent colour is worked out to be the exact opposite colour of any given congruent colour, e.g. blue is the opposite of red. The opponent colour is used because Nikolić, Lichti and Singer (2007) found that the colour of the incongruent condition can influence the magnitude of the interference effect. They compared two types of incongruent conditions in a Stroop design, similar to the experiments described thus far. The incongruent conditions were: the opponent colour of the congruent colour condition (180 degrees offset on the colour wheel) and an independent incongruent condition (90 degrees offset on the colour wheel). It was found that when colour-naming, the synaesthetes were slower at colour-naming for incongruently coloured graphemes. However, the incongruent opponent colours were significantly slower than the second condition.

Therefore, in order to maximise Stroop interference, the incongruent trial condition colours are calculated using a 180 degree offset (opposite) on a colour wheel. Colours are coded on a computer, using a combination of three values, namely: red, green and blue (RGB). Each value has a range between 0 and 255, and the higher the value, the greater the brightness of the colour. For example, the RGB for the colour green is (0,255,0), while dark blue is (0,112,192). To calculate the opposite RGB colour codes for the incongruent condition, the RGB code for the congruent colour is converted by simply subtracting 255 from each RGB value and multiplying it by negative one. For example, the RGB colour code for the colour red is (255,0,0) if 255 is subtracted from each value and multiplied by negative one the resulting values are (0,255,255) which is the RGB code for blue, which is the opposite colour of red.

3.3.2.4 Colour Squares

Colour-naming task: The participant is shown a coloured square (one of the congruent letter colours) and is required to name the colour of the square (e.g., participants are presented with a colour square in the colour ‘green’, and are required to say ‘green’).

Letter-naming task: The participant is shown a coloured square and has to name the letter associated with that colour (e.g. if a trainee's colour for the letter 'e' is green, when presented with a green-coloured square, they are required to respond with 'e').

The purpose of the colour square depends on the task. In the colour-naming task, it isolates 'pure' colour-naming without the letter stimulus. In this way, it serves as a baseline for colour-naming without a letter stimulus, and provides a way of checking whether or not participants had any issues with seeing colours normally (Mills, 1999). In the letter-naming task, the colour square condition relates to the reverse synaesthesia described in Chapter Two. For most grapheme synaesthetes, a letter elicits a colour experience; however, the reverse, where a colour can evoke a letter, is also possible. In order to test the directionality of activation, i.e. testing whether the colour elicits a letter, participants must convert the colour square into the associated letter. The naming times are expected to be longer, because participants will more than likely need to use memory to recall the letter associated with the colour square.

3.4 HYPOTHESES

Two characteristics are tested. The first characteristic is the involuntary characteristic of synaesthesia, which can be tested with a crowding test e.g. (see Chapter 2 Colizoli et al., 2012; Ramachandran & Hubbard, 2001). However, the same criterion can be tested with a Stroop test. In Mills (1999), a genuine grapheme synaesthete had similar colour-naming times for her black digits and congruent digits. This is because, when the synaesthete sees the black letter, it involuntarily evokes a colour which is similar to a genuine perceptual process, in this case, seeing and naming the colour of a coloured letter (see section 2.3.1). Therefore, if any of the participants in this study have similar reaction times for their black letter and congruent conditions, it would suggest they are having an involuntary experience. One value was calculated to represent the involuntary reaction time by subtracting the congruent condition from the black letter condition. The genuine synaesthete Mills (1999) tested is used as a guideline, having a difference of 46ms between her black and congruent conditions. An involuntary reaction time value was calculated for the pre- and post-tests and compared for significant differences between groups. However, it is expected that the participants in this study will not be significantly different, because, as shown in Chapter Two, it takes a long time to develop this characteristic of synaesthesia.

Hypothesis 1: In both groups, there will be a significant difference between the black letter and the congruent condition reaction times after reading.

The second hypothesis tests the automaticity of synaesthesia by creating Stroop interference between the inducing letter and the corresponding colour. Synaesthetes are slower at naming incongruently coloured letters than congruently coloured letters (see section 2.3.1). In order to test the second hypothesis, the Stroop reaction time must be calculated by subtracting the congruent from the incongruent condition. If there is a significant difference between the pre- and post-Stroop reaction time, it would suggest that the participants learnt the automatic characteristic of synaesthesia.

Hypothesis 2: Trainees will show a significant difference with the control group in *Stroop reaction time* after colour-reading training.

3.5 RESEARCH PARTICIPANTS

Volunteers were recruited through convenience sampling: an introductory email was sent to the researcher's circle of contacts and circulated via Facebook™ posts, requesting volunteers for participation in a Master’s research dissertation. The communication was supplemented with information about synaesthesia, and detailed the research aims and procedures.

The volunteer trainees were accepted into the study based on the following requirements. The individuals are ‘literate’, i.e. must have at least a Matriculation certificate. First language should be English, and they should *not* exhibit any form of synaesthesia naturally, including amongst immediate family members. According to a familial study conducted by Barnett et al. (2008), synaesthetes are more likely to have family members with synaesthesia.

Table 3.1 shows the biographical data of all the participants (n=24). The participants were not specially grouped, given the nature of the study (i.e. a large portion of time spent reading). They were assigned to the reading group depending on their willingness to read a colour-altered book. There were a total of 16 people in the colour-reading group and seven people in the control group. There was only one person in the web group.

The participants were not screened for synaesthesia via a consistency test. Due to time constraints, the researcher was obliged merely to ask a series of informal questions to ascertain if the participants were already synaesthetic, e.g. "do you see letters in colour?"

Table 3.1: Demographic of participants

Group	Participant Code	Gender	Age	Training Medium
Book	B1	M	38	Print
	B2	M	29	Print
	B3	M	63	Screen
	B4	F	27	Screen
	B5	F	27	Print
	B6	F	42	Print
	B7	F	43	Print
	B8	F	49	Print
	B9	M	32	Screen
	B10	M	29	Print
	B11	F	27	Print
	B12	M	27	Print
	B13	M	28	Screen
	B14	F	30	Print
	B15	F	28	Print
	B16	F	28	Screen
Control	C1	F	31	n/a
	C2	F	29	n/a
	C3	M	28	n/a
	C4	F	20	n/a
	C5	F	28	n/a
	C6	M	28	n/a
	C7	M	28	n/a
Web	W1	F	26	Screen

3.6 RESEARCH INSTRUMENTS

3.6.1 Personalisation of colours and letters

In Chapters 1 & 2, synaesthesia was described as personal in nature, that is, each grapheme corresponds with a unique colour (Hochel and Milán, 2008), and is consistent over time (Baron-Cohen, Wyke, & Binnie, 1987). What this means is that any form of synaesthesia is idiosyncratic. Therefore, in this experiment, the researcher did not set *many* restrictions for participants in terms of exactly what letters they would be learning, or what those letters' colours would be. It is assumed that when learning synaesthesia, personalisation may be needed in order to obtain successful results.

In this experiment, a total of four colour-letters were trained and tested. The letters were separated into two groups, consisting of two control letters and two own choice letters. The control letters are the letters ‘e’ and ‘t’. These letters were chosen for the same reason Colizoli et al. (2012) used them, namely because they are the two highest-occurring letters in the English alphabet (n.d.). The assumption is that because these letters occur frequently, any book the participants were likely to read would include these two letters more frequently than others. A higher-occurring letter is beneficial to colour-letter training, because the participants would see the colour-letter more often, and would increase the amount of time spent learning. Table 3.2 displays each participant’s estimated frequency for each letter, and the estimated word count for the colour-altered books.

Table 3.2: Estimated word count and letter frequency for colour-altered books.

Participant Code	Word Count	Frequency 'e'	Frequency 't'	Second Vowel	Frequency	Second Consonant	Frequency
B1	103958	50445	37788	a	33854	n	28848
B2	54600	31437	22628	u	6050	n	15553
B3	93717	51208	37683	o	28130	d	19068
B4	278467	140178	96670	a	64282	d	52781
B5	136489	67318	50353	o	43561	k	5514
B6	153368	86928	58521	u	18136	c	17762

B7	153368	86928	58521	a	56717	d	33842
B8	153368	86928	58521	o	52160	k	6311
B9	102911	56348	43678	u	12894	s	26138
B10	150293	70922	51152	i	50253	r	50253
B11	90173	46596	34026	o	28661	k	4067
B12	57716	31302	23205	o	20545	f	5003
B13	73736	40015	29816	o	25014	s	20441
B14	135570	70649	47483	a	46129	p	8414
B15	1737734	74536	55327	a	47573	m	14097
B16	239490	129230	85981	a	82580	s	68412

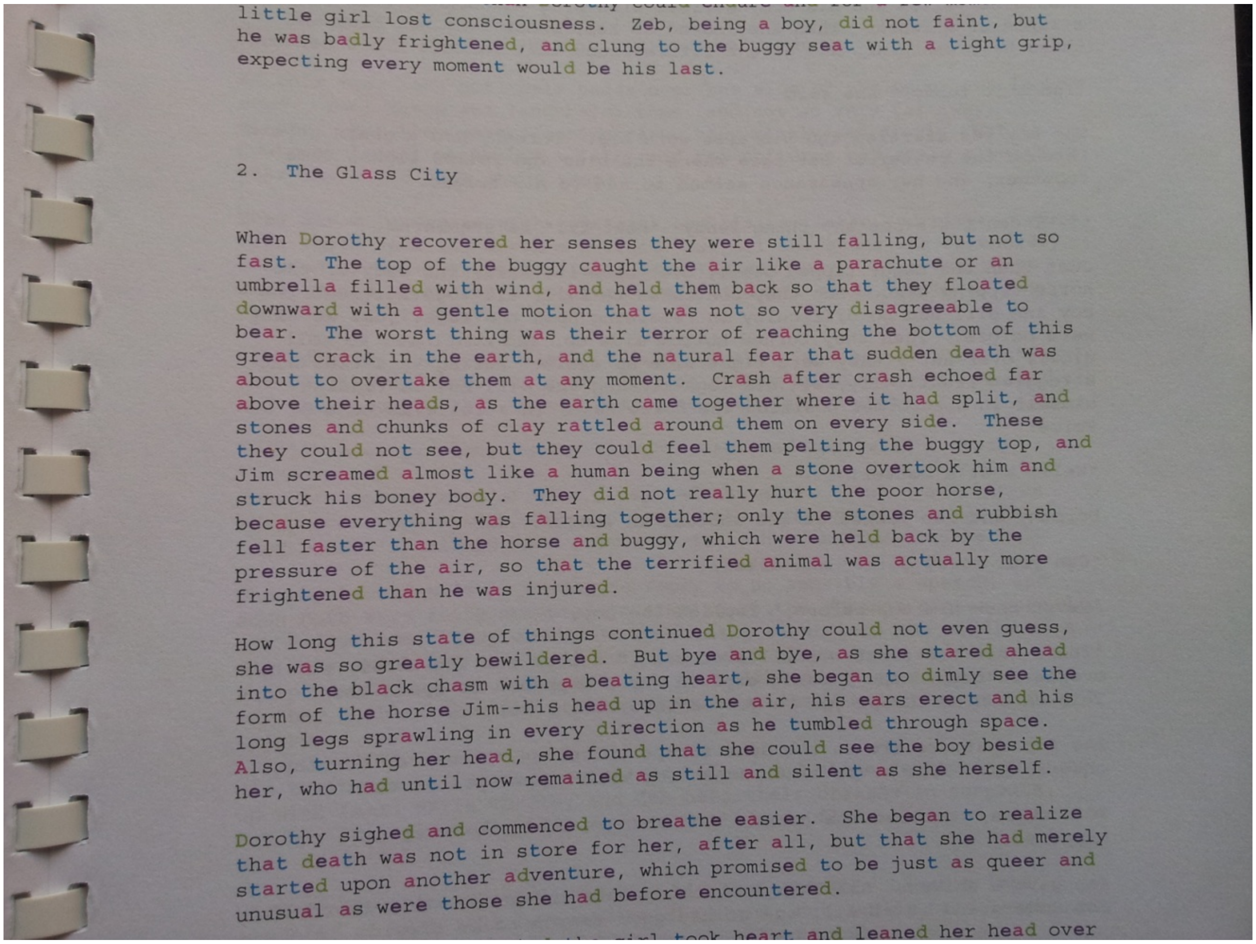
Additionally, the remaining two letters were selected by the trainees (one vowel and one consonant), provided their choices did not conflict with the two control stimulus letters. The trainees were free to choose the colours for each of the four stimulus letters. However, there was one guideline, namely that participants were asked not to choose colours that were either too bright or too dark. The reasoning for this was that colours such as yellow become difficult to see when printed on white paper, and the colour brown is difficult to distinguish from normal black letters.

This is in contrast to the study of Colizoli et al. (2012), where the participants were allowed to combine the letters and colours themselves, but the available letters and colours were all pre-selected. Participants were asked to associate the colours orange, green, red and blue with the letters 'e', 't', 's' and 'a' in whatever combination they preferred.

3.6.2 Preparation of colour-altered books

The volunteers were asked to select free books from Project Gutenberg (n.d.). Project Gutenberg hosts free, editable and out-of-copyright books. The books selected by volunteers were customised according to the personal preference of each trainee. A word processor’s search and replace function was used to change the selected stimulus letters (uppercase and lowercase) into colour, accordingly. The colour-altered books were printed in Courier New, size 10 font, double-sided and bound together. The trainees were instructed to read the entire book. See the Figure 3.2 for an example of a page from a printed colour book. Some participants read on electronic devices (see

Table 3.1). This sub-group was not created by design, but included for convenience during the study, due to printing costs. One participant read on a colour e-reader, another on a tablet computer and three others read on computer monitors.



little girl lost consciousness. Zeb, being a boy, did not faint, but he was badly frightened, and clung to the buggy seat with a tight grip, expecting every moment would be his last.

2. The Glass City

When Dorothy recovered her senses they were still falling, but not so fast. The top of the buggy caught the air like a parachute or an umbrella filled with wind, and held them back so that they floated downward with a gentle motion that was not so very disagreeable to bear. The worst thing was their terror of reaching the bottom of this great crack in the earth, and the natural fear that sudden death was about to overtake them at any moment. Crash after crash echoed far above their heads, as the earth came together where it had split, and stones and chunks of clay rattled around them on every side. These they could not see, but they could feel them pelting the buggy top, and Jim screamed almost like a human being when a stone overtook him and struck his boney body. They did not really hurt the poor horse, because everything was falling together; only the stones and rubbish fell faster than the horse and buggy, which were held back by the pressure of the air, so that the terrified animal was actually more frightened than he was injured.

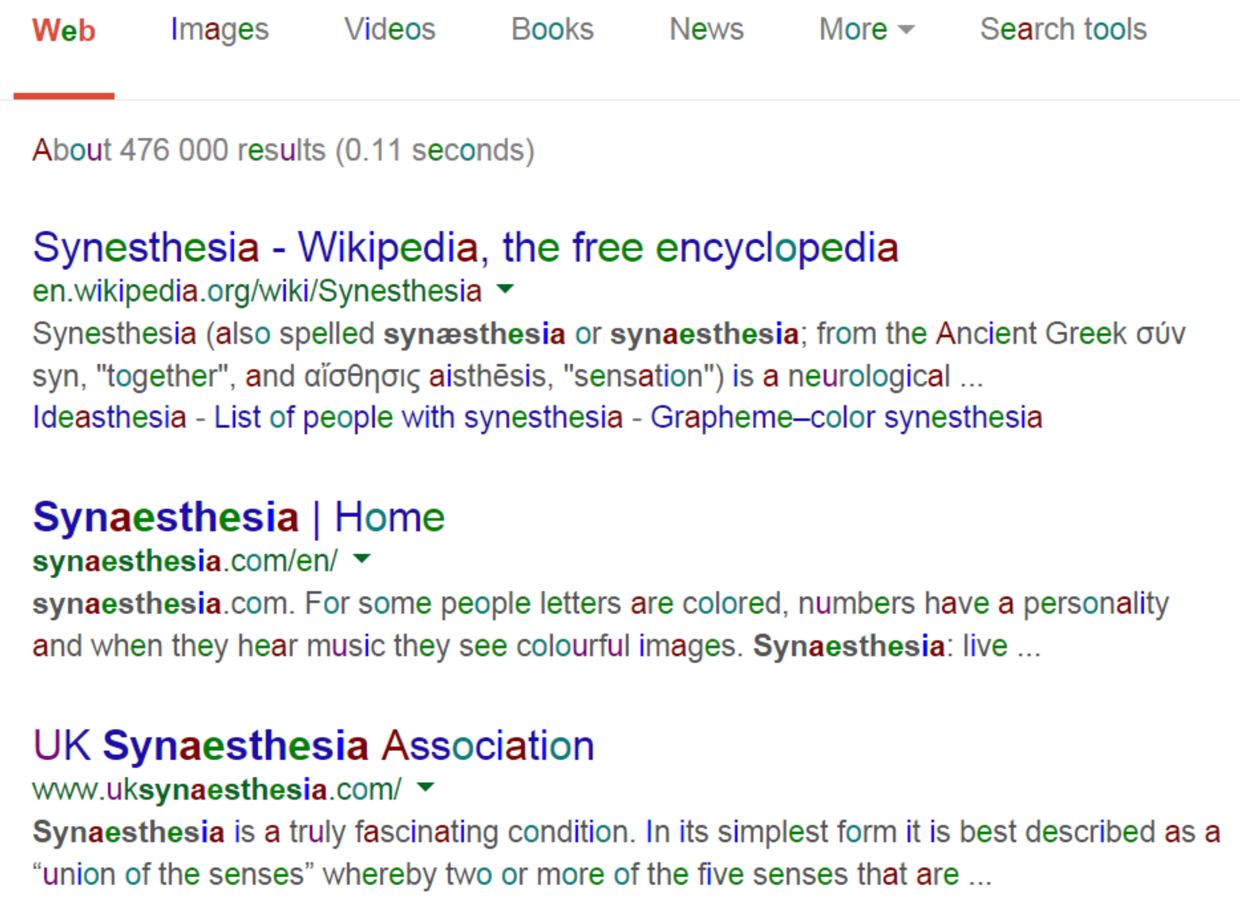
How long this state of things continued Dorothy could not even guess, she was so greatly bewildered. But bye and bye, as she stared ahead into the black chasm with a beating heart, she began to dimly see the form of the horse Jim--his head up in the air, his ears erect and his long legs sprawling in every direction as he tumbled through space. Also, turning her head, she found that she could see the boy beside her, who had until now remained as still and silent as she herself.

Dorothy sighed and commenced to breathe easier. She began to realize that death was not in store for her, after all, but that she had merely started upon another adventure, which promised to be just as queer and unusual as were those she had before encountered.

Figure 3.2: Picture of a page from a printed colour book.

3.6.3 Web letter colour installation

The Synesthetize Chrome Extension™ can be found by doing a search on Google Chrome™ Webstore. The Extension requires a colour code in order to convert the letter to colour. Each participant who opted to use this form of training was emailed the codes for their letters to enter into the Extension. A screenshot of a website with the letters in colour was emailed back to the researcher to show that it was working properly. See Figure 3.3 below for an example of what a google search would look like using the Synesthetize.



About 476 000 results (0.11 seconds)

Synesthesia - Wikipedia, the free encyclopedia
en.wikipedia.org/wiki/Synesthesia
Synesthesia (also spelled **synæsthesia** or **synaesthesia**; from the Ancient Greek σύν syn, "together", and αἴσθησις aisthēsis, "sensation") is a neurological ...
Ideasthesia - List of people with synesthesia - Grapheme–color synesthesia

Synaesthesia | Home
synaesthesia.com/en/
synaesthesia.com. For some people letters are colored, numbers have a personality and when they hear music they see colourful images. **Synaesthesia**: live ...

UK **Synaesthesia** Association
www.uk**synaesthesia**.com/
Synaesthesia is a truly fascinating condition. In its simplest form it is best described as a “union of the senses” whereby two or more of the five senses that are ...

Figure 3.3: Screenshot of Synesthetize Chrome Extension™ converting colour on a Google search for synaesthesia.

3.6.4 FLXLab©: Experimental testing software

The implementation of the modified Stroop test was done with FLXLab©, which is a free software solution for computer-based psychological experiments (n.d.). Trainees were fitted with a headset microphone to capture their verbal response using active voice key. The voice key is triggered by any sufficiently loud sound immediately proceeding the trial onset beep sound. For example, at the start of the trial a beep sounds to indicate the trial has begun, and any sound the microphone detects after the beep that is over a certain volume threshold is assumed to be the participants’ verbal response. The programme measures the duration between the onset of the stimulus letter (as indicated by the beep sound) and the participants’ verbal response and saves them to a text file. FLXLab© is programmed with a script text file to execute the Stroop test. A custom script had to be made for each participant. An example of the script can be found in Appendix A.

In contrast, Colizoli et al. (2012) participants' responses were recorded via a keyboard. The voice was used in the current study because it did not require additional training to complete the Stroop test. For example, Colizoli et al. (2012) used a four button input, with each finger associated with a particular button, where each button corresponds to one of the colours in the Stroop test. This type of user input requires the participants to obtain training on the keyboard first, before the test can be completed. In the current study, a verbal response is used as input because it is more natural, and less time is required to start the test. The voice key is also closer to the Mills (1999) experiment, done with a genuine grapheme synaesthete. The main disadvantages of using a voice key are discussed below in the reliability section.

3.6.4.1 Modified Stroop script

Instructions regarding the test and what the test involves are presented on the introduction screen. Participants are informed that they will be shown letters and that their task varies between naming the colour and naming the letter, depending on the task. They are also told to keep speed and accuracy high, without sacrificing one for the other. Participants begin with a practice set of 16 trials for each task. One trial consists of a sequence of three screens. On the first screen, a fixation cross (+) is displayed at the centre of the monitor for 1500ms. The participants must focus their attention on the fixation cross until it refreshes to the second screen. On the second screen, a beep sounds, indicating the start of the trial, and simultaneously the fixation cross is replaced with one of the four possible conditions in the Stroop test. Figure 3.4 and Figure 3.5 below are examples of what the second screen looked like.

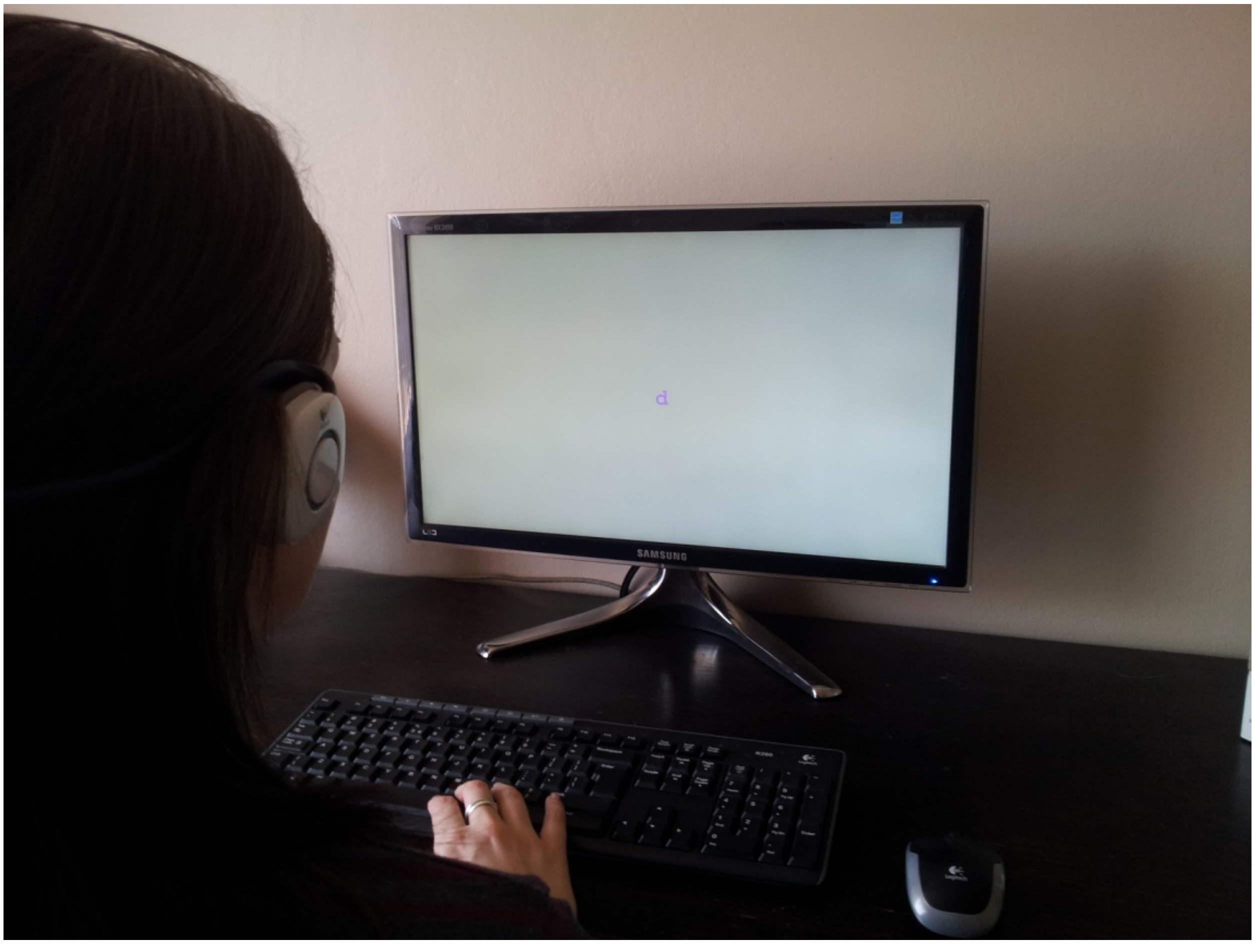


Figure 3.4: An example of FLXLab© presenting a coloured letter (i.e. congruent or incongruent condition).

Figure 3.5: An example of FLXLab© presenting a colour square.

Figure 3.4 is an example of a coloured letter, which could have been congruent or incongruent, and Figure 3.5 is an example of the colour square condition. The stimulus letter or square remains on the second until the participant responds verbally, at which point, the voice key triggers (headset microphone). The accuracy of the responses is marked in Chapter 4, where for example, participants must say the correct colour name of the stimulus letter or colour block. The FLXLab© records the duration of the response from the beginning of the second screen/onset beep, until the verbal response input. Following each response, the participant must push a key input to move to the next trial, which returns to the first again with a fixation cross.

3.6.4.2 Configuration of trials and tests

Pre- and post-testing consisted of 352 trials, which included 32 practice trials (16 colour-naming and 16 letter-naming). There were four blocks of 80 trials, with two blocks for each task in alternating order. Each block contained five sub-blocks made of 16 items. A sub-block is a randomised list of each of the four stimulus letters, appearing in each of the four stimulus conditions once.

The order of the tasks was counterbalanced between participants and test sessions to ensure that the order of the tasks (i.e. letter-naming and colour-naming) did not affect the overall test. For example, if one participant's pre-test was ordered as letter-naming, colour-naming, letter-naming, colour-naming, then another participant would get the reverse order, namely: colour-naming, letter-naming, colour-naming, letter-naming. The order of the post-test for each participant was the reverse order of their pre-test.

3.6.5 Test Apparatus

The participants were all tested with the same equipment. The Stroop test was administered on an Intel™ Core 2 Duo with 2 GB of RAM on a Samsung™ LED monitor. A Logitech™ microphone headset was used to trigger the voice key and to record the audio.

3.7 DATA COLLECTION METHOD

Individual appointments were made with volunteer trainees to come in for briefing and initial Stroop testing. The participants' colour-letter preferences were emailed to the researcher beforehand in order to prepare the Stroop test scripts and print the colour-altered books.

Trainees were fully informed about the details of the experiment, except for how the Stroop test works; it was felt that too much information about the assessment may influence results. Once the consent form was signed (see Appendix B), the participant was given the modified Stroop test. The volunteers were all tested in the same room, around the same time of day, and on the same monitor, to ensure that colour settings would be consistent. The book-based trainees were given three to four weeks to read the colour-altered book, depending on the book length. The web browser-based trainees were asked to use the extension for approximately 3 to 4 weeks before returning. In practice, the time between testing varied somewhat amongst participants, as the post-test was scheduled according to availability. Participants were encouraged to return soon after they finished reading.

Upon conclusion of the post Stroop test, more information about the assessment was divulged, including how the test worked. Participants were also informally interviewed with some open-ended questions about how they experienced the study. Each debriefing was voice recorded and integrated into the analysis chapter.

3.8 VALIDITY AND RELIABILITY

3.8.1 Reliability

The reliability or consistency of the Stroop test is dependent on accurate reaction time data. The software FLXLab$^©$ was used to record reaction time data, but there were reliability issues with this method of data collection. During the marking phase of data cleaning, inconsistencies were observed. The voice key introduced a number of false items, because of erroneously attributed noises, such as a participant clearing their throat, or other environmental sounds. In order to ensure reliable reaction time data, the audio recordings for each test session were imported into audio editing software so as to measure each trial reaction time accurately. Further details are provided in Chapter Four.

There are other possible reliability issues in terms of the environmental context of the test setting. To minimise the effect of testing context, the same room and equipment were used for all tests. However, there may have been other factors, such as participant fatigue or distractions that may have had an effect on attention and reliability.

3.8.2 Validity

3.8.2.1 Screening: Genuine synaesthetes, colour vision and letter naming task

The validity of the Stroop test is based on comparing the stimuli conditions to check certain assumptions made about the participants. The colour square condition serves as a baseline measure of colour-naming, as there are no letters involved. In Mills (1999), the genuine synaesthete's colour-naming times for her colour square condition were similar to her congruent condition. Colour vision is checked by comparing the congruent condition to colour square condition. The colour square condition tests colour exclusively and should be the fastest naming time, because there is no letter stimulus. If the colour square condition is significantly slower than the congruent condition, it could mean there was a problem with the participant’s colour vision, or maybe they did not follow instructions, for example, where they had difficulty seeing the colour clearly, or they hesitated when naming colours of colour squares to increase accuracy which slows response time.

The second assumption is that the participants are not genuine synaesthetes. Mills (1999) found that genuine synaesthetes have similar colour-naming times for black and for the congruent condition. Therefore, if any of the trainees or controls in the current study had similar reaction times for their black and congruent condition in the pre-test, they may be genuine synaesthetes. However, it is expected that the participants will need to rely on memory to recall the letter-colour combination for black letters, and will be slower than the congruent condition.

Lastly, we look at the purpose of the additional letter-naming task controls for any confounding letter effects. In the colour-naming task, the participant's attention is drawn to the colour of the letter, but in the letter-naming task, attention is focused on the letter. This is done to ensure that the participant does not have any problems with seeing and naming letters normally (Mills, 1999). The letter-naming task also tests reverse synaesthesia (bidirectional activation) in the colour square condition, because participants have to convert the colour square into the associated letter (see Chapter Two).

3.8.2.2 Consistency between printed colour letters and post-Stroop test colours

One of the key criteria for grapheme synaesthesia is the consistency between the letter inducers and colour concurrents (see Chapter Two). What this means is that the colours used in the congruent colour condition in the Stroop test (i.e. colour on the computer screen) must be accurately matched to the given synaesthete's colours. In other Stroop tests, genuine synaesthetes select their own colours for the experimental letter stimulus (Mills, 1999). Additionally, the synaesthetes rate how close each real colour is to their synaesthetic experience, thereby allowing the researchers to use only the highest-rated items as stimuli for the Stroop test, so maintaining high congruency between real colours and synaesthetic colours. Using the exact same colours is important, because the Stroop test must have an accurate measure of the 'correct' colour or congruent colour. If the colours are not correctly matched, then any colour letter the synaesthete sees may inadvertently act as an incongruent colour, causing slower reaction times.

The situation is different in the current study, because the participants have not yet learnt their letter-colour associations. The problem becomes apparent when considering how to ensure that the colours the participants learn from a colour-altered book are consistent with the colour on the computer screen administering the post Stroop test. At the beginning of the study, it was assumed the colours in Stroop test (pre- and post-) were consistent with the coloured letters in the colour altered book (i.e. printed congruent letters), because the same RGB colour values were used to program them both. However, what I did not account for was that once the books were printed, the way the coloured letters looked on a page were not exactly the same as those seen on a computer screen. For example, a computer screen has backlight illumination, whereas printed letters need extra environmental lighting to see the page, which can have a subtle effect on the appearance of a colour. If the participants learn the coloured letter from the book, it is logical to assume that the *quality* of that colour may also be learnt, e.g. hue or saturation. This may have introduced a potential consistency problem into the Stroop test, which must be acknowledged, because the colours presented in the post-Stroop test (i.e. colours letters displayed on a computer screen) may not be fully matched to the printed colour letters from which participants trained. The mismatch between the learnt printed colours and the post Stroop test could affect the validity of the test.

In order to check if this was a problem, a comparison between the pre- and post-congruent condition was preformed, looking for participants with a slower reaction time in the post-test. It was assumed that participants should be faster in post-testing due to practice effect, and that therefore, if a participant was slower at naming congruent colours in the post-test, this may mean that the colours were not matched correctly to the particular colour they learnt. In Chapter Four an analysis was done to check if there were consistency issues before hypothesis testing.

3.9 ANALYSIS OF RESULTS

Before the analysis, there was extensive data cleaning to remove unwanted trials. To remove unwanted trials the researcher listened to each trial to ensure the verbal responses were correct, i.e. the participant said the correct colour name for a particular colour. The validity issues mentioned above were checked before testing the two hypotheses. The pre- and post- means were calculated for the involuntary RT and Stroop RT. Any differences between the group mean are tested for using a repeated measure analysis of variance (ANOVA) (see Chapter Four).

3.10 ETHICAL CONSIDERATIONS

Synaesthesia is not known to be harmful and no harmful effects from synaesthesia training have been reported. Congenital synaesthetes do not complain about their synaesthetic abilities, or describe them as a burden. In fact, most synaesthetes do not know that they perceive the world differently from most other people - most are surprised to find out that they are unique (Cytowic & Eagleman, 2009). However, Day (2005) presents a case where it seems synaesthesia may have been causing learning problems for a seven-year-old boy, who was having problems with mathematics because his grapheme synaesthesia would influence him to select more ‘aesthetically pleasing' numbers when solving arithmetic problems. For example, adding '1' to '5' would equal '6', but he would rather write '4', because it 'looked better' to him. There was no problem with his addition skills, but his synaesthesia made it appear as though something was wrong. He was later taught about his synaesthesia and the problem worked itself out.

Although the outcome of the experiment expects that participants may exhibit automaticity similar to that of a grapheme synaesthete, the effect will likely not be permanent. Colizoli et al. (2012) attributes this to the lack of continuous practice, finding that upon calling the participants three months after the experiment, most could not remember their chosen letter colours. The current study obtained ethical clearance from the Department of Psychology at Unisa (in full for a study such as this) before proceeding with data collection.

3.10.1 Informed consent

All the participants were asked to sign a consent form after being fully briefed about what the study involved, and what was required from them (see Appendix B). They were informed that the purpose of the study was to teach them grapheme synaesthesia and that part of the training would be a Stroop interference test. The purpose of the test may have become apparent to them after the first practice trials; however, all groups were not initially fully informed about the way the assessment works. This was done to prevent test bias.

If any participant felt training caused them any harm or discomfort, or wished to discontinue for any other reason, he or she was free to discontinue training without resolution. There was one participant who elected to withdraw because the colours caused her eye discomfort.

3.11 CHAPTER SUMMARY

In this chapter, the method of learning letter-colour associations with colour books is discussed with regard to the letters and colours learnt by participants: which books they read; how the books were coloured; and the design of a modified Stroop test to measure the automaticity between the trained letter colours. The colour reading group and a control group were tested before and after reading their colour-altered books; the control group were tested after a sufficient time had passed, and did not read books. The pre- and post- results were compared using ANOVA.

CHAPTER 4: ANALYSIS

4.1 INTRODUCTION

The results were analysed with statistical software packages JMP 11 (n.d.) and SPSS 20 (2014), and with the assistance of a statistician (see acknowledgments). The first part of this chapter concerns data collection and cleaning, which involved capturing the reaction time (RT) for each trial and removing unwanted trials. Before hypothesis testing, a number of checks concerning the validity of the Stroop test were performed, which included determining that the participants a) had normal colour vision; b) did not have genuine grapheme synaesthesia during pre-testing; c) pre- and post- test colours were consistent; and d) determining whether participants can see and name letters normally (i.e. letter-naming task). Once the validity issues were addressed, the two hypotheses were tested with repeated measures ANOVA to determine whether there were any differences between the colour reading group and the control. All reported values were measured in milliseconds (ms), and rounded off. All confidence levels were set to five percent.

4.2 DATA CAPTURING AND CLEANING

During the data-cleaning phase of the current study, the audio recordings of each test were listened to in order to a) capture/measure the elapsed time from the beginning of the onset beep to the start of participant's verbal response, i.e. reaction time (RT); b) mark each trial right or wrong, i.e. participant must say the correct colour/letter name; and c) remove erroneous trials.

Originally all RTs were captured by the experimental software FLXLab©, and although it was capable of presenting the Stroop test, the built-in voice key feature proved to be inaccurate in many instances. The problem was discovered when comparing the RTs recorded by FLXLab© voice key to the audio recording of the test session. Figure 4.1 is a screenshot of the audio software Audacity®, with a sample of audio captured from a participant's trial (n.d.).

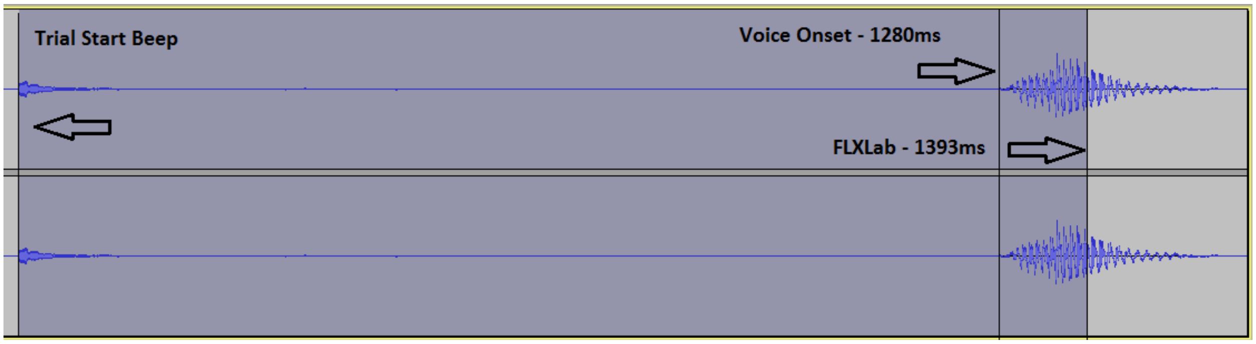


Figure 4.1: Audacity® screenshot showing the audio recording for one of the participants.

Audacity® was used to measure the elapsed time from the beginning of the onset trial beep to the beginning of the participant's response. As shown in Figure 4.1, FLXLab© recorded the end of the trial at 1393ms; however, if the measurement was made manually using Audacity®, the beginning of the participant's verbal response actually started at 1280ms. The latency in this case was around 100ms, between the real voice onset and that which FLXLab© recorded. The source of this inaccuracy could possibly be due to computer latency, which is a normal delay between computer processing events. In some cases, however, the latency was much higher (200ms), possibly because of unknown background computer processes that may have been running in the background during the Stroop test. It may also be that because a single computer was used to present the test (FLXLab©) and record the audio (Audacity®), computer resources may have been strained. Due to these problems, every trial had to be manually captured for each participant using Audacity®. For each participant the average discrepancies between FLXLab© RTs and the manual RTs measurements are shown in Table 4.1.

Table 4.1: Individual differences between average manual RTs and FLXLab© RTs.

Participants	Manual RT	FLXLab RT	Difference
B1	713	743	29
B2	999	988	-11

B3	1041	1076	35
B4	770	852	83
B5	903	956	53
B6	732	809	77
B7	904	976	72
B8	1011	1044	33
B9	860	909	49
B10	828	918	90
B11	758	838	81
B12	800	879	79
B13	758	854	96
B14	797	872	75
B15	615	669	54
B16	813	895	81
C1	718	762	44
C2	890	984	94
C3	918	975	57
C4	641	723	82
C5	1029	999	-30
C6	780	914	134
C7	787	858	71
W1	674	742	68

Overall, on a group level, the discrepancy is not large, (62ms) but on an individual level it was noted that the FLXLab© RTs were more inconsistent for certain participants than they were for others. Some participants varied in the way they pronounced certain colour words and letter names, which had an effect on detection by FLXLab© voice key. For example, participant C5 had the highest difference of 134ms, which was due to the unique way in which she spoke. Similar pronunciation reasons caused negative difference in RTs (B2 and C4), because they were triggering the voice key too early. Another observation was that in general, certain colour words were more accurately measured by the voice key than others. For example, purple and blue were picked up more accurately than were red or yellow, possibly because the ‘b’ in blue makes a definite sound right at the beginning of the word, which triggered the voice key faster. For the rest of the analysis, the manually measured RTs were used instead of the FLXLab© RTs.

While capturing trial RTs, each trial was marked as correct or incorrect, e.g. if the participant was shown a red 'e' and said red, which is correct. Incorrect responses were removed from the main analysis. Trials were only included if the participant clearly articulated the colour word or letter name. Trials were not included if the participant fumbled the word or self-correct midway through a response (e.g. “blu…..no…green”). Listening to the audio recordings of each test also helped to eliminate a number of erroneous trials, such as distractions in the testing room, or other noises compromising the participants' attention. Table 4.2 shows the number of trials that had to be removed.

Table 4.2: Erroneous trials removed.

Included	Excluded	Percentage
15032	210	1.40%

Amongst all participants, there was a small percentage of 1.4% of trials excluded. On an individual basis, one participant had a high percentage of 4.2% trials removed, four participants had between 2.0% and 2.9% trials removed, and the rest were below 1.9 percent. The majority of the removed trials were also close to the beginning of a new block, when the task switched from colour-naming to letter-naming or vice versa, e.g. changing from the letter-naming task to colour-naming task would often lead to incorrect answers, such as saying the letter instead of the colour. It was judged that, overall, the proportion of erroneous responses was low enough, and the degree of variance among participants sufficiently limited, to justify the removal of erroneous responses without compromising the results.

4.2.1 Preliminary Descriptives

The total number of people in colour-reading was seventeen, and the total number of people in the control group was seven. The colour reading group included the single participant who used the web colour letter browser add-on. Table 4.3 displays the group mean RTs for all conditions in the colour-naming task, both pre- and post- colour reading.

Table 4.3: Summary of group mean RTs for the colour-naming task in all conditions pre- and post- testing.

	Pre-Test				Post-Test			
	Black Letters	Congruent Colours	Incongruent Colours	Colour Squares	Black Letters	Congruent Colours	Incongruent Colours	Colour Squares

Colour Reading	1491	840	947	786	1105	737	853	719
Control	1322	851	947	831	1103	725	866	706

Table 4.4 shows the group mean RTs for the letter-naming task in all conditions pre and post colour reading.

Table 4.4: Summary of group mean RT's for the letter-naming task in all conditions pre- and post- reading.

	Pre-Test				Post-Test			
	Black Letters	Congruent Colours	Incongruent Colours	Colour Squares	Black Letters	Congruent Colours	Incongruent Colours	Colour Squares
Colour Reading	596	593	594	1288	548	536	530	1059
Control	659	664	656	1222	561	552	550	1003

4.2.2 Outliers

There is no strict rule for removing outliers. Sometimes an outlier is obvious, for example, by removing one extreme value, the distribution may normalise. However, a consistent method should be used to remove them. It is common practice to remove any trials greater than two or three standard deviations above the mean, but this method is controversial, because it may remove good data. In the current study, no method was used to remove outliers, because any erroneous data were already removed manually during data preparation, and only correctly answered trials were considered, so there was no reason to suspect any more extreme values.

4.3 SCREENING PARTICIPANTS

Before continuing to the main analysis, a number of assumptions about the participants needed to be checked (see section 3.8.2 in Chapter Three for details).

4.3.1 Colour vision

The first assumption was that each participant could see colours correctly. The colour square condition was used as the baseline for normal colour-naming, as it requires quick recognition and the naming of a coloured square. The pre-test mean RTs for the colour square condition and congruent condition were compared, because these two conditions measure the same colour for each participant, but in two different forms. One condition measures the pure colour RT (colour square condition), and the other measures the coloured letter RT (congruent condition). As a guide for the comparison, it is assumed that naming the colour of a colour square should be faster than naming the colour of the congruent letter condition, because the congruent condition involves an extra letter stimulus. Table 4.5 shows the difference between the congruent and colour square condition highlighting positive values. Positive values indicate whether the participants were slower at the colour-naming of colour squares than congruent letters. Most of the participants' differences were negative, because the colour square condition was faster, but there were some positive values. There were seven positive values and the three highest were 142ms (B8), 117ms (B12) and 54ms (B4), while the rest were below 24ms.

Table 4.5: Colour vision of difference between colour square and congruent conditions.

ID	Pre Congruent	Pre Colour Square	Difference
B1	726	710	-16
B2	871	824	-47
B3	1075	875	-200
B4	761	815	54
B5	964	907	-57
B6	698	698	0
B7	883	799	-84
B8	1088	1230	142
B9	819	729	-90
B10	981	767	-214
B11	795	652	-143
B12	869	986	117
B13	819	677	-142
B14	817	840	23
B15	639	607	-32
B16	807	644	-163
C1	785	677	-108
C2	731	692	-39
C3	974	971	-3
C4	714	738	24
C5	1053	996	-57
C6	907	930	23
C7	793	814	21

W1	667	594	-73

A distribution of the differences is shown in Figure 4.2. The minimum difference was 214ms (B10), and the maximum was 142ms (B8); the upper and lower means were -6.12 and -82.54; with the mean -44.33 (SD 90.48). If any participants had a very high positive value, it could be inferred that there was a problem either with their colour vision, or perhaps the participant was hesitant during testing so as to increase accuracy. The differences between the colour square and congruent condition were not excessively high, even for participants B8 and B12; and it was therefore decided that the participants had acceptable colour vision, and the congruent condition was an acceptable measure of a congruent colour.

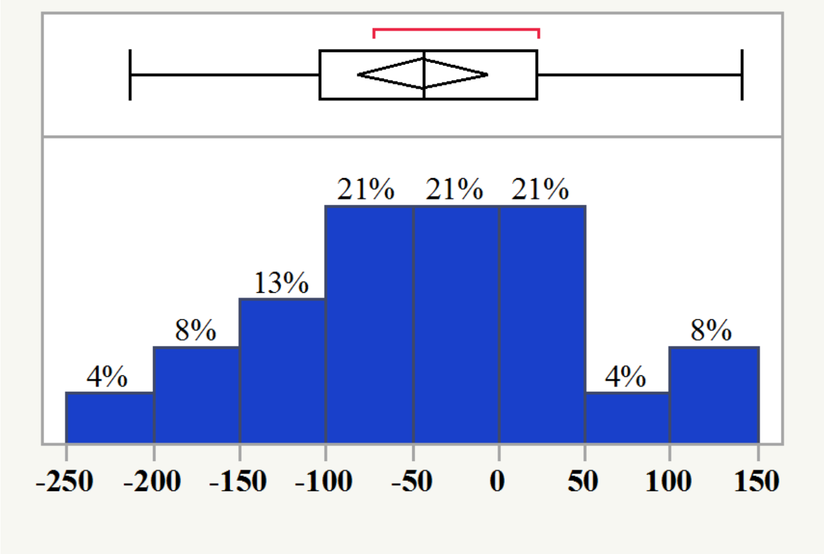


Figure 4.2: Distribution of the differences between the colour square and congruent condition.

4.3.2 Genuine synaesthetes

The second assumption was that none of the participants were genuine synaesthetes. This can be checked by comparing the black letter and congruent conditions in the colour-naming task. Genuine synaesthetes have similar RTs for both conditions (Mills, 1999). Therefore, if any of the participants had similar colour-naming times for the congruent condition, and black letter condition during pre-testing, it could be interpreted as meaning they are genuine synaesthetes. Table 4.6 shows the differences between the black letter and congruent conditions. The black letter condition was the slowest, compared to the congruent condition for all participants in the pre-testing, and all differences were very large, signifying that none of the participants were genuine grapheme synaesthetes.

Table 4.6: The difference between colour-naming task pre-black letter and pre-congruent conditions.

ID	Black letter	Congruent	Difference
B1	1217	726	491
B2	2423	871	1552
B3	2034	1075	959
B4	1301	761	540
B5	1600	964	636
B6	1223	698	525
B7	1575	883	692
B8	1447	1088	359
B9	1803	819	984
B10	1336	981	355
B11	1379	795	584
B12	1704	869	835
B13	1057	819	238
B14	1496	817	679
B15	1204	639	565
B16	1596	807	789
C1	1294	785	509
C2	1308	731	577
C3	1404	974	430
C4	856	714	142
C5	2070	1053	1017
C6	1273	907	366
C7	1049	793	256
W1	948	667	281

A distribution of the differences is shown below in Figure 4.3. The minimum of 142 (C4) and maximum of 1552 (B2); upper and lower mean of 730.66 and 466.08; mean of 598.37 (SD 313.29). The large differences suggest that none of the participants had genuine grapheme synaesthesia. Participant C4 did have a low difference, but not close enough to a zero to signify genuine grapheme synaesthesia. The differences would need to be around 46ms to signify genuine synaesthesia based on the genuine synaesthete test by Mills (1999).

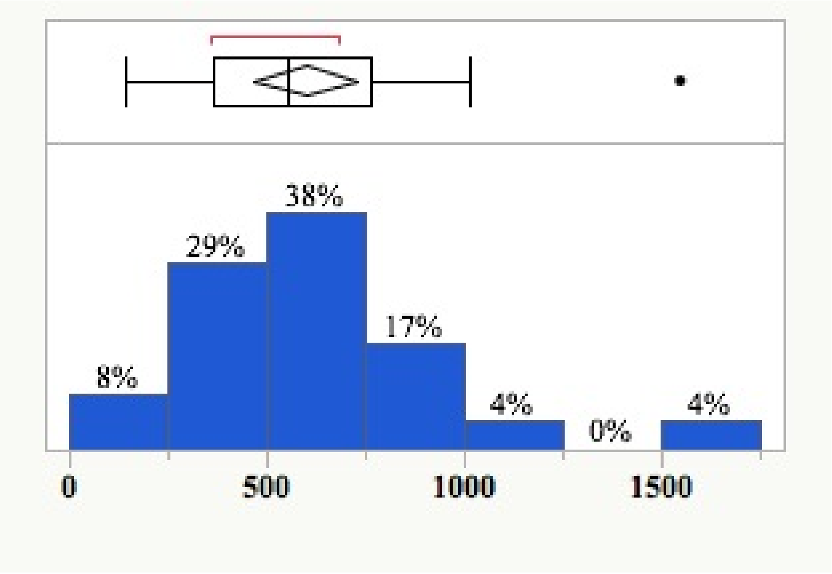


Figure 4.3: Distribution of the difference between the black letter and congruent condition.

4.3.3 Colour consistency

The third assumption that required checking was the consistency between the pre- and post-congruent conditions. This had to be done to ensure that the colours displayed on the computer screen in the pre-Stroop test were consistent with the colours displayed in post-Stroop test. In Chapter Three it was explained that the colours on the computer screen used for administering the post-Stroop test may not have been entirely consistent with the colour letters the participants learn from their printed colour letters, because the quality of the colour changes when printed on a physical medium, as opposed to appearing on a computer screen. The pre- and post- congruent conditions were compared, looking for participants who had slower post-test RTs. If the post-congruent condition was slower than the pre-congruent, it would be assumed that something was affecting the consistency. Table 4.7 below shows the differences between the pre- and post-congruent conditions. As expected, the majority of the RTs differences were negative, indicating that participants were generally faster in post-testing due to a practice effect. However, there were three participants with positive differences (B4, B6 and C2), indicating that there may have been a problem with colour consistency.

Table 4.7: Differences between pre- and post-congruent colour-naming condition.

	Pre Congruent	Post Congruent	Difference
B1	726	610	-116
B2	871	779	-92
B3	1075	997	-78
B4	761	798	37
B5	964	786	-178
B6	698	755	57
B7	883	824	-59
B8	1088	998	-90
B9	819	711	-108
B10	981	812	-169
B11	795	702	-93
B12	869	623	-246
B13	819	715	-104
B14	817	626	-191
B15	639	514	-125
B16	807	659	-148
C1	785	641	-144
C2	731	848	117
C3	974	694	-280
C4	714	570	-144
C5	1053	924	-129
C6	907	717	-190
C7	793	684	-109
W1	667	627	-40

Investigating further, the differences for each stimulus letter were examined. Table 4.8 shows the differences between the pre- and post-congruent condition, but divided into the four stimulus letters. Participants with two or more letters with positive values are highlighted in red, and participants with one letter are highlighted in orange.

Table 4.8: Difference between pre- and post-congruent condition divided into four stimulus letters.

	Difference			
	Congruent Condition			
ID	First Letter	Second Letter	Third Letter	Fourth Letter
B1	-79	-102	-140	-158
B2	-113	5	-94	-128
B3	-126	-91	-135	56
B4	-73	32	24	149
B5	-98	-141	-160	-313
B6	184	-10	-20	72
B7	-193	50	-95	-13
B8	-18	23	-192	-224

B9	-119	-220	-125	29
B10	-134	-211	-118	-213
B11	-133	-25	4	-225
B12	-185	-421	-120	-249
B13	-131	-89	-86	-111
B14	-117	-247	-231	-172
B15	-86	-235	-80	-96
B16	-130	-107	-103	-247
C1	-216	-113	-88	-149
C2	1	14	248	249
C3	-239	-347	-223	-312
C4	-314	-50	-80	-120
C5	-22	-200	-137	-157
C6	-169	-127	-181	-260
C7	-61	-105	-183	-85
W1	-71	-53	13	-57

Positive values indicate that during post-testing, the participants were slower at naming the colour of a particular letter. The majority of the participants' RTs were negative except for seven participants' having at least one letter as a positive value (B2, B3, B7, B8, B9, B11 and W1). The same participants with overall positive RTs seen in Table 4.7 had two or more letters with positive RTs (B4, B6 and C2). For participant B4, three of her letters were positive, and it was noted during the post-test that she disagreed with the colours of her congruent letters, in particular saying that they did not look right. Participant B6 said her printed colours were not the same as the colour letters on the computer screen administering the Stroop test, but she was still willing to continue with the test, which could be why the difference is so large for one of her letters (see Chapter 5 for more on this). As for C2, having positive values could be related to fatigue, as the participant did mention he was tired during his post-test. It was therefore decided to remove the three participants B4, B6 and C2, due to a concern over low consistency between the pre- and post-congruent conditions, which is important for testing the hypotheses. This left 15 people in the colour-reading group, and six people in the control group.

4.3.4 Letter-naming task

Figure 4.4 shows the mean RTs for the letter-naming task for the colour-reading and control group in each condition. The letter-naming task tested whether the participants could name letters normally, and whether there was any indication of reverse synaesthesia, i.e. a colour evoking a letter (see Chapters Two and Three). In the pre-test the black letter, congruent and incongruent conditions had similar RTs, except for the colour square condition, which had the slowest RT for both groups. The pre-test results were similar to the post-test results, but showing the expected improvement due to practice effect between testing.

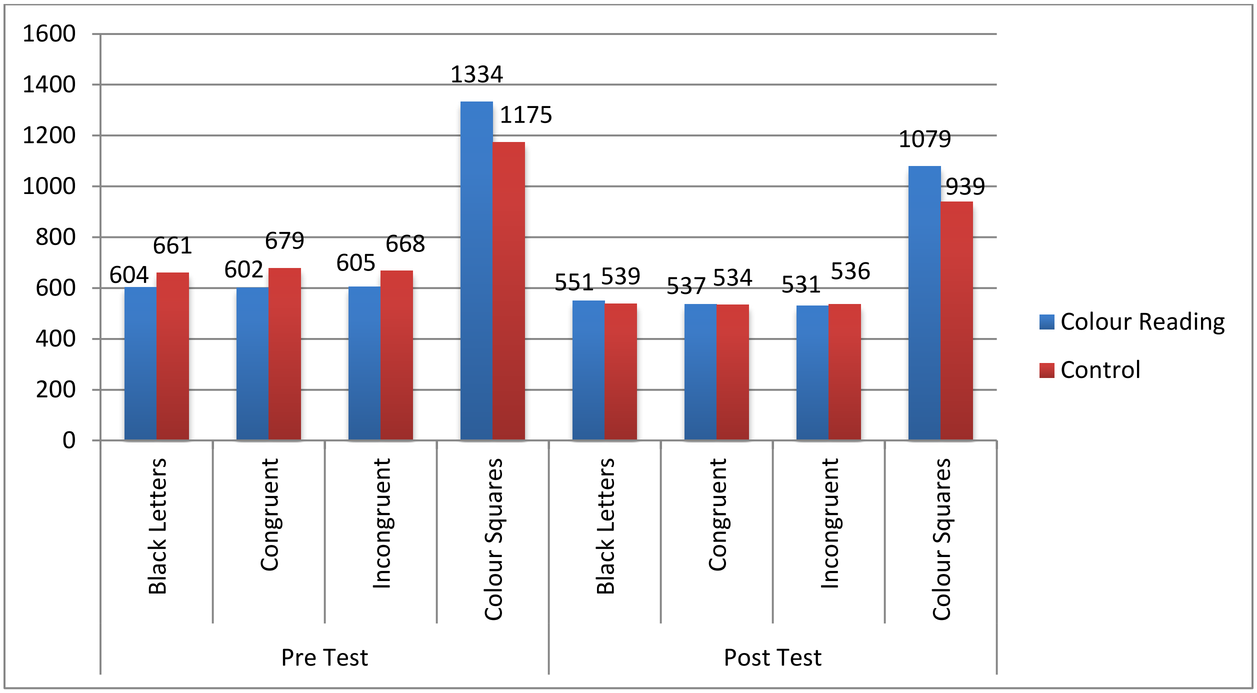


Figure 4.4: Letter-naming task pre- and post- average RTs for each condition in both groups.

In general, there is not much difference between the two groups, with the differences becoming smaller in the post-test. The similar RTs between the black, congruent and incongruent conditions suggest that there were no differences in letter-naming between the groups.

The colour square condition tested if any of the participants had reverse synaesthesia, i.e. a colour-evoking a letter. The pre- and post-colour square condition would have a similar mean RT to the congruent condition. However, this was not the case, because it is more likely that the participants would have had to rely on memory to answer with the correct letter associated with that particular colour square, which takes longer to retrieve from memory, and hence, is slower.

To determine whether there were any significant differences between the groups, the mean RTs were subjected to t-tests for each of the eight variables, beginning with the pre-black letter condition. Before proceeding, normality and equal variances were checked for with Shapiro-Wilk's and Levene's tests. Both tests were not significant for all variables (all p values above 0.05), except for two post-test variables instances. The post-incongruent condition Levene's test made significance (p= 0.05) and the post-colour square condition Shaprio-Wilks test was significant (p=0.00) for the colour-reading group. For these two conditions, Mann-Whitney's U is more appropriate, due to non-normality and unequal variances. Table 4.9 below shows the results of the t-test on the means of the first six variables, and the last two variables incongruent and colour square conditions ranked values are tested with the Mann-Whitney's U.

Table 4.9: T-tests comparing the colour-reading and control group mean RTs for the letter-naming task (post-incongruent and colour square condition tested with Mann-Whitney's U).

Variables		Colour reading mean RT	Control mean RT	T-ratio/*Mann-Whitney U	P-value	Sig
Pre Test	Black Letters	604.06 (SD 112.23)	660.5 (SD 193.80)	0.84	0.4	ns
	Congruent	601.87 (SD 90.07)	679.17 (SD 171.99)	1.36	0.18	ns
	Incongruent	604.533 (SD 111.01)	667.50 (SD 180.62)	0.98	0.33	ns
	Colour Squares	1333.67 (SD 304.73)	1174.50 (SD 225.45)	-1.15	0.26	ns
Post Test	Black Letters	551.06 (SD 83.22)	539.16 (SD 110.72)	-0.26	0.79	ns
	Congruent	536.73 (SD 78.04)	533.83 (SD 114.79)	-0.06	0.94	ns
	Incongruent	530.53 (SD 62.54)	536 (SD 131.75)	*37.50	0.55	ns
	Colour Squares	1079.00 (SD 303.42)	939.33 (SD 232.82)	*25.00	0.11	ns

Degrees of freedom 20

None of the results were significant, suggesting that there were no differences between the colour-naming and control group in the letter-naming task. The two groups were not significantly different in letter naming in any of eight variables. More importantly, the RTs for the colour square did not suggest reverse synaesthesia.

4.4 HYPOTHESIS TESTS

4.4.1 Hypothesis 1: Involuntary RT

The first hypothesis is to determine if the colour reading group learnt the involuntary characteristic of synaesthesia. The involuntary RT is represented by the difference between the congruent condition and black letter condition. If a genuine grapheme synaesthete did the same Stroop test, there would be little difference (around 46ms) between the congruent and black letter conditions (Mills, 1999). The involuntary RT is calculated by subtracting the mean congruent condition RT from the mean black letter condition RT. Figure 4.5 shows the pre- and post-group mean involuntary RTs. The colour reading group mean involuntary RT for the pre-test is 667 (SD 336.72), and the post 376 (SD 194.43); the control group mean involuntary RT for the pre-test is 453 (SD 304.91) and post-test is 341(SD 206.85).

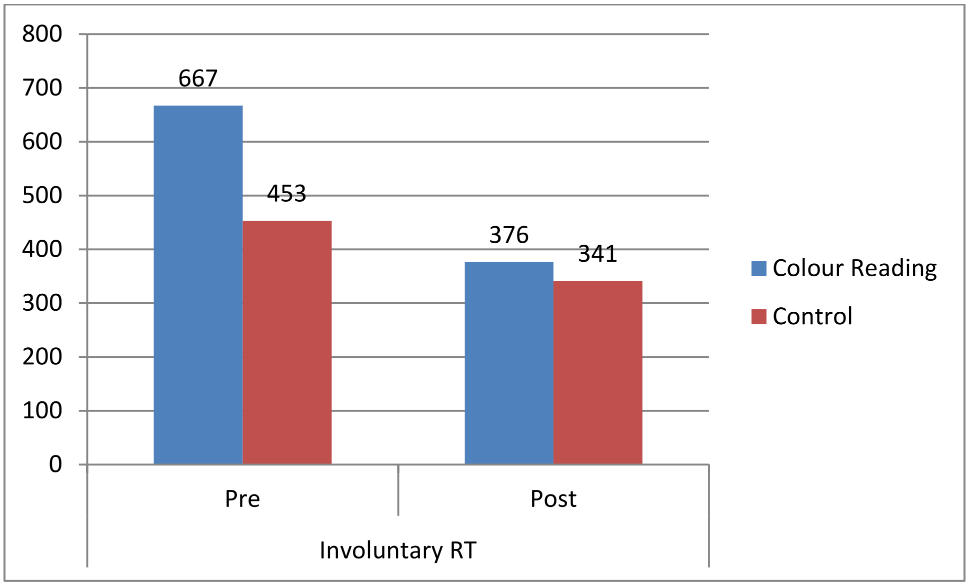


Figure 4.5: Pre- and post-test group mean involuntary RTs.

The difference between the groups is large in the pre-test, but becomes much smaller in the post-test. According to the genuine synaesthete tested by Mills (1999), the post-test involuntary RTs need to be around 46ms to indicate that any of the participants have the involuntary characteristic. The pre- and post-group mean involuntary RTs were compared using ANOVA. The assumptions of the parametric testing had to be checked again, as three participants were removed. The distributions for the pre/post test RTs for each group were normal - Shapiro-Wilk's tests showed that all p values were above 0.05 and Levene's tests were all not significant, with all p>0.05 indicating equal variances between groups. The results of the ANOVA show a significant effect on the involuntary RTs, indicating a significant difference between the pre- and post-test RTs, F(1,19) = 11.03, p=0.003s. This suggests a change in performance between testing in both groups. However, there was no significant group effect F(1,19) = 1.14, p=0.29 ns, suggesting that there were no differences between the colour-reading group and control group in their involuntary RTs. Therefore, neither the colour-reading group nor the control learnt the involuntary characteristic of synaesthesia. There were also no significant interactions F (1,19)=2.15, p=0.15ns.

4.4.2 Hypothesis 2: Automaticity

The second hypothesis tests whether the participants have learnt the automatic characteristic of synaesthesia. The difference between the involuntary characteristic tested above and the automaticity characteristic is that the first is a perceptual process and the latter is conceptual. The involuntary characteristic was tested by comparing it to a perceptual event, in this case, the RT for naming the colour of a letter. The automatic characteristic is tested by measuring the degree to which it is possible to interfere with an automatic response. Genuine grapheme synaesthetes are slower in naming incongruently coloured letters than they are in naming congruently colour letters (Mills, 1999). The difference between the congruent condition and incongruent condition represents the Stroop interference or Stroop RT (Colizoli et al., 2012). The larger the Stroop RT is, the more automatic a response. If reading in colour had an effect, the colour reading group should have a significantly larger interference than the control group. The mean Stroop RT was calculated for each group by subtracting the congruent condition from the incongruent condition. Figure 4.6 below shows the pre- and post- mean Stroop RTs for both groups. The colour reading group mean Stroop RT for the pre-test is 94 (SD 86.64) and the post-test is 126 (SD 66.88); the control group mean Stroop RT for the pre-test is 100 (SD 109.97) and post-test 148 (SD 72.33).

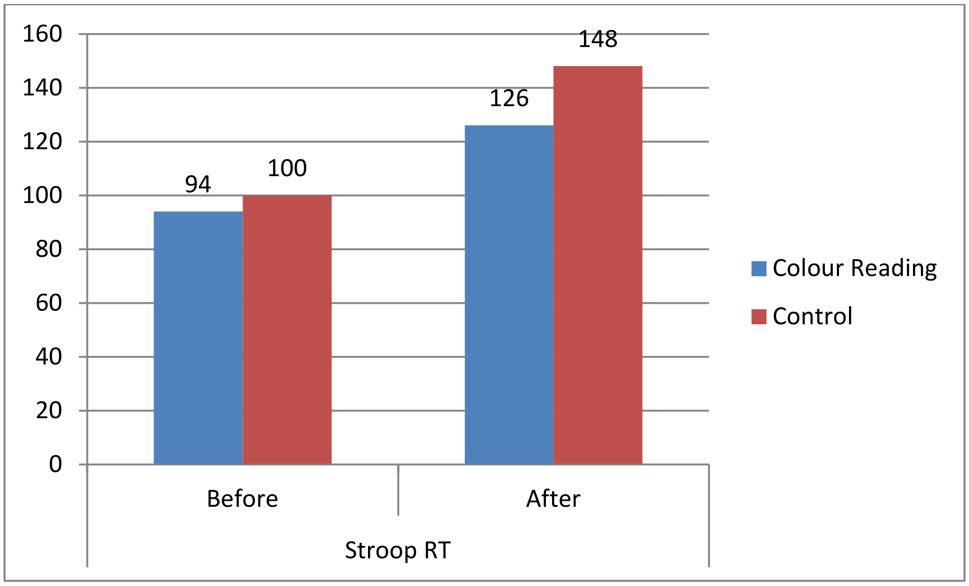


Figure 4.6: The group means pre- and post-Stroop RT.

The Stroop RT became slower in the post-test for both groups, but only slightly slower for the control group. The pre- and post- group mean Stroop RTs were compared using ANOVA. The assumptions of the parametric testing were checked again. The distributions for the pre/post Stroop RTs for each groups were normal, and a Shapiro-Wilk's test found that all p values were above 0.05, and Levene's tests were all not significant, with all p>0.05 indicating equal variances between groups. The results of the ANOVA showed a significant effect on the Stroop RTs, indicating a significant difference between the pre- and post-RTs, F(1,19) = 4.75, p=0.04s. It is curious that both groups had a larger Stroop RT between testing. It may be the better the participants became at the test the stronger the larger Stroop RT. There was no significant group effect F(1,19)=0.15, p=0.70 ns, suggesting that there was no difference between the colour reading group and control group Stroop RTs. There were also no significant interactions F(1,19) = 0.21, p=0.64ns.

4.5 CONCLUSION

In this chapter, a number of assumptions about the participants had to be checked before testing the main hypotheses. The first assumption checked the colour baseline (i.e. colour square condition) to make sure participants could see and name colours correctly (i.e. colour vision). The second assumption ruled out the possibility that any of the participants were genuine synaesthetes during the pre-test. Thirdly, the consistency between the pre- and post-congruent conditions was compared to ensure consistency between the colours on the computer screen administering the Stroop test, and the colours the participants learnt. The last assumption that was checked was if all the participants could see and name letters correctly, and ruled out any reverse synaesthesia. Two hypotheses were tested. The first hypothesis tested for group differences in the involuntary RT and found no significant differences between the colour reading group and the control group. The second hypothesis tested for group differences in the Stroop RT, and also found no significant differences between groups. In the next chapter a discussion of the results will outline some possible reasons for the non-significant difference between the groups, and will make recommendations for further enquiry.

CHAPTER 5: CONCLUSION

5.1 INTRODUCTION

This chapter concludes the current study into the question of whether or not it is possible to learn grapheme synaesthesia. Two main objectives were set. The first objective was to put into practice the training technique described by Colizoli et al. (2012), in which participants read books in colour. Secondly, the participants who read colour books had to be tested, in order to determine whether they did learn grapheme synaesthesia, which was done with a modified Stroop test. The first section of this chapter is a review and discussion of the results of the modified Stroop test. The second portion of the chapter presents recommendations to improve future experiments in this field of study.

5.2 DISCUSSION

The Stroop test in this study is based on the work of Mills (1999) and tests for two key characteristics of genuine synaesthesia, i.e. involuntary and automatic characteristics (see Chapter Two). This section will discuss the hypotheses and the relevant stimuli conditions in the Stroop test for testing these two key characteristics. There were other stimuli conditions in the Stroop test related to the validity of the test, which involved screening the participants to ensure they had normal colour vision (i.e. colour square condition); were not genuine synaesthetes during pre-testing; were consistent in colour naming of congruent colours between the pre- and post-test; and lastly, the letter-naming task ensured participants could see and name letters normally, and also eliminated any possible reverse synaesthesia (see Chapter Two for more on reverse synaesthesia). During this screening process, three participants (two colour reading and one control) had to be removed from the final analysis, because they were not consistent between pre- and post-testing in their colour-naming times for congruent letter-colours (see section 4.3.3), consequently lowering the sample size (15 colour reading and six controls). More on this consistency issue can be found in the recommendations section below. For a detailed discussion about the validity issue, please see the discussion about Stroop test validity in Chapter Three (section 3.8.2) and Chapter Four (section 4.3).

The first key characteristic tested with the modified Stroop test in this study was the involuntary characteristic of genuine synaesthesia. If a genuine grapheme synaesthete sees an inducing letter or number, they will have an involuntary colour experience, and because synaesthesia is not consciously evoked, the experience will be very similar to a perceptual process such as seeing real colours (see Chapter Two). Mills (1999) showed this involuntary characteristic with a genuine digit synaesthete by asking her to name the colours of black numbers and congruently coloured numbers (congruent in the sense of being matched to her synaesthetic colour). The speed at which the synaesthete names the colour of the black condition is a measure of the degree to which her synaesthetic experience is involuntary. However, a comparison needs to be made with another involuntary experience to establish a baseline. The congruent condition is a comparable involuntary process, where a real coloured number must be perceived and named quickly. The congruent condition must be the same as her synaesthetic colour experience, because a mismatch in colour would cause her interference, and a slower naming time. It was found that she had similar colour-naming times for both the black and congruent conditions (46ms difference), suggesting synaesthesia is an involuntary experience, because perceiving synaesthetic colour and perceiving real colour are comparable. The participants who read colour-altered books in this study would therefore need to have an involuntary colour response, comparable to a genuine grapheme synaesthete.

The black and congruent conditions were adapted into the current study's modified Stroop test to measure the involuntary characteristic participants may have after reading in colour. The participants had to name the colour of a black letter or a congruent letter as quickly and accurately as possible. The congruent letter condition was a coloured letter that was the same colour as the one participants saw in their colour-altered books. The black letter condition involved the same letters the participants read in colour, but appearing in black. It was hypothesised that if the black letter condition and congruent condition were not significantly different, it would be reasonable to suggest that the participants were having an involuntary colour response when seeing black letters. For each group, the black letter and congruent condition means were subtracted from one another to calculate the differences (Involuntary RT) for the pre- and post-tests. The differences would need to be small (around 46ms) to suggest an involuntary experience.

The results showed that both groups had very large differences in the pre-test - the colour reading group had a high difference of 667ms and the control group had a 453ms difference (see Figure 4.5). In the post-test, the differences improve, with the colour reading group difference going down to 376ms, and the control to 341ms. Even with the improvement, the differences are still too high to suggest an involuntary experience. It is more likely that participants would still have had to rely on their memory to answer with the correct colour for the particular black letters. A repeated measures ANOVA found no significant differences between the colour reading group and control group, indicating that colour-reading did not have a great enough effect to differentiate the groups. As was evident from the improved reaction times, there was a significant difference between the pre- and post-tests, indicating a significant improvement between testing. It should be noted that the involuntary characteristic can also be tested with a separate test, such as the crowding test (see Chapter Two), but using the black letter condition is convenient, as it only needs one test. Colizoli et al. (2012) used a crowding test to determine whether any of their colour reading participants had an involuntary colour response to the letters they read in colour, but the results showed no difference in performance after reading. In this regard, the current study finds a similar non-significant involuntary response, suggesting that reading in colour is not enough to learn the involuntary characteristic of grapheme synaesthesia.

These findings are also in line with cross-activation theory (see Chapter Two). According to cross-activation theory, structural connections are required in the early perceptual areas of the brain for cross-modal interactions to occur, and this is why synaesthesia is experienced as involuntary (Ramachandran and Hubbard, 2001a, 2001b). The lack of significant involuntary reactions can be interpreted as meaning that reading in colour is not enough to rewire the brain. However, this does not strictly rule out the potential of reading in colour to learn the involuntary characteristic of synaesthesia. It was suggested in Chapter Two that in order for the brain to rewire it may take a longer period of time training. It may be that the participants in this study did not have enough time to read in colour. One could extend the training to examine how effective prolonged training is on the involuntary characteristic. Furthermore, the participants were asked during debriefing if they saw colour letters outside of the colour-altered book, e.g. ”Do you see colour letters in your everyday life, such as licences plates or newspapers?” This was asked because in Chapter Two various phenomenological differences between synaesthetes were discussed (e.g. projector/associator synaesthetes). Projector synaesthetes describe their colours as projected onto the letters. None of the participants saw colours projected onto their letters in any context. This is also in line with the cross-activation theory because it was suggested in Chapter Two that projected synaesthetic colours may be more reliant on cross-activation in early visual brain areas (e.g. V4/V8). The earlier visual areas may be more consolidated/rigid and harder to rewire. The short period of colour-reading may not be enough for normal hebbian learning to rewire these early visual areas (see section 2.6.1 on hebbian associative learning).

The second key characteristic tested with the modified Stroop test in this study was the automaticity characteristic of genuine synaesthesia. Automaticity should not be confused with the involuntary characteristic. The difference is that automaticity is a later cognitive process, whereas the involuntary characteristic is a perceptual process (see Chapter Two). Stroop (1935) first showed automaticity in a well-practiced response or automatic response by interfering with it using incongruent stimuli. He asked his participants to name the colour of colour words but the colour word appeared in a mismatched colour (e.g. colour word 'red' printed in blue ink). It was found that the mismatch between the colour word and its physical colour caused a delay in naming times, whereas naming times for colour words semantically matched to the physical colour were named faster. When the participants saw the mismatched colour word, the automatic response of reading out a colour word aloud undergoes interference, and takes longer, because the person is required to think about the answer. A longer delay means that there was greater interference, and depending on how automatic the particular response is, the delay will be larger. The same principle can be applied to synaesthesia by creating interference between a triggering inducer stimulus and the concurrent synaesthetic colour. For example, Mills (1999) took note of the exact colours a number colour synaesthete has when she sees numbers, and devised an experiment to measure the automaticity between the inducing numbers and the experienced synaesthetic colour. The synaesthete was asked to name the colour of coloured numbers, but the numbers were either shown in a congruent colour, which was the same as her synaesthetic colours for that particular number, or an incongruent condition which was not the same as her synaesthetic colours. It was found that the incongruent or mismatched condition had significantly slower naming times than the congruent or matched condition. When she saw the incongruent number, her synaesthetic colour response conflicted with the real colour of the number, therefore taking her longer to name the colour.

The participants in the current study thus ought to have had a slower colour-naming time for a similar incongruent coloured condition after reading their colour-altered books, more so than the control group. The participants were presented with congruent letters or incongruent letters. The same congruent letter condition was used as in the above involuntary characteristic, i.e. the same coloured letters that were read in their colour-altered books. The incongruent coloured letter was the exact opposite colour of that used in the congruent condition (see section 3.3.2.3). For each group an overall Stroop RT value was calculated by subtracting the mean congruent RTs from the mean incongruent RT conditions. The results for each group were similar in the pre-test, with the colour reading group having a 94ms and the control group had 100ms Stroop RT. In the post-test both groups RTs increased, with the colour-reading group having a 126ms Stroop RT and the control increasing to 148ms Stroop RT. The increase in both groups during post-testing suggests that colour-reading may not have had enough of an impact to differentiate between groups. The repeated measure ANOVA confirms that there was no significant difference between the colour reading and the control groups. However, both groups did show a greater Stroop RT (i.e. more interference) in post-testing, and there was a statistically significant difference between the pre- and post-test. Colizoli et al. (2012) also used a Stroop test and the same conditions for their colour reading participants, and similar to this study, there was an increase in Stroop RT in post-testing, but it was not statistically significant.

The lack of significant differences between those who read colour-altered books and the controls could have been due to the low sample size in the control group (n=6). However, even with a small group, it would appear that merely doing the Stroop test is enough to learn an automatic response to the colours, and hence to become prone to Stroop interference. As the participants progress through the Stroop test, they get better with each passing trial, and subsequently get faster at colour-naming congruent colours, but this also means getting slower at naming incongruent colours (i.e. the more automatic a response the more interference can be experienced).

According to the Disinhibition theory (see Chapter Two) synaesthesia is mediated by regions in the brain where different modal pathways converge (Grossenbacher and Lovelace, 2001). These already existing neural connections between sense modalities are ordinarily inhibited in normal brains to prevent cross-modal interaction. Synaesthetes may have disinhibition between their modal pathways, thereby facilitating cross-modal interaction. If new connections are not required the disinhibition hypothesis could explain why the participants learnt the automatic characteristic of synaesthesia. The participants may have learnt to disinhibit the pathways in the convergence areas between the grapheme recognition and colour regions. It was already mentioned that Stroop interference is a higher order cognitive process occurring later in perceptual processing and associated with higher brain activity in the parietal regions of the brain (Esterman et al., 2006). The participants in this study may have had enough training to only learn their colour letters on a higher order/cognitive level but not on a deeper perceptual level. That is, the short amount of time training was not enough to rewire early perceptual areas (i.e. cross-activation) but it was enough to affect higher order processes.

5.3 RECOMMENDATIONS

5.3.1 Stroop design

It can be speculated that the inclusion of the black letter condition in the design of the modified Stroop test in this study was the cause of finding significant Stroop interference, regardless of colour-reading. In the Stroop test the participants had to name the colour of the black letters presented to them, i.e. the participant says the congruent colour associated with that particular letter. The participants had to rely on their memory to recall the associated congruent colour. It is possible that the black letter condition provided one extra instance/practice for the congruently coloured letters. For example, for every one congruent condition there was one incongruent condition (1:1 ratio). However, the addition of the black letter condition, in a manner of speaking, adds an extra instance where the ‘congruent’ colour must be recalled. The effect of recalling the correct ‘congruent’ colour associated with a letter may have introduced an imbalance in ratio between the congruent and incongruent conditions. In this way recalling the congruent colour could have reinforced the congruent association more during the progression of the test than for the incongruent condition. This may be why the control group also had significant Stroop interference, because the black letter condition may have been more effective at teaching the congruent colour letters than the colour-reading. There was also another weakness identified in the Stroop test, related to the consistency issue (see below). The purpose of the black letter condition in this study was to test the involuntary characteristic of synaesthesia. If it is removed, another method for testing the involuntary characteristic could be used (e.g. crowding test). However, the issue could be rectified in future designs by reducing the ratio of black letter to congruent conditions. Lowering the number of black letter trials could reduce the practice effect for the congruent condition.

5.3.2 Stroop test consistency

A Stroop test must represent the congruent colours of the synaesthete accurately; if the colours are not matched properly, they will inadvertently act as incongruent colours. Normally in a Stroop test done with genuine synaesthetes, the congruent colours are chosen by the synaesthete, which is why the researcher can be certain that the colours are accurately matched. In this study, one set of RGB colour codes were used to program each participant's colour-altered books, and their Stroop test (both pre- and post-). It was assumed that the colours in each participant's Stroop test were an accurate representation of the coloured letters they read. However, the way the colours looked on the computer screen administering the Stroop test is not the same as when it is printed on paper. It is speculated that this is where the consistency issue may have arisen, because once the participants read their colour-altered books, it would make sense that they learn how the colour letters look on paper. If the way the coloured letters looked on paper did not match how they look on a computer screen, it may be that the post-Stroop test colours were not accurately matched, and hence, congruent colours would have looked more like incongruent colours to the participants (see section 3.8.2.2).

During the screening process in this study, three participants (B4, B6 and C2) were removed from the final analysis, because of this consistency issue between the Stroop test and printed colours (see Table 4.8). The single control subject C2 was most likely fatigued. However, during debriefing with B6, she mentioned that the colours on the computer screen were different to the coloured letters in her colour-altered book. The same statement was made by B4, saying that her colours didn't look right on the computer screen administering the post-Stroop test. If the congruent colour letters looked wrong to them, it would act as an incongruent condition, which may be why they were slower at naming congruent colours in the post-test.

Furthermore, B4 read on an electronic screen, whereas B6 read a printed colour book. One would have assumed that those who read on an electronic screen would not have a consistency issue, because the electronic screen administering the Stroop test would look more similar to another computer screen, such as the one the participant read on, or at the very least, be a closer match than a printed colour letter. However, B4 may have become accustomed to the subtleties of that particular screen, and noticed too much of a difference between the way the colour letters looked on the screen administering the Stroop test and the way they looked on her computer screen.

Although B4 and B6 were affected by consistency, it is a question as to why there were not more people as severely affected in the study. There were nine participants overall who had inconsistent letters (see Table 4.8 - excluding C2). Only B6 and B4 had more than one inconsistent letter, which is why they were removed from the final analysis. There were seven other participants who had one inconsistent letter, four of whom read a printed medium, and three who read on electronic screens. This suggests that the inconsistency issue is relevant to both electronic and print media, and that some people seem to be less affected than others. The consistency issue may also be mediated by how much each participant read, for example B4 had the highest word count (see Table 3.2), which could be why she was affected.

The consistency issue outlined thus far could be the cause of the lack of significant differences between the colour-reading and control group in this study. It is recommended that in future, colour-reading researchers should ensure that the colour-reading medium (i.e. print or screen) be consistent with the test stimuli (e.g. Stroop test). For example, in this study, a paper version of the Stroop test may have been more appropriate for those who read a printed book. The computer Stroop test may still be appropriate for those who read on electronic screens, but as seen with B4, this does not guarantee better consistency; therefore, the researcher should also have the participants verify the colours of the test stimuli after colour-reading.

5.3.3 Web colour letters

There was another part of this study which included electronic colour reading on the internet, with a second experimental colour-reading group that used the browser add-on Synesthetize. This group was different in that they did not read books; instead, they browsed the internet with coloured letters. There were three people in this group originally, but only one person managed to use the add-on for a sufficient period of time and return for post-testing. The browser add-on showed certain merit, but ultimately needs more development to improve user experience. For the add-on to be effective, it would need to work consistently across all websites, which is difficult to implement, because websites are coded in a large variety of different ways. The participants reported that some of the websites they visited would not display correctly (e.g. garbled code). This would lead to the add-on being turned off by the participant. Another problem was that sometimes the coloured letters would be a similar colour to the background colour of a particular webpage, causing the letters to blend into the background. In future, a temporary solution could suffice. If participants come across situations such as the one described above, they could make use of a simple on/off button, allowing them to disable the add-on at any time. The on/off button could also automatically reactivate after a specified period of time, in case it was forgotten to turn it back on. Another feature could be not to change the letters on websites that are flagged as problematic by the user. For research purposes, the add-on should also collect statistics, such as the number of times a letter was changed into a colour on an active webpage.

5.3.4 Participant feedback

At the conclusion of the post-Stroop test, each participant was debriefed about the particulars of this study. They were asked open-ended questions about their colour reading experience. All participants reported that it took their eyes some time to adjust to the colours, and each person varied in how long it took for their eyes to adjust. This was not the case for everyone; participant B5 said that colour-reading induced a headache, but she was motivated to continue, so she took frequent breaks. There was also one participant who dropped out of the study very early because the colours reportedly hurt her eyes. Perhaps the colour-reading could be adapted for individuals who are overwhelmed by many colours. In this study, the colour-altered books consisted of four colour letters, appearing throughout the book; perhaps it may be more beneficial to space out the training of each letter into different books. For example, a participant could read four books, wherein each book has only a single colour letter appearing throughout. If the colour reading is spaced out to have one coloured letter per book, it could be less overwhelming for the person whose eyes may need a longer time to adjust. There does not necessarily need to be four separate books; it could be one book, divided into sections, with one unique colour letter in each section.

Participants were asked how they felt about their colour-letter combinations after having read the colour books. The overall response was that there were some letter-colour pairs they were not comfortable with, or found challenging to remember as a combination. For example, B5 said some colour letter pairs made more sense to her than others, because she imagines where the letter falls in the alphabet and depending on how far down it is on this list, the darker the colour of the letter appears to her. Her technique was rather unique, as other participants were bothered by having 'odd' semantic combinations, e.g. a blue 'o' or a red 'b'. In Chapter One, it was mentioned that young synaesthetes’ colour-letter pairs take time to consolidate; perhaps the same process should be integrated into colour reading, by allowing participants an opportunity to change their letter-colour combinations. They could be given a shorter book consisting of maybe 40 to 50 pages and then given the chance to change colours.

Three participants each brought up similar statements regarding the lack of differentiation between some of their colour letters, for example, B6 and B7 said their blue and purple letters became too similar. However, B7 said this could have been because of a poor reading lamp she keeps next to her bed when she reads. Ambient lighting can affect how colours appear. The quality of the colour printing could also have been a factor in differentiating colour letters. This problem could be solved by reading on an electronic device, as colours will stand out better due to the backlighting in a screen; alternatively it is suggested to improve the quality of the printing when it comes to texts presented in hard copy.

It is recommend that more single participant or small group designs are incorporated in future synaesthesia training studies, because there may be more subtleties to learning synaesthesia that could be better explored with motivated individuals. In conversation with the participants, it was clear that some people were more motivated than others to read in colour. This was most likely related to which book they read, for example B2 said that his book was not engaging, so he only read to finish it, whereas some of the participants who enjoyed their books did appear to have a higher Stroop interference in the post-test. However, motivation is beyond whether or not the book was an engaging read. For example, during the post-test debriefing, there were participants who asked me more questions about synaesthesia, and were generally more enthusiastic about the study. Motivation may be a key aspect to learning synaesthesia, which is why finding motivated individuals may be more important than studying a large sample of people. Many new insights can come from the personal observations that participants make themselves, and having a larger sample may mean sacrificing the time it takes to give each person enough attention.

5.4 CONCLUSION

The colour-reading method used in this study was not enough to differentiate between the results of those who read colour-altered books and those who did not. The groups were tested for two key characteristics of synaesthesia. Both groups did not show an involuntary reaction to letters, although the groups were significantly better in the post-test. Both groups did show automaticity between the letter and colour, reflected in an increase in Stroop interference in the post-test, suggesting that merely completing this particular Stroop test is enough to develop some automaticity to colour letters. Developing synaesthesia takes time, as is evident from the literature review, and it seems that it is possible to learn the automatic characteristics, but that this is not enough for a colour letter to become more than memory, or to be involuntary. Colizoli et al. (2012) use the term pseudo-synaesthesia to indicate that this is not real synaesthesia; however, it may be more appropriate to describe this as *partial* synaesthesia or *incomplete* synaesthesia. In this study, partial synaesthesia is distinguished as only satisfying one of the two central characteristics, namely involuntary or automatic. The groups in this study did show significant automaticity, and although this could be attributed to the Stroop test, it could be argued that they did learn grapheme synaesthesia, but only partially and to a lesser degree.

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APPENDIX A

FLXLab© Modified Stroop Script

```
## Adapted from the stroop demos found on FLXLab website
## Copyright (C) 2009 Todd R. Haskell (todd.haskell@wwu.edu)
## This script can be entered into the FLXLab© programme to replicate the experiment reported on in this dissertation

# Colours to use for the experiment
DefineColor grey            128 128 128
DefineColor red_con          255 0 0
DefineColor blue_opp         255 79 175
DefineColor green_con       0 176 80
DefineColor pink_opp        255 79 175
DefineColor blue_con        0 112 192
DefineColor orange_opp      255 143 63
DefineColor purple_con      95 73 122
DefineColor green_opp       160 182 133

# Get the subject id from the user
EditDialog subject_id "Enter subject id:"
# Use the subject id to generate the name of the data file
JoinStrings data_file "data_files $path_separator $subject_id .txt"
# Set the name of the data file
UseDataFile $data_file
ClearScreenEvent clear_screen
SelectObject screen
Color grey

# Define block for instructions
LoadTextFromFile instructions_text1 introduction.txt
TextBoxEvent introduction $instructions_text1
LoadTextFromFile practice_one practice_instructions_1.txt
TextBoxEvent practice_instructions_colourname $practice_one
LoadTextFromFile practice_two practice_instructions_2.txt
TextBoxEvent practice_instructions_lettername $practice_two
LoadTextFromFile colour_name colourname.txt
TextBoxEvent colourname_instructions $colour_name
LoadTextFromFile letter_name lettername.txt
```

```
TextBoxEvent lettername_instructions $letter_name
LoadTextFromFile thanks_text thank_you.txt
TextBoxEvent thank_you $thanks_text

WaitEvent wait_for_key "until key any"
BlockEvent do_introduction
AddEvent clear_screen
AddEvent introduction
AddEvent wait_for_key
BlockEvent do_practice_colourname
AddEvent clear_screen
AddEvent practice_instructions_colourname
AddEvent wait_for_key
BlockEvent do_practice_lettername
AddEvent clear_screen
AddEvent practice_instructions_lettername
AddEvent wait_for_key
BlockEvent do_colourname
AddEvent clear_screen
AddEvent colourname_instructions
AddEvent wait_for_key
BlockEvent do_lettername
AddEvent clear_screen
AddEvent lettername_instructions
AddEvent wait_for_key

#Define a block for saying thank you
BlockEvent do_thank_you
AddEvent clear_screen
AddEvent thank_you
AddEvent wait_for_key

#Define a trial
# Create labels for the three columns in the stimulus file
StimulusList stimulus_list charlotte_list.txt
LabelListColumn 1 item_number
LabelListColumn 2 item_type
LabelListColumn 3 stimulus_letter
LabelListColumn 4 stimulus_color
LabelListColumn 5 block_color
```

```
TextObject text "+"
FontSize 80
DisplayEvent warning_signal
DefinePosition my_center 50% 52%
AddObject text my_center
DelayEvent pause 500
RectangleObject rectangle
Size 3% 5%
Color $block_color
Filled
TextObject stimulus $stimulus_letter
Color $stimulus_color
TextBackgroundColor $block_color
#making it play a sound before onset of stimulus
JoinStrings sound_file "sound_files $path_separator saywhen_trialonset.wav"
PlaySoundEvent onsetbeep $sound_file
FontSize 80
FontFace URWNimbusBold
DisplayEvent display
DefinePosition my_center2 50% 51%
AddObject rectangle my_center
AddObject stimulus my_center2
# Reaction times will be relative to the onset of the stimulus
ResetDataTime
VoiceKeyEvent toggle_microphone
WaitEvent wait_for_voice "until voice_key"
DataEvent record_response
DataColumn $item_number
DataColumn $item_type
DataColumn $stimulus_letter
DataColumn $time
DelayEvent pause2 1000
TrialEvent trial
AddEvent pause2
AddEvent warning_signal
AddEvent pause
AddEvent clear_screen
AddEvent onsetbeep
AddEvent display
```

```
AddEvent toggle_microphone
AddEvent wait_for_voice
AddEvent toggle_microphone
AddEvent record_response
AddEvent wait_for_key
BlockEvent practice_block1 "until $item_number equals 16"
AddEvent trial
BlockEvent practice_block2 "until $item_number equals 32"
AddEvent trial
BlockEvent lettername_block "until $item_number equals 112"
AddEvent trial
BlockEvent colourname_block "until $item_number equals 192"
AddEvent trial
BlockEvent lettername_block2 "until $item_number equals 272"
AddEvent trial
BlockEvent colourname_block2 "until $item_number equals 352"
AddEvent trial
# Combine all blocks into experiment
ExperimentEvent stroop_test


AddEvent do_introduction
AddEvent do_practice_colourname
AddEvent practice_block1
AddEvent do_practice_lettername
AddEvent practice_block2
AddEvent do_lettername
AddEvent lettername_block
AddEvent do_colourname
AddEvent colourname_block
AddEvent do_lettername
AddEvent lettername_block2
AddEvent do_colourname
AddEvent colourname_block2
AddEvent do_thank_you
Start stroop_test
```

APPENDIX B

INFORMED CONSENT FORM

Title of the research: Learning Grapheme Synaesthesia
Researcher's name: Nicholas Forssman
Researcher's position: Master's student
Department: Psychology
Address: P.O Box 392 UNISA 0003 South Africa
Contact telephone no: - work: -
Email: -

IMPORTANT MESSAGE TO PARTICIPANT

Dear Participant

Thank you for volunteering to be part of this study. During the course of the study you are welcome to discontinue training at any time should you experience any discomfort or distress as a result of the training material (colour altered book or web browser add-on) and/or computer test. Please do not hesitate to contact me at any of the convenient numbers provided above if you have further question related to the research.

As a participant in the study we would like you to: 1) read the entire training material consisting of one (1) colour-altered book chosen by yourself (the participant) and/or install and use the web browser add-on for a period of three to four weeks. 2) Complete two test sittings of the computer based test, once before and once after the training material has been consumed (both meetings shall be scheduled individually per participant). If you are only doing the computer training, you must come in for testing and training twice with a three to four week gap between sessions.

Test results will be treated confidentially, and will only be accessible to the researcher. No participant names will be published. The researcher will ensure that all the material remains confidential and stored safely. The final report of the study will be made available to those participants who wish to read it.

This is to confirm that I (name)____
consent to participate in the study. I understand that I can withdraw from the study at any time.

Signature of participant:______________________________

Signature of researcher:________________________________

Date:____________________________

Thank you for participating in this study.