Effects of synaesthetic colour and space on cognition

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Declaration

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

Signature:

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Preface

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Elements of this research have been presented at the following conferences: *UK Synaesthesia Association Annual Conference* (Jonas & Ward, 2008; 2010); *British Psychological Society Annual Conference* (Jonas, Taylor, & Ward, 2009); *European Workshop on Cognitive Neuroscience* (Jonas, Taylor, & Ward, 2009); *Experimental Psychological Society London Meeting* (Jonas, Taylor, & Ward, 2009).

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Summary

A small proportion of the population experiences synaesthesia, in which a stimulus (the inducer) causes a percept (the concurrent) in its own sensory domain, *and* in another domain, or another sub-domain of the same sense. This thesis is concerned with synaesthesiae in which numbers and letters take on spatial locations or colours.

In Paper 1, alphabet-form synaesthesia is investigated. The majority of alphabet forms belonging to native English speakers are straight, horizontal lines. Any breaks, gaps or direction changes tend to fall in line with the parsing of the Alphabet Song. Synaesthetes show greater inducer-concurrent consistency than controls; their spatial attention can also be cued by letters.

In Paper 2, synaesthetes with alphabet forms and number forms took part in case or parity judgement tasks. Synaesthetes behave similarly to controls on the parity judgement tasks (i.e. both groups categorise small numbers more quickly with the left hand than the right hand). In the case judgement task neither group shows an equivalent effect for letters of the alphabet. Controls alone show a QWERTY effect, in which letters on the left of the keyboard are categorised more quickly with the left hand than the right hand.

A large-scale study of letter-colour and number-colour synaesthesia in Paper 3 shows that correlations between letter frequency and saturation, alphabetical position and saturation, magnitude and luminance, magnitude and saturation are seen when luminance and saturation are considered as across-hue and within-hue variables.

Papers 4 and 5 are concerned with synaesthetic bidirectionality, wherein concurrents can elicit implicit mental representations of their inducers. While no experiment in these papers shows evidence for bidirectionality, this may be due to the presentation of concurrent colours as graphemes instead of colour blocks. However, priming effects appear during a synaesthetic Stroop task when numbers are presented as digits, suggesting a stronger role for digits than other notations in number-colour synaesthesia.

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Overview

1 *Synaesthesia*

Since RSW learned to read, she has always perceived numbers as having particular colours: 2 is yellow, 3 is pink, and 5 is apple green. The perceptions of synaesthetes such as RSW are automatic and involuntary, and can be both helpful (Rothen & Meier, 2010) and unhelpful (Green & Goswami, 2008). RSW's particular synaesthetic experiences are just one example of a wide range of potential synaesthetic connections between and within senses, and even between concepts and senses. Approximately 4% of the population experiences some kind of cross-modal or intramodal synaesthesia (Simner et al., 2006) and the number may rise as high as 33% when synaesthesiae involving spatial sequences are included (Sagiv, Simner, Collins, Butterworth, & Ward, 2006).

2 *Terms*

When discussing synaesthesia, researchers refer to *inducers* (the sensation or concept that gives rise to a second perceptual experience) and *concurrents* (the illusory perception that results from the inducer). Typically, different forms of synaesthesia are referred to by their inducer-concurrent pairing, e.g. sound-colour (Ward, Huckstep, & Tsakanikos, 2006), lexical-gustatory (Simner & Logie, 2007), and so on.

A distinction is made between those synaesthetes who perceive their concurrents as existing outside their bodies (e.g. letters on the page take on colour) and those who perceive them as existing in the mind's eye (e.g. a block of colour is imagined in response to seeing a letter). The former type of synaesthete is known as a *projector*, and the latter type as an *associator* (Dixon, Smilek, & Merikle, 2004). Ward, Li, Salih, and Sagiv (2007) have made a case for further subdividing grapheme-colour projectors' concurrents into *surface* (on the inducer) and *near-space* (between the inducer and the synaesthete) types, and associators' into *see* (pictured in the mind's eye) and *know* (non-perceptual knowledge that an inducer belongs with a particular concurrent) types. These subdivisions can be extended to some other synaesthesia types, so that a music-colour synaesthete might see their colours on the source of the music (*surface projection*) or near the source (*near-space projection*), perceive colours in the mind's eye (*see-associator*) or simply know that a musical note goes with a colour (*know-associator*).

Finally, and most importantly for this review, it has been argued that for number-colour synaesthesia a distinction could be made between *lower synaesthetes*, for whom the physical appearance of an inducer gives rise to the concurrent, and *higher synaesthetes*, for whom the concept of the inducer is the cause of the concurrent (Ramachandran & Hubbard, 2001). Usually, number-colour synaesthetes report their concurrents for numbers presented as digits, independent of font; that is, most synaesthetes are higher synaesthetes because the alteration of the percept does not affect their synaesthesia (see Simner, 2011, for a discussion on the possibility of the majority of synaesthetes of all types responding to concept rather than percept). Higher synaesthetes may also respond to any other familiar notation (e.g. dot patterns, Roman numerals, number words, finger counting). As digits have privileged access to the mental representation of number (Damian, 2004), even in higher synaesthetes digits would be likely to induce stronger concurrents compared to other notations.

3 *Testing for synaesthesia*

As Ramachandran and Hubbard (2001) acknowledged, convincing a non-synaesthete that synaesthesia exists can be a very difficult task, as synaesthesia is essentially known only to the perceiver. The synaesthete, therefore, can be misunderstood as an attention-seeker, as someone in need of treatment for a mental illness, or, due to synaesthesia's similarity to experiences under hallucinogens such as ayahuasca (Shanon, 2003), a drug abuser. Unlike hallucinogenic experiences, however, synaesthetes' inducer-concurrent pairings tend to be remarkably stable once they are established (see Simner, Harrold, Creed, Monro, & Foulkes, 2009, for a discussion of unstable synaesthesia in childhood) and remain the same over the course of many years (Jordan, 1917; Simner & Logie, 2007)[1].

[1] Synaesthesia may not, in fact, be inherently stable. Synaesthetes joining the Sussex-Edinburgh database of synaesthete participants often report unstable inducer-concurrent pairings, despite possessing many of the other characteristics of developmental synaesthesia such as *automaticity* and presence of concurrents since childhood. Unstable concurrents may, perhaps, be the result of very weak synaesthesia, which would make it hard for the synaesthete to choose the correct concurrent in the same test at two different times. Stability in synaesthesia is, however, useful for researchers because consistency is very hard to fake, providing a stronger test for synaesthesia than might otherwise be the

This tendency to stability enables researchers to test for synaesthesia. One method uses the verbal labels that synaesthetes apply to their concurrents (Simner & Logie, 2007; Simner et al., 2005). For those with colour concurrents, the exact hue, saturation, and luminance (HSL) values of those concurrents (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007) make for a very precise test. These methods are not without their pitfalls – the largest being differences in consistency – but do exclude synaesthetes who are not likely to respond in the same way to the same stimuli time after time, providing researchers with a set of inducer-concurrent pairings that are likely to produce the same behavioural effects in repeated experiments.

Less time-consuming as a test of synaesthesia is the modified *Stroop test*, most commonly used for synaesthetes with colour concurrents. The inducer is presented in its own colour, the colour of another inducer (Mills, Boteler, & Oliver, 1999) or, less commonly, a colour that does not appear in their concurrent range (Nikolić, Lichti, & Singer, 2007). The synaesthete is quicker to name a colour with its own digit than with any other digit (e.g. Mills et al., 1999).

4 *Synaesthesia and typical cognition*

Debate on whether synaesthesia is similar to or different from typical cognition has focused on whether there are functional or structural differences between synaesthetes and non-synaesthetes. In terms of subjective experience, one might ask the equivalent question of whether it is possible or impossible for non-synaesthetes to

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case. The danger is that excluding unstable synaesthetes means that a biased picture of synaesthesia may result.

have synaesthesia-like experiences under hypnosis (Cohen Kadosh, Henik, Catena, Walsh, & Fuentes, 2009) or while using drugs. Even a swift consideration of these hypotheses will show that synaesthesia as a tool in the investigation of typical cognition has widely varying applications, depending on the pathway that synaesthesia takes.

Five main types of theory have emerged (see Bargary & Mitchell, 2008, for a review):

i. The *neonatal hypothesis*, espoused by Maurer and Mondloch (2005), states that all newborns are unable to distinguish between inputs from different senses as their cortex is undifferentiated. Later, neural pruning removes most of these connections, leading to synaesthetic links between senses in cases where there is less pruning and to unconscious cross-modal links in cases where there is more pruning. Skelton, Ludwig & Mohr (2009) have shown that synaesthesia may 'fade' from projection to association over the course of a lifetime. In this view, synaesthetes are structurally different from non-synaesthetes.

ii. A different version of the neonatal synaesthesia hypothesis is the *cross-modal transfer* hypothesis (Baron-Cohen, 1996; Meltzoff & Borton, 1979), in which direct pathways between senses exist for synaesthetes, but never for controls (who instead recognise objects in multiple senses by creating an abstract mental representation) – again, making synaesthetes' brains structurally different from non-synaesthetes'.

iii. The *disinhibited feedback model*, put forward by Grossenbacher & Lovelace (2001; Weiss & Fink, 2009) is also based on a functional difference between synaesthetes and controls, but the path from inducer to concurrent passes through multimodal sensory areas rather than directly from one unimodal area to another. The theory posits that feedback from multimodal to (concurrent) unimodal sensory areas becomes *disinhibited*. Brang and Ramachandran (2008) have hypothesised that this disinhibition might be mediated by serotonergic pathways.

iv. The *re-entrant hypothesis*. As Smilek, Dixon, Cudahy, and Merikle (2001) describe, colour and form are initially segregated during visual processing. The meaning of a form is processed in the inferior temporal lobe, and in synaesthetes this causes feedback to hV4 (a colour-processing area). This model is neutral with respect to the structure/function distinction.

v. The *hyperbinding model*, in which normal parietal mechanisms of *binding* (e.g. of colour and shape) are overactive in synaesthetes, leading to binding of real inducers to unreal concurrents (Esterman, Verstynen, Ivry, & Robertson, 2006).

Structural accounts of synaesthesia have been supported by studies showing increased white matter compared to controls in the fusiform gyrus and intraparietal sulcus of grapheme-colour synaesthetes (Rouw & Scholte, 2007; Weiss & Fink, 2009). Cohen Kadosh and Walsh (2008), however, have challenged this view, saying that this connectivity could be the result of *Hebbian learning* rather than the cause of synaesthesia; their point is backed up by the finding that non-synaesthetes receiving a posthypnotic suggestion of digit-colour synaesthesia behaved in a similar way to projector synaesthetes on a subsequent digit detection task (Cohen Kadosh et al., 2009). On the other hand, Elias, Saucier, Hardie, and Sarty (2003) have reported a single case study of a non-synaesthete participant who associates numbers with colours due to years of cross-stitching (in the pattern, numbers represent certain colours) – she, too, behaved like a synaesthete, but did not show the same pattern of brain activation as a synaesthete when asked to calculate using dice patterns or auditorily presented numbers. However, since she showed similar brain activation to the synaesthete in a modified Stroop task, the cross-stitch expert could be considered to have acquired know-associator synaesthesia. Again, this is supportive of functional explanations of synaesthesia.

5 *Interactions between letters, numbers and colour in synaesthetes*

Visual symbols used to represent aspects of language can be classified into four groups, in a hierarchy of most literal to most figurative (Besner & Coltheart, 1979):

i. Pictographic, pictures of ideas (e.g. road signs).
ii. Ideographic, which stand for ideas but do not resemble those ideas (e.g. digits, Japanese Kanji).
iii. Syllabic, which encode syllables (e.g. Japanese Kana).
iv. Alphabetic, which encode phonemes (e.g. the Roman and Hebrew alphabets).

Some symbols can encode more than one level (e.g. Roman letters are typically used alphabetically to create words, but can also be considered as ideograms when used in algebra to represent unknown quantities). Due to the differing nature of these representations, Besner and Coltheart argued, their brain basis should also differ; this is supported by their observation that the physical size of stimuli can affect judgements of numerical magnitude when they are presented as digits (ideographic) but not as number words (alphabetic). Similarly, Hebrew-speaking participants found that physical size was harder to ignore for judgements involving digits than for those involving Hebrew (alphabetic) number names (Razpurker-Apfeld & Koriat, 2006). In the same experiment, participants found the physical size of gematria (letter symbols which can also be interpreted as numbers) to be harder to ignore than those of letter names, showing that the level at which symbols are processed may be altered by task demands. Other forms of behavioural experiment, such as Parkman's (1971) study in which participants were asked to judge which of a pair of numbers was greater and which of a pair of letters came later in the alphabet, also reveal differences between letters and numbers. A substantial proportion of the variance in Parkman's participants' reaction times in the number task could be accounted for by the magnitude of the minimum number presented (e.g. the pair 2 5 would elicit a shorter reaction time than the pair 4 7), but the same was not true for the ordinal position of the earlier letter presented in the letter task (e.g. the pair B E would not elicit a shorter reaction time than the pair D G).

Leet, an internet 'alphabet' in which some letters are replaced by numbers or symbols S0 7H4T 7H3 R3$UL7!NG ME5S4G3 L00K5 R4TH3R L1K3 7H1S – D!$C0NC3RT1NG, BU7 C4N ST!LL B3 RE4D F41RLY E4S!LY – is also a useful tool in determining whether symbols can change levels. Initially, Perea, Duñabeitia, and

Carreiras (2008) showed that priming a word to be identified with a masked leet equivalent (e.g. M4T3R1AL or MΔT€R!ΔL was used to prime MATERIAL) allowed it to be identified as quickly as an identical masked prime, and more quickly than non-resembling leet primes such as M6T2R76L or M☐T%R? ☐L. Non-resembling leet primes in turn facilitated identification more than non-resembling letter primes such as MOTURUOL. However, letters cannot be used to prime number identification in the same way (Perea, Duñabeitia, Pollatsek, & Carreiras, 2009), suggesting that the physical characteristics of numbers that resemble letters are sufficient to activate letter representations, but the reverse is not true for letters resembling numbers.

Together, these findings suggest that (providing the step is up the hierarchy of symbol types) cross-system physical resemblance is a more powerful cueing tool than within-system non-resemblance. This is not surprising if numbers and letters are coded for in different ways. If number and letter representations were mixed, it would be equally important to be able to distinguish across symbol systems as it would within a single system. The reason why this may happen is that letters are temporally clustered with other letters, and numbers with other numbers, leading to Hebbian learning and thereby cortical separation of letters and digits (Polk & Farah, 1995).

This Hebbian model is supported by lesion studies that have shown that numbers can be spared in *alexia* (Anderson, Damasio, & Damasio, 1990; Starrfelt, 2007). In neglect patients, who fail to attend to the left side of space after right parietal damage, mental bisection of alphabet intervals (e.g. M-U, midpoint Q) sometimes does not show the classic rightward shift seen in mental bisection of number intervals (Nicholls & Loftus, 2007; Zorzi, Priftis, Meneghello, Marenzi, & Umiltà, 2006). Visual field (VF) asymmetries are also seen for numbers presented as digits and words, where a stronger advantage is seen for the right VF in numbers presented as words (e.g. FOUR) than numbers presented as digits (e.g. 4, Peereman & Holender, 1985), and for numbers presented in American Sign Language (an ideographic symbol system) compared to digits, where interference between physical size and magnitude was stronger in the left VF for digits and in the right VF for signs (Vaid & Corina, 1989). Later, Polk et al. (2002) showed that an area around the left fusiform gyrus (possibly the visual word form area, or vWFA) responds preferentially to letters over digits. Ordinal decisions involving numbers activate the left parietal cortex, compared to those involving letters activating the right parietal cortex, both approximately 70-200ms after stimulus onset (Szűcs & Csépe, 2004). Szűcs and Csépe also showed a stimulus-specific activation in the right parietal region approximately 150-300ms after stimulus onset (however, Zhou et al., 2006, have found left parietal activation for both backward counting and backward recitation, though this may be related to task demands).

Generally, number-colour and letter-colour synaesthesias are considered as a unitary phenomenon, grapheme-colour synaesthesia, despite the above evidence on the differences between numbers and letters, and, more obviously, despite some synaesthetes reporting that only one of the two grapheme types induces colour. Much of the research on grapheme-colour synaesthesia has failed to distinguish between grapheme types, so I initially present an overview of grapheme-colour synaesthesia followed by a consideration of numbers and letters as separate inducer types.

5.1 Graphemes

Some of the experiments that use numbers and letters as interchangeable inducers have shown that synaesthesia appears to take place at a relatively early stage in the processing of the grapheme. For example, in two synaesthetes, presenting a flanked grapheme in the periphery of the visual field evokes colour even though the grapheme itself cannot be identified (Ramachandran & Hubbard, 2001).

Hubbard, Arman, Ramachandran, and Boynton (2005) found activation in the early visual cortex of six synaesthetes (V1-V4) viewing graphemes, noting that the strength of activation correlated positively with better performance on a *flanker task*[2]. This pattern of activation fits with Ramachandran and Hubbard's (2001) description of lower synaesthesia, postulated to take place in the fusiform gyrus. However, only three synaesthetes were tested in this study, and a group effect of synaesthetic superiority was not seen.

However, studies indicating pre-attentive synaesthesia are in the minority, and both the studies above had very few participants. Prevalence of lower and higher synaesthesia has not been calculated, but there is strong behavioural evidence that higher synaesthesia exists and, if sample sizes are a good representation of the relative

[2] It should be noted that only three synaesthetes outperformed non-synaesthete controls on the flanker task, one of whom appeared to outperform controls because they did poorly, not because the synaesthete had done well. Group-level superiority on the flanker task was not seen in synaesthetes.

proportions of higher and lower synaesthetes in the population, higher synaesthetes are more common than lower.

Tasks in which colour can be used to find a target in the absence of serial search (‘pop-out’ tasks), independent of the number of distractors, can also provide insight into higher and lower synaesthesia. When participants are asked to identify a shape (triangle, circle, square, or diamond) made of 2s in a field of 5s at a presentation time of 1000ms, mixed evidence of higher synaesthesia results. Synaesthetes’ performance is superior to controls’ (Hubbard et al., 2005; Ward, Jonas, Dienes, & Seth, 2010), but Ward et al. found that the majority of the 36 synaesthetes they tested did not perceive colours during the experiment, suggesting a strong role for attention in synaesthesia. In addition, a visual search task (in which 13 of the 14 participants saw only number stimuli) by Edquist, Rich, Brinkman, and Mattingley (2006) has shown that synaesthetes are not aided in visual search by their concurrents, suggesting post-attentive synaesthesia.

There is some imaging evidence for synaesthesia occurring in the angular gyrus (the posited location of higher synaesthesia in Ramachandran and Hubbard’s 2001 paper). Esterman et al. (2006) and Muggleton, Tsakanikos, Walsh, and Ward (2007) both report attenuation of synaesthesia following transcranial magnetic stimulation (TMS) over the angular gyrus. Furthermore, greater than usual grey matter volume, indicating increased connectivity, has also been found in both the IPS (intraparietal sulcus, neighbouring the angular gyrus) and the fusiform gyrus by diffusion tensor imaging in synaesthetes (Weiss & Fink, 2009). This last piece of research could indicate mixed synaesthesia, in which either the concept or the percept of number can activate a concurrent, or a mix of lower and higher synaesthetes in the sample, perhaps due to the presence of letter-colour and number-colour synaesthetes.

5.2 Comparing letter-colour and grapheme-colour synaesthesia

Direct comparisons of number-colour and letter-colour synaesthesia have, so far, not been made. However, using a range of behavioural studies which have only considered one of these two types of grapheme, we can build up a picture of the relative places of each.

Numbers show strong links between magnitude, saturation and luminance (Cohen Kadosh, Henik, & Walsh, 2007), as well as between number frequency and saturation (Beeli, Esslen, & Jancke, 2007; Smilek, Carriere, Dixon, & Merikle, 2007). Large-scale studies of the colours commonly paired with letters have shown that linguistic links are most important in determining concurrents, since commonly used letters tend to induce linguistically common colours (Simner & Ward, 2008). There are also simple linguistic links between letters and the colours they induce; for example, G is commonly green, Y is commonly yellow (Simner et al., 2005). Transfer of letter-colour synaesthesia between English and Russian for a multilingual synaesthete is also based on simple sensory attributes of the letters – their sounds and shapes (Mills et al., 2002). For example, the Russian letter Ц (pronounced *zz*, as in *pizza*) is coloured like the visually similar U, while Л (pronounced *l*, as in *bull*) is coloured like the phonologically similar L. In addition, an English-speaking synaesthete who learned

Hebrew reported colours for many Hebrew letters that resulted from phonemic similarities between Roman and Hebrew letters (Mills, Metzger, Foster, Valentine-Gresko, & Ricketts, 2009). While there are some reports of ‘refrigerator magnet’ synaesthetes (Witthoft & Winawer, 2006), whose synaesthetic pairings are based on experiencing letters and colours in certain arbitrary pairings in books or on refrigerator magnets, very few synaesthetes report inducer-concurrent pairings resembling any alphabet book that they would have been likely to read (Rich, Bradshaw, & Mattingley, 2005).

Perhaps the best evidence for number-colour synaesthesia as a conceptually mediated phenomenon is that of *bidirectionality*. Bidirectionality has recently become an area of debate in synaesthesia research, with some (e.g. Cohen Kadosh & Henik, 2007) arguing that bidirectional links are synaesthetic and others (e.g. Berteletti et al., 2010) that they result from a lifetime of unidirectional links between number and colour and are therefore semantic. In terms of informing models of numerical cognition this is important, because a synaesthetic link means that colour is effectively another number notation (and one which is privileged because of its strong link to digits rather than any other notation), while a semantic link implies a less central role for colour in models of synaesthetic numerical cognition.

For number-colour synaesthetes, numbers can interfere heavily with tasks involving colour. In Johnson, Jepma, and de Jong’s (2007) reverse Stroop task, synaesthetes were asked to name the digit belonging to a presented colour (e.g. *5* presented in the colour of *4* required the participant to answer “four”), which gave rise to a reverse Stroop effect. Bidirectionality effects also appear in numerical tasks where colour is irrelevant, such as parity judgement (Gebuis, Nijboer, & van der Smagt, 2009b), magnitude judgement (Cohen Kadosh et al., 2005), and even line length judgement (Cohen Kadosh & Henik, 2006c). A single case study by Dixon, Smilek, Cudahy and Merikle (2000) in which a synaesthete took longer to complete a mental addition task when an embedded colour-naming task involved a colour incongruent to the answer, indicates that self-generated numbers may also be affected by synaesthesia. A slight modification by Jansari, Spiller, and Redfern (2006) shows that this congruency effect appears even when digits are presented auditorily rather than visually.

Arguably, the fact that colour can be the same for upper-case and lower-case letters, and across fonts (Ramachandran & Hubbard, 2003) indicates that letter-colour synaesthesia may be 'higher' synaesthesia. Indeed, letters may be conceived of as higher inducers in the presence of other letters. For example, when ambiguous graphemes (e.g. those that could be perceived as a 2 or a Z) are presented in the context of other letters, their colour becomes harder to name if it is the colour of the number, and the reverse is seen when a letter-coloured grapheme is presented among numbers (Myles, Dixon, Smilek, & Merikle, 2003). More convincingly, Weiss, Kalckert, and Fink (2009) presented synaesthetes with words missing a letter (e.g. _iete, which can become the high-frequency Miete – "rent" – or low-frequency Niete – "blank"). A block of colour, corresponding to the letter that completes the low-frequency word, in the place of the blanked letter primed synaesthetes to name the lower-frequency word.

In neurological terms, the division between numbers and letters is rather unclear. Gebuis, Nijboer & van der Smagt (2009a) found parietal activation in synaesthetes during number-related tasks in their event-related potential (ERP) study; similarly, Weiss, Zilles & Fink (2005) found posterior and anterior parietal activation while their synaesthetes viewed letters. Additionally, the lingual gyrus of the occipital lobe has been implicated in both forms of synaesthesia (Elias et al., 2003; Rich et al., 2006), as has the intraparietal sulcus (Cohen Kadosh, Cohen Kadosh, & Henik, 2007; Esterman et al., 2006). Unique to letter-colour synaesthesia are V4/V8 (Rich et al., 2006; Sperling, Prvulovic, Linden, Singer, & Stirn, 2006), and the fusiform gyrus (Weiss et al., 2005). For number-colour synaesthesia, unique sites are the supramarginal and angular gyri (Cohen Kadosh, Cohen Kadosh et al., 2007; Elias et al., 2003).

6 *Spatial synaesthesia*

The relatively underexplored area of *spatial synaesthesia* relates to those kinds of synaesthesia where the concepts of ordered sequences such as numbers, the alphabet, and days of the week induce the sense of specific spatial locations. Spatial synaesthesiae are believed to have implicit counterparts in the general population, which cannot be seen but still affect behaviour. The best-known of these is the *mental number line*, or MNL (Dehaene, Bossini, & Giraux, 1993), which in Westerners is arranged with small numbers on the left and large numbers on the right; similarly, the *mental alphabet line* (MAL) is arranged with early letters on the left and late letters on the right. Spatial forms in synaesthesia can be differentiated from these implicit arrangements by their more idiosyncratic layouts (but see Eagleman, 2009[3]) and their perceptual reality to synaesthetes. Additionally, while implicit spatial forms seem to be restricted to numbers, letters and perhaps time, some synaesthetes report that a wide variety of sequences can take on shapes (Hubbard, Ranzini, Piazza, & Dehaene, 2009).

Concurrents can be located in peripersonal space (projection) or in the mind's eye (association), but it is unclear whether projectors have visual or proprioception-like concurrents. Some evidence for the role of vision in spatial synaesthesia does exist, however, as Price (2009) has shown that time-space synaesthetes have superior mental imagery strictly in the visual, rather than spatial, domain (but see Simner, Mayo, & Spiller, 2009, for an account of superiority in both visual and spatial processing). This is reflective of experiments with other types of synaesthesia that show synaesthetes' superiority in the concurrent domain (e.g. Banissy, Walsh, & Ward, 2009). Additionally, Brang, Teuscher, Ramachandran, and Coulson (2010) report that time-space synaesthetes are more capable of memorising other synaesthetes' concurrent locations than are controls, again indicating superiority of visual or spatial processing.

Chapter 2 of this thesis marks the first time that letter-space synaesthesia has been systematically experimented on (previously it has merely been reported as a potential accompaniment to other spatial synaethesias, as in Sagiv et al., 2006), so in

[3] Eagleman (2009) did not, however, test for consistency in his group of participants, so his finding of predominantly linear month-space synaesthesia may not be valid.

this Introduction I present data on number-space and time-space synaesthesia only. Time sequences, like the alphabet, encode ordinality (the elements of the sequence have a fixed order) but not magnitude (February is not bigger than January and B is not bigger than A), making time-space synaesthesia a useful proxy for letter-space synaesthesia.

7 *Interactions between number, time and space in synaesthetes*

Month-space synaesthesia, in which months are perceived in a spatial 'calendar form', has been the focus of the majority of research so far carried out on spatial synaesthesia. Calendar forms show some regularity across synaesthetes despite their idiosyncratic natures, such that months in the first half of the year tend to be to the left of months in the second half of the year (Eagleman, 2009). Unlike number forms, the perspective from which calendar forms are viewed may change over time (e.g. the synaesthete may perceive herself as being 'in' the current month, or a circular form may rotate around the head or the body so that the current month is always in the field of view). There is some dispute over the most common shape that calendar forms take: Eagleman (2009) reports linear forms as the most frequent, while Brang, et al. (2010) report circular forms. Eagleman did not include a consistency test in his experiment, meaning that Brang et al.'s data, while more conservative, are also more reliable[4].

[4] As time-space synaesthesia may change over time, consistency is not necessarily a useful test. One way around this is to ask synaesthetes to describe their calendars on two days exactly one year apart, but this may not be easy to do.

For synaesthetes with calendar forms, the appearance of a month can cue spatial attention (Price & Mentzoni, 2008; Smilek, Callejas, Dixon, & Merikle, 2007; Teuscher, Brang, Ramachandran, & Coulson, in press), something which is not reliably true for non-synaesthetes[5] (Dodd et al., 2008; Gevers et al., 2003; Price & Mentzoni, 2008). The location of the calendar-form representation seems to be parietal (Teuscher et al., in press), which is perhaps not surprising given that months implicitly encode numerical information, potentially meaning that month forms initially arise from explicit number forms or implicit MNLs, both of which have been associated with parietal activation (Göbel, Walsh, & Rushworth, 2001; Tang, Ward, & Butterworth, 2008).

Number-space synaesthesia was first reported by Galton (1880a; 1880b) and is rather idiosyncratic, though like month-space synaesthesia there is some agreement amongst those who have it; for example, most number forms run from right to left in counting order (Sagiv et al., 2006). Number forms have been reported by some synaesthetes as an aid to calculation (Phillips, 1897; Seron, Pesenti, Noel, Deloche, & Cornet, 1992), though in fact possessing one appears to slow addition and multiplication, but not subtraction (Ward, Sagiv, & Butterworth, 2009). The perceptual reality of number forms is generally confirmed using consistency tests (Sagiv et al., 2006), which are less reliable here than in the case of colour synaesthesia as they tend to rely on the categorisation of diagrams drawn at two different times as same or different rather than verbal labels or HSL values. More recently, genuineness has been

[5] I use this term loosely as Dodd, Van der Stigchel, Leghari, Fung, and Kingstone (2003) and Gevers, Reynvoet, and Fias (2003) did not separate synaesthetes and controls.

tested using parity judgement tasks. While Western non-synaesthetes[6] respond to low numbers more quickly with the left hand and high numbers with the right hand (Fias, Brysbaert, Geypens, & d'Ydewalle, 1996), synaesthetes tend to respond in line with the characteristics of their number forms (Jarick, Dixon, Maxwell, Nicholls, & Smilek, 2009), though one single-case study has shown that synaesthetes may not always do so (Hubbard et al., 2009). Another synaesthete showed both a typical left-low/right-high effect resulting from his MNL and a left-high/right-low effect resulting from his synaesthesia (Piazza, Pinel, & Dehaene, 2006). This last finding may be explained by Tang and colleagues' (2008) observation of automatic activation of the bilateral anterior IPS (coding for cardinal, or quantity-related, properties) in response to a number, and task-related activation of the bilateral posterior IPS which appears to be involved in coding for an ordinal number form, indicating that an MNL and a non-MNL shaped number form could co-exist.

8 *Informing cognition using synaesthesia*

At the grossest level, synaesthesia is useful as a tool in researching cognition because it is a type of cross-modal association. All humans make cross-modal associations, though generally in a less structured way than in synaesthesia. Synaesthesia can be very similar to these implicit associations – for example, rough textures are associated with dark colours and smooth textures with light colours by synaesthetes and non-synaesthetes alike (Ward, Banissy, & Jonas, 2008); similarly,

[6] Again, I use this term loosely as many experiments using the SNARC (spatial-numerical association of response codes) task (see later) have not explicitly excluded synaesthetes from their samples.

high-pitched noises are associated with lighter colours than low-pitched noises in both groups (Marks, 1982; Ward et al., 2006). These associations can be used to inform sensory substitution hardware such as the vOICe (Merabet et al., 2009), which converts a head-mounted webcam's image into a soundscape, allowing blind users to navigate their environments more easily.

More particularly, synaesthesia involving graphemes can be used to inform a variety of aspects of numerical cognition and letter and word recognition:

i. The mental number line. Number-space synaesthesia can be viewed as an overt form of the MNL, but as Tang et al. (2008) have shown, number forms appear to be ordinal in nature, while the MNL is generally considered to be magnitude-related (Dehaene, 1992). This important distinction can be used to lever apart the ordinal and cardinal properties of numbers.

ii. The mental alphabet line. Like its numerical counterpart, letter-space synaesthesia may be a conscious version of the MAL. However, the evidence for the existence of the MAL is even more inconclusive than it is for the MNL, suggesting that the presence of letter-space synaesthetes with MAL-compatible alphabet forms among participants in experiments probing the MAL may be the sole source of this apparent spatial bias. By screening for letter-space synaesthesia before carrying out these experiments, it will be possible to ascertain if this is the case.

iii. Models of number processing. I discuss in more detail in Paper 5 how synaesthesia can be useful here, but in brief, synaesthetic concurrents could be bound to a single notation-specific representation, multiple notation-specific representations, or an amodal representation of number, each of which would result in different behaviours for tasks where synaesthesia interacts with numbers.

iv. Differences in letter and number perception. Several lines of evidence (e.g. imaging, lesion, and priming studies) indicate that letters are not processed in the same way as numbers, though this distinction has often been lost in experiments on synaesthesia (e.g. Hubbard et al., 2005; Jäncke, Beeli, Eulig, & Hanggi, 2009; Johnson et al., 2007; Muggleton et al., 2007; Rouw & Scholte, 2007, 2010; Schiltz et al., 1999; Weiss & Fink, 2009). Synaesthesia research, therefore, becomes more widely useful in psychology if this distinction is rigorously maintained.

9 *Graphemes, colour, and space in non-synaesthetes*

9.1 Learning to count

The process of understanding number begins well before a child can speak: quantities can be differentiated by preverbal infants (Xu & Spelke, 2000). Consequently, when a child learns to say number words, she is applying labels to principles that she has already begun to understand.

Gelman and Gallistel's (1978) list of principles that a child must acquire before she can truly be said to understand counting includes some items that are universal in sequence learning (stable order of number words, one-to-one correspondence between those words and objects to be counted) and some that are very different (the understanding that one can use counting words to enumerate any item, that the last number spoken when counting represents the whole set of objects that have been counted – cardinality – and that if one is counting to assess the cardinality of a group, order is irrelevant). This process takes place from approximately two to six years of age (Butterworth, 2005). Subsequently, the child will start to discover that there are many uses to which numbers can be put, from cookery to calculus.

9.2 Different number formats

Number can be presented in a variety of ways. In the Western world, the digit system is the most frequent (Dehaene, 1997). This dominance is reflected by the ease with which digits activate mental representations of number – digits induce a spatial-numerical association of response codes (SNARC) effect, which was first discovered by Dehaene et al. (1993) in a task where participants were asked to press one of two lateralised response keys to categorise a digit from 0-9 as odd or even. In participants whose mother tongue is written left-to-right, reaction times were quicker with the left hand to small numbers and with the right hand for large numbers, but in a graded fashion so that 1 is more left-dominant than 2, and 8 is more right-dominant than 7. While this effect appears to depend on culture (e.g. Shaki, Fischer, & Petrusic, 2009, showed that Arabic readers, whose written language runs from right to left, showed a reversed SNARC effect), it has been replicated many times for numbers presented as digits (Dodd et al., 2008; Fias, 2001; Fias et al., 1996; Fischer, 2003; Fischer, Warlop, Hill, & Fias, 2004). Furthermore, even when attending to a number is not necessary to complete a task, it can still cue spatial attention to one side or the other (Fischer, Castel, Dodd, & Pratt, 2003). This has been interpreted as evidence for the MNL – which directly influences response times (Dehaene et al., 1993). However, other number notations do not produce SNARC effects in such a wide variety of tasks (Fias, 2001). Damian's (2004) number-naming and magnitude judgement experiments suggest a possible explanation: that digits have privileged access to meaning, while number words have privileged access to the lower-level aspect of number naming.

Other ways of representing number also dissociate, depending on their place in the pictographic-ideographic-syllabic-alphabetic hierarchy. Kana (syllabic) and Kanji (ideographic) symbols produce different distance effects[7] (Takahashi & Green, 1983) and different results in a size incongruity paradigm, where participants must decide which of two numbers of different physical sizes is numerically larger (Ito & Hatta, 2003). Conversely, number symbols belonging to the same level of representation provide similar results on the size incongruity paradigm (Ganor-Stern & Tzelgov, 2008).

Number words appear to belong to a special category of notation that falls somewhere between non-number words and digits. Digits and number words produce different size incongruity effects (Cohen Kadosh, Henik, & Rubinsten, 2008), but number words are not processed in the same way as other words, either. Cohen, Verstichel, and Dehaene (1997) speculated that number words are not broken down beyond the word level, instead of being broken down into phonemes as are non-number words. This assertion is supported by Messina, Denes, and Basso (2009),

[7] Moyer and Landauer (1967) first described the distance effect as a property of numerical decision tasks: when a pair of numbers is presented on screen and the participant is asked to decide which is larger, the task takes longer when the numbers are close in magnitude (e.g. 5 6) than when they are far in magnitude (e.g. 2 8).

whose analysis of 165 aphasic patients showed that they found number words more difficult to process than other words, and that different classes of errors were typically made in reading and repetition tasks (lexical substitutions for number words and phonological errors for other words).

That different representations of number are reacted to differently by participants has led to the development of several models of numerical cognition that attempt to account for it. These models are split into those that claim that numbers are converted to an abstract representation and those that claim that number processing is notation-dependent all the way through.

9.3 Models of number processing

9.3.1 Abstract-modular (McCloskey, 1992; McCloskey, Caramazza, & Basili, 1985)

In this model, number comprehension and number production are served by different systems, each of which is split into verbal and Arabic numeral components. Furthermore, numbers in each component can be understood or produced lexically (individually, e.g. the 3 of 356) or syntactically (holistically, e.g. the 3 of 356 denotes three hundred rather than thirty or three). A final subdivision occurs in the lexical part only, so that spoken numbers and written numbers are processed by different subsystems. Comprehension and production are linked by an amodal calculation system, which can recognise and process the symbols used in calculation (e.g. +), retrieve arithmetic facts (such as the times table), and carry out calculations.

9.3.2 Encoding-complex (Campbell, 1994; Campbell & Clark, 1988; Campbell & Epp, 2004)

Unlike the abstract-modular model, the encoding-complex model is based around specific representations of number (e.g. lexical, phonological, analogue). While these representations are able to interact with each other (see triple-code model below), some are used more easily than others for specific tasks (e.g. arithmetic and magnitude comparisons may be most easily carried out with Arabic numerals). These task-specific uses of particular representations are individual and depend on a variety of factors such as culture and the way in which arithmetic is taught to an individual.

9.3.3 Triple-code (Dehaene, 1992)

The triple code model posits that numbers may be mentally represented in one of three ways: verbal, visual Arabic, or analogue magnitude (equivalent to the MNL), each of which has its own functions that are not carried out by any other representation. Any of these representations can be (approximately) turned into another through a ‘translation path’, but, in contrast to the encoding-complex model, these inter-representational links are additive (i.e. the numerical distance effect should remain the same between stimulus notations in the triple-code model) rather than interactive (i.e. notation type interacts with the distance effect in the encoding-complex model).

10 *Interactions between number, space and colour in non-synaesthetes*

Colour can interact with numbers, though there is no evidence that colour can interact with letters below the word level. In tasks where participants must decide which number is darker or numerically larger (Cohen Kadosh & Henik, 2006a) there is mutual interference between magnitude and luminance. This is the only study of its kind to report interference between these two properties; previously, an interaction was found between luminance and size, and size and magnitude, but no direct interference between luminance and magnitude (Pinel, Piazza, Le Bihan, & Dehaene, 2004). However, Cohen Kadosh and Henik's finding is in line with the tendency for number-colour synaesthetes to report that large numbers are duller and darker than small numbers.

The dominant representation of number appears to be spatial, though there are a few situations in which verbal memory is also used – for example, when carrying out simple multiplication, answers may be retrieved verbally through rote recall of multiplication tables (Koshmider & Ashcraft, 1991). However, evidence from the SNARC effect regarding the initial processing of numbers suggests a predominantly spatial representation.

Nuerk, Iversen and Willmes (2004) have claimed that there is another spatial representation of number that arises not from links between magnitude and space, but between linguistic labels and space. Using the linguistic categories of marked and unmarked words[8], they demonstrated that participants respond more quickly to even numbers with the right hand and odd numbers with the left hand, regardless of magnitude. They argued that this is because the marked verbal labels *left* and *odd* are associated, as are the unmarked labels *right* and *even*, and referred to this as the linguistic markedness of response codes (MARC) effect. Further research has shown that both the SNARC and the MARC effects may be due not to the spatial properties of particular sets of numbers, but to task demands (Fischer, 2006), creating an extra stage of processing in which numbers are categorised according to the task rules before a response is made (Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006; Notebaert, Gevers, Verguts, & Fias, 2006; Proctor & Cho, 2006).

Supporting evidence for this interpretation of the SNARC effect is growing. Fischer, Shaki and Cruise (2009) showed that the SNARC effect is present in Russian-Hebrew bilinguals (who have two competing dominant directions of reading) when the target digit is preceded by a Russian number word, but that it disappears when the target digit is preceded by a Hebrew number word, while Hung, Hung, Tzeng, and Wu (2008) found that Taiwanese participants' SNARC effects altered orientation from horizontal to vertical depending on the mode of number presentation (digits, presented horizontally in written Chinese, or Chinese number words, presented vertically in the same material). Bächtold, Baumüller, and Brugger (1998) have shown that asking participants to imagine a clock face while carrying out a SNARC-type task

[8] In pairs of complementary words (e.g. *negative-positive*), one is termed *marked* and the other *unmarked*. This is a result of a particular property of complementary pairs: one is defined relative to the other. For example, we define *lioness* in relation to *lion*, making lioness the marked word and lion the unmarked word. *Even-odd* and *right-left* are two other such complementary pairs.

can reverse the SNARC effect. Similarly, Cho and Proctor (2007) have shown that the MARC effect can be modified to a rule-of-three effect (so that numbers that divide by three are responded to more quickly with one hand and those that do not are responded to more quickly with the other hand).

One type of evidence for the number line that is not readily explained by task-dependent mapping comes from neglect patients whose failure to attend to the left side of space extends to the putative MNL, so that when asked what the midpoint is between, say, 10 and 15, neglect patients tend to answer with a number higher than 13 (Zorzi, Priftis, & Umiltà, 2002). However, this may be due to limitations on spatial working memory in neglect rather than the result of spatial representation of sequences (Doricchi, Guariglia, Gasparini, & Tomaiuolo, 2005).

In summary, interactions between number and space in non-synaesthetes appear to be flexible and depend mostly on the task at hand. This is not the case for synaesthesia, where one spatial layout of number persists over a whole lifetime. It may therefore be useful to assess synaesthete and non-synaesthete groups on tasks like those of Hung et al. (2008) or Bächtold et al. (1998)

11 Learning the alphabet

The process of learning letters is rather different from that of learning numbers, largely because numbers encode a more complex range of information than letters. In most English-speaking countries, children are taught a song to help them learn the order of the alphabet, usually before they are able to recognise the letter that goes with each sound (Ehri, 2009). This song groups the alphabet into the chunks ABCDEFG, HIJK, LMNOP, QRS, TUV (alternatively QRST, UV), WXYZ to the tune of Twinkle, Twinkle, Little Star (Klahr, Chase, & Lovelace, 1983)[9]. This verbal representation of the alphabet persists into adulthood (Hamilton & Sanford, 1978; Klahr et al., 1983), though Scharroo, Leuwenberg, Stalmeier, and Vos (1994) showed that in countries where the Alphabet Song is not learned, chunking is more individualised. Even in countries where it is learned, the chunks do not necessarily follow the song (Hovancik, 1985). These chunks may, then, be the result of pauses or speed changes to aid articulation or memory, which are generalised in situations where a particular way of reciting the alphabet is common.

As well as showing that the Alphabet Song is used to chunk the alphabet verbally in adulthood, Hamilton and Sanford (1978) provided the first evidence for an alphabetic ‘distance effect’. Subsequently, this effect was replicated by Grenzebach and McDonald (1992) and Jou and Aldridge (1999), but not by Fulbright, Manson, Skudlarski, Lacadie, and Gore (2003).

Neurologically speaking, letters appear to be a special category of regular shape. As Lachmann and van Leeuwen (2008) have shown, same-different judgements for letters are aided less by a congruent surrounding shape (e.g. an A surrounded by a triangle) than are pseudoletters and shapes. Further, unlike numbers, which can be primed by their neighbours in the counting sequence (Zorzi & Butterworth, 1999),

[9] The parsing of the Alphabet Song is based mainly on pauses for breath (e.g. between ABCDEFG and HIJK) but one pair of chunks (HIJK/LMNOP) is parsed according to a change in speed of letter recitation at this point. There is also one pause which is not mentioned by Klahr et al. (1983): between ‘WX’ and ‘Y-and-Z’.

letters are primed by forward and backward masked physically similar letters, e.g. lower-case c may prime upper-case C, or E may prime F (Jacobs & Grainger, 1991; Ziegler, Ferrand, Jacobs, Rey, & Grainger, 2000). Across-case priming is greater where letters are near-identical in each case (e.g. *cC*) than when they are dissimilar (e.g. *aA*). Perea et al. (2009) have shown that letters are regularised more than numbers, indicating that letters are initially processed based on their physical characteristics while numbers are not.

12 *Interactions between letters and space in non-synaesthetes*

Another possible representation of the alphabet is in a visuospatial format (the MAL), which is also compatible with a distance effect. The MAL is assumed to run in a horizontal line from A on the left to Z on the right, in the direction of languages that use the Roman alphabet. This assumption has been directly tested by Dehaene et al. (1993), who asked participants to decide if a presented letter belonged to the group ACE or the group BDF, and to respond with the left or right hand depending on group. If there is a spatial representation of the alphabet in the form described above, one would expect to find that participants responded more quickly to the letters ABC with the left hand and to DEF with the right hand. This was not found to be the case, but there were several methodological problems with the experiment. For example, the division of stimuli (based on the odd-even distinction made for numbers) is rather arbitrary (Gevers et al., 2003) and the stimuli are all drawn from early on in the alphabet so potential reaction time differences between left and right hands would be minimised. Later research correcting for these problems has produced mixed results (Dodd et al., 2008; Gevers et al., 2003); it seems that the only reliable way to produce a spatial bias during letter judgements is to ask participants explicitly to think about alphabetical order. It is also possible that this spatial representation is more active when participants are asked to think about the alphabet in the reverse order of its usual recitation, since this preferentially activates the intraparietal sulcus (IPS), an area known to be involved in visuo-spatial working memory (Todd & Marois, 2004), over forwards recitation of the alphabet (Zhou et al., 2006).

Currently, it is unclear whether the MAL truly exists. Here, again, synaesthesia may provide useful information: by directly comparing non-synaesthetes and synaesthetes with MAL-compatible forms on tasks tapping the effects of the MAL, it can be established whether the putative MAL is due to the presence of these synaesthetes in an experimental sample (see Paper 2). So far, only the prevalence of spatial alphabet forms is known (Sagiv et al., 2006); in order to understand how likely it is that synaesthetes could affect experimental outcomes in these types of task, an investigation of the shapes that spatial alphabets take is also called for (see Paper 1).

13 *Overview of current research*

The main themes of this thesis are related to the methodology of psychological research involving synaesthesia and implicit equivalents in the general population. Firstly, spatial synaesthesia for letters and numbers is investigated and contrasted to the MAL and MNL. Secondly, letters and numbers are contrasted as inducers in spatial form and grapheme-colour synaesthesia. Finally, different forms of number are investigated in number-colour synaesthesia. Ultimately, the goal of this thesis is to bring increased rigour to the methods used in synaesthesia research and closely related fields, by illustrating what happens when synaesthetes and non-synaesthetes are asked to complete tasks which should produce similar outcomes in both groups according to theories of numerical-spatial cognition and when letters and different number notations are separated in grapheme-colour synaesthesia.

13.1 Paper 1: Visuo-spatial representations of the alphabet in synaesthetes and non-synaesthetes

The first paper explores the as yet uncharted territory of synaesthetic alphabet forms, beginning with an overview of the various shapes that these forms take in native speakers of English and German. Subsequently, we investigated the impact of alphabet forms on verbal navigation of the alphabet (e.g. what letter comes before/after R?) and detection of lateralised targets following presentation of a letter.

Our results show that the parsing of the Alphabet Song, commonly learned in English-speaking countries, is in line with the locations of line breaks, gaps, and direction changes (collectively, features) in synaesthetes' alphabets. There is also a tendency for alphabets to have features at or near the midpoint of the alphabet. However, the forms of German synaesthetes (who tend not to learn the Alphabet Song) also have features in the same locations, suggesting a role for cross-cultural constraints such as memory or articulation. Features do not influence alphabet navigation, perhaps because the task requires verbal responses. Consistency of (imagined) spatial forms is higher in synaesthetes than in non-synaesthetes and cueing effects of individual letters are present only in the synaesthete group. This is in contrast to numbers, which can act as cues in both groups (Dehaene et al., 1993; Jarick et al., 2009). A more in-depth investigation of the differing roles of numbers and letters in synaesthetic cognition is presented in the following Papers.

13.2 Paper 2: Beware the Boojum: What does synaesthesia do to the SNARC effect?

Spatial compatibility effects of numbers and letters in lateralised decision tasks were examined for synaesthetes and non-synaesthetes. In two similar tasks, participants categorised graphemes with a lateralised button-press: numbers as odd or even, and letters as upper-case or lower-case. In this experiment, all synaesthetes reported number and/or alphabet forms that take the form of Westerners' implicit MNL and MAL, from left to right.

Contrary to the evidence from Paper 1, we found that neither synaesthetes nor controls reacted more quickly to MAL-compatible letter-response key combinations, while for numbers, synaesthetes showed a trend towards a stronger SNARC effect than non-synaesthetes. However, the control group alone did show a cueing effect based on the keyboard layout, so that Q, A and Z were more quickly categorised with the left hand than were K, O, and P. This indicates that (for computer-literate non-synaesthetes) there is a spatial layout of the alphabet that competes with the MAL, which could explain the weak evidence for the existence of the MAL.

13.3 Paper 3: Synaesthetic interactions between colour, ordinality and linguistic frequency for letters and numbers

Previous research on grapheme-colour synaesthesia has shown that small single-digit numbers tend to be brighter and lighter than large numbers. The same is true of frequently-used letters compared to rarely-used letters. However, it is unclear whether these correlations are due to direct links between magnitude, frequency, saturation and luminance or the result of early and frequent letters and numbers taking on light, bright colours such as yellow, while late and infrequent letters and numbers take on dull, dark colours such as brown. Data from 100 letter-colour and number-colour synaesthetes were used to investigate this question; it was found that even within hues, early numbers and frequent letters tend to be more luminant and more saturated than their late, infrequent counterparts. In addition, it was found that letter-colour synaesthesia is influenced by a wide range of factors such as linguistic links between letters and colour names (e.g. G is often green), and correlations between ease-of-generation of colour names and letter frequency, while numbers' colours appear to be purely due to a direct correlation between magnitude and luminance.

13.4 Paper 4: The influence of grapheme-colour synaesthesia on lexical and mathematical decisions

Participants were asked to categorise sums as correct or incorrect, or letter strings as words or non-words. The second operand in each sum could be coloured congruently or incongruently with the participant's synaesthesia, providing sums that were correct and congruent (e.g. $2 + 5_5 = 7$, where the subscript number indicates the colour of the second operand), correct and incongruent (e.g. $2 + 5_4 = 7$), incorrect and congruent (e.g. $2 + 4_4 = 7$), incorrect and incongruent (e.g. $2 + 4_6 = 7$), or incorrect and incongruent, but coloured so as to imply a correct answer (e.g. $2 + 4_5 = 7$). Similarly, one letter of each string was coloured congruently (e.g. SC$_C$AR or SM$_M$AR), coloured to make a non-word from a word or a word from a non-word (e.g. SC$_M$AR or SM$_C$AR), or coloured to make another word or another non-word (e.g. SC$_T$AR or SM$_H$AR). Thus, the bidirectionality of number-colour and letter-colour synaesthesia could be assessed by reaction times and proportion of errors, which should both be higher in situations where incorrect sums are coloured to make the correct sum, words coloured to make non-words, and non-words coloured to make words. In turn, participants should be slower and make more errors in 'simple' incongruent conditions (i.e. incorrect sums coloured incongruently, non-words coloured to make other non-words, and words coloured to make other words) than in congruent conditions. However, the two experiments of this paper revealed very little evidence for bidirectionality. Given the evidence for bidirectionality at individual and group levels in past research, it is likely that the experimental method used obscured bidirectionality effects because of complex task demands and, possibly, the location of the congruent or incongruent target within the sum or letter string.

13.5 Paper 5: The mental representation of number: Insights from number-colour synaesthesia

Paper 5 extends the idea of differences between ideographic and alphabetic inducers (digits and number words, respectively) to compare these two with each other and with pictographic inducers (dice patterns) in number-colour synaesthesia. Synaesthetes showed Stroop-type effects for numbers presented as digits and as number words (regardless of their subjective experience of number words as possessing colours), but not for dot patterns. Additionally, participants showed a priming effect in the digit condition, wherein a number coloured as its neighbour (e.g. 6 in the colour of 5) gained a faster reaction time than any other incongruently coloured stimulus (e.g. 6 in the colour of 4, 3, 2, or 1). The first of these results may indicate a strong verbal link in number-colour synaesthesia, so that the colour is elicited by the sound of the number rather than its appearance. The second result, however, indicates primacy for the digit notation of number in synaesthesia which may be due to a stronger link between digit and colour than between any other notation and colour, or to digits activating a stronger mental representation of number than any other notation, and that it is this abstract mental representation that gives rise to the colour.

14 *Discussion*

Returning to the main themes of the research in this thesis, it is now possible to answer the overarching questions identified earlier.

14.1 How is spatial synaesthesia for letters similar to and different from the MAL?

The majority of synaesthetes reported straight-line forms running from left to right, identical to the MAL. In addition, those forms which were not straight-line had features that corresponded to the parsing of the Alphabet Song, which also influences the verbal representation of the alphabet in non-synaesthetes. However, there are also several differences between alphabet forms and the MAL: letters can cue spatial attention in synaesthetes, but not in controls; synaesthetes' form consistency is greater than controls' imagined form consistency, and having an alphabet form appears to 'protect' against the QWERTY effect. This pattern of similarities and differences implies that the idea of the MAL is a result of synaesthetes participating in experiments supposedly testing implicit relationships between letters and space. If most synaesthetes have a form like the MAL, and therefore most behave as though they have a MAL (while controls do not), it is important that future research takes the potential presence of synaesthesia into account.

14.2 How do letters and numbers differ as inducers in spatial form synaesthesia?

Paper 2 shows that letters may induce synaesthesia more weakly than numbers, as alphabet-form synaesthetes with MAL-compatible forms asked to make a case judgement about letters showed no letter-SNARC effect, while number-form synaesthetes with MNL-compatible forms did show a SNARC effect in a parity-judgement task. There are, however, other explanations that do not rely on inducer strength. For example, the two tasks are not equivalent – in the case judgement task, each letter can be categorised as upper-case or lower-case, while for numbers each number can only be odd or even, never both.

14.3 How do letters and numbers differ as inducers in grapheme-colour synaesthesia?

Making use of a large sample of synaesthetic inducer-concurrent pairings, it is possible to see that number and letters do work differently as inducers: according to the findings of Paper 3, links between number and colour appear to rely on direct links between magnitude and luminance; letter-colour pairings result from linguistic factors such as ease-of-generation and initial letters of colours, and frequency of letters. While Paper 4 showed no behavioural evidence for a difference between numbers and letters as inducers, this is the only time in the synaesthesia literature that a direct comparison between the two grapheme types has been made. Therefore, experiments which apparently reveal characteristics of grapheme-colour synaesthesia may in fact be revealing characteristics of either letter-colour or number-colour synaesthesia, but not both.

14.4 How do different number notations affect synaesthetes' experiences and behaviours?

In Paper 5, a Stroop test using three different notations of number (digit, word and dice pattern) revealed congruency effects only in the digit and word conditions. This provides some clues as to the location of number-colour synaesthesia with respect to models of numerical cognition. Firstly, because dice patterns did not produce a Stroop effect, the mental representation of number that creates synaesthetic experience cannot be amodal. Secondly, the appearance of a Stroop effect in number words even when synaesthetes reported no (or conflicting) colours for this number notation suggests that there is a link between number and colour that is not completely exclusive to digit synaesthesia, indicating a role for phonology, or that some number notations (i.e. digits and number words) have stronger links with colours than do others (i.e. dice patterns). An effect of priming seen in the digit condition only suggests that this notation possesses the strongest links to synaesthetic colour, in line with the preferential use of digits to represent number in Western culture.

14.5 Conclusion

Overall, the research in this thesis indicates a need for greater rigour when investigating synaesthesia and when using it as a tool in wider cognitive research. Though the papers in this thesis have not consistently demonstrated differences between synaesthetes and non-synaesthetes, or between letters and numbers as inducers in synaesthesia, there is enough evidence for these two divisions to be considered as more important than they previously have been. In order to achieve greater rigour, awareness of synaesthesia and its uses in the wider realm of cognitive psychology needs to be increased. In turn synaesthesia researchers, who are now beginning to use synaesthesia as a research tool in addition to exploring it for its own sake, should educate themselves more fully on aspects of typical cognition to aid effective comparison with synaesthetic experience. The goal of increased rigour can be achieved through greater collaboration between synaesthesia researchers and those interested in the areas of numerical and spatial cognition, reading, and wherever else synaesthesia intersects with typical cognition.

Paper 1

Visuo-spatial representations of the alphabet in synaesthetes and non-synaesthetes

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Abstract

Visuo-spatial representations of the alphabet (so-called 'alphabet forms') may be as common as other types of sequence-space synaesthesia, but little is known about them or the way they relate to implicit spatial associations in the general population. In the first study, we describe the characteristics of a large sample of alphabet forms visualised by synaesthetes. They most often run from left to right and have salient features (e.g. bends, breaks) at particular points in the sequence that correspond to chunks in the 'Alphabet Song' and at the alphabet midpoint. The Alphabet Song chunking suggests that the visuo-spatial characteristics are derived, at least in part, from those of the verbal sequence learned earlier in life. However, these synaesthetes are no faster at locating points in the sequence (e.g. what comes before/after letter X?) than controls. They tend to be more spatially consistent (measured by eye-tracking) and letters can act as attentional cues to left/right space in synaesthetes with alphabet forms (measured by saccades), but not in non-synaesthetes. This attentional cueing suggests a dissociation between numbers (which reliably act as attentional cues in synaesthetes and non-synaesthetes) and letters (which act as attentional cues in synaesthetes only).

1 Introduction

Visuo-spatial forms are generally considered to be a variety of synaesthesia in which ordinal sequences, such as units of time, numbers and letters of the alphabet, take on explicit spatial locations in the mind's eye or in peripersonal space (Sagiv, Simner, Collins, Butterworth, & Ward, 2006). There is very little information on synaesthetic spatial alphabets; they are mentioned in passing by Sagiv et al. (2006), Seron, Pesenti, Noel, Deloche and Cornet (1992) and Spalding and Zangwill (1950) as spatial forms that may co-occur with number forms, but have not themselves been the subject of experimental investigation. Spatial alphabets might be just as prevalent as those for numbers or the calendar (Sagiv et al., 2006). However, unlike calendar forms and number forms, there is no obvious use for alphabet forms. Units of time in spatial representation have a certain advantage to the synaesthetes who have them: they can be used for planning (Price & Mentzoni, 2008), for manipulation of time series (Mann, Korzenko, Carriere, & Dixon, 2009) or for recall (Simner, Mayo, & Spiller, 2009). Similarly, number forms can be used for calculation (Seron et al., 1992; Ward, Sagiv, & Butterworth, 2009). The spatial alphabet is unlikely to be used frequently in this way because of the rarity of needing to place data in alphabetical order. However, it is still useful to study spatial alphabets as they allow insight into the general processes underlying the initial acquisition, storage and retrieval of this linguistic ordinal sequence and the mechanisms by which this information that is normally verbally represented is additionally coded visuo-spatially. There is also great interest in understanding how numerical cognition is supported (or not) by spatial processes, and learning more about the spatial representation of non-numerical sequences is an important part of that research.

In the general population, there is strong evidence that there are implicit spatial representations of numbers that influence behaviour but are not consciously reported as a number form. In an odd/even judgment task, the left hand responds more quickly than the right to numerically smaller numbers from the response set, but the reverse is true of numerically larger numbers (Dehaene, Bossini, & Giraux, 1993). This has been termed the SNARC effect (Spatial-Numerical Association of Response Codes). Similarly in attentional cueing tasks, smaller numbers facilitate detection of subsequent targets on the left whereas larger numbers facilitate detection of subsequent targets on the right (Fischer, Castel, Dodd, & Pratt, 2003). Results such as these are taken as evidence that there is a left-to-right oriented (mental) number line that supports numerical cognition. However, evidence for an equivalent spatial representation of the alphabet in the general population is inconclusive. Dehaene, Bossini and Giraux (1993) found no equivalent SNARC effect when categorising letters (using lateralised responses) as belonging to either of the groups A, C, E or B, D, F. Fischer (2003) also failed to find a SNARC effect for letters when participants were asked to point at targets either side of a cueing letter in a consonant/vowel judgment task. One can argue of Dehaene and colleagues' task that not using the full range of the alphabet might diminish any effects to be found; additionally, that the participant pool (N = 10) is not large enough, or that the task is rather arbitrary. Gevers, Reynvoet and Fias (2003) identified and addressed these concerns, instead asking their 24 participants to decide if a letter came before or after O, or whether a letter was a consonant or a vowel; they found spatial biases in both of these tasks, consistent with a left-to-right A-to-Z alphabet line. Other evidence for an implicit left-to-right spatial representation of the alphabet comes from patients with visuo-spatial neglect. These patients tend to neglect the left side of physical lines and, hence, bisect lines towards the right of the true centre (Marshall & Halligan, 1990). Analogous effects are found when asked to bisect numbers (e.g. “what is midway between 4 and 9?”, Zorzi, Priftis, & Umiltà, 2002). More recently, these studies on neglect patients have been extended to the alphabet with consistent positive results (e.g. “what is midway between N and V?”, Nicholls, Kamer, & Loftus, 2008; Nicholls & Loftus, 2007; Zamarian, Egger, & Delazer, 2007; Zorzi, Priftis, Meneghello, Marenzi, & Umiltà, 2006).

It has generally been assumed that the same number-space (and letter-space) representations affect performance across a wide range of tasks. An alternative proposal is that many different types of spatial association may be created ‘on the fly’ according to the demands of the task. In support of this, neglect may affect number bisection tasks but not the SNARC effect (Priftis, Zorzi, Meneghello, Marenzi, & Umiltà, 2006) and a case study of a synaesthete with a right-to-left number form shows a conventional left-to-right SNARC effect (Piazza, Pinel, & Dehaene, 2006). It has recently been suggested that bisection errors of ordered sequence in neglect may reflect spatial working memory limitations rather than a tendency to represent sequences spatially (Doricchi, Guariglia, Gasparini, & Tomaiuolo, 2005). This would explain why letters and numbers behave similarly on these tasks, but not on other kinds of task.

Numbers and letters appear to dissociate in their propensity to act as attentional cues in the general population. Fischer et al. (2003) found that centrally presented numbers can orient attention by facilitating detection of a subsequently presented target on the left or right, such that small numbers (e.g. 1, 2) directed attention to the left and large numbers (e.g. 8,9) to the right. Dodd, Van der Stigchel, Leghari, Fung and Kingstone (2008) failed to replicate this effect with letters acting as cues, except if participants had to make a judgment about the alphabetical position of the letter after each trial (before or after M). Similarly, Casarotti, Michielin, Zorzi, & Umiltà (2007) found that numbers produce lateral shifts of attention in a temporal order judgment task but letters do not. None of these studies directly contrasted the less common, consciously perceived, synaesthetic alphabet forms with the more common implicit spatial associations between letters and space that may be found in the general population. While the two possible ways in which the alphabet can be represented spatially seem very similar, this may not actually be the case. Synaesthetes may have structurally or functionally different brains from non-synaesthetes, and one (indirect) way of assessing which of these is true is to compare synaesthetic alphabet forms to their implicit counterparts.

Why do sequences tend to be represented spatially either as consciously experienced forms (in some synaesthetes) or implicitly (in the neuro-typical population)? One suggestion is that these associations occur because spatial processes and mechanisms for representing ordered series (such as time and number) share overlapping neural substrates. These are generally proposed to reside in the left parietal lobe (Hubbard, Piazza, Pinel, & Dehaene, 2005; Walsh, 2003). The further assumption is that the sharing of this neural substrate is not a coincidence but rather reflects an evolutionary solution for the representation of abstract concepts by employing more ancient mechanisms concerned with spatial cognition. Alphabets may tend to gravitate towards this same mechanism of representation even though they are effectively ordered labels rather than concepts. A somewhat different account has recently been put forward by Eagleman (2009), who argues that spatial forms are cognitively equivalent to the 'structural description' (Humphreys, Riddoch, & Quinlan, 1988) of objects and may be represented within the ventral visual stream. The internal structure of a spatial form (e.g. January on the left, other months arranged in an anti-clockwise ellipse) may be represented in the same way as other multi-part objects (e.g. those that specify the visuo-spatial arrangements of the limbs, tail, etc. of an animal). Agreeing with Hubbard et al. (2005), Eagleman (2009) argues that the anatomical closeness of sequential concepts and visuo-spatial processes facilitates the formation of spatial forms but, unlike Hubbard et al. (2005), his hypothetical placement of spatial forms is in the (right) temporal cortex rather than the (left) parietal cortex.

According to these accounts, the association between sequence and space reflects functional neuro-anatomy. However, the precise arrangement in space may be moderated by cultural factors. The left-right direction of the SNARC effect is modulated by cultural differences in reading direction (Dehaene et al., 1993; Shaki, Fischer, & Petrusic, 2009). Synaesthetic number forms, in Western participants, usually run from left to right (Sagiv et al., 2006) as do synaesthetic calendar forms (Eagleman, 2009). The internal structure may also be determined by the nature of the concept and the significance attached to points in the sequence. Around 20% of calendar forms are circular or elliptical (Eagleman, 2009) but these shapes are hardly ever found for numbers (Sagiv et al., 2006). In number forms, there is often a break or bend at each decade (10, 20, 30, etc., Sagiv et al., 2006) and spatial forms for days of the week are anecdotally noted to give importance (i.e. more space) to Saturdays and Sundays (Ward, 2008). Many of Galton's (1880b) number forms gave prominence to the number 12. This fact was remarked on by his contemporaries in other countries who did not find this in their samples (e.g. Phillips, 1897) and attributed it to the greater use of duodecimal systems in nineteenth century Britain (e.g. shillings, inches). Some recent computational models attempt to explain these characteristics (Grossberg & Repin, 2003; Makioka, 2009). They use self-organising networks in which there are initially random connections between numbers and space. An emergent property of these networks is that similar numbers come to be represented in similar regions of space, such that 5 is next to 4 and 6, and so on. Co-occurrence would have a comparable effect, so that January may be next to December (despite being at opposite ends of a sequence) and 1 next to 12 (because they appear together on a clock face). What is unclear about these models is whether the input is numerical magnitude (Makioka, 2009), ordinality, or verbal sequences (Grossberg & Repin, 2003). Galton (1880a) himself believed that number forms start life as verbal-spatial associations that come to incorporate the visual sequence of Arabic digits at a later age:

> "I believe the forms to have been mnemonic diagrams, invented by the children when they were learning to count verbally, the sounds of the successive numerals being associated with the successive points of the form. Also, that when the children learned to read, the visual symbols of the numerals quickly supplanted the verbal ones, and established themselves permanently in their place" (p495)

In English-speaking countries, it is common for children to learn the alphabet through the Alphabet Song (Ehri, 2009). This divides the alphabet into mostly-rhyming segments: ABCDEFG, HIJK, LMNOP, QRST, UV (alternatively QRS, TUV), WXYZ (Klahr, Chase, & Lovelace, 1983)[10]. This chunking of the verbal sequence is retained into adulthood and affects participants' judgments about letter order. Klahr et al. (1983) presented American English-speaking participants with a letter and asked them to say what letter comes before or after it in the alphabet. Performance was slower when judgments crossed chunks (e.g. 'what comes after G?', 'what comes before H?') than occurred within chunks (e.g. 'what comes after F?', 'what comes before G?'). Although this choice of chunking may be culture-specific, there may be a general tendency to chunk the alphabet according to general constraints (e.g. ease of breathing, articulation). Scharroo, Leeuwenberg, Stalmeier, and Vos (1994) note that Dutch speakers show inter-subject agreement in their preferences for chunking the alphabet (e.g. at J/K, T/U, W/X) even though these breaks do not agree with those in the English system. Whatever its origin, there are within-culture regularities in the verbal chunking

[10] Please see footnote 9 in the Introduction.

of the alphabet and, if alphabet forms are derived from a verbal code (Galton, 1880b), we may expect to find evidence of this chunking in theirf visuo-spatial representation (e.g. Makioka, 2009). We assess this in Experiment 1, using a large survey of synaesthetes. In Experiment 2, we examine whether having an alphabet form affects performance on the task of Klahr et al. (1983), given that synaesthetes have both a verbal and a visual representation of the alphabet. In Experiment 3, we compare more closely how visuo-spatial representations of the alphabet may differ between synaesthetes and the neuro-typical population in tests of attention/gaze cueing and consistency.

2 Experiment 1

In this preliminary study, a previous questionnaire item was analysed in which self-reported synaesthetes were asked whether they experienced the alphabet spatially and, if so, to draw or describe it. The characteristics of the forms are analysed here. The prediction is that they will tend to run from left-to-right, as is found for other forms such as spatial calendars and number lines. If the internal structure is influenced by verbal learning then we further expect deformations in the alphabet form to be concentrated around the pauses in the Alphabet Song (i.e. at G/H, P/Q, S/T or T/U, V/W and W/X). Deformations may also appear between K and L, where the song abruptly changes speed.

2.1 Methods

2.1.1 Participants

At the time of analysis, 474 native English-speaking synaesthetes had completed a questionnaire asking them about various aspects of their synaesthesia (www.syn.sussex.ac.uk). Synaesthetes had a mean age of 43.52 years (S.D. = 15.68; range = 12-91) and 383 were female.[11] They had spontaneously contacted our research group over a number of years. They had not been specifically recruited for having this type of synaesthesia and nor had we recruited them via questionnaires in lectures (and so on) which may be likely to elicit false claims of synaesthesia (e.g. Simner et al., 2006). Of these, 358 (75.5%) reported grapheme-colour synaesthesia and 192 had been tested for grapheme-colour consistency using the methods of Eagleman, Kagan, Nelson, Sagaram, and Sarma (2007) or Simner et al. (2005). The alphabet forms from 'verified' grapheme-colour synaesthetes did not differ from the others and we pool them here.

In addition, 16 participants were selected who were native German speakers and reported alphabet forms with breaks or changes in direction. German speakers do not have the equivalent of an Alphabet Song.

[11] Six synaesthetes did not state their date of birth or age and one did not state his/her sex.

2.1.2 Materials and procedure

As part of the Synaesthesia Research Group's initial screening questionnaire, each synaesthete was asked the question "Do you think about the letters of the alphabet being arranged in a specific pattern in space (e.g. in a line, or circle)?" and asked to indicate on a 5-point Likert scale whether they strongly disagreed, disagreed, neither agreed nor disagreed, agreed or strongly agreed. If they agreed or strongly agreed, they were asked to provide a diagram of this pattern.

The patterns were visually inspected for line breaks, gaps or changes in orientation (hereafter collectively referred to as *features*; see Figures 1a, b and c respectively for examples of these).

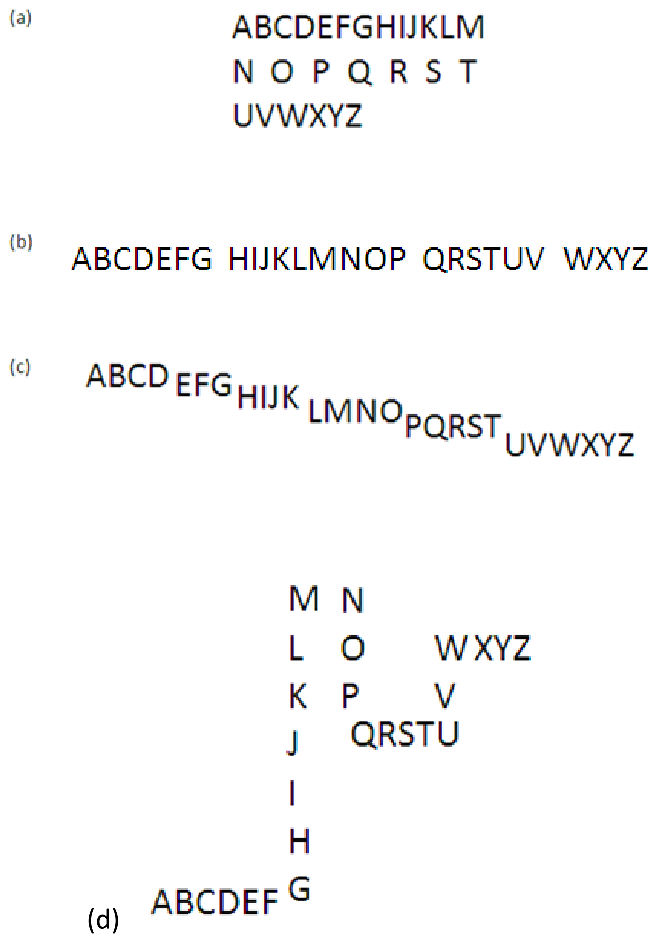

Figure 1: (a) CJ's spatial alphabet, with line breaks at M/N and T/U; (b) JD's spatial alphabet, with gaps at G/H, P/Q and V/W; (c) SS's spatial alphabet, with orientation changes at D/E, G/H, K/L, O/P and T/U;(d) RH's spatial alphabet with a change of direction at G/H, M/N, N/O, Q/R, U/V and W/X.

2.2 Results

Of the 474 English-speaking synaesthetes who completed the questionnaire, 252 (53.2%) reported an alphabet form that is stable over time and provided a drawing and/or description. A further 40 (8.4%) reported a form but did not supply a complete diagram or description; another 19 (4.0%) said that the shape of the form was not stable over time; and another 27 (5.7%) did not answer this question.

The general characteristics of the alphabet forms from the 252 respondents are summarised in Table 1. The most common configuration is a single unbroken straight line. Most were arranged in a left-to-right direction (73.5%), with only 2.4% reporting a vertical line (the rest were described or drawn as linear but a clear direction was not given, and no synaesthete explicitly reported an alphabet that ran in a right-to-left direction). The next most common configurations were a sudden change in direction without line breaks or gaps, as in the example of RH (see Figure 1d) and a configuration in which the alphabet form contained line breaks, as in the example of CJ (Figure 1a).

Table 1: Self-reports of spatial alphabet shapes among 252 synaesthetes reporting unchanging spatial alphabets (percentages in parentheses).

Format of alphabet self-report	**Frequency**
Single, unbroken straight or curved line of letters (horizontal)	114[12] (45.2)
Single, unbroken straight or curved line of letters (diagonal)	18 (7.1)
Single, unbroken straight or curved line of letters (vertical)	6 (2.4)
Linear (unspecified direction)	24 (9.5)
Circular	2 (0.8)
Single, jagged line that changes direction with every letter	1 (0.4)
Sudden direction changes (without gaps or line breaks)	46 (18.3)
Line breaks (without direction changes or gaps)	29 (11.5)
Gaps (without direction changes or line breaks)	6 (2.4)
Combinations of gaps and/or line breaks and/or direction changes	6 (2.4)

[12] 22 of these could be classified as diagonal, but the deviation from horizontal is so slight that it is probably a result of inaccurate drawing.

In Figure 1a-c, features were coded as existing at the obvious places (e.g. M/N and T/U in 1a, G/H, P/Q and V/W in 1b). Some synaesthetes reported features in which letters appeared at the corner of a direction change (as in Figure 1d). For the purposes of this analysis, gaps and breaks were marked as existing between the letter on the corner of the curve and the next letter (e.g. the L/M/N change was marked as an M/N change). Additionally, there were some repetitions of letters either side of a gap or line break (e.g. ABCD DEF); these were marked as existing between the second incidence of the letter and the following letter. The positions of features were coded in the 87 synaesthetes who had them (Table 1, last 4 lines: 46 +29 + 6 + 6= 87), generating a total sample of 263 features. The frequency of features between each letter pair is shown in Figure 2. Binomial distribution indicates that features are significantly (p <.05) more likely than chance to occur between letter pairs at 7 positions: G/H, L/M, M/N, N/O, P/Q, T/U and U/V (black columns in Figure 2). Three of these cluster around pauses in the Alphabet Song (G/H, P/Q, and T/U). The other salient aspect, not represented in the Alphabet Song, is for features to concentrate near the letters M and N (at L/M, M/N and N/O), this being the mid-point of the alphabet.

We were able to obtain 72 features from the German-speaking synaesthetes. Given the relatively small number of features, we did not analyse them over the entire alphabet but rather grouped them into three bins: features occurring at chunk boundaries in the Alphabet Song (G/H, K/L, P/Q, T/U, V/W), around the midpoint (L/M, M/N, N/O) and at the seventeen remaining locations. The data are summarised in

Table 2. A chi-square test showed that there was no difference between observed and expected frequencies (χ^2 (2) = .17; p = .92), indicating that German speakers and English speakers have features in similar places in the spatial alphabet. Nine of the participants reported no awareness of the English Alphabet Song, four were aware of it, and three did not provide information.

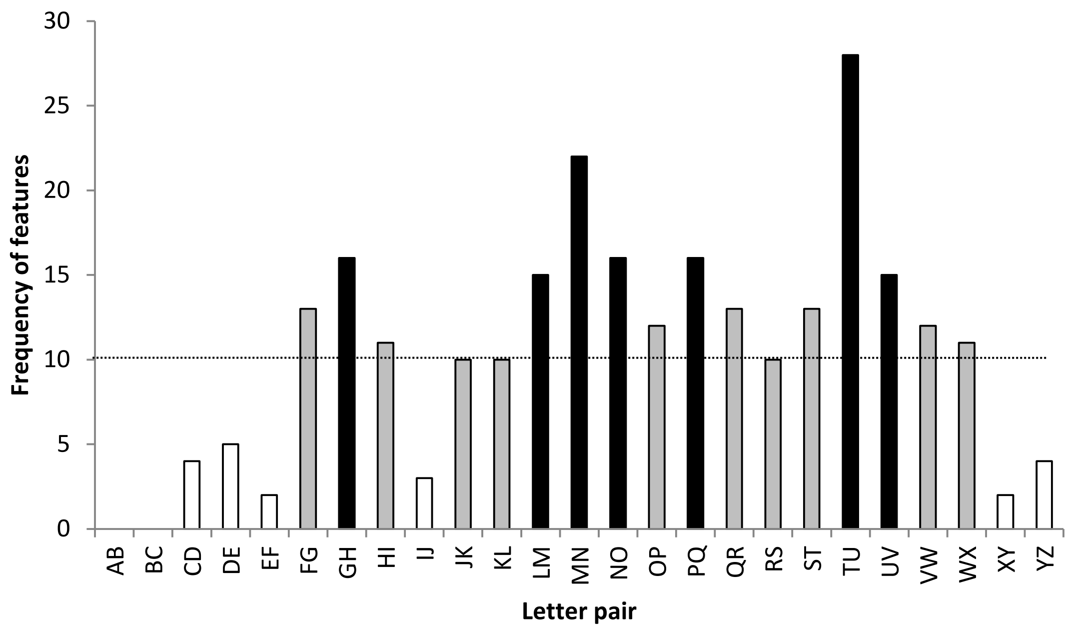

Figure 2: Frequency distribution of breaks, gaps and direction changes in spatial alphabets. The dotted line indicates the average distribution across all letter breaks. Black columns indicate significantly higher frequencies of breaks than expected; white columns indicate significantly lower frequencies of breaks than expected; grey columns indicate frequencies that are not significantly different from what was expected.

Table 2: Locations of features in English and German synaesthetes' alphabets (percentages in parentheses).

Feature location	English	German
Song chunk boundaries	82 (31.2)	21 (29.2)
Midpoint	53 (20.2)	14 (19.4)
Elsewhere	128 (48.7)	37 (51.4)
Total	263	72

2.3 Discussion

In English speakers, although spatial alphabet forms are idiosyncratic they are not random. Instead they are constrained by two influences: the chunking pattern of the Alphabet Song, and a tendency to divide the alphabet close to the midpoint. The K/L break expected from the song may be missing because it is dominated by (or merged with) the midpoint, or because the parsing here is based on a change in speed rather than a pause. Similarly, the expected V/W break was absent in the data although the nearby T/U and U/V breaks were found to be represented more than chance would suggest (the latter two may be more significant than the former). The X/Y break (predicted based on the fact that there is a pause in the recitation of letters here, though not one acknowledged by Klahr et al., 1983) is also missing, perhaps, like the V/W break, lost because of the end of the alphabet being very close. This is interesting from a developmental point of view, because the recitation of the Alphabet Song precedes literacy acquisition (Ehri, 2009). This raises the possibility that verbal-spatial synaesthetic associations are established before visual representations of letters are acquired, as proposed by Galton (1880a). This is reminiscent of a single case study by Jarick, Dixon, Stewart, Maxwell and Smilek (2009). This person viewed her spatial calendar form from different perspectives depending on whether she heard or read month names. They speculated that the auditory viewpoint (right-to-left arrangement) may have been acquired first, but reversed to the more conventional left-to-right arrangement during schooling.

However, it seems that exposure to the Alphabet Song is not necessary for features to appear in line with its phrasing, as German synaesthetes’ alphabets have features in similar places to English synaesthetes’ alphabets. This does not, however, preclude a verbal-spatial arrangement prior to learning the visual appearance of letters, as the parsing of the Alphabet Song neatly divides the alphabet into chunks of two to seven letters. Young children may use this chunking strategy as a memory aid when learning the sounds of the alphabet and then later apply those chunks to a visual representation of the letters.

3 Experiment 2

The consequences of having a spatial alphabet on manipulations involving the alphabet are not yet clear. Examples of such manipulations are ordering according to alphabetical principles, categorizing letters as early or late in the alphabet, and reporting what letter comes before or after another in the alphabet. In the current experiment, we follow the procedure used by Klahr et al. (1983) and Scharroo et al. (1994) of asking respondents to say which letter comes before or after a given letter. Response times showed a series of peaks and troughs corresponding to conventional ways of verbally chunking the alphabet. However, synaesthetes with alphabet forms may be expected to treat this task more like scanning of a mental image (Finke & Pinker, 1982), so we predict their performance to be faster overall. Moreover, we would expect their peaks and troughs to follow the structure of their alphabet form (i.e. requiring internal shifts of attention from one location to another at features) more closely than the putatively verbally-based chunks of the Alphabet Song – synaesthete SS (Figure 1c), for example, should show a peak in reaction time at D/E, whereas a control should not. Finally, the previous studies reported that performance tended to be slower at the end of the alphabet, attributing the fact to later items being less well rehearsed. We predict this effect to be diminished or absent if synaesthetes can scan a mental image of the alphabet.

3.1 Method

3.1.1 Participants

Fourteen spatial-alphabet synaesthetes and fourteen age-matched controls took part in this experiment. Nine had previously been included in Experiment 1. The mean age of the synaesthetes was 26.29 years (S.D. = 9.63; range = 18-55) and the mean age of the controls was 26.71 years (S.D. = 9.47; range = 18-55).

Three of the synaesthetes reported straight line alphabet forms, and the remaining 11 reported features in at least three locations. The location of these features was categorised in one of four ways: as crossing chunks (i.e. answering requires using two phrases of the Alphabet Song) within the Alphabet Song but not the spatial form (Song Only, e.g. P/Q in Figure 1c); as crossing chunks within the spatial form (i.e. answering requires using two letters in the alphabet that are either side of a feature) but not the Alphabet Song (Form Only, e.g. D/E in Figure 1c); as crossing chunks that occur both at song boundaries and form boundaries (Song+Form, e.g. G/H in Figure 1c); and those that do not cross chunks at all (No Feature, e.g. M/N in Figure 1c). For this analysis, data from controls were yoked with those from synaesthetes and split into the same categories.

3.1.2 Materials and procedure

Upon coming to the laboratory for testing, controls were given a brief explanation of spatial-alphabet synaesthesia and asked if they experienced anything similar. Synaesthetes were asked to draw their spatial alphabet before beginning the experiment in order to draw their attention to the possibility of using it during the task.

Following Klahr and colleagues' (1983) Experiment 1 and Scharroo et al. (1994), we asked participants to sit at a monitor, where they were presented (using E-Prime 2.0) with a fixation cross for 500ms, followed by an upper-case letter of the alphabet. In one task, letters B to Z were presented and the participant was asked to name the letter preceding it in the alphabet (*backwards task*); in the other task, letters A to Y were presented and the participant was asked to name the letter following it in the alphabet (*forwards task*). Participants gave their responses into a microphone; response times (RTs) were recorded using a serial response box attached to the microphone. In each task, each letter was presented five times in a random order, for a total of 125 trials. The order of tasks was counterbalanced so that half the participants did the forward task first and half did the backwards task first. Synaesthete-control pairs always did the tasks in the same order.

Before analysing the data, trials in which the microphone had failed to register a response, in which the participant had made an error, or which had a RT of less than 300ms were removed (accounting for 13.1% of the data[13]).

3.2 Results

Figure 3 shows the mean response times for synaesthetes and controls in both the forwards and backwards tasks. The response times show peaks and troughs that tend to coincide with the structure of the Alphabet Song as noted by Klahr et al. (1983), the effect being more pronounced in the more difficult backwards task. In the first analysis, the overall performance of synaesthetes versus controls was compared in a 2x2x25 mixed ANOVA on group (synaesthete, control), task (forwards, backwards) and position in the alphabet (A/B to Y/Z). As expected, there were main effects of task ($F(1, 21) = 72.14$; $p < .001$) and position ($F(24, 54) = 10.18$; $p < .001$) and these two main effects interacted ($F(24,504) = 4.68$, $p < .001$). However, there was no evidence that synaesthetes' performances significantly differed from controls': i.e. no main effect of group ($p = .86$) and no interactions between group and task ($p = .66$) or group and position ($p = .49$).

[13] This unusually high error rate is likely to have been caused by the difficulty of this experiment, particularly in the backwards task.

To test for differences in increases in RT across the alphabet in synaesthetes and controls, regression slopes were calculated for each individual's RTs against position in the alphabet. Slope values were then compared against zero (i.e. no increase in RT) using a one-sample t-test and between the two groups using a between-subjects t-test. Both mean slopes were positive and significantly different from zero (*p*s < .001) but mean slopes did not differ between groups (*p*s > .4), indicating that synaesthetes and controls find the task equally and increasingly difficult towards the end of the alphabet.

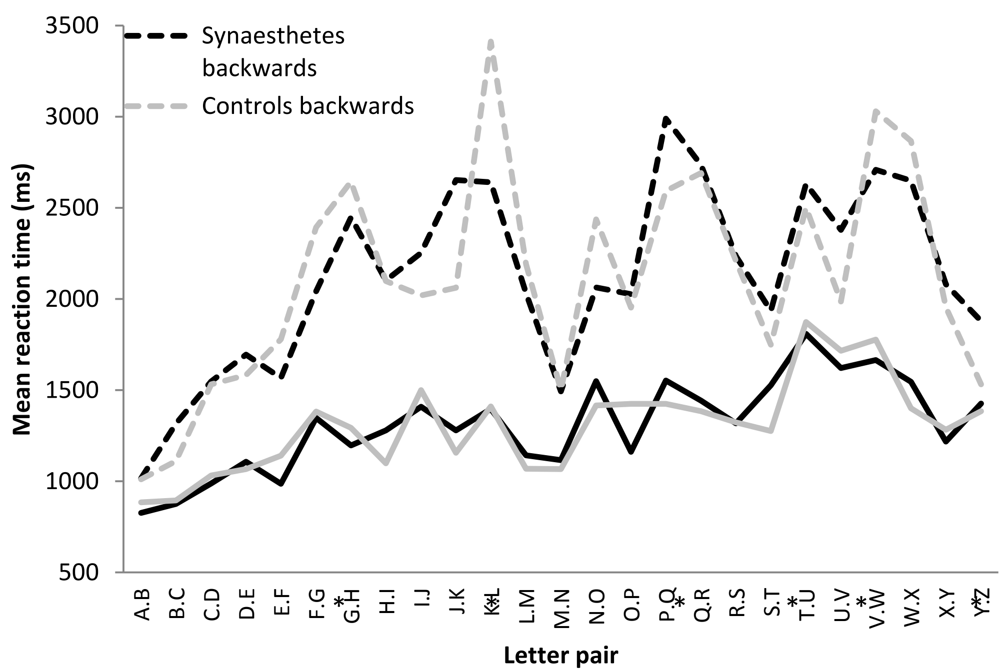

*Figure 3: Mean reaction times of synaesthetes and controls asked to state what letter of the alphabet came before (backwards) or after (forwards) a visually presented letter. 'Letter pair' indicates the presented and target letter (e.g. A.B indicates A was presented and B the target in the forwards task, and vice versa in the backwards task). * indicates position of parsing boundaries in the Alphabet Song.*

Given the idiosyncratic nature of the alphabet forms in this study, a second analysis compared performance between synaesthetes and controls at critical positions in the alphabet. This is summarised in Figure 4. The data were analysed in two 2x2x2 mixed ANOVAs contrasting group (synaesthete, control), task (forwards, backwards) and letter pair type (Song Only, No Feature *or* Form Only, No Feature). Given that some features were present in some synaesthetes and not in others, the number of participants in each analysis differed. There were 14 synaesthetes/controls for the comparison of 'Song Only' with 'No Feature' and 10 synaesthetes/controls for the comparison of 'Form Only' and 'No Feature'.

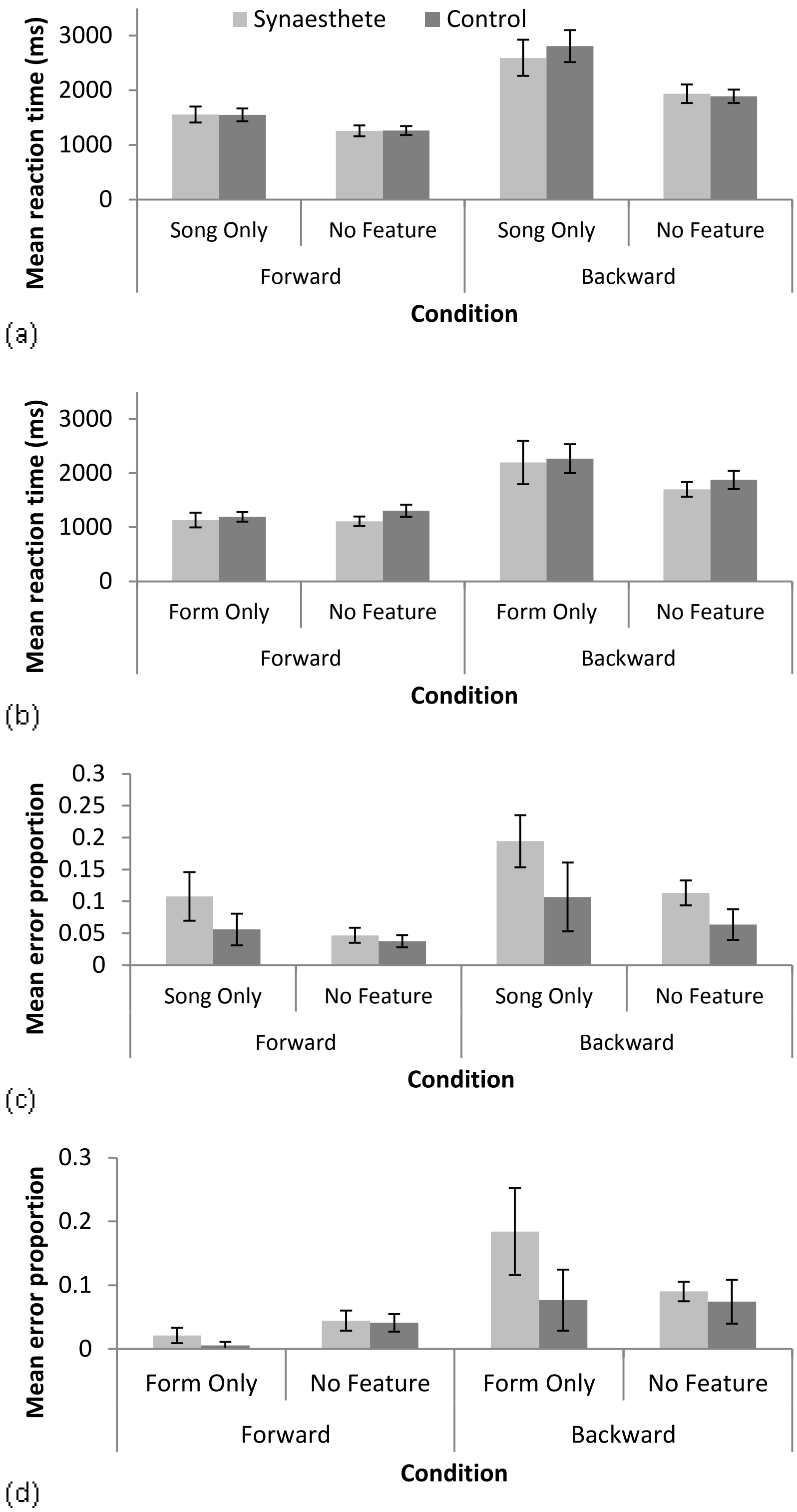

Figure 4: Mean reaction times of synaesthetes and controls when compared on (a) Song Only/No Feature and (b) Form only/No feature letter pairs; error rates for (c) Song Only/No Feature and (d) Form only/No feature letter pairs. Error bars show ± 1 S.E.M.

Comparing ‘Song Only’ positions with ‘No Feature’, there was a significant main effect of letter pair type ($F(1, 26) = 31.00$; $p < .001$)) showing that people are slower when they need to find letters across verbally defined chunks (as in Klahr et al. 1983) but, contrary to our hypothesis, the effect was equally as strong in synaesthetes as controls (no interaction or group effect). Comparing ‘Form Only’ positions with ‘No Feature’ revealed a significant main effect of letter pair type ($F(1,18) = 4.59$; $p < .05$) and a significant interaction between letter pair type and task ($F(1,18) = 8.72$; $p < .05$), due to ‘No Feature’ pairs being reacted to more quickly than ‘Form Only’ pairs in the backwards task but, crucially, there were no differences between groups and no interactions with group. (The data from ‘Song and Form’ features were not analysed as there is no way of knowing whether any differences are due to the song or the form.)

When the same analyses were performed on error rates, significant (ps < .05) effects of task were found, as more errors were made in the backwards than in the forwards task, and more errors were found to be made for ‘Song Only’ letter pairs than for ‘No Feature’ pairs ($F(1,24) = 11.07$; $p < .01$). There were no significant main effects or interactions involving group, again suggesting that synaesthetes and controls perform this task in the same way. This may be due to the modality in which the stimulus was presented (if alphabet forms are recruited less by visual presentation of letters), or to the modality in which the response was made (a verbal response may not recruit as strong a representation of the form as a gaze or finger movement).

In summary, there is no evidence that people with an alphabet form perform this task by scanning a 'mental image' rather than by retrieval from a conventionally-chunked verbal code.

3.3 Discussion

This experiment replicates previous findings by Klahr et al. (1983) but fails to find any difference between synaesthetes reporting a visuo-spatial representation of the alphabet and controls who do not. Our interpretation is that synaesthetes rely on their verbal representation of the alphabet for this task, as do controls. Even if they relied on a local portion of the form we would expect their performance to be enhanced, unless visualisation time is very slow. It is to be noted that they were not explicitly instructed to use a non-verbal strategy, but our hypothesis was that such a strategy would be automatically evoked in these individuals and would lead to benefits over conventional verbal strategies. This does not appear to be the case. Whether or not subtle variations in the task format could spontaneously induce a change in strategy is unknown. In this task, participants were presented with centred letters and asked to give a verbal response. Alternative procedures could be to present pairs of letters ('is GH in the correct order?') rather than having them generate a letter verbally ('what comes after G?'); or to present single probe letters in positions of the screen consistent with their internal representation. Of course there is another explanation that cannot be ignored at this stage: namely that the participants with synaesthesia are no different from controls. Evidence from Experiment 3 speaks against this view.

4 Experiment 3

Tests of consistency are considered the ‘gold standard’ for testing the reality of synaesthetic perceptions, because they are so hard to circumvent (Rich, Bradshaw, & Mattingley, 2005). The synaesthete is presented with the inducer and asked to state the location, colour, taste, etc., of the concurrent; they are then retested weeks or months later without warning. Controls, on the other hand, are asked to act ‘as if’ they have spatial synaesthesia and know they are to be retested only a few weeks later. In the spatial domain, consistency has previously been measured by asking participants to project the shape of their form onto a computer screen (Brang, Teuscher, Ramachandran, & Coulson, 2010; Piazza et al., 2006; Smilek, Callejas, Dixon, & Merikle, 2007). In the first part of this experiment, we follow the same general protocol but use eye movements to the location rather than a mouse click.

In the general population, numbers can act as attentional cues to left or right space depending on their numerical magnitude (Fischer et al., 2003) and can induce an oculomotor bias to the left or right side in SNARC tasks (Fischer, Warlop, Hill, & Fias, 2004). In synaesthetes with calendar forms, a centrally presented month (e.g. January) can direct attention towards or away from a subsequent visual target according to the idiosyncrasies of their own spatial configuration (Jarick et al., 2009; Price & Mentzoni, 2008; Smilek et al., 2007). There is mixed evidence for the existence of an implicit left-to-right oriented calendar in non-synaesthetes (Gevers, Reynvoet, & Fias, 2003; Price, 2009; see Simner, 2009, for a review). For letters, Dodd et al. (2008) found no evidence that letters act as attentional cues (except when the cueing trial was immediately followed by an alphabetic order judgment).

The experiment below is conceptually related to those summarised above but uses saccades to a lateralised target rather than target detection with a button press. The SNARC effect does not appear solely in manual button-press tasks but also in, for example, pointing tasks (Fischer, 2003). As Fischer et al. (2004) point out, this indicates that the SNARC effect is abstract; indeed, they go on to show that a SNARC effect appears when eye movements are used to categorise numbers as odd or even. In line with these findings from the domain of numbers, we predict that the spatial representation of letters is abstract in synaesthetes and expect to find an attentional cueing effect to letters in the synaesthetes with alphabet forms that run from A to Z in alphabetical order in the horizontal dimension, but none (or a weaker one) in the controls.

4.1 Methods

4.1.1 Participants

Twenty spatial-alphabet synaesthetes and twenty age-matched controls took part in the first part of this experiment (9 synaesthetes had participated in Experiment 1). The mean age of the synaesthetes was 30.75 years (*S.D.* = 12.96; range = 18-60) and the mean age of the controls was 30.45 years (*S.D.* = 13.26; range = 18-65). The experiment consisted of a test of consistency and then, for the 13 synaesthetes with an alphabet which ran from A-Z in the horizontal direction (and their yoked controls), an attentional cueing test. Twelve pairs of synaesthetes and controls returned for the second part of the experiment, which was a retest of consistency over a longer interval. The mean number of days between testing for controls was 17.25 (S.D. = 6.06; range = 14-32) and for synaesthetes it was 85.67 (S.D. = 17.34; range = 64-119).

4.1.2 Materials and procedure

These studies were run using Experiment Builder and eye movements were recorded with Eyelink II (SR Research, Ontario). This has a spatial resolution of approximately 0.25 degrees and a temporal resolution of 2ms. Participants were seated on a modified office chair that prevented any rotational movement, approximately 70cm from the computer screen. Stimuli were displayed on a 21 inch CRT monitor at a refresh rate of 100Hz and a resolution of 1280 x 1024 pixels.

Before starting the consistency test, controls received a brief explanation of spatial-alphabet synaesthesia and were asked to imagine that they had a two-dimensional spatial alphabet (in any form the participant chose) for the duration of each testing session. Controls were warned that they would be re-tested on the same experiment in approximately two weeks' time. Synaesthetes were not warned that they would be re-tested in approximately three months' time. A brief 9-point calibration was carried out before the experiment and repeated if necessary between blocks. Each trial was preceded by a brief drift-correction procedure. Participants were asked to ‘project’ or ‘imagine’ their spatial alphabet on the computer screen in front of them, which was entirely white except for a black central fixation dot. After participants heard a letter read aloud, the trial began. A blank screen was displayed for 5000ms and participants moved their eyes to the location where they had mentally projected or imagined the given letter and focused at this location on the computer screen until the fixation dot reappeared. Each letter of the alphabet was probed twice (in a pseudo-randomised order with the constraint that the same letter was never spoken twice in a row) for a total of 52 trials.

The attentional cueing experiment was conducted in the first session only, after the consistency experiment. The same calibration and drift-correction procedures were used as in the consistency experiment. The procedure for each trial is summarised in Figure 5. During the experiment, the participant saw a central dot until the trial started, followed by a central fixation cross for 680ms and then one of four centrally-presented capital letters. Finally, at a stimulus onset asynchrony (SOA) of 150 or 600ms, a target dot appeared to the left or right of the letter. Participants were asked to saccade to the target dot as quickly and as accurately as possible after it appeared. Four letters of the alphabet were selected for each participant. Each letter was followed by a target to the left and right equally often, and the SOA was orthogonal to the target side. Each type of trial (one of four letters, left/right, short/long SOA) was presented 10 times, making a total of 160 trials. An additional 16 trials were added as practice trials. Trials were presented in two blocks of 80, with further breaks if the participant asked for them.

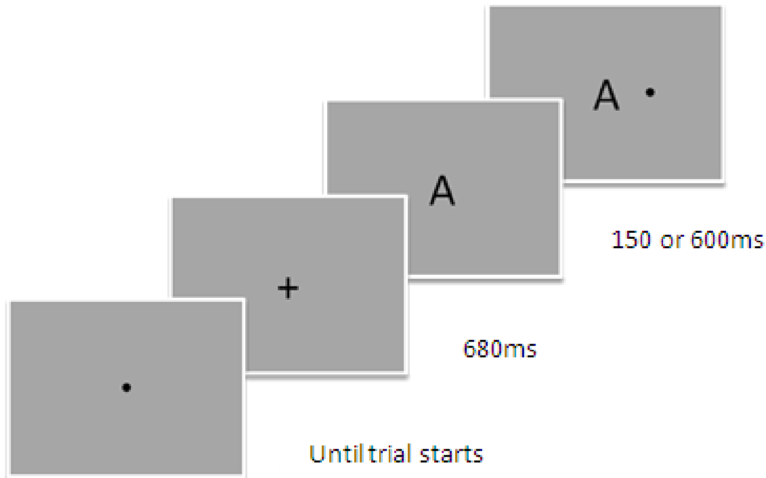

Figure 5: Format of presentation for trials in the attentional cueing experiment, with A used as an example letter.

4.2 Results

For the consistency test, two sets of data (one synaesthete's and one control's, both in the first part of the experiment only) were removed from analysis due to a technical fault. For each trial, the longest fixation period and the associated pixel co-ordinates for this period were determined. For synaesthetes the mean longest fixation time was 2663ms (*S.E.M* = 253) and for controls was 2694ms (*S.E.M* = 231); these means did not significantly differ. The average distance, in pixels, between longest fixations to the same projected letter was calculated for trials within sessions (all participants) and across sessions (for those who came back in session 2). These results are summarised in Table 3. Synaesthetes were more consistent than controls both within and across sessions, though this only reached significance across sessions.

Table 3: Comparison of synaesthete and control performance on within-session and across-session distance using one-tailed independent measures t-tests. S.E.M.s are given in brackets. Asterisks by t-values indicate significance at the .05 level.

Comparison	**Synaesthete mean (*S.E.M.*)**	**Control mean (*S.E.M.*)**	**DF**	**t-value**
Within-session distance	105 (17) pixels	128 (15) pixels	36	1.00
Across-session distance	102 (15) pixels	155 (23) pixels	22	1.93*

For the attentional cueing task, trials in which an error occurred were removed (e.g. an eye movement away from the target), as were those with a RT of less than 80ms. Data were split into groups by SOA; outliers beyond 3 standard deviations from the mean were removed and this procedure was repeated until no outliers remained. For each participant and each SOA, difference in RT between right and left responses (dRT) was calculated and regressed on alphabetical position. This method is frequently used to analyse the SNARC effect (for a discussion of the advantages of this method, see Fias & Fischer, 2005). It enables an assessment of relative differences between leftwards and rightwards effects and avoids the need to categorise each trial as ‘left’ or ‘right’. A slope of, say, -1ms implies an estimated RT difference over 26 letters of 26ms. That is to say, it would take 13ms longer to respond to Z with the left hand than with the right hand, 12 ms longer to respond to Y, 11ms for X, etc. Conversely, it would take 13ms longer to respond to A with the right hand than with the left hand, 12ms for B, 11 ms for C, etc. The data is summarised in Figure 6.

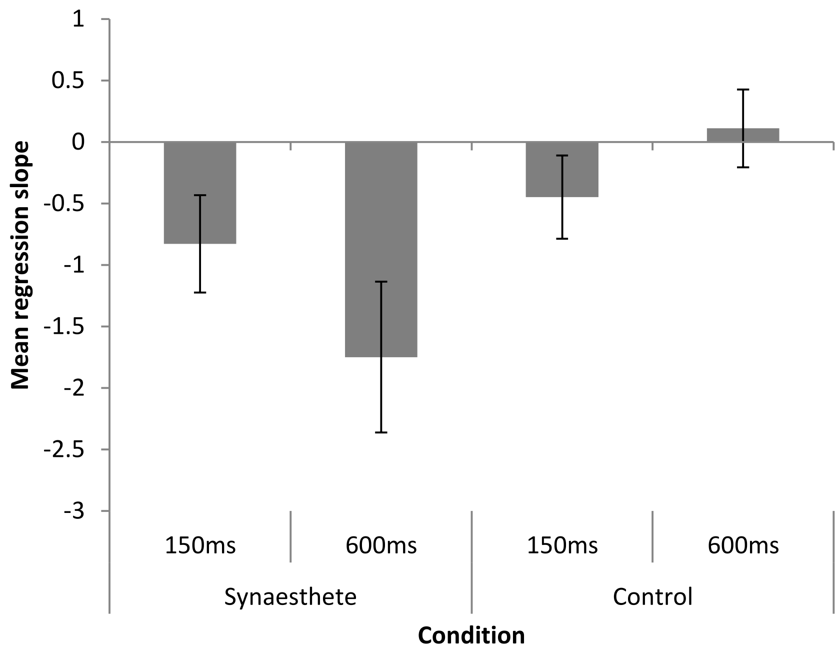

Figure 6: Mean regression slopes (in milliseconds) for dRT on alphabetical position in synaesthetes and controls at 150ms and 600ms SOAs. A negative slope indicates faster reactions to right-side targets with letters early in the alphabet and left-side targets with letters late in the alphabet; positive slopes indicate the reverse. Error bars show ± 1 S.E.M.

One-sample t-tests can be used to ascertain whether the slopes differ from an expected value of zero. Only in the 600ms SOA condition did synaesthetes show an effect of spatial cueing ($M = -1.75$; $t(12) = 2.75$, $p < .05$), although the 150ms SOA condition approached significance ($M = -.83$; $t(12) = 2.02$, $p = .07$). For controls, neither the 600ms ($M = -.45$; $t(12) = 1.29$, $p = .22$) nor the 150ms ($M = .11$; $t(12) = .33$, $p = .75$) was significant. A 2x2 mixed ANOVA was used to compare slopes for different groups (synaesthete/control) and SOAs (150/600ms). A significant main effect of group ($F(1,24) = 4.59$; $p < .05$) was found, caused by synaesthetes' slopes being larger than the controls'. There was also a marginally significant interaction between SOA and group ($F(1,24) = 4.23$; $p = .05$), caused by synaesthetes' slopes being more negative in the 600ms condition than in the 150ms condition, while the controls showed the opposite pattern.

4.3 Discussion

The findings of the first part of the experiment suggest that synaesthetes with alphabet forms tend to be more consistent in their spatial placement of letters than controls instructed to imagine an alphabet form. This is consistent with other studies using a similar methodology for calendar forms (Brang et al., 2010; Piazza et al., 2006; Smilek et al., 2007) and number forms (Piazza et al., 2006), though our methodology is somewhat different in that we used gaze fixation rather than mouse movement as the dependent measure. It is also consistent with the suggestion that sequence forms are represented in the brain as objects with a fixed internal structure, but with some variability in where these structures may be placed relative to the observer (Eagleman, 2009).

The results of the second part of this study indicate that letters can act as attentional cues but only in synaesthetes with alphabet forms, not in non-synaesthetes. Our results suggest that attentional cueing from letter stimuli is greater at long rather than short SOAs, suggesting that the association may be weaker and/or less automatic. However, Smilek et al. (2007) used the same SOAs and noted a comparable effect at both. The extent to which sequences (as against more perceptually based cues, such as arrows) are ‘early’ or ‘late’ attentional cues could be determined using ERPs (event-related potentials). Teuscher, Brang, Ramachandran, and Coulson (in press) recently report ERP evidence consistent with late attentional cueing (600-900ms post-cue onset) for month names in synaesthetes with calendar forms, but no cueing effects for controls.

4.4 General Discussion

This study documents, for the first time, the characteristics of synaesthetic alphabet forms. As with other synaesthetic sequences in Western samples, they tend to be directed from left to right and are most frequently linear. However, the proportion of non-linear forms with various features in them (gaps, bends or breaks) is significant). They are comparable to features in number forms which tend to be found at particular places such as at 12 (e.g. Galton, 1880a) or at decades (10, 20, etc.). However, in alphabet forms they appear to be related to conventional ways of reciting the alphabet such as the Alphabet Song. For example, alphabet forms frequently contain a feature at the G/H boundary where “G” is the last letter of the first phrase of the song, and “H” is the first letter of the next phrase. In addition, features are found around the midpoint of the alphabet (the letter M) which we assume derives from spatial constraints (to reduce the length) rather than from recitation. We predicted that speakers of other languages who do not learn using this song would not show features at these boundaries. However, German synaesthetes with alphabet forms showed a similar trend to native English speakers. Cultures, including the German one, that do not learn the alphabet via an Alphabet Song still show some within-culture agreement as to how to divide the alphabet into chunks (Scharoo et al. 1994), and it is possible that similarities across cultures emerge due to common articulation, breathing, and memory constraints. Thus, English speakers explicitly recall the Alphabet Song, but Germans may obey similar rules when reciting the alphabet, even in the absence of the song. In Experiment 2, we hypothesised that, if synaesthetes can scan a mental image of the alphabet, they should be faster at deciding which letter comes before or after a probe. However, synaesthetes performed no differently from controls, suggesting that both relied on a verbal strategy to perform the task. In Experiment 3, we demonstrated that synaesthetes with an alphabet form show greater spatial consistency than non-synaesthetes given imagery instructions, and show evidence of attentional cueing (making lateralised saccades after a non-predictive letter prime), unlike non-synaesthetes.

In the wider literature, there is a debate about whether letters and numbers have equivalent spatial associations or whether number-space associations are special by virtue of the fact that they represent magnitude (or cardinality) in addition to the ordinal information common to other sequences. For example, one suggestion is that the number-space associations derive from the spatial association between the concepts ‘small’ and ‘big’ with ‘left’ and ‘right’ (Gevers, Verguts, Reynvoet, Cessens and Fias, 2006). Given that letters and the calendar sequence cannot be ranked by size, they may be less likely to take on this association. Three kinds of task have been used in the literature to compare numbers with other types of sequence:

a. Tasks in which a stimulus (e.g. a letter or number) is presented and is required to be categorised in some way, making a lateralised response. In this kind of task, the stimulus is task-relevant (although its magnitude or ordinality may or may not be). The classic example is the SNARC effect for numbers (Dehaene et al. 1993) and another is deciding whether a stimulus comes before or after some fixed value (e.g. 5).
b. Tasks in which a stimulus (e.g. a letter or number) is presented but is not directly relevant to the task (insofar as it does not require a response to it). An example would be attentional cueing paradigms in which letters or numbers act as non-predictive cues for some later event (e.g. Fischer et al., 2003).
c. Tasks involving bisection of a sequence from two given stimuli, typically in patients with neglect arising from neurological damage (e.g. Zorzi et al., 2006).

In all three types of task, numbers show evidence of having an associated spatial representation (e.g. Fias & Fischer, 2005). However, the evidence for other sequences is inconclusive. For months of the year, Gevers et al. (2003) reported a SNARC-like effect when respondents were asked to decide if a month occurs before or after July (for days of the week, Gevers, Reynvoet, & Fias, 2004) but Price and Mentzoni (2008) failed to find this effect in the comparable task of asking participants whether a month is in the first or second half of a year when using a 2x2 (response hand by half of year) ANOVA to analyse the data (a reanalysis using the regression slope method outlined in Experiment 3 of this paper also did not show an effect – see Price, 2009). Using the ANOVA technique, they also failed to find an effect in non-synaesthetes asked to decide whether the number associated with a month (e.g. February = 2) is odd or even (Price & Mentzoni, 2008; but regression-slope reanalysis by Price, 2009, showed a significant negative slope for these data). Such effects are found for synaesthetes with calendar forms and the spatial association follows the idiosyncrasies of their form (Price & Mentzoni, 2008). Similarly, months of the year act as attentional cues for synaesthetes with calendar forms but not for non-synaesthetes (Smilek et al., 2007)[14]. Zamarian et al. (2007) found that months of the year do not show a rightward bisection error in neurological patients with neglect. One explanation for the discrepancy between months and numbers is that the usual spatial representation for the calendar is circular rather than linear (Brang et al., 2010; but see Eagleman, 2009). Another possibility is that normative spatial representations of the calendar are more likely to shift in perspective (e.g. so past months are on the left, future months on the right). Either way, synaesthetes with calendar forms show evidence of time-space associations that are either weaker or absent altogether in non-synaesthetes.

The evidence for a normative left-right arrangement of the alphabet in non-synaesthetes is more convincing, but falls short of that described for numbers. Letters

[14] Smilek et al. (2007) did not analyse their control data to test for a left-right arrangement of months. We have replicated their paradigm with non-synaesthetes but found no evidence of a left-right arrangement of months.

tend to show the same kinds of neglect bisection errors as numbers (e.g. Zorzi et al., 2006), but it is unclear whether this reflects the use of long-term sequence-space associations or whether it reflects a temporary demand on spatial working memory for the specific purposes of this task (Doricchi et al., 2005). In a SNARC-like task, Gevers et al. (2003) found evidence of a left-right alphabet-space association in a consonant/vowel judgment task but Fischer (2003) did not. Both Fischer et al. (2003) and Dodd et al. (2008) found no evidence that letters can act as attentional cues, although Dodd et al. (2008) found this only when participants had to make a subsequent ordinal judgment about the letter. None of these studies contrasted non-synaesthetes with synaesthetes with alphabet forms; our study is the first to attempt this. We replicate the findings of Fischer et al. (2003) and Dodd et al. (2008) that letters do not normally act as attentional cues in non-synaesthetes but show, for the first time, that they do in synaesthetes with alphabet forms. It would be interesting to repeat other studies in the literature (e.g. Gevers et al., 2003) contrasting synaesthetes with non-synaesthetes. It is possible that some previous findings have been biased by the presence of people with sequence forms in the sample.

It could be said that having spatial forms for letters or the calendar may serve to make these sequences more 'number-like'. SNARC-like and attentional cueing effects, reliably found for numbers in non-synaesthetes, are not reliably found for letters and months in non-synaesthetes. But they are reliably found in synaesthetes with calendar forms (e.g. Price & Mentzoni, 2008; Smilek et al., 2008) and alphabet forms (as shown here). This suggests that these individuals, but not non-synaesthetes, have long-term visuo-spatial representations of these sequences that others do not normally possess, except in the case of numbers.

Paper 2

Beware the Boojum: what does synaesthesia do to the SNARC effect?

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Abstract

Dehaene's (1992) triple-code model of numerical cognition postulates the existence of an amodal analogue magnitude representation, taking the form of an implicit mental number line (MNL) which runs from left to right in Westerners. Analogous to the MNL is an equivalent for the alphabet (Nicholls & Loftus, 2007), the mental alphabet line (MAL). Evidence for the existence of the MNL is given by the spatial-numerical association of response codes (SNARC) effect, in which small numbers are responded to more quickly with the left hand than with the right hand and vice versa for large numbers during a parity judgement task. Evidence for the MAL, however, is weaker. Most research on the MNL and MAL has failed to take into account the potential presence of number-space and alphabet-space synaesthetes, who experience numbers/letters as having explicit spatial locations. We separated number-space synaesthetes from non-synaesthetes on a parity judgement task and found that there was a trend for the SNARC effect to be diminished in the control group compared to the synaesthete group, indicating a weaker link between space and number in the population than is generally thought to exist. Neither alphabet-space synaesthetes nor non-synaesthetes showed a SNARC-equivalent effect in a case judgement task with letters, indicating a weak spatial ordinal association in both groups. However, the control group alone showed evidence of a QWERTY effect (differences between reaction times for stimuli located on either side of the keyboard).

1 Introduction

According to the triple-code model of numerical cognition (Dehaene, 1992), number is represented in one of three ways: a visual Arabic number form (e.g. 5), an auditory verbal word frame (e.g. “five”) and an analogue magnitude representation (mental number line, or MNL) that implicitly links number and space. One behavioural consequence of the MNL is that Western participants carrying out a parity judgement task tend to respond more quickly to small numbers with the left hand and large numbers with the right hand (Dehaene, Bossini, & Giraux, 1993); in participants whose language reads right to left, the difference in response times between hands is reversed (Shaki, Fischer, & Petrusic, 2009). This effect, termed the spatial-numerical association of response codes, or SNARC, has since been replicated repeatedly (see de Hevia, Vallar, & Girelli, 2008, for a review). It appears to be independent of input notation as long as the task accesses a semantic representation of number (Fias, 2001), and independent of task as long as the input notation is Arabic numerals (Fias, Brysbaert, Geypens, & d'Ydewalle, 1996). It is also present for a variety of output methods such as gaze and finger pointing (Fischer, 2003; Fischer, Warlop, Hill, & Fias, 2004) and when required to judge the orientation of an image superimposed on a task-irrelevant number (Fias, Lauwereyns, & Lammertyn, 2001). This last finding suggests that Arabic numerals can automatically activate a mental representation of number even when they are not relevant to the task at hand.

The SNARC effect can be diminished or abolished in certain circumstances. Bächtold, Baumüller, and Brugger (1998) showed that when participants were asked to assign numbers 1-11 to the categories ‘before 6 o’clock’ or ‘after 6 o’clock’, a reverse SNARC effect, in line with a clock-face, appeared. Similarly, Bae, Choi, Cho, and Proctor (2009) found that the SNARC effect could be moderated by practice on a magnitude task prior to a parity task, reversing it when large magnitudes were assigned to a left response key and small magnitudes to a right response key in the practice task. SNARC effects have also been shown in vertical space (Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006) and in terms of distance from a starting point (Santens & Gevers, 2008).

There are also effects of culture beyond reading direction: if asked to use all ten fingers to categorise numbers, Italians (who typically count from thumb to little finger on the right and then left hand when using finger-counting) find their typical finger-to-digit mappings easier to use than SNARC-congruent mappings (Di Luca, Granà, Semenza, Seron, & Pesenti, 2006). SNARC effects have also been shown to appear and disappear from trial to trial within the same participant. During a parity task with Russian-Hebrew bilinguals, Fischer, Shaki, and Cruise (2009) intermixed trials of digits and number words in Russian (a left-to-right script) or Hebrew (a right-to-left script in which numbers are read left-to-right), finding that the SNARC effect for digits was as usual if they followed written Russian number words but that it disappeared following written Hebrew number words.

Several other ordinal sequences are thought to interact with space, though research on these sequences is scarcer and evidence from the research that does exist is more ambiguous. The alphabet consistently produces a SNARC-type effect if a task is order-relevant, such as determining whether a letter comes before or after M, but not necessarily if it is order-irrelevant, such as deciding if a letter belongs to one of the groups ACE or BDF (Dehaene et al., 1993; Dodd, Van der Stigchel, Leghari, Fung, & Kingstone, 2008; Gevers, Reynvoet, & Fias, 2003). Research on a SNARC-type effect for months of the year shows an even more inconsistent pattern, not always appearing even when the task is order-relevant (Dodd et al., 2008; Price, 2009).

One reason why the link between the alphabet and space is weaker than the link between number and space may come from use of a verbal code for representing the alphabet sequence. Studies of alphabet navigation (e.g. what letter comes before/after Q) have shown that reaction time for each pair of letters is influenced by the Alphabet Song (Grenzebach & McDonald, 1992; Klahr, Chase, & Lovelace, 1983; but see Scharroo, Leeuwenberg, Stalmeier, & Vos, 1994), learned by many native English speakers as an aid to memory. The song splits the alphabet into small chunks, to be sung to the tune of 'Twinkle, Twinkle, Little Star': ABCDEFG, HIJK, LMNOP, QRST, UV (alternatively QRS, TUV), WXYZ. Even in adulthood, navigating the alphabet is easier within these chunks than across them, suggesting a strong verbal representation of the alphabet. Going against this view, there is evidence from neglect patients (who do not attend to the left side of space following right parietal lesions) that bisection of intervals in the alphabet (e.g. what letter comes midway between P and T?) is subject to the same neglect, shifting responses rightward so that, for example, the midpoint is claimed to lie at S instead of R (Nicholls & Loftus, 2007; Zamarian, Egger, & Delazer, 2007). This is consistent with reports of a rightward shift in bisection of physical lines (Marshall & Halligan, 1990) and, importantly, of the MNL (Zorzi, Priftis, & Umiltà, 2002), in neglect.

Commonly, the SNARC effect is viewed as the result of a direct and automatic link between mental representations of number and space in the parietal cortex (Hubbard, Piazza, Pinel, & Dehaene, 2005), but it has been argued by Gevers, Verguts, Reynvoet, Caessens, and Fias (2006) and Proctor and Cho (2006) that there is an intermediate step of categorisation into verbally-mediated polarities of, for example, odd and even, or small and large. The concepts of left and right also have polarity, so when stimulus and response side polarities match, the participant is quicker to respond than when they are mismatched. Polarity matching can be graded, producing the linear SNARC effect, or absolute, producing the categorical linguistic markedness of response codes (MARC) effect, which results from the status of some words as marked or unmarked (see Nuerk, Iversen, & Willmes, 2004, for an explanation of linguistic markedness). In the case of right-left and even-odd, right and even are unmarked (positive) and left and odd are marked (negative), making these pairs more readily associated than their converse, right-odd and left-even.

Van Dijck, Gevers and Fias (2009) recently provided empirical evidence for the polarity-matching hypothesis by showing that SNARC effects can be abolished by preloading verbal working memory in a parity task and by preloading spatial working memory in a magnitude task. Gevers et al. (2010), furthermore, showed that the SNARC effect can be reversed when participants are asked to respond using buttons labelled ‘left’ and ‘right’ on their respective opposite sides (i.e. ‘left’ on the right and ‘right’ on the left) during parity and magnitude judgement tasks, again indicating a verbal, rather than visual, link between number and space.

Another possible source of confounds for the SNARC effect is the neurological condition of synaesthesia. Synaesthetic inducers may be conceptual, in that an amodal mental representation, rather than a particular stimulus, leads to synaesthesia (Cohen Kadosh et al., 2005). One type of conceptual synaesthesia is number-space, in which numbers take on explicit spatial locations in the mind’s eye or around the body (number forms, Galton, 1880a, 1880b). Related to this, other ordinal sequences such as months (Seymour, 1980), letters of the alphabet (Sagiv, Simner, Collins, Butterworth, & Ward, 2006) and units of measurement (Hubbard, Ranzini, Piazza, & Dehaene, 2009) may also take on spatial locations. The prevalence of number-space synaesthesia in the general population is approximately 12% and the majority (63%) of number forms increase in magnitude from left to right between 1 and 10 (Sagiv et al., 2006) in a sample that is mostly composed of Westerners. Therefore, the prevalence of number forms that explicitly resemble the assumed shape of the MNL in Westerners is 7.6%. Based on Sagiv et al. (2006) and Paper 1 of this thesis, we can calculate a similar prevalence rate for alphabet forms that resemble the MAL. Sagiv et al. report 15% of the population as possessing alphabet forms, while Paper 1 indicates that 42.5% of alphabet forms in native English speakers run from left to right horizontally; this gives a prevalence of 6.4%. However, it is not known how having a MNL-compatible number form or a MAL-compatible alphabet form would affect a participant’s results in tasks tapping implicit versions of these forms.

So far, the only data from SNARC-tapping tasks on the effect of number-space synaesthesia are from single case studies. Piazza, Pinel, and Dehaene (2006) report a case in which a number form running in the opposite direction to the MNL did not interfere with the SNARC effect, suggesting that a number form may have no effect at all on this test (this is compatible with the finding by Tang, Ward, & Butterworth, 2008, that number forms appear to be ordinal rather than cardinal in nature). However, Jarick, Dixon, Maxwell, Nicholls, and Smilek (2009) found that a synaesthete with a vertically oriented number form showed a significant vertical SNARC effect but no horizontal SNARC effect, and Hubbard et al. (2009) also found no significant horizontal SNARC effect for their synaesthete with a SNARC-incompatible form. In all of these studies, the control groups, which were presumably tested for synaesthesia, showed a significant SNARC effect, indicating that (in some tasks, at least) the SNARC effect is present in the absence of synaesthesia.

So far, there have been no studies on the effects of alphabet forms on SNARC-type tests. However, it may be possible to extrapolate from time-space synaesthesia, as time sequences such as months and days share the ordinal property of the alphabet, but lack the cardinal property of counting. Price and Mentzoni (2008) have shown that time-space synaesthetes show a SNARC-type effect for months (dependent on their calendar form), as did non-synaesthetes asked to decide if months were odd or even (e.g. March, the third month, is ‘odd’). However, non-synaesthete participants did not show a SNARC-type effect for months when asked to decide if months were from the first or the second half of the calendar year (Price, 2009). Price also showed that prompting non-synaesthetes to use a specific mental image of the year produced SNARC-type effects in line with that image, again indicating that mapping sequences onto space in the absence of synaesthesia might be the result of a task-based strategy rather than any implicit association. As Eagleman (2009) points out, the majority of calendar forms have early months (January-June) to the left of later months (July-December) and are linear, in line with the purported direction of implicit time-space associations. Once again, this presents a problem for SNARC-type experiments in which spatial synaesthetes have not been conclusively excluded from the sample.

The aim of the current study was to find out what might happen if number-space and alphabet-space synaesthetes with forms like the implicit MNL and MAL were present in a sample carrying out SNARC-type tests. Synaesthetes and controls were asked to take part in parity judgement and case judgement tasks. It was hypothesised that a SNARC effect would appear in both groups for the parity task, but that it would be stronger for the synaesthete group due to the explicit nature of their associations. In the case judgement task, it was predicted that synaesthetes would show a SNARC-type effect but that non-synaesthetes would not, since order is not relevant to the task. The data were also analysed to search for a spatial bias relating to the layout of the keys (the QWERTY effect), such that Q, W and Z would be reacted to more quickly with the left hand and P, O and M with the right hand. If SNARC-type effects are the result of task demands, then synaesthetes should be less susceptible to this effect than controls, since alphabet forms are inflexible. Finally, a MARC effect was predicted to be present in both groups as number forms explicitly encode information about space and order but not about verbal polarity, meaning that synaesthetes are as susceptible as controls to polarity-matching.

2 Experiment 1

2.1 Methods

2.1.1 Participants

Twenty self-reported synaesthetes with number forms (recruited from the Sussex-Edinburgh database of synaesthete participants) and twenty non-synaesthetes took part in this experiment. All synaesthetes reported number forms which increased in magnitude from left to right in the horizontal axis between 0 and 10, but have not been tested for consistency. Synaesthetes had a mean age of 25.50 years (*S.D*. = 9.85, range = 19-62; 14 female) and controls had a mean age of 24.40 years (*S.D*. = 8.85, range = 18-57; 13 female). All participants were native speakers of English.

2.1.2 Materials and procedure

Participants were seated in front of a monitor, on which was presented a central fixation cross for 1000ms, followed by a number in the range 1-9 in 24-point Courier New, until a response was made. Participants were asked to press either the backslash (\) or full stop (.) key on a standard keyboard to indicate a decision that the presented number was odd or even, and to do so as quickly and accurately as possible. Numbers were presented in a randomised order. In one version of the experiment, the backslash key was designated ‘odd’; in the other version, it was designated ‘even’. Participants completed both tasks (to control for hand-response assignment), and the order of tasks was counterbalanced across participants (to control for practice effects). In each version of the task, each number was presented 20 times, for a total of 360 trials across versions.

2.2 Results

Before analysis, all data were screened for errors and RTs under 300ms (under this threshold, responses are unlikely to be the result of a conscious decision to press a particular button). Subsequently, outliers beyond 3 *S.D.* from the mean were removed and this process repeated until no outliers remained (following Smilek, Callejas, Dixon, & Merikle, 2007).

2.2.1 MARC effect

As a MARC effect could obscure any SNARC effect to be found, we first looked for evidence of shorter reaction times when odd numbers required a leftward response and even numbers a rightward response. Mean reaction times were calculated for odd and even stimuli by response side and group (Figure 1). A 2x2x2 mixed ANOVA was used to compare the data along these three axes. There was a significant interaction of parity with response side ($F(1,38) = 5.00$; $p < .05$), in line with the MARC effect, and a significant main effect of group ($F(1,38) = 5.76$; $p < .05$), caused by synaesthetes (M = 583ms) taking longer than controls (M = 527ms). There were no other main effects or interactions (all ps > .27). Consequently, when analysing the data for a SNARC effect, reaction times were collapsed into bins for magnitudes 1/2, 3/4, 6/7 and 8/9 to avoid any confound with the MARC effect.

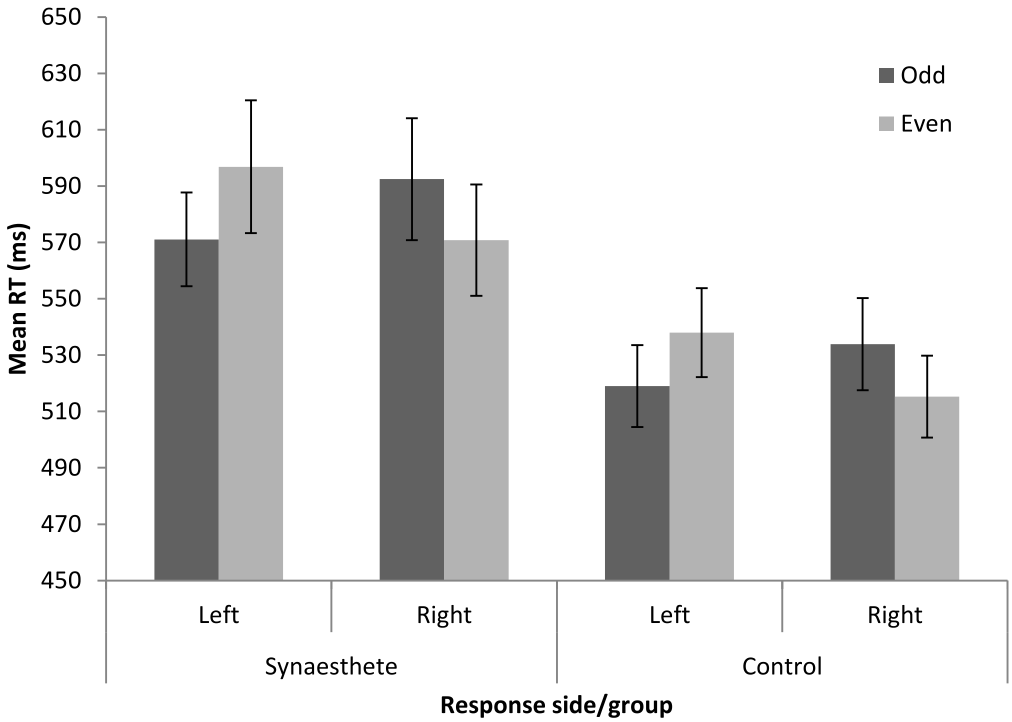

Figure 1: Reaction times to odd and even stimuli for left and right hands in synaesthete and control groups. Error bars show ± 1 S.E.M.

2.2.2 SNARC effect

To determine whether a SNARC effect existed in our two groups of participants, we used the method of Fias et al. (1996), taking a regression slope on difference in mean RTs between right and left hands (dRT) on binned magnitude (1/2, 3/4, 6/7, 8/9) for individual participants and then comparing those slopes against zero (i.e. no dRT) using a one-sample t-test.

Figure 2 shows regression slopes for grand mean dRTs on magnitude in the synaesthete and control groups. One-sample t-tests showed that the synaesthetes' slopes were significantly different from zero ($t(19) = 2.14$, $p < .05$; mean slope = -6.33ms) but the controls' were not ($t(19) = 1.78$, $p = .09$; mean slope = -2.34ms). However, a between-subjects t-test showed that there was no significant difference between groups ($t(38) = 1.23$, $p = .23$).

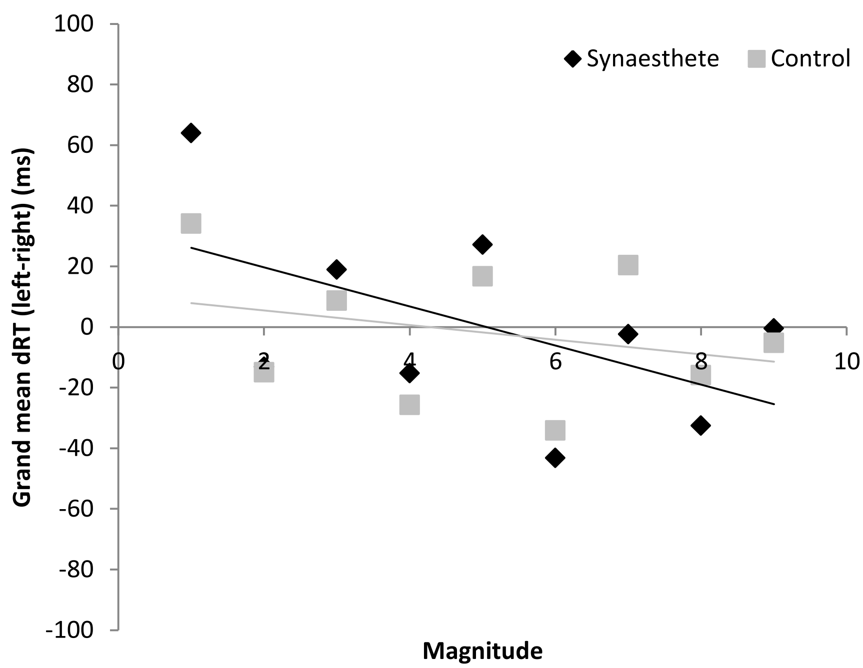

Figure 2: Difference in RT between right and left hand at different stimulus magnitudes for synaesthetes and controls.

2.3 Discussion

MARC effects are seen in both synaesthetes and control groups, which may suggest a similar representation of number in each group. MARC effects can appear in both groups because number forms do not explicitly encode parity information and thus cannot affect judgements about parity.

SNARC effects, however, appear in the synaesthete group but not the control group according to the one-sample t-tests, though the between-subjects t-test carried out suggests that there is no difference between the two groups. SNARC effects may have similar or different causes in each group. If Dehaene (1992) is correct, then both groups are responding to number lines – one group to an implicit mental version, the other to an explicit synaesthetic version. However, if the polarity-matching hypothesis (e.g. Santens & Gevers, 2008) is correct, then the control group must be using verbal labels to categorise numbers with the side-effect of a SNARC effect while synaesthetes could be using verbal labels or relying on their mental number line. Either of these possibilities could lead non-synaesthetes to show a somewhat weaker SNARC effect than their synaesthete counterparts.

Furthermore, synaesthetes are significantly slower than controls at the parity judgement task. In tasks where synaesthetes' inducer-concurrent perceptions are challenged (e.g. numbers requiring a response on the 'wrong' side of the body), this is likely to be because synaesthetes are aware that some trials will be incongruent and adopt a cautious response strategy, whereas controls have no explicit 'right' and 'wrong' side for numbers and do not need to be so cautious.

3 Experiment 2

3.1 Methods

3.1.1 Participants

Fourteen self-reported synaesthetes with alphabet forms (recruited from the Sussex-Edinburgh database of synaesthete participants) and fourteen non-synaesthetes took part in this experiment. All synaesthetes had alphabet forms which were in alphabetical order from left to right in the horizontal axis, but again, had not been tested for consistency. Synaesthetes had a mean age of 28.57 years (*S.D.* = 13.19, range = 19-53; 12 female) and controls had a mean age of 22.79 years (*S.D.* = 4.98, range = 19-30; 8 female). All participants were native speakers of English.

3.1.2 Materials & Procedure

The procedure for Experiment 2 closely followed that of Experiment 1. Instead of a parity task, participants completed a case judgement task (e.g. deciding if B is upper-case or lower-case) in the same way as the parity judgement task was done. In each version of the task (left = upper-case and right = upper-case), each letter was presented 10 times (5 upper-case and 5 lower-case), for a total of 520 trials across versions.

3.2 Results

Before analysis, all trials involving the letters I/i and L/l were removed, as several participants had reported difficulty distinguishing the upper-case I and lower-case l due to the font used in the experiment. The data were cleaned in the same manner as Experiment 1, and then binned by pairs of letters (AB, CD, EF, GH, JK, MN, OP, QR, ST, UV, WX, YZ) for the SNARC-type test and by keyboard position (QAZ, WSX, EDC, RFV, TGB, YHN, UJM, KOP) for the QWERTY effect test.

3.2.1 SNARC effect

Using a similar method to Experiment 1 (i.e. regressing dRT on binned ordinal position of letters for individual participants, then a one-sample t-test to determine if the slopes in each group of participants differed from 0), we found that neither synaesthetes ($t(13) = 1.14$, $p = .27$; mean slope = 0.35ms) nor controls ($t(13) = 1.80$, $p = .09$; mean slope = 2.60ms) showed a SNARC-type effect. Figure 3 shows regression slopes for grand mean dRTs on binned ordinal position in the synaesthete and control groups.

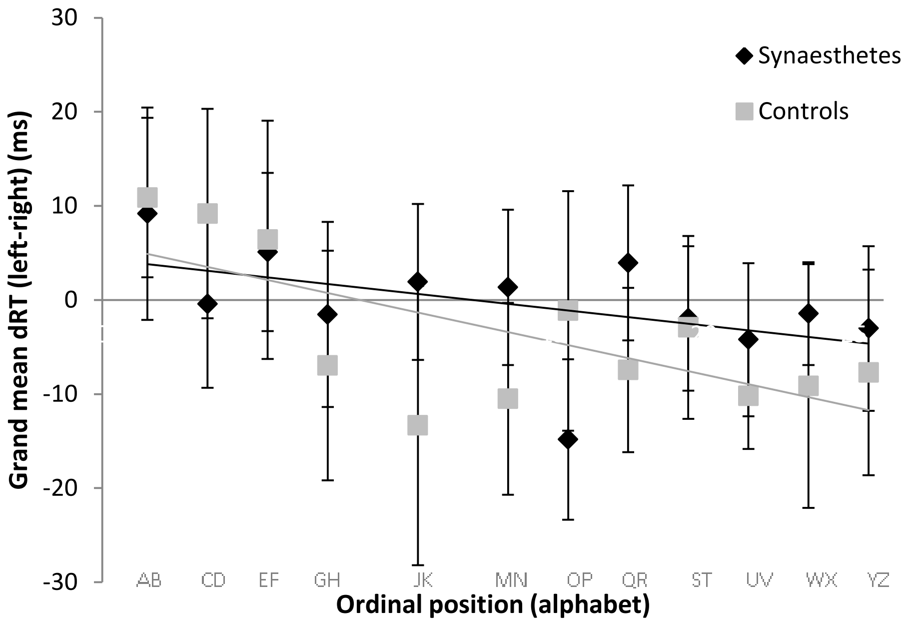

Figure 3: Difference in RT between right and left hand at different stimulus alphabetical positions for synaesthetes and controls. Error bars show ± 1 S.E.M.

3.2.2 QWERTY effect

Again, we used a variation on the Fias et al. (1996) method, with dRT regressed on ordinal position of the keyboard bins from left to right (i.e. QAZ =1, WSX = 2, etc.). Synaesthetes did not show a QWERTY effect ($t(13) = 1.60$, $p = .13$; mean slope = -1.76ms), but controls did ($t(13) = 2.36$, $p < .05$; mean slope = -2.60ms). An independent-measures t-test to compare the two groups directly was not significant ($t(26) = 2.37$, $p = .60$). Figure 4 shows regression slopes for grand mean dRTs on binned keyboard position in the synaesthete and control groups.

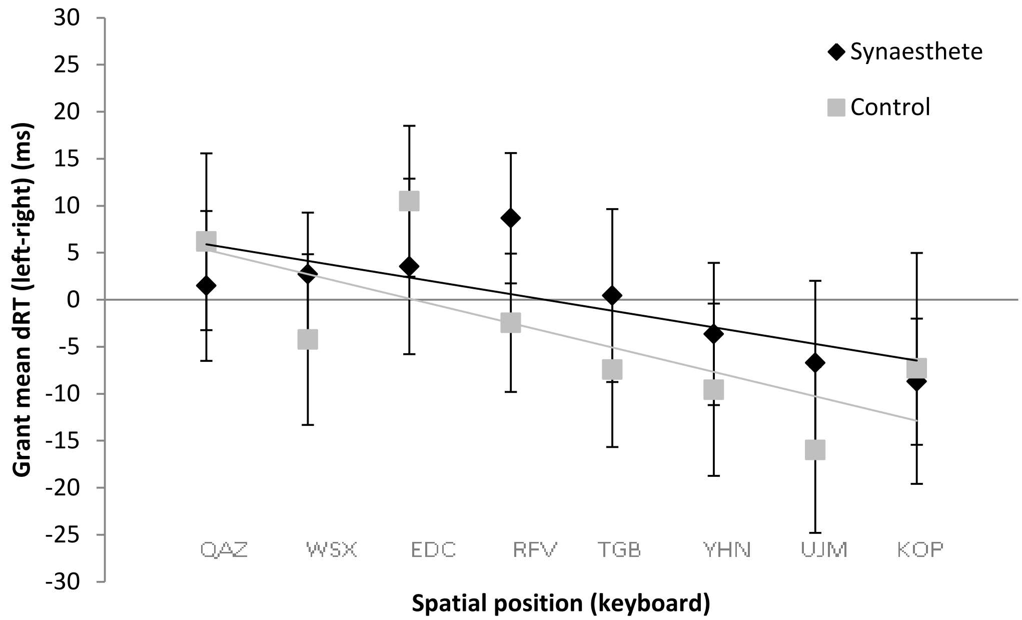

Figure 4: Difference in RT between right and left hand at different stimulus keyboard positions for synaesthetes and controls. *Error bars show ± 1 S.E.M.*

A second analysis using a 2x2x2 (stimulus keyboard side by response side by group) mixed ANOVA provided some further information on the QWERTY effect. There was a significant interaction of stimulus keyboard side with response side ($F(1,26) = 7.11$; $p < .05$), as expected, but also a near-significant interaction of stimulus keyboard side with group ($F(1,26) = 3.74$; $p < .06$). Paired t-tests with a Bonferroni correction (α of .05/6 = .008) showed that this was due to the controls showing a near-significant QWERTY effect with the left hand only ($t(13) = 2.88$, $p < .01$; left keyboard stimulus M = 518ms, right keyboard stimulus M = 530ms). No other significant differences were found.

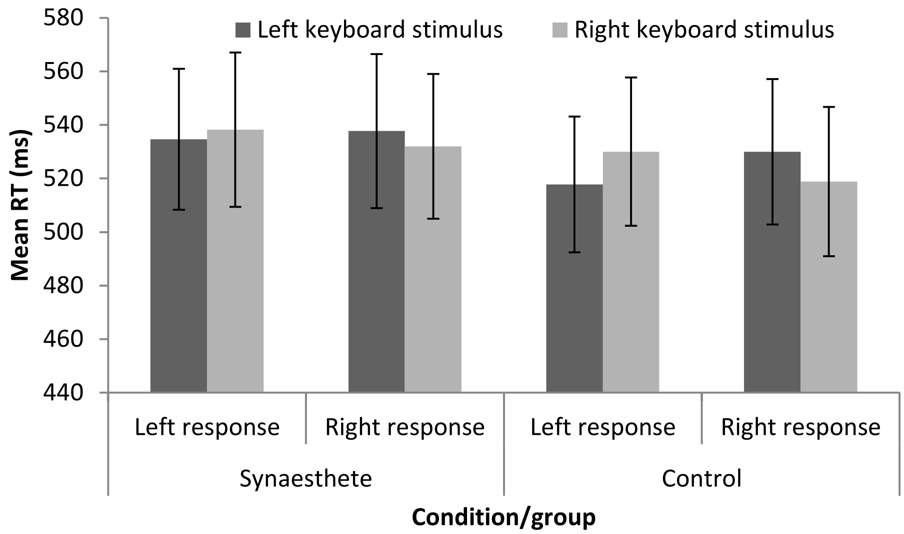

Figure 5: Reaction times to left keyboard and right keyboard stimuli for left and right hands in synaesthete and control groups. Error bars show ± 1 S.E.M.

3.3 Discussion

For the case judgement task, neither synaesthetes nor controls show a SNARC-type effect. The control group show a QWERTY effect (based on the one-sample t-test and ANOVA findings) but according to a between-samples t-test they do not differ significantly from the synaesthetes in the strength of their SNARC effect.

One possibility is that our controls (and any other computer-literate groups) have an implicit spatial representation of the alphabet that is not in a straight line but in the layout of the keyboard. Since our synaesthetes are unlikely to be less computer-literate than our controls, it is worth asking why some of the analyses above suggest that synaesthetes do not show a QWERTY effect. The most obvious explanation is that an implicit QWERTY layout is interfering with an explicit left-to-right layout of the alphabet. Reaction times, then, could vary from trial to trial depending on which spatial representation is uppermost in the synaesthetes' mind.

Alternatively, as discussed above in relation to the SNARC effect, it could be that the QWERTY effect results from task demands rather than a spatial representation of the alphabet; in this case, one would expect the QWERTY effect to disappear if participants gave their responses using an unlabelled button-box rather than a keyboard, and a stronger SNARC effect to emerge in synaesthetes.

4 General discussion

In summary, our results are mixed, showing that number-form synaesthetes and controls are equally susceptible to the MARC effect, but that synaesthetes show a SNARC effect while controls do not (or that the two groups do not differ, depending on the statistical analysis used). They also show that neither alphabet-form synaesthetes nor controls showed a SNARC-type effect for the alphabet, and that controls were susceptible to a QWERTY effect while synaesthetes were not (again, depending on the statistical analysis used, there may also be no difference between the groups). While our results show that synaesthetes' slope coefficients are significantly different from zero and that controls' slopes are not, they are not significantly different from each other. Following from Bächtold et al. (1998), this could indicate that the SNARC effect in controls is a strategic response to the parity judgement task but, additionally, that the default response is a left-to-right number line because it fits in with reading habits (see also Gevers, Verguts et al., 2006).

Comparing our mean slope coefficients for the number SNARC effect with those found in other studies (Table 1), it can be seen the controls' (-2.34ms) falls at the lower end of the scale and that the synaesthetes' (-6.33ms) is close to the average. While both slopes fall in the range of previously recorded coefficients, they are rather smaller than were expected in the light of previous research. The smallness of the control slope is easy to explain – the coefficient is smaller than usual because the SNARC effect is not as strong as it would be with synaesthetes included. However, the synaesthete slope should be towards the higher end of the range of coefficients previously noted (according to our hypothesis). This may be due to individual variability in the strength of synaesthetic associations which cannot easily be controlled for, and indeed the synaesthetes' range of individual slope coefficients (-48.15ms to 19.59ms) is three times as large as the controls' range (-15.21ms to 6.95ms). Additionally, as Bull and Benson (2006) have shown, participants with lower ratios between second and fourth fingers (2D and 4D) show a stronger SNARC effect than those with higher digit ratios. 2D-4D digit ratio is a sexually dimorphic trait that is, on average, smaller in men than in women (Manning et al., 2000), so our large proportion of female participants (70% of synaesthetes and 65% of controls) could have weakened the SNARC effect. Backing this up, Table 1 shows percentages of female participants in experiments where this data was provided and a Pearson's correlation indicates that the higher the proportion of female participants, the weaker the SNARC effect (r = .52, n = 16, p < .05).

Taking the prevalence of number-space synaesthetes in the general population at 12% (Sagiv et al., 2006), it is possible to calculate what our slope coefficient might have been if we had not explicitly asked participants about synaesthesia: (-6.33 x .12) + (-2.34 x.88) = -2.82ms. Depending on the strength of a participant's synaesthesia, this effect on parity judgement tasks might be much smaller or larger. There is also a possibility that some representations of number interact more easily with number forms than others; for example, written number words might activate a number line to a lesser extent than digits or auditory number words. Additionally, a less common number form (e.g. right-to-left or vertical, Sagiv et al., 2006) might weaken a SNARC effect. Manipulations designed to alter the SNARC effect (Bächtold et al., 1998; e.g. Fischer et al., 2009; Santens & Gevers, 2008) may also fail to work on synaesthetes; this is an obvious area for future research. A second area for future research is related to the slower overall RT in the synaesthete group compared to the control group. This slowness is likely the result of a cautious response strategy (see Section 2.3) and could be masking some effects of synaesthesia. One way to deal with this is to force participants to respond more speedily and analyse error rates rather than reaction time. The effects of this depend to some extent on how quickly the number form arises for synaesthetes following exposure to a number; very rapid elicitation of the number form would allow synaesthetes an explicit reference point and therefore fewer mistakes than non-synaesthetes, while a number form that is slow to arise would mean that synaesthetes and non-synaesthetes should behave in a similar fashion.

Table 1: Mean slope coefficients and percentage of female participants for a range of past experiments on the SNARC effect.

Paper	Expt	Task	% female Ps	Mean slope (ms)
Bae et al. (2009)	1	Parity task after magnitude task (compatible)	-	-23.57
		Parity task after magnitude task (incompatible)	-	10.06
	2A	Parity task after stimulus-response compatibility (SRC) task (compatible, 72 trials)	-	-11.35
		Parity task after SRC task (incompatible, 72 trials)	-	-13.14
	2B	Parity task after SRC task (compatible, 600 trials)	-	-10.58
		Parity task after SRC task (incompatible, 600 trials)	-	-16.27
	3	Parity task after orthogonal SRC task (compatible)	-	-15.08
		Parity task after orthogonal SRC task (incompatible)	-	10.34
Fias et al. (1996)	1	Classic parity judgement (0-5)	66.7	-10.18
	1	Classic parity judgement (4-9)	66.7	-7.19
	2	Phoneme search in number words	52.2	-6.01
Fias (2001)	1	Parity judgement for number words	90.0	-3.50
Fias et al. (2001)	1	Triangle orientation judgement with irrelevant number	70.8	-2.03
	2	Colour judgement with irrelevant number	70.8	1.95
	3	Colour judgement with irrelevant number	83.3	0.50
	4	Line orientation judgement with irrelevant number	83.3	-3.74
	5	Shape judgement with irrelevant number	45.0	-0.36
Fischer et al. (2004)	-	Parity judgement via eye movement	53.3	-4.13
Fischer et al. (2009)	1	Visual digit parity judgement following visual Russian number word	56.3	-11.02
	1	Visual digit parity judgement following visual Hebrew number word	56.3	-1.60
	1	Visual Russian number word parity judgement	56.3	-8.70
	1	Visual Hebrew number word parity judgement	56.3	-4.25
	2	Auditory Russian number parity judgement	38.5	-16.24
	2	Auditory Hebrew number parity judgement	38.5	-11.15
Gevers, Verguts, et al. (2006)	1	Classic parity judgement	-	-4.21
	2	Arbitrary category judgement for digits	-	-8.59
Gevers et al. (2010)	2	Parity judgement using touchscreen	-	-3.37
Hubbard et al. (2009)	4b	Classic parity judgement	-	-9.04
Piazza et al. (2006)	3	Classic parity judgement	-	-9.00
Average				**-6.60**

Turning to the SNARC-type effect of alphabetical position, neither group showed an effect of position on dRT. This unexpected result may arise from the task design. Asking participants whether a letter is upper-case or lower-case is a useful way of making sure that every letter in the alphabet is probed, but may not be an ideal method for eliciting RT differences between hands. Previously, Gevers et al. (2003) have successfully elicited a SNARC-type effect using a vowel/consonant decision task, which is closer to the odd/even decisions that participants made in Experiment 1 and may also cause letters to be processed more deeply than a case decision task. Given the nature of spatial alphabets, one would expect to see evidence of their existence in all tasks involving the alphabet, but as Paper 1 shows, this is not the case even in tasks which involve order-related decisions, which seem the most likely to elicit the use of the spatial alphabet. This provides further support for the idea raised in Paper 1 that the verbal representation of the alphabet is stronger, perhaps through more common use, than the spatial representation.

Despite the lack of predicted differences between the synaesthete and control groups in the experiments of this paper, some useful theoretical and practical implications have arisen that may guide future research. Firstly, it would be wise to screen for synaesthetes before conducting any task intended to tap implicit spatial references. Secondly, while both synaesthetes and controls show a SNARC effect in the parity judgement task, the root causes of the effect may be different in each group. In the future, tasks in which the polarity-matched pairs of left-odd and right-even are challenged (akin to the MARC-altering task used by Cho & Proctor, 2007) could be used to separate out those with flexible number-space mappings from synaesthetes, whose mappings are inflexible.

Paper 3

Synaesthetic interactions between colour, ordinality and linguistic frequency for letters and numbers

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Abstract

Some previous studies on grapheme-colour synaesthesia have attempted to link colour categories with different graphemes, whereas others have linked luminance and saturation (but not colour categories) to different graphemes. However, it is important to directly compare these approaches because they are not completely independent (some colour categories, such as purple and yellow, have different luminances). The current experiment attempts to disentangle these influences on grapheme-colour pairings by considering luminance and saturation separated by hue. Our results show that within some hues, earlier and more frequently used letters and numbers tend to be more saturated and more luminant. However, a comparison of letters and numbers indicates that the same rules do not apply to all kinds of grapheme-colour synaesthesia, suggesting it may be more useful to consider letter-colour and number-colour synaesthesia separately than to consider them as a single phenomenon.

1 Introduction

In the familial condition of synaesthesia, unisensory stimuli result in two perceptions – one in the original, or inducer, domain, and the other in a second, or concurrent, domain. Synaesthesia arguably extends to include conceptual inducers; for example, when the thought of a number gives rise to the sensation that the number has a location.

It is well established that inducer-concurrent pairings are not random. Ward and Simner (2003) showed that one lexical-gustatory synaesthete presented a complex pattern of associations between words and tastes that are influenced by, for example, conceptual links, phoneme order and phonology. In sound-colour synaesthesia, low-pitched sounds tend to be dark and high-pitched sounds bright (Ward, Huckstep, & Tsakanikos, 2006). The inducer-concurrent relationships in the preceding examples are not contested. Research to date suggests that grapheme-colour synaesthesia, in which digits and/or letters take on colours, is not so straightforward.

The earliest modern investigation of patterns in digit-colour synaesthesia was carried out by Shanon (1982), who asked synaesthetes to provide colour names for each of the digits 0-10 and found that there was a tendency for low-magnitude numbers to be paired with colours early on in the Berlin-Kay typology (the order in which colour names tend to enter languages, Berlin & Kay, 1969, cited in Kay & Maffi, 1999), and higher-magnitude numbers with colours later on in the typology. Baron-Cohen et al. (1993) and Day (2001) both carried out similar studies with letter-colour synaesthetes but did not draw any conclusions with regard to the alphabet as a whole. Both studies, however, reported that *I* was commonly a light colour and *O* generally white. There was disagreement on *U*, though: Day reported that it was usually dark and Baron-Cohen et al. that it was yellow to light brown.

Simner et al. (2005) extended Day's (2001) study by testing a very large number of independently verified synaesthetes, and by asking non-synaesthetes to provide colours for letters. Synaesthetes' inducer-concurrent pairings often have non-explicit counterparts in the general population (e.g. Dehaene, Bossini, & Giraux, 1993; Marks, 1982), though usually the way in which senses link in these counterparts is less idiosyncratic than the way they link in synaesthesia (for example, number and space are considered to have implicit linear left-to-right links, but number-space synaesthesia does not always follow this pattern). In the case of letter-colour synaesthesia, synaesthetes and controls choose the same colours for at least half of the alphabet on average. However, there are also indications that colour vocabulary may influence letter-colour combinations more for controls than synaesthetes; for example, *o* is generally white for synaesthetes but orange for (English-speaking) controls. Similarly to Shanon (1982), Simner et al. looked for a correlation between the Berlin-Kay typology and alphabetical position of letters, but found nothing significant for synaesthetes. However, they did find a positive correlation between letter frequency and the Berlin-Kay order, as well as between letter frequency and colour name frequency. This highlights a problem inherent with studies of inducer-concurrent pairings in digit-colour synaesthesia, which Beeli, Esslen and Jäncke (2007) also bring up: ordinality (the order in which numbers progress), magnitude (the size of the class of objects to which a number refers) and rank linguistic frequency are perfectly correlated for numbers, so any of these could be driving digit-colour synaesthesia.

Subsequent studies have tended to use intersubjective measures of colour: hue, saturation and luminance (HSL). Hue is what is typically thought of as ‘colour’, (red, green, purple, etc.); saturation is the intensity of the colour; and luminance is the lightness of a colour (e.g. pink is typically lighter than red). Each of these values can be altered independently of the other two. Beeli et al. (2007) avoided this problem by using frequency for digits taking second position in multi-digit numbers (which do not have a perfect rank order correlation with magnitude) when they asked a sample of 19 native German-speaking grapheme-colour synaesthetes[15] to provide HSL values for digits and letters. For numbers, they found that frequency and luminance correlated strongly and positively, while magnitude and saturation correlated negatively (though this was reversed when 0 and 1, commonly white and black, were removed from the analysis). Letter frequency, on the other hand, did not correlate with luminance at all, and weakly but significantly and positively with saturation. A very similar experiment, with a larger sample size of 55 synaesthetes, by Smilek, Carriere, Dixon and Merikle (2007) showed that there was a weak positive correlation between letter frequency and luminance for synaesthetes. Smilek et al. also extended their experiment to include non-synaesthetes, finding that even in those without explicit colour

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[15] In fact, Beeli et al.’s synaesthetes stated that they perceived colours on *hearing* letters and digits, so it is possible that the grapheme-colour associations reported here are in fact sound-colour associations.

associations a weakly positive correlation can be seen between frequency of use and luminance for both digits and letters, again indicating an underlying similarity in the synaesthete and non-synaesthete populations.

Another source of confound, as Simner and Ward (2008) argued, is that the linguistic frequency of colour terms is negatively correlated with saturation; the digit-saturation correspondence found by Beeli et al. (2007), then, may be between frequency of colour terms and frequency of graphemes – decreasing saturation with frequency could be a mere by-product of this association. Cohen Kadosh, Henik and Walsh (2007; 2009) attempted to disentangle these possible influences in a different ordinal sequence by asking Hebrew-speaking synaesthetes to provide colours for days of the week, providing a series which is ordinal but not cardinal. Saturation and luminance do not correlate with this series, suggesting that it is not the ordinal properties of numbers that give rise to particular colours (though it remains unclear whether frequency or magnitude is the driving force). However, saturation does negatively correlate with linguistic frequency of day name. In turn, the less frequent the day name, the less frequent its associated colour name tends to be. It must be noted, however, that this data comes from only eight synaesthetes. In addition, it is questionable whether it is useful to compare different semantic orders when they may be processed in very different ways; this point is returned to in the discussion.

There are three other factors which may affect inducer-concurrent pairings in grapheme-colour synaesthesia. Firstly, it is possible that childhood reading materials, such as alphabet books, could provide initial pairings. While there is a single case study that reports a synaesthete's associations to be in line with her childhood refrigerator magnets (Witthoft & Winawer, 2006), a large-scale study of grapheme-colour synaesthetes has shown that these explicit external prompts are rarely in line with actual synaesthetic experience (Rich, Bradshaw, & Mattingley, 2005).

Secondly, it is possible that the sound of an inducer is the source of a colour perception or association. If this is the case, one would expect to see synaesthesia 'spreading' from letters (arguably the purest visual representation of a sound) to numbers, days and other sequential inducers, such that the first or dominant phoneme has the most effect on the colour of a word belonging to a sequence. However, this does not appear to be the case (Barnett, Feeney, Gormley, & Newell, 2008) except for months; instead, each sequence appears to have its own set of colours that has little to do with the sound of the words it contains.

Thirdly, Spector and Maurer (2008) found some evidence of simple associations between shape and colour that do not rely on ordinal, cardinal or acoustic properties of sequences when they asked non-synaesthetic pre-literate children, literate children and adults to decide what colour box a clear plastic shape would be found in. When the choice was between black and white for *O* and *X*, participants of all ages consistently picked the white box for *O* and the black box for *X*. However, when the decision was between red and green for *A* and *G*, only literate participants chose the red box for *A* and the green box for *G*, suggesting a role for reading experience of red apples and green grass. The reasons for the *O*-white/*X*-black choice must therefore be based on shape, but it is not clear what aspect of shape influences the choice.

The aim of the present study is to investigate whether correspondences between sequence measures (ordinality, magnitude and frequency) and colour measures (hue, saturation and luminance) are due to direct or indirect links, particularly in letter-colour synaesthesia where shape and phonology may influence colours. If links are direct, breaking down data into separate hues will produce correlations between sequence measures, saturation and luminance for each hue. However, if links are indirect, these correlations should break down when analysed within hues.

2 Methods

2.1 Participants

One hundred letter-colour and 100 number-colour synaesthetes took part in this experiment. Seventy-one synaesthetes provided both letter and number data. Synaesthete status was determined using the Eagleman consistency score (a measure of red-green-blue colour value consistency over three trials, Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007), for the grapheme-colour picker test (less than 1.00) and the speed-congruency accuracy percentage (85% or more). Participants who met either of these two criteria were classed as synaesthetes.[16]

Of the number-colour participants, 66% were native English speakers, 13% were non-native English speakers, and the mother tongue of the remaining 21% was unknown. For letter-colour participants, these percentages were 70, 13 and 17 respectively.

2.2 Materials and Procedure

Participants provided colours for digits and/or upper-case letters using the Synaesthesia Battery at www.synesthete.org, or by modifying a Microsoft Word document containing numbers so that the RGB values of each number matched their synaesthetic experience. For those who used the Eagleman battery, colours were asked for three times. Later, the experimenters took a mean of each RGB value for each number or letter across these three trials. Where synaesthetes indicated that they perceived no colour for two or more trials of any grapheme, 'no colour' was recorded. RGB values were converted to HSL values for analysis.

To assess the colour name for each RGB value, colours were randomised and presented, using E-Prime 2.0, as coloured blocks on a grey background to two non-synaesthete, native speakers of English. They were asked to decide which of the

[16] Note: In cases where synaesthetes provided both letter and number data, consistency and accuracy were collapsed across the two grapheme types; in the letter-colour condition, 5 participants did not complete the Eagleman battery but instead provided colours by modifying red-green-blue (RGB) values of numbers in a Microsoft Word document.

eleven basic English colour terms (black, white, red, green, blue, yellow, brown, grey, orange, purple and pink) best described the colour. No upper limit was placed on decision time. In cases where there was disagreement between raters, a third rater was asked to decide between the two colour terms.

3 Results

3.1 Linguistic frequency of colour terms

To determine whether colours were randomly associated with letters and numbers, binomial distributions were used. Following the method of Simner et al. (2005), the proportion of times any letter was a particular colour was used as a baseline (e.g. 346 of a total 2600 letters were green, giving a baseline for green of .13; the proportion of all *G*s classified as green is .40, a highly significant ($p < .001$) result). These results are presented in Figures 1 and 2.

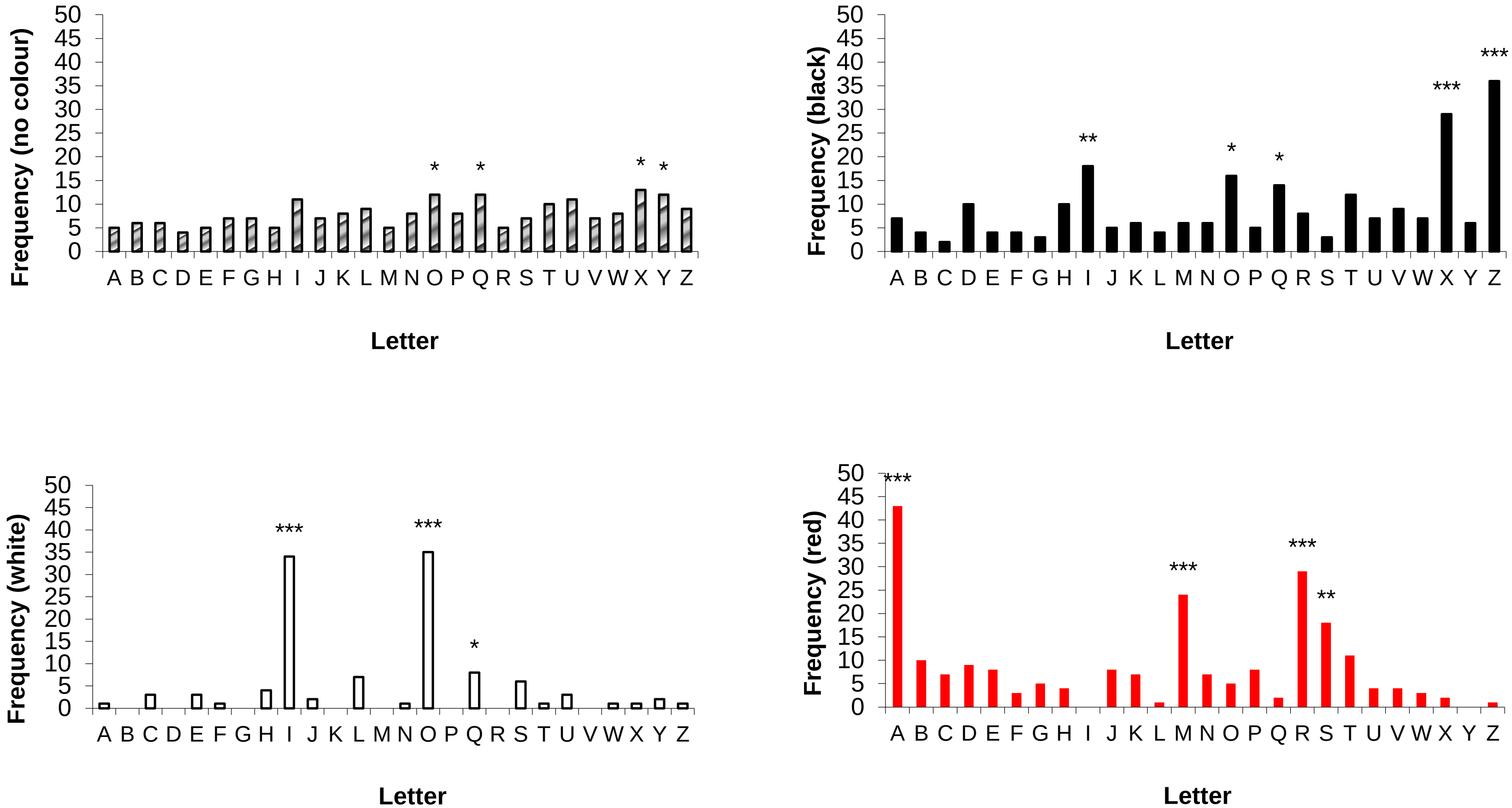
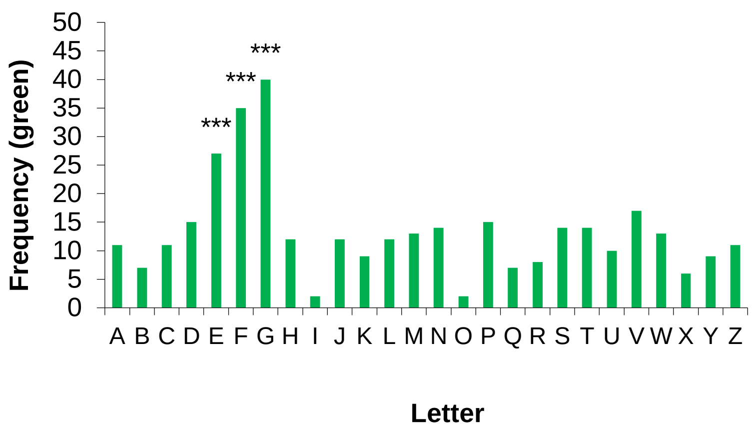
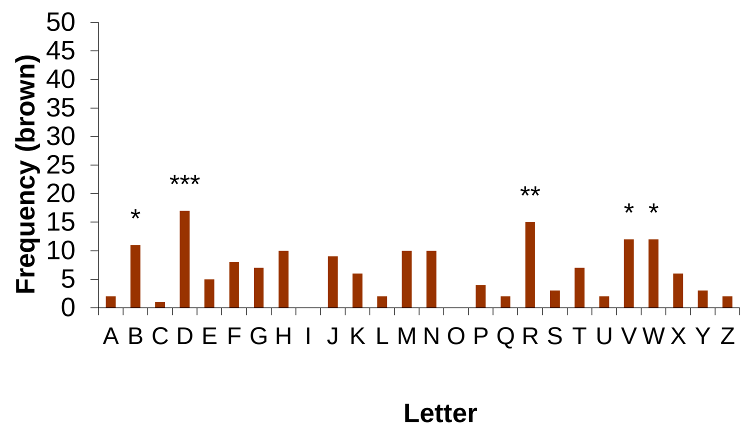
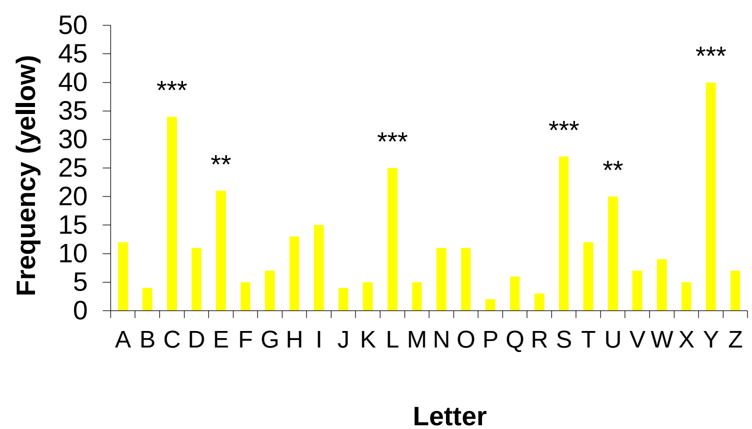


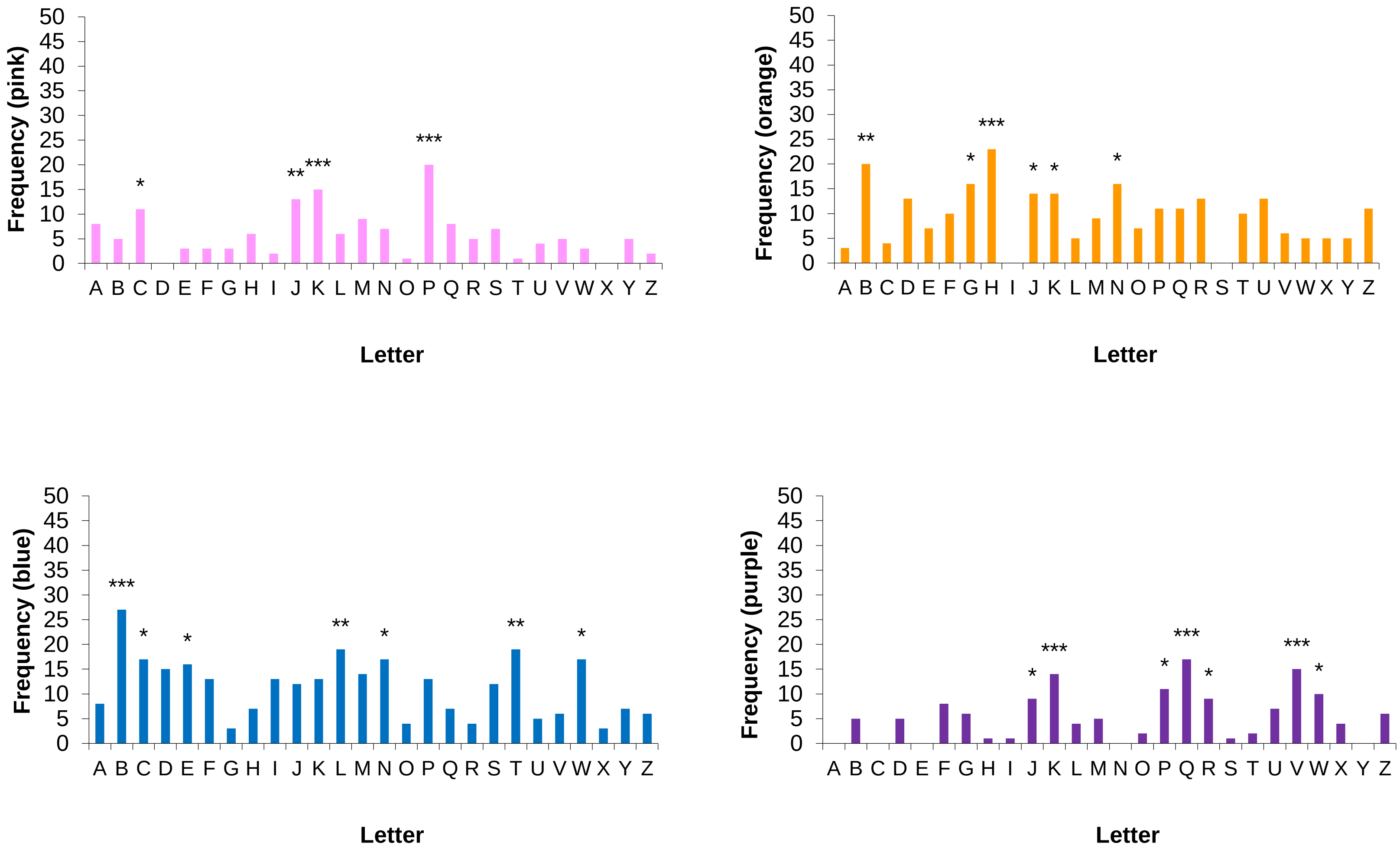
Figure 1: Frequency distribution of colour terms (eleven basic terms plus 'no colour') for letters A-Z. Asterisks indicate significantly higher frequencies than expected by chance (= .05, ** = .01, *** = .001).*


Frequency (green)
50
45
40
35
30
25
20
15
10
5
0
A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
*** *** ***
Letter


Frequency (brown)
50
45
40
35
30
25
20
15
10
5
0
A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
* *** ** * *
Letter


Frequency (grey)
50
45
40
35
30
25
20
15
10
5
0
A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
*** ** ** *** *
Letter


Frequency (yellow)
50
45
40
35
30
25
20
15
10
5
0
A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
*** ** *** *** ** ***
Letter


Frequency (pink)
Frequency (orange)
Frequency (blue)
Frequency (purple)
Letter
A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
0 5 10 15 20 25 30 35 40 45 50

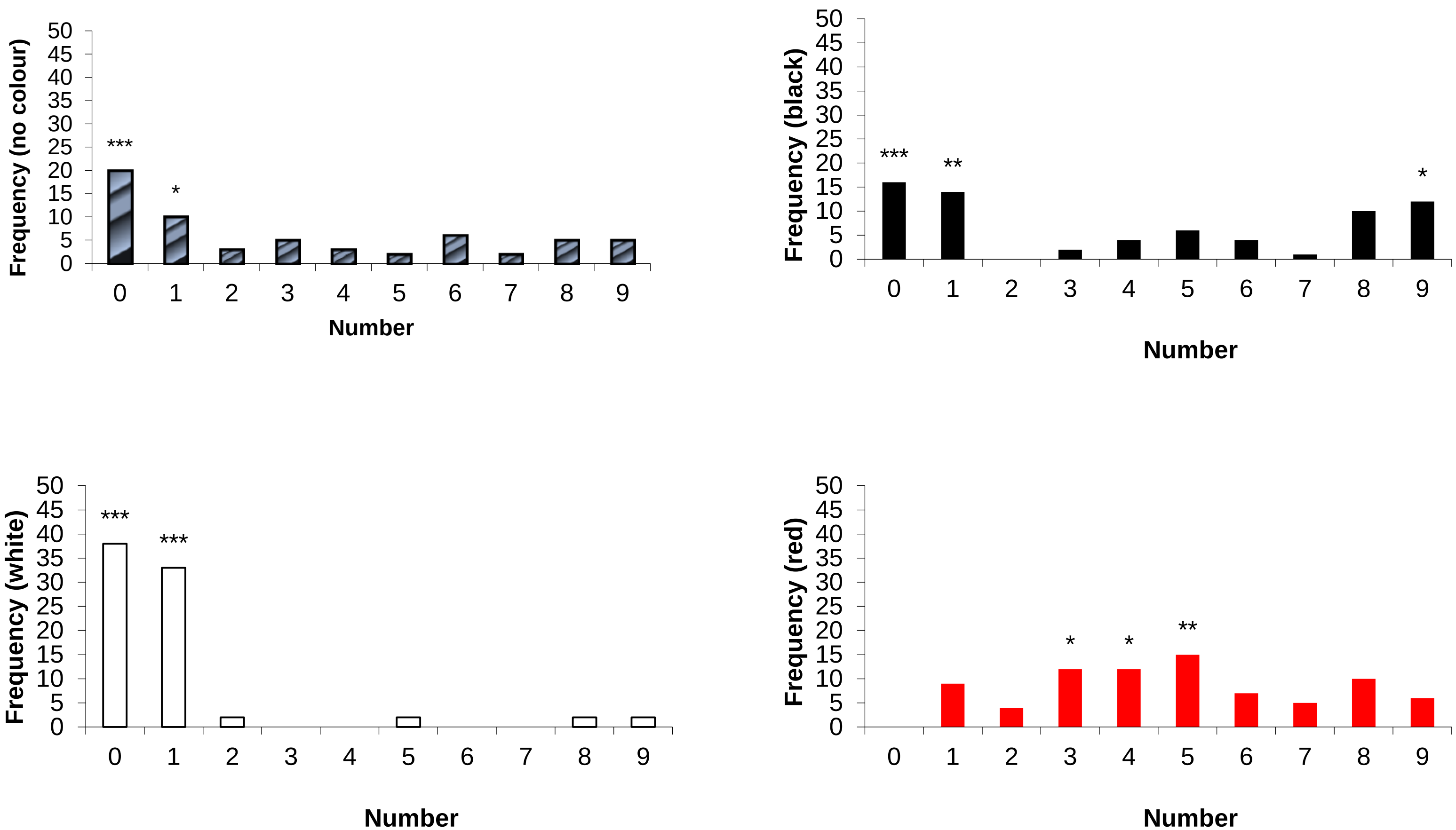
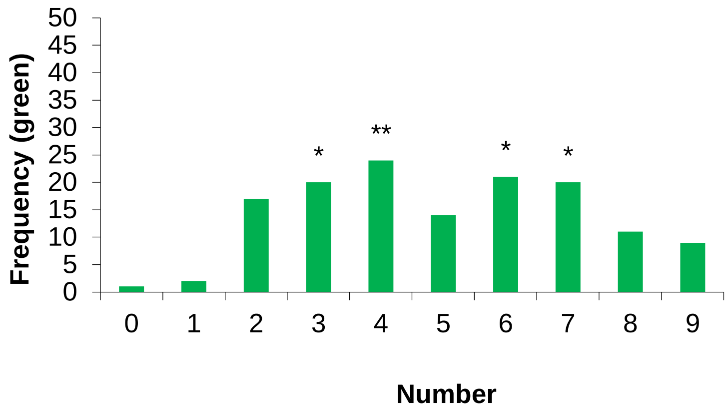
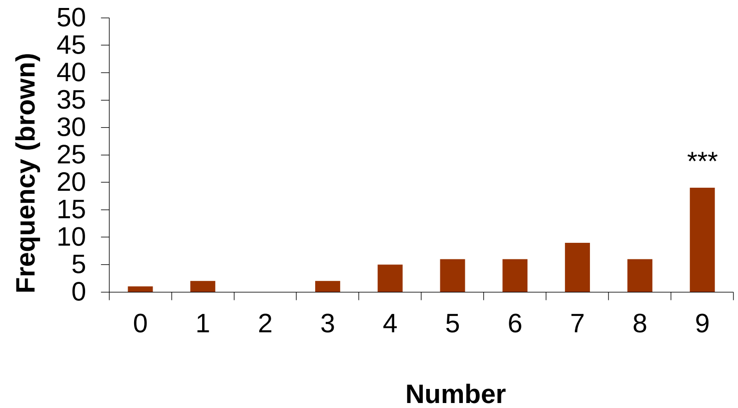
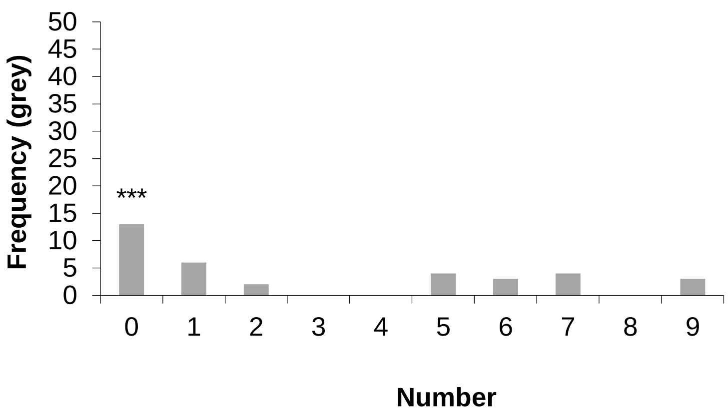
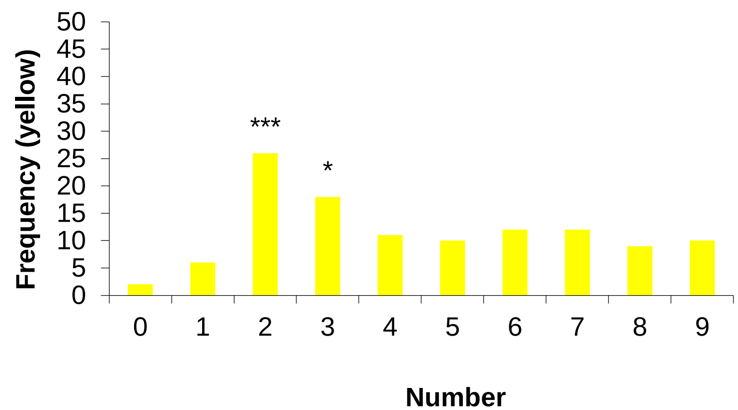


Figure 2: Frequency distribution of colour terms (eleven basic terms plus 'no colour') for numbers 0-9. Asterisks indicate significantly higher frequencies than predicted by chance (= .05, ** = .01, *** = .001).*


Frequency (green)
Number
50
45
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9
*
**
*
*


Frequency (brown)
Number
50
45
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9
***


Frequency (grey)
Number
50
45
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9
***


Frequency (yellow)
Number
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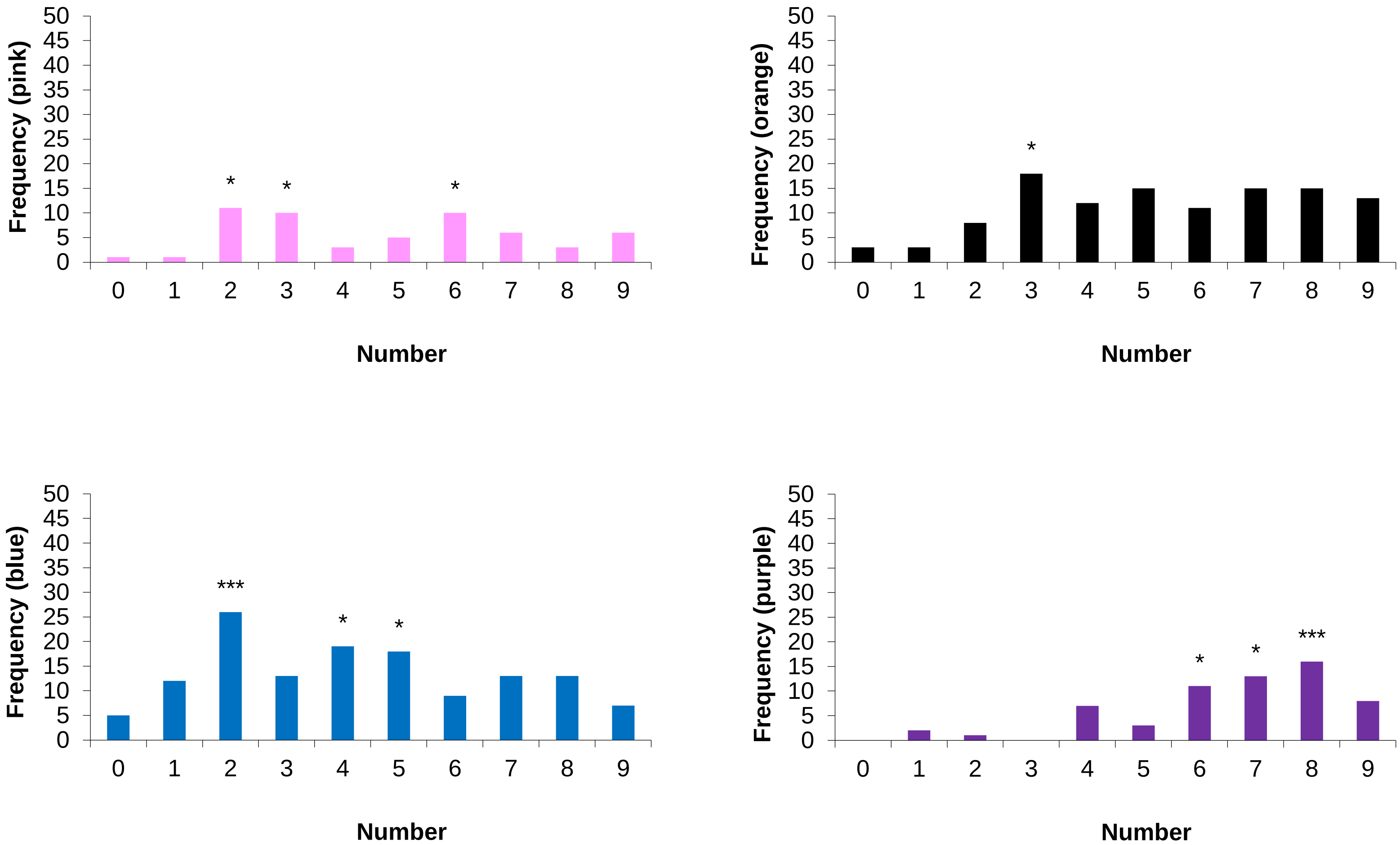
45
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9
***
*


Frequency (pink)
Frequency (orange)
Frequency (blue)
Frecquency (purple)
Number
0 1 2 3 4 5 6 7 8 9
0 5 10 15 20 25 30 35 40 45 50
*
***

Synaesthetes who took part in this experiment are moderately in agreement with the English-speaking synaesthetes who took part in Simner et al. (2005) in terms of common inducer-concurrent pairings (e.g. Q is purple in both, but H is orange only in the current sample and R is green only in Simner and colleagues' sample). Though Rich et al. (2005) used a different method to find significant associations (percentage of a letter in a particular colour that is more than 2 S.D. above the mean for that colour over all letters), one can still make a comparison with their study. As Barnett et al. (2008) did not examine letters as individual inducers, a comparison is not made with their study.

Of the 70 letters which are associated significantly more than expected with a particular colour (in all 3 experiments), 14 appear in all 3, 17 appear in both Simner et al. and our study, 20 in Simner et al. alone and 19 in ours alone (Table 1). Several of the letter-colour pairings appearing in all three studies have an obvious linguistic link: *B* is blue, *R* red, *P* pink, *V* purple (or violet) and *Y* yellow; *B* is also brown for both Simner et al. and the current sample, and *P* is purple in the current sample alone. In none of the studies is *W* white, *B* black, *G* grey, or *O* orange, linking to Spector and Maurer's (2008) study in which children who could not yet read looked in a white box for the letter *O* and a black box for the letter *X*. Spector and Maurer argued that this was indicative of colour-shape pairings rather than letter-shape pairings. As our synaesthetes also paired black and white with *O* and *X* (also for *I*, another simple shape), this endorses Spector and Maurer's hypothesis of a pre-literate form of shape-colour synaesthesia for simple shape letters and de-saturated colours which becomes part of a wider, literate, letter-colour synaesthesia as children learn to read.

Table 1: Significant letter-colour associations in Rich et al. (2005), Simner et al. (2005) and the current study.

Colour	**Significantly associated letters**			
	Rich et al., Simner et al. and current study	**Simner et al. and current study**	**Simner et al. only**	**Current study only**
Black	IXZ	O	T	Q
White	IO	-	U	-
Red	AR	MS	J	-
Green	-	EFG	HR	-
Brown	D	B	FGNM	VW
Grey	X	UY	LQ	VW
Yellow	Y	CES	H	LU
Pink	P	C	Q	JK
Orange	J	-	BGHKN	FW
Blue	B	TW	DP	CELN
Purple	V	JQ	-	KPRW

Because of the similarity of *0* and *1* to *O* and *I*, these two numbers may also provide a starting point for number-colour synaesthesia through shape-colour associations: *0* and *1* are significantly more likely to be black, white, grey or no colour than chance suggests, while no other numbers are likely to take on these colours. More generally, of the 26 current significant number-colour pairings, four also appear in Rich et al. (2005), but none appear in Rich et al. that do not appear in the current study. This is not as strongly in agreement with the current results as the Simner study with respect to letters, but the small number of significant pairings in the Rich et al. study may be due to the statistical method they used; the same study also showed only 13 significant letter-colour pairs compared to 49 in the current study and 48 in Simner et al. (2005).

Beyond these fairly obvious pairings, there are other associations which are not so readily explained (e.g. red *M*, purple *8*). Simner et al. (2005) suggested that there may be correlations between ways in which colours can be ordered and ways in which graphemes can be ordered, so that more commonly used letters or numbers are assigned more commonly used colours. The Berlin-Kay typology (the order in which colours enter languages) has been discussed in the introduction, but Simner et al. also looked at colour name frequency in English (according to the British National Corpus, or BNC) and ease-of-generation (Battig-Montague typology). As in Simner et al., significant letter-colour and number-colour pairings were noted and then rank positions of letter position, letter frequency and number position/frequency (the latter two have exactly the same order) were correlated with rank positions of the colour name in each of the three typologies above. For example, the significant association of A with red was coded as A = alphabetical position 1, red = Berlin and Kay position 3. The same coding was used for all other significant associations, and then this data was used to calculate the correlation of alphabetical position with each colour order norm. These results are presented in Table 2.

Table 2: Two-tailed Spearman's ρ values for correlations between sequence and typology measures. Asterisks indicate significance levels (< .05, ** < .01, *** < .001).*

Sequence measure	**Typology**		
	Berlin-Kay	**BNC**	**Battig-Montague**
Number position/frequency	.29	.31	-.09
Alphabetical position	.03	-.09	.31*
Letter frequency	.34*	.11	.40**

Unlike Shanon's (1982) results, these data show no significant correlation between the Berlin-Kay typology and number position; the BNC and Battig-Montague orders did not correlate with number position either. This may be due to the slightly different analysis used by Shanon, in which he took the mean value of numbers that each colour was assigned to (e.g. two people assigned grey to 8 and two assigned it to 9, giving a mean of 8.50) and correlated with Berlin-Kay's rank positions for colours. A reanalysis of the data using Shanon's method also results in a non-significant correlation ($\rho = .44$; $p = .18$).

Our results are partly in agreement with Simner et al. (2005) as there is no significant correlation of alphabetical position, but a significant positive correlation of letter frequency, with the Berlin-Kay ordering. There was also no significant correlation between alphabetical position and Berlin-Kay ordering in Simner et al.'s sample, but the remainder of our results do not agree with their findings (a positive correlation between letter frequency and colour name frequency and no correlations between the Battig-Montague order and alphabetical position or letter frequency). Possibly, this is the result of including non-native speakers of English in the sample. To counter this possibility, all synaesthetes not known to be native English speakers (N = 29) were removed from the letter-colour sample and two analyses recalculated (binomial distributions to find significantly higher than chance letter-colour pairings and then the Spearman correlations for alphabetical position and letter frequency, as shown in Table 1). The pattern of results does not greatly change as a result of this alteration – all correlations are in the same direction as before and all remain significant or non-significant as before.

3.2 Hue, saturation and luminance

To test whether there are direct correlations between physical characteristics of colour and letters or numbers, average saturation and luminance were calculated (hue was excluded as it is a circular variable) for each grapheme and then correlated these means with letter and number ranks using Spearman's correlations. Results are shown in Table 3 and Figures 3 and 4.

Table 3: Two-tailed Spearman's ρ values for correlations between sequence and colour measures. Asterisks indicate significance levels (< .05, ** < .01, *** < .001).*

Sequence measure	**Colour measure**	
	Saturation	**Luminance**
Number position/frequency (0 and 1 included)[17]	.01	-.93**
Alphabetical position	-.53**	-.24
Letter frequency	-.46*	-.09

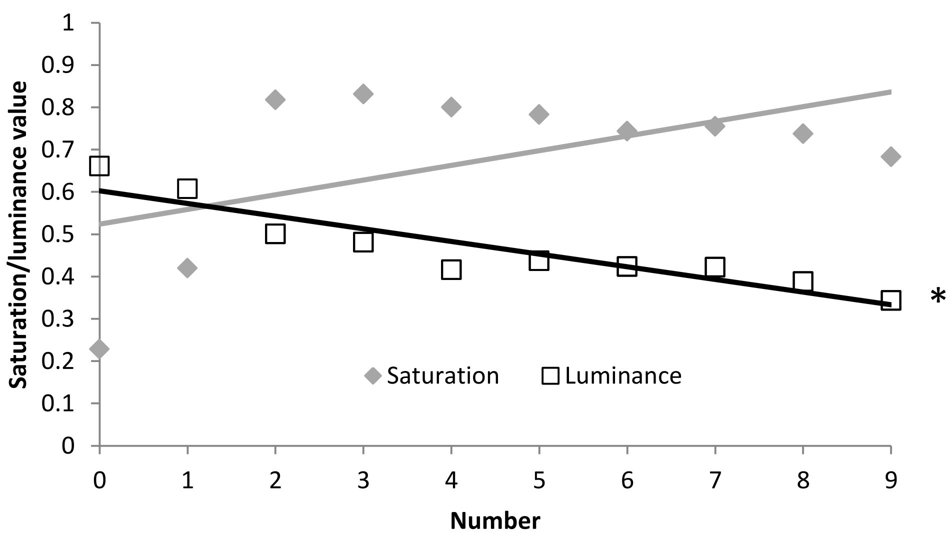


Figure 3: Grand mean luminance and saturation values for each number. Asterisk indicates significant correlation.

[17] Beeli et al. (2007) removed 0 and 1 from their data analysis and found a significant negative correlation between saturation and luminance by doing so. Repeating their analysis here gains the same result (r = -.95, p < .01)

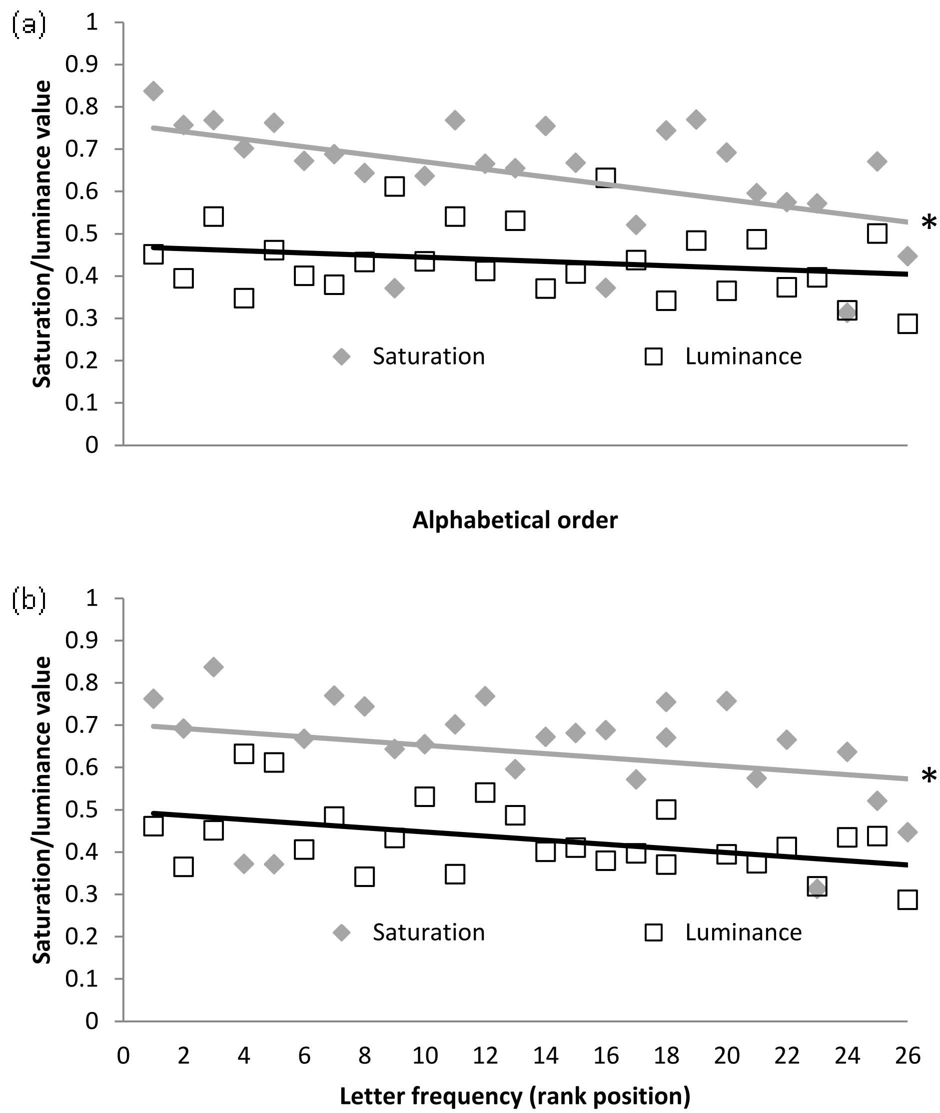


Figure 4: Grand mean luminance and saturation values for each letter, by (a) alphabetical order and (b) letter frequency. Asterisks indicate significant correlations between saturation/luminance measures and rank positions.

Our results for numbers are similar to those of Cohen Kadosh et al. (2007) for luminance and saturation. For letters, alphabetical position and letter frequency correlate strongly and negatively with saturation but are not significantly correlated with luminance. The frequency-saturation correlation is in the opposite direction to the relationship found by Beeli et al; in the current data, however, there is no correlation between frequency and luminance (though Smilek et al., 2007, found a weak positive correlation). Discrepancies with Beeli et al. may be due to language – letter frequencies in German and English are different – but Smilek et al. used letter frequencies in English. Smilek et al., therefore, may have had different proportions of native speakers of different languages from the current sample, which might have affected linguistically mediated inducer-concurrent relationships (e.g. as Simner et al., 2005, point out, for German synaesthetes the *P*-purple pair is replaced by *L*-lila).

Simner and Ward (2008) argued that past findings demonstrating a link between saturation and alphabetical position in fact resulted from the tendency of less frequent (and less saturated) colour terms to be paired with less frequent letters. Though this may not be the case for our sample, given the lack of correlation between letter frequency and colour name frequency, it is still a question worth addressing and extending to other significant correlations in Table 2. This possibility was assessed by splitting the data by hue and recalculating the saturation-letter position correlation, taking a mean saturation value for each number within a hue and correlating it with the rank position of the letter. This was then repeated with the luminance-magnitude correlation. Black and white were excluded as luminance and saturation do not vary widely for these colours[18]. A summary of these correlations is presented in Tables 4 and 5 and Figures 5 and 6.

[18] We also excluded grey from saturation, but not luminance, analyses.

Table 4: One-tailed Spearman's ρ values for correlations of saturation values, split by colour, with letter position and letter frequency. Asterisks indicate significance levels (< .05, ** < .01, *** < .001).*

Colour	Letter position	Letter frequency
Red	-.17**	-.18**
Green	-.09*	-.13**
Brown	.02	.00
Yellow	-.08	-.16**
Pink	-.15	-.11
Orange	.03	.02
Blue	-.10*	-.09
Purple	-.04	-.05

Table 5: Two-tailed Spearman's ρ values for correlations of luminance values, split by colour, with magnitude. Asterisks indicate significance levels (< .05, ** < .01, *** < .001).*

Colour	Luminance (0-9)
Red	-.14
Green	-.26**
Brown	-.40**
Grey	-.77*
Yellow	-.12
Pink	-.13
Orange	-.05
Blue	-.25**
Purple	-.13

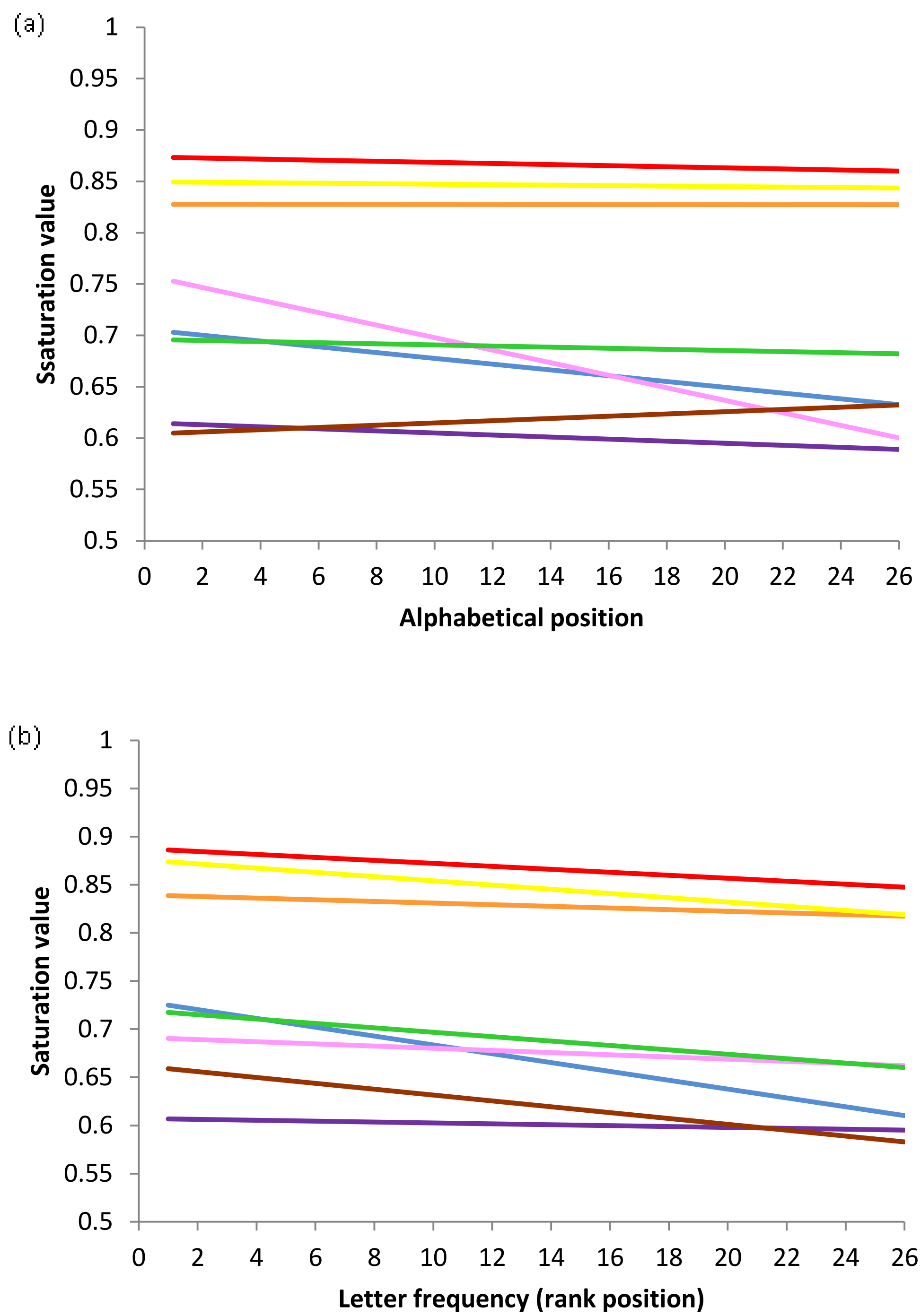


Figure 5: Mean saturation values for each letter (split by colour), presented by letter position (a) and letter frequency (b).

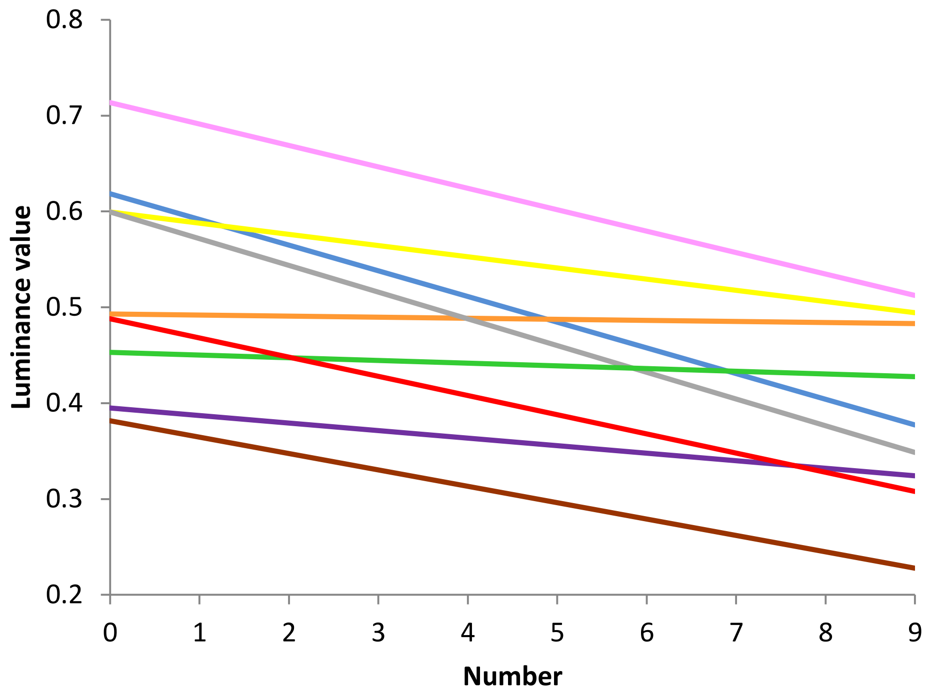


Figure 6: Mean luminance slopes for each number (split by colour).

For most colours, correlations between letter position and saturation at least trend in the same direction as the overall correlation; the same is true of letter frequency and saturation. However, the only significant correlations between position and saturation are in the red, green and blue domains, while for frequency and saturation only red, green and yellow are significant. For numbers and luminance, the significance of these correlations is only a little more widespread.

At this point, it is tempting to dismiss the correlations within colours and claim that the overall correlations between sequence measures and colour measures are due solely to the different average luminance and saturation values of the varying colours. However, this may not be the case. The range of saturation in each colour for the letter data can be anywhere from .55 (red and orange) to .99 (brown). In this data set, red, green and yellow (the colours in which significant correlations exist between saturation and letter frequency) are the least varying colours, along with orange. Blue (for which letter position correlates significantly with saturation) is the third most variable colour, after brown and purple. This may suggest illusory correlations in the letter data.

Turning to numbers, luminance range varies from .29 (red) to .76 (blue). Here, the four colours which vary most (blue, grey, green and brown) are also the only colours in which significant correlations between luminance and magnitude are seen.

4 Discussion

The present results replicate previous research (e.g. Shanon, 1982; Simner et al., 2005) in demonstrating that inducer-concurrent pairings in grapheme-colour synaesthesia are not random.

Number-colour correlations appear to be strongly influenced by links between magnitude, saturation and luminance – the larger the number, the less luminant (see discussion of *O* and *X* below, where shape-colour correspondences are discussed). However, there were no correlations between number position and colour frequency, ease-of-generation or order of entry into languages. The latter finding is inconsistent with past research (e.g. Shanon, 1982) but could be explained by the methodology used in each of the two studies. Whereas Shanon asked synaesthetes to provide their own colour labels for each number, we asked synaesthetes to provide RGB values which were then categorised by naïve raters. There are several implications to this change in methodology. Firstly, since the synaesthetes in the current study used a colour palette rather than colour labels, a greater and more precise range of colour choices was available to them, allowing finer-grained distinctions between colours that are perceived to be correct and colours that are perceived to be close to correct. On occasion these distinctions may have crossed colour boundaries (e.g. from a greenish blue to a bluish green). Secondly, since synaesthetes did not provide colour labels, the links they may make between numbers/letters and colour in terms of linguistic frequency, ease-of-generation, and order of entry may have been diminished or altered. Thirdly, it is possible that the raters did not choose the same labels as the synaesthetes themselves might have chosen. This is particularly likely to be the case where synaesthetes are not native speakers of English, because the perceived boundaries between colours are different for speakers of different languages (see, for example, Winawer, Witthoft, Frank, Wu, Wade, & Boroditsky, 2007). This could have resulted in a synaesthete's bluish green being interpreted by a rater as a greenish blue, or another similar change.

Letter-colour synaesthesia shows a strong pattern of linguistic influences (e.g. yellow-*Y*); additionally, some letter-colour pairs agree with the results of Spector and Maurer (2008), where colour was found to influence a forced-choice task when searching for letters (white *O* and black *X*), indicating that some grapheme-colour correspondences may start out as pre-literate shape-colour associations, but the remainder cannot be easily classified on either of these bases. These remaining letter-colour pairings may be explained by significant positive correlations between letter frequency and the order in which colours enter languages (Berlin-Kay typology) and ease-of-generation (Battig-Montague), as well as a positive correlation between alphabetical position and ease-of-generation. There is also a strong negative correlation between alphabetical position and saturation, independent of a significant correlation between colour-term frequency and letter frequency (previously demonstrated by Simner & Ward, 2008).

To assess whether the relationship between physical properties of colour and order measures was direct or due to the fact that some colours are typically more luminant than others (e.g. yellow is generally more luminant than purple) or more saturated than others (e.g. pink is typically less saturated than red), the data was split by hue and correlations for letter-saturation and number-luminance were recalculated. Most individual hues were in agreement with the overall correlations, some significantly so. Among the letters, those colours which had least range in their saturation values tended to be those which produced significant luminance-frequency/position correlations; among the numbers, those colours which had most range in their luminance values were those which produced significant luminance-magnitude correlations.

Letter-colour synaesthesia may reflect a wider range of influences than has previously been acknowledged, and is certainly more of a mixture than number-colour synaesthesia, with its clear correlations between colour properties, colour names and number magnitude. This may partly be due to strong correlations between different ways of ordering numbers (e.g. magnitude, ordinality) – all the potential causes of inducer-concurrent pairings can line up in a way that is impossible for letters or any other semantic sequence.

Two potentially erroneous assumptions have been made in grapheme-colour synaesthesia research. The first is that researchers have not consistently distinguished between letter-colour and number-colour synaesthetes (e.g. Hubbard, Arman, Ramachandran, & Boynton, 2005; Jäncke, Beeli, Eulig, & Hanggi, 2009; Muggleton, Tsakanikos, Walsh, & Ward, 2007; Nikolić, Lichti, & Singer, 2007; Rouw & Scholte, 2010; Weiss & Fink, 2009). The second assumption is that letter-colour (or any other sequence-colour) synaesthesia can inform number-colour synaesthesia. Despite the outward similarity of numbers and letters, they represent quite different systems of symbols. Besner and Coltheart (1979) mention the distinction between the two systems (and two other types):

> "The principles by which visual symbols represent language are many and various; but they may be classified into four broad categories. The simplest, and historically the first to evolve, is the pictographic: the visual symbol is a picture of the word or idea. The ideographic principle resembles the pictographic in that a single visual symbol stands for a whole word or idea, but differs in that the relationship of symbol to word or idea

> is arbitrary rather than pictorial. A third principle is the syllabic: here the visual symbols stand not for whole words but for the syllables from which the spoken forms of words are composed. The fourth and final orthographic principle is the alphabetic: here orthographic symbols correspond to components of speech which are smaller than syllables – very roughly, each alphabetic symbol corresponds to a phoneme." (Besner & Coltheart, 1979).

Numbers, then, are ideographic symbols (though arguably the number 1 is actually pictorial), but letters are alphabetic symbols. This conceptual distinction may have a neurological correlate. At early stages in processing, numbers and letters seem to be coded for in similar ways (Perea, Duñabeitia, Pollatsek, & Carreiras, 2009). However, at some point these codes must split, as lesion studies (Anderson, Damasio, & Damasio, 1990; Starrfelt, 2007) have shown that despite damage to letter processing, number can be spared. Therefore, the usefulness of comparing number-colour and letter-colour synaesthesia depends on the location(s) of these synaesthesias. In terms of the neurological processes involved, early-stage synaesthesia means that numbers and letters can usefully be directly compared, but late-stage synaesthesia may mean this is not so useful.

This research supports previous findings of correlations between linguistic aspects of letters, numbers and colours and between sequence measures and physical characteristics of colour. It also provides novel evidence for the existence of relations between sequence ordering (through ordinality or linguistic frequency), saturation and luminance independent of hue. Together, these results provide evidence that numbers and letters should be considered as separate entities in synaesthesia research.

Paper 4

The influence of grapheme-colour synaesthesia on lexical and mathematical decisions

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Abstract

Past research on number-colour and letter-colour synaesthesia has shown evidence for bidirectionality (i.e. a colour can implicitly activate a grapheme as well as a grapheme explicitly activating a colour). The current study extends this research to assess whether incongruent colouring of a single operand in an addition (e.g. 4 + 2 = 6, where 2 may be in the colour of 3) or a single letter in a word (e.g. STAR, where T is in the colour of C) can influence synaesthetes' reaction times when categorising stimuli. While little evidence for bidirectionality was found, it is likely that this null result was due to aspects of the methodology such as task complexity and location of incongruent elements in the stimuli. These findings can therefore be used to inform future methodology for experiments on bidirectionality in number-colour and letter-colour synaesthesia.

1 Introduction

All humans make cross-modal associations in order to understand their world. For example, when we hear a dog barking, we can locate the source of the sound to an extent simply by using our ears, but may make a final decision based on visual recognition of a dog-like shape in the surroundings. This linking together of different sensory modalities, and different aspects of the same modalities, is known as binding. A small percentage of the population, however, goes beyond these links to bind together real sensory input with self-generated perceptions, so that sounds can cause the perception of colour (Mills, Boteler, & Larcombe, 2003), or seeing somebody else touched can cause the feeling of touch on one's own body (Blakemore, Bristow, Bird, Frith, & Ward, 2005). This neurological phenomenon is known as *synaesthesia*, from the Greek *syn* (together) and *aisthēsis* (sensation). It is characterized by its automaticity and consistency over time: for a synaesthete, the same sensory input, or inducer, will always cause the same illusory percept, or concurrent.

1.1 Stroop tests and bidirectionality

In the original Stroop test, Stroop (1935) asked participants to name the colours in which stimuli were printed. Two sets of stimuli were presented: square coloured blocks and incongruent colour words (e.g. 'red' printed in blue). The reactions times for the latter were slower. This test can be modified to test for the genuineness of number-colour or letter-colour synaesthesia, by comparing participants' reaction times to name the colour in which a stimulus is printed in congruent and incongruent colours (e.g. Mills, Boteler, & Oliver, 1999; Nikolić, Lichti, & Singer, 2007). Versions of this test have also been used to assess bidirectionality in synaesthesia.

Most synaesthetes report that they experience unidirectional synaesthesia; that is, while a number induces a colour, a colour does not induce a number. However, there may be implicit links from colour to number.

Johnson, Jepma, and de Jong (2007) reversed the usual Stroop test, asking participants to name digits presented in congruent or incongruent colours, and found that incongruently-coloured stimuli elicited slower reaction times than did congruently coloured stimuli. Gevers, Imbo, Cohen Kadosh, Fias, and Hartsuiker (2010) have extended this in a single case study on a synaesthete who perceives unique colours for numbers above 9 to show that it is possible to influence a decision as to whether a multiplication problem had the correct answer or not by altering the colour of the stimulus background to show the correct solution (e.g. the colour of 35 for 5 x 7 = 35), a table-related solution (e.g. the colour of 28 for 5 x 7 = 35), an unrelated solution (e.g. the colour of 31 for 5 x 7 = 35) or a neutral white.

Several other studies have shown that implicit bidirectionality effects exist in synaesthesia. Knoch, Gianotti, Mohr, and Brugger (2005) used a modified mental dice task, illustrating that when asked to randomly generate colours associated with the numbers 1-6 (i.e. imitating the rolls of a die), synaesthetes showed fewer repetitions of the same colour and more runs of colours belonging to consecutive numbers than would be expected by chance, the same behaviours seen when humans attempt random number generation. Control participants trained on the same number-colour associations did not show these behaviours when generating colours, indicating that the lack of repetitions and preponderance of runs were due to synaesthetic rather than semantic links from colour to number (see Berteletti, Hubbard, & Zorzi, 2010, for a discussion of 'pseudosynaesthetic' bidirectionality).

Cohen Kadosh et al. (2005) used a modification of the size incongruity paradigm, in which participants are asked to decide which of two numbers, mismatched in physical size, is numerically larger. If the physically larger number has the smaller magnitude, participants’ reaction times are slowed compared to stimuli where the physically larger number has the larger magnitude. In Cohen Kadosh and colleagues’ task, pairs of numbers were presented in colours congruent to their participants’ synaesthesia, in colours which amplified the numerical distance between the members of the pair (facilitation condition, e.g. 4 and 5 in the colours of 2 and 7), or which diminished the distance between the members of the pair (interference condition, equivalent to a magnitude-size mismatch in the original size incongruity paradigm, e.g. 2 and 7 in the colours of 4 and 5). Though the synaesthetes who took part in the experiment did not report explicit bidirectionality, the facilitation condition decreased reaction times, suggesting an influence of colour on number.

The above studies have concentrated solely on number-colour synaesthesia, but Meier and Rothen (2007; 2009) have shown that there may be bidirectional links between all graphemes and colours. They conditioned synaesthetes to expect a startling noise for a colour associated with a particular grapheme (but not the grapheme itself), then showed that skin conductance response, a measure of autonomic arousal, increased during both the startle trials and the trials in which the corresponding grapheme appeared. This effect did not appear in non-synaesthetes trained to associate letters with specific colours.

Bidirectionality effects have also been shown for letters alone. Weiss, Kalckert and Fink (2009) presented their German-speaking participants with a word-completion task in which strings of letters that could be turned into a low- or high-frequency word by adding one more letter – e.g. _atze could be turned into the low-frequency *Tatze* (paw) or the high-frequency *Katze* (cat). Usually, the high-frequency word is more likely to be chosen, but the authors increased synaesthetes' tendency to choose the low-frequency word by replacing the blank space in the string with a block of colour corresponding to the letter that would create a low-frequency word (e.g. _atze would be preceded by a block in the colour of *T*).

1.2 The current study

The two experiments of this study were designed to allow (a) further investigation into the effects of colour on mathematical operations and lexical decisions in synaesthesia and (b) a comparison of the relative extent of bidirectionality in number-colour and letter-colour synaesthesia.

In the mathematical task, we presented participants with addition problems in which the second operand was coloured congruently or incongruently with synaesthesia. The participants' task was to judge whether the question was correct or incorrect. Extending Mills, Metzger, Foster, Valentine-Gresko, and Ricketts (2009), we split the congruent condition into two: mathematically correct or mathematically incorrect. The incongruent condition was split into three: mathematically correct; mathematically incorrect, coloured so as to imply a correct answer (e.g. 2 + 3 = 7, with 3 in the colour of 5, hereafter shown as 2 + 35 = 7); and mathematically incorrect, coloured so as to imply an incorrect answer (e.g. 2 + 34 = 7) – see Table 1. Here, it was predicted that all participants would take longer on incorrect trials than on correct trials. Additionally, assuming that bidirectionality in number-colour synaesthesia exists, it was predicted that synaesthetes, but not controls, would show congruency effects on correct and incorrect trials, and that synaesthetes alone would take longer and make more errors in trials which were mathematically incorrect and incongruent (but the colouring implied a correct answer) than in trials which were mathematically incorrect and incongruent (but the colouring implied an incorrect answer).

In the lexical decision task, participants were presented with strings of letters that were either words (e.g. ZONE) or pseudo-words (e.g. SONE). The participants' task was to judge whether the string was a word or a non-word. There were two congruent and four incongruent conditions (see Table 2). In the congruent conditions, the stimulus could be either a word or a non-word. In the incongruent conditions, the stimulus could be a non-word coloured so as to make another non-word (e.g. SONE with S in the colour of J, hereafter S_JONE); a non-word coloured so as to make a word (e.g. S_CONE); a word coloured so as to make another word (e.g. C_ZONE); or a word coloured so as to make a non-word (e.g. Z_JONE). Matching the hypotheses from the mathematical task, we predicted that all participants would take longer in trials with non-words than in trials with words. Assuming that bidirectionality exists in letter-colour synaesthesia, we also predicted that synaesthetes alone would show congruency effects on word and non-word trials, and that synaesthetes alone would take longer and make more errors in incongruent trials where a non-word implied a word (and vice versa) than in trials where a non-word implied a non-word, or a word implied a word. Finally, it was predicted that controls would always take longer to categorise the lower-frequency word of a quartet than the higher-frequency word, but that synaesthetes would not show this effect in trials where a word is coloured so as to imply another word, due to bidirectionality effects.

2 Experiment 1

2.1 Methods

2.1.1 Participants

Twelve number-colour synaesthetes (11 female, *M* = 23.45 years, *S.D.* = 8.91, range = 19-48) were recruited from the Sussex-Edinburgh database of synaesthete participants. All had completed the synaesthesia battery at www.synesthete. org (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007) and achieved a consistency score of 1 or under and/or a Stroop test accuracy of 85% or over. Twelve controls (sex-matched and age-matched to within 5 years) who reported no number-colour associations, also took part.

2.1.2 Materials and procedure

Using E-Prime 2.0, participants were shown a white fixation cross on a grey background for 1000ms, followed by a mathematical equation that could be correct (e.g. 5 + 4 = 9) or incorrect (e.g. 5 + 4 = 11), until a response was made. Participants were asked to decide as quickly and accurately as possible whether the equation was correct or incorrect and to press the G or H key on a standard keyboard to indicate their response, using the left and right index fingers (the functions of G and H were counterbalanced across participants, with the constraint that synaesthete-control pairs always received the same instructions).

Equations were presented in black on a grey background, with the exception of the second operand, which was presented in a colour congruent or incongruent to the participant's (or their yoked synaesthete's) synaesthesia. Combined with the equation's mathematical correctness, this gave rise to five stimulus types, summarised in Table 1. This paradigm is similar to that used by Simner and Hubbard (2006) to investigate the interaction of grapheme-colour synaesthesia and ordinal linguistic personification.

Table 1: Stimulus types in Experiment 1. Subscript in equations did not appear in the stimulus but indicates the colours in which the second operands appeared.

Condition	Mathematical correctness	Congruency	Example
1	Correct	Congruent	$2 + 3_3 = 5$
2	Correct	Incongruent	$2 + 3_4 = 5$
3	Incorrect	Congruent	$2 + 4_4 = 5$
4	Incorrect (synaesthesia implies incorrect)	Incongruent	$2 + 4_6 = 5$
5	Incorrect (synaesthesia implies correct)	Incongruent	$2 + 4_3 = 5$

All operands were single digit; every equation from 2 + 3 = 5 to 8 + 9 = 17 was used, with the exception of tie sums (e.g. 2 + 2 = 4) and sums involving the number 1 (e.g. 9 + 1 = 10), which were restricted to the 10 practice trials at the beginning of the experiment, as these are liable to produce very swift answers that may not be affected by synaesthesia. 32 unique equations were used, presented in both ascending and descending order (e.g. 2 + 3 = 5 and 3 + 2 = 5 were both used), creating 64 equations in all. Each equation was presented five times, for a total of 320 trials in blocks of 40, in pseudorandom order with the constraint that the same equation did not appear twice in a row. Incongruently coloured operands were constrained to be within a numerical distance of 2 from the congruent colour (e.g. 5 could be presented in the colour of 3, 4, 6 or 7) and were never the congruent colour for the correct sum (e.g. $2 + 3_5 = 5$ was disallowed).

Three synaesthetes did not report colours for all numbers 1-9, so they and their controls were shown datasets that excluded any uncoloured number as the second operand. Trials where the colour of the missing number was required were also removed.

2.2 Results

One synaesthete was excluded from analysis as her mean reaction time was more than 3 *S.D.* above the mean of the rest of the synaesthete participants. A second synaesthete was excluded as she reported explicit bidirectionality. The yoked controls of these participants were also excluded. After the removal of errors and trials with reaction times (RTs) below 300ms, a recursive RT analysis was used to remove any data beyond 3 *S.D.* from the mean of each participant's RT.

Reaction time data from all conditions are summarised in Figure 1. To determine whether participants took longer on incorrect than correct trials, and whether there were congruency effects for synaesthetes, data from correct congruent, correct incongruent, incorrect congruent and incorrect incongruent conditions were subjected to a 2x2x2 (correctness by congruency by group) mixed ANOVA. There was a significant interaction of correctness, congruency and group ($F(1,18) = 7.74$, $p < .05$). Paired t-tests showed that this was due to a significant difference in reaction times for the controls, but not for the synaesthetes, between correct congruent (M = 1554ms) and incorrect congruent conditions (M = 1670ms, $t(9) = 4.10$, $p < .01$) and between incorrect incongruent (M = 1708ms) and correct incongruent (M = 1527ms, $t(9) = 3.78$, $p < .01$) conditions. All other main effects and interactions were not significant (ps > .09).

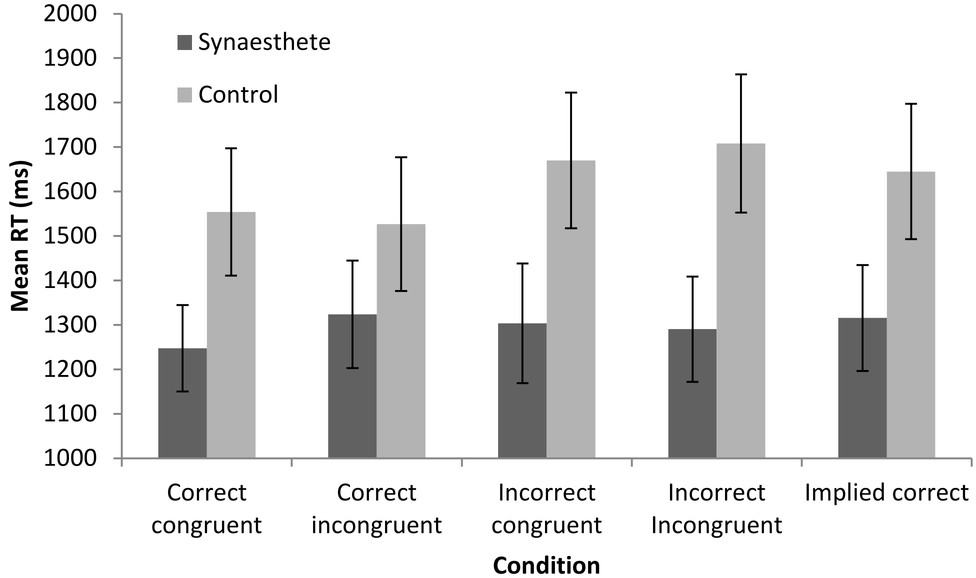

Figure 1: Mean reaction times of synaesthetes and controls in correct and congruent (2 + 3_3 = 5), correct and incongruent (2 + 3_4 = 5), incorrect and congruent (2 + 4_4 = 5), incorrect and incongruent (2 + 4_6 = 5) and implied correct (2 + 4_3 = 5) conditions. Error bars show ± 1 S.E.M.

Secondly, to assess whether incorrect trials in which the colour implied the correct result would take longer for synaesthetes than incorrect trials in which the colour implied another incorrect result, a 2x2 (colour implication by group) mixed ANOVA was conducted on the data from incongruent incorrect and implied correct conditions. There was a near-significant main effect of group ($F(1,18) = 3.72$, $p = .07$), caused by controls (M = 1676ms) taking longer to react than synaesthetes (M = 1303ms) and a significant interaction between colour implication and group ($F(1,18)$ = 8.50, $p < .01$). However, paired t-tests on colour implication in the synaesthete and control groups showed that this was not due to synaesthetes taking longer in the incorrect incongruent condition (M = 1290ms) than in the implied correct condition (M

= 1315ms, $t(9) = 1.23$; $p = .25$), but to controls taking longer in the incorrect incongruent condition (M = 1707ms) than in the implied correct condition (M = 1645ms, $t(9) = 2.84$; $p < .05$).

Error proportion data were subjected to the second analysis only, to test whether synaesthetes were more likely to make errors when synaesthesia and mathematical correctness are in conflict. A 2x2 (colour implication by group) mixed ANOVA produced no significant main effects or interactions (all ps > .57).

2.3 Discussion

The results of Experiment 1 indicate that participants are equally quick to categorise correct and incorrect equations. However, there is a significant interaction between correctness, congruency and group, caused by controls taking longer to categorise incorrect stimuli regardless of congruency, an effect which did not occur in the synaesthete group. This result, along with the near-significant smaller reaction time in synaesthetes compared to controls, is likely to be because the synaesthete group is faster at rejecting incorrect answers than the control group. As synaesthetes made no more errors than controls, this is not due to a speed-accuracy tradeoff. Since we did not control for mathematical ability, synaesthetes could simply be quicker mathematicians than controls (i.e. they do not need to go through a ‘check’ stage when rejecting an incorrect answer). It is unclear whether this is simply a coincidence, due to number-colour synaesthesia, or the result of a high proportion of number-space synaesthetes in the control group. The last is a possibility since number-space synaesthesia, the perception of numbers as belonging to certain spatial locations, is known to lead to slow addition (Ward, Sagiv, & Butterworth, 2009), and participants were not screened for number forms. However, number forms are much more common in groups whose members have another kind of synaesthesia (Sagiv, Simner, Collins, Butterworth, & Ward, 2006), meaning that the number-colour synaesthetes who took part in this experiment were in fact more likely to show the pattern of responses that controls did.

Controls alone showed a significantly longer reaction time for the implied-incorrect condition than for the implied-correct condition. This goes against the hypothesis in two ways: it occurs in the wrong group, and if it had occurred in the synaesthete group one would expect a longer reaction time in the incorrect-implied correct condition because of the conflict between synaesthesia and mathematical correctness. Thus, it is likely to be a Type I error.

3 Experiment 2

3.1 Methods

3.1.1 Participants

Ten number-colour synaesthetes (8 female, *M* = 23.33 years, *S.D.* = 7.91) were recruited from the Sussex-Edinburgh database of synaesthete participants. All had completed the synaesthesia battery at www.synesthete.org (Eagleman et al., 2007) and achieved a consistency score of 1 or under and/or a Stroop test accuracy of 85% or over. Ten controls (sex-matched and age-matched to within 5 years), who reported no number-colour associations, also took part. All participants were native speakers of English. Fourteen participants (7 synaesthetes and their yoked controls) also took part in Experiment 1; to avoid practice effects, the order of tasks was counterbalanced among participants.

3.1.2 Materials and procedure

Using E-Prime 2.0, participants were shown a white fixation cross on a grey background for 1000ms, followed by a string of four upper-case letters that could be a word (e.g. CAKE) or a pseudo-word (e.g. CADE), until a response was made. Participants were asked to decide as quickly and accurately as possible whether the string was a word or non-word and to press the G or H key on a standard keyboard to indicate their response using the left and right index fingers (the functions of G and H were counterbalanced across participants, with the constraint that synaesthete-control pairs always received the same instructions)

Letter strings were presented in black on a grey background, with the exception of one critical letter, which was presented in a colour congruent or incongruent to the participant's (or their yoked synaesthete's) synaesthesia. Combined with the status of the stimulus as a word or non-word, this gave rise to six stimulus types, summarised in Table 2. A full list of stimuli can be found in Appendix A.

Table 2: Stimulus types in Experiment 2. Subscript in letter strings did not appear in the stimulus but indicates the colour in which the second operand appeared.

Stimulus	Word/non-word	Congruency	Example
1	Word	Congruent	CH_HIN
2	Word (synaesthesia implies different word)	Incongruent	CH_OIN
3	Non-word	Congruent	CL_LIN
4	Non-word (synaesthesia implies different non-word)	Incongruent	CL_RIN
5	Non-word (synaesthesia implies word)	Incongruent	CL_HIN
6	Word (synaesthesia implies non-word)	Incongruent	CH_LIN

24 quartets of words and non-words differing by one letter (e.g. CHIN, COIN, CLIN, CRIN) were used. Six quartets differed on the first letter, six on the second letter, and so on. For each stimulus type, either of the words or non-words could be presented, so, for example, CH_OIN appeared as often as CO_HIN. Each stimulus type appeared once in each of these versions, creating 12 trials per quartet, 288 trials in total, presented in blocks of 36. Stimulus order was pseudorandom with the constraint that a string from the same quartet could not appear twice in a row. Word frequency and neighbourhood size were determined using the English Lexicon Project (Balota et al., 2007). Neighbourhood size did not differ significantly between the word and non-word groups ($t(94) = .83$, $p = .41$).

Four synaesthetes did not report colours for all letters, so they and their controls were shown datasets that did not include letters without colours as the critical letter. Trials that would have required the colour of the missing letter were also removed.

3.2 Results

One synaesthete was excluded from analysis as her mean reaction time was more than 3 S.D. above the mean of the rest of the participants; her yoked control was also excluded. After the removal of errors and trials with RTs below 300ms, a recursive RT analysis was used to remove any data beyond 3 *S.D.* from the mean of each participant's RT.

Reaction time data from all conditions are summarised in Figure 2. To determine whether participants took longer on non-word than word trials, and whether there were congruency effects for synaesthetes, data from conditions 1, 2, 3 and 4 were subjected to a 2x2x2 (word/non-word by congruency by group) mixed ANOVA. While words (M = 643ms) were categorised significantly faster than non-words (M = 688ms; $F(1,16) = 14.08$, $p < .01$), there were no other significant main effects or interactions (all ps > .13).

In letter- colour synaesthetes, words often acquire their dominant colour from the first letter or stressed syllable (Simner, Glover, & Mowat, 2006), so it is likely there are several cases where the coloured letter is not the one which has the most effect on the word as a whole. Therefore, the data were split into four groups according to the position of the coloured letter in the letter string and the above analysis was repeated for each position.

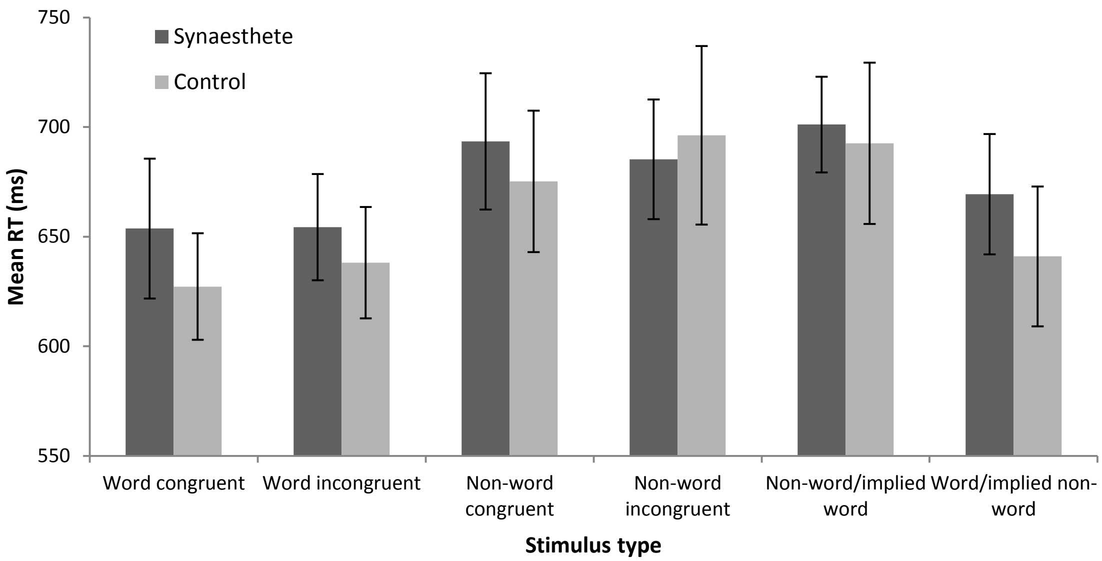

Figure 2: Mean reaction times of synaesthetes and controls in word congruent (CH_HIN), word incongruent (CH_OIN), non-word congruent (CL_LIN), non-word incongruent (CL_RIN), non-word/implied word (CL_HIN) and word/implied non-word (CH_LIN) conditions. Error bars show ± 1 S.E.M.

For trials in which the first letter was coloured, words were categorised significantly faster (M = 642ms) than non-words (M = 709ms; $F(1, 16) = 21.34$, $p < .001$). The same pattern was seen in trials in which the second letter was coloured (word M = 634ms; non-word M = 703ms; $F(1, 16) = 18.94$, $p < .001$) in addition to an effect of congruency (congruent M = 655ms; incongruent M = 683ms; $F(1, 16) = 13.29$, $p < .01$). No other main effects or interactions were significant for any position of the coloured letter.

To assess whether non-word trials in which the colour implied a word/word trials in which the colour implied a non-word (colour implication mismatch) would take longer for synaesthetes than non-word trials in which the colour implied another non-word/word trials in which the colour implied another word (colour implication match), a 2x2x2 (word/non-word by colour implication match or mismatch by group) mixed ANOVA was conducted on the data from conditions 2, 4, 5 and 6. Again, words (M = 650ms) were categorised faster than non-words (M = 693ms, $F(1,16) = 17.89$, $p < .001$). There were no other significant main effects or interactions (all *p*s > .11). However, there was a trend towards an interaction between colour implication and group ($F(1,16) = 2.85$, $p = .11$), caused by synaesthetes, but not controls, taking longer in trials which featured a colour implication mismatch (synaesthete M = 685ms, control M = 667ms) than in those which featured a colour implication match (synaesthete M = 670ms, control M = 667ms).

Again, data were split in by the position of the coloured letter and the analysis repeated. When the first letter was coloured, words were categorized significantly faster (M = 647ms) than non-words (M = 710ms; $F(1, 16) = 28.82$, $p < .001$). This pattern persisted for the second letter (word M = 652ms; non-word M = 698ms; $F(1, 16) = 11.45$, $p < .01$) and the third letter (word M = 646ms, non-word M = 689ms; $F(1, 16) = 9.45$, $p < .01$). When the third letter was coloured, there was also a main effect of colour implication, with matched words (M = 659ms) being categorised more quickly than mismatched words (M = 676; $F(1, 16) = 5.35$, $p < .05$).

Finally, to test whether controls alone took longer to categorise lower-frequency words than higher-frequency words, while synaesthetes did not show this effect, data were taken from condition 2 (word incongruent, CH_OIN) alone. For example, in the quartet STAR-SCAR-SHAR-SMAR, STAR is the more frequently used word and SCAR the less frequently used word. In condition 2, the participant would see either SC_TAR (low-frequency word coloured as a high-frequency word) or ST_CAR (high-frequency word coloured as a low-frequency word). Using a 2x2 (frequency of written word by group) mixed ANOVA, the mean reaction times for high-frequency and low-frequency words in synaesthete and control groups were compared. No significant main effects or interactions were found (all *p*s > .45). Since even the control group showed no difference in reaction time between low- and high-frequency words, this result is likely to be at least partly due to insufficient differences in frequency between words in each pair.

Dividing the data from condition 2 by position of coloured letter and repeating the ANOVA garnered a significant effect of frequency when the third letter was coloured ($F(1, 16) = 5.65$, $p < .05$) due to high-frequency words being categorised more slowly (M = 661ms) than low-frequency words (M = 618ms). No other significant main effects or interactions were found.

Error proportion data (Figure 3) were subjected to the 2x2x2 (word/non-word by colour implication by group) mixed ANOVA, revealing only a significant main effect of word/non-word ($F(1,16) = 7.56$, $p < .01$), as participants had made more errors in the word condition (M = .014) than in the non-word condition (M = .009).

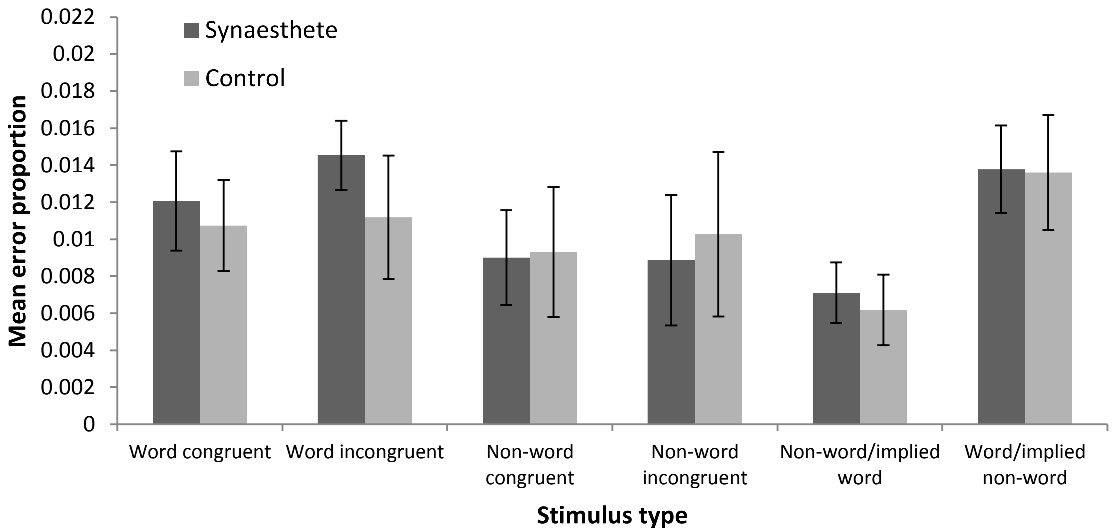

Figure 3: Error proportions of synaesthetes and controls in word congruent (CH_HIN), word incongruent (CH_OIN), non-word congruent (CL_LIN), non-word incongruent (CL_RIN), non-word/implied word (CL_HIN) and word/implied non-word (CH_LIN) conditions. Error bars show ± 1 S.E.M.

Splitting the data by the position of the coloured letter showed that when the second letter was coloured, mismatched (i.e. word implying non-word/non-word implying word) strings were associated with a lower error proportion (M = .004) than matched (i.e. word implying another word/non-word implying another non-word) strings (M = .011; $F(1, 16) = 4.75$, $p < .05$). The same pattern was seen for strings in which the third letter was coloured (mismatched M = .005; matched M = .008; $F(1, 16) = 5.03$, $p < .05$). However, when the coloured letter was in the fourth position, the reverse result was seen (mismatched M = .015; matched M = .010; $F(1, 16) = 6.40$, $p < .05$). Participants also made a higher proportion of errors on words than on non-words when the third letter was coloured (word M = .009; non-word M = .004; $F(1, 16) = 6.86$, $p < .05$) and when the fourth letter was coloured (word M = .019; non-word M =

.007; $F(1, 16) = 6.40$, $p < .05$). No other significant main effects or interactions were found.

3.3 Discussion

In Experiment 2, it was predicted that participants would have longer reaction times to non-words than to words, which proved to be the case; participants also made more errors in the word than the non-word condition, perhaps indicating a general cautiousness in responding. However, there was little indication of bidirectionality in the synaesthete group. A non-significant trend for synaesthetes to take longer to categorise colour implication mismatches than colour implication matches was not seen in the control group. The reasons behind these findings are assessed in the General Discussion.

When data were split into categories based on which letter in the string was coloured, it was found that some letters played a more important role than others. Letter 1 or 2 (and less strongly, letter 3) being coloured results in words being categorised more quickly than non-words, and congruent words are categorised more quickly than incongruent words only when letter 2 is coloured. Letter 3 being coloured also means that high-frequency words are categorised more slowly than low-frequency words and that strings which are matched (e.g. a non-word implying another non-word) are categorised more quickly than strings which are mismatched (e.g. a non-word implying a word). Letter 3 or 4 being coloured results in a higher error rate for words than non-words, and letter 4 alone being coloured means that there are more errors in the mismatch conditions than in the match conditions (this reverses when letter 2 or 3 is coloured). None of these findings show any indication of a difference between the synaesthete and control groups, suggesting that they are the result of a shared process of reading in both groups. Therefore, it seems likely that the colour of letters affects controls' reaction times as well as synaesthetes', but it is unclear whether this is the result of specific letter-colour combinations or simply a particular letter taking on a (surprising) colour when other letters do not.

4 General Discussion

The current results provide little support for bidirectionality in number-colour and letter-colour synaesthesia, going against several prior studies (Cohen Kadosh & Henik, 2006b; Cohen Kadosh et al., 2005; Gevers et al., 2010; Johnson et al., 2007; Knoch et al., 2005; Weiss et al., 2009). It would be fairly easy to dismiss claims of implicit bidirectionality as an interesting, but rare, phenomenon if only the first three studies were considered, as all had only one or two synaesthetic participants. However, the studies by Johnson et al. and Weiss et al. involved 10 synaesthetes, and the Knoch et al. study 20. Comparing the methodologies of these studies with the current experiments may shed some light on the reason for the conflicting evidence.

Johnson et al (2007) and Knoch et al. (2005) both asked their participants to complete fairly simple tasks – colour naming of digit stimuli, and random generation of colours, respectively. The current experiment's demands were greater, as more than one number had to be attended to and manipulated in order to respond correctly to the stimulus. It may be that the demands of the task, and the marginal superiority of the synaesthetes at dismissing incorrect answers, obscured any bidirectionality effects. However, given the similarity of the current experiment to Gevers et al. (2010), which did produce bidirectionality effects, there is evidently another layer to the problem. The major difference between Gevers et al. and the current study is to do with the type of mathematics involved (multiplication vs. addition). Multiplication and addition are postulated to involve separate processes (Koshmider & Ashcraft, 1991): multiplication usually involves recall since it is learned by rote (i.e. using the times table), while addition is usually applied from abstract principles case-by-case. These different processes may interact with synaesthesia in different ways. Alternatively, the current study is the only experiment we know of that has involved manipulation of an operand rather than the solution (compare Dixon, Smilek, Cudahy, & Merikle, 2000; Gevers et al., 2010; Jansari, Spiller, & Redfern, 2006). Potentially, the solution of a mathematical problem has a stronger mental representation than the operands, in turn creating greater interference with any bidirectionality.

Weiss et al. (2009) have previously shown bidirectionality in another letter-colour task in which synaesthetes added an initial letter to letter strings to create a word. This raises a problem – does bidirectionality exist or not in letter-colour synaesthesia? As in Experiment 1, our task is more complex than the Weiss et al. task, as the colour presented takes the form of a letter rather than a block. This is likely to be the most important difference between the two studies: as the letter is absent in the Weiss et al. task, the colour becomes important. However, when a colour was presented in our study, the fact that it was in the shape of a letter made it less relevant to the completion of the task. In addition, participants were swifter in our task than they were required to be by the Weiss et al. task. Though we did not set a time limit for responding, participants were encouraged to answer as quickly as possible, resulting in reaction times of approximately 700ms. By contrast, Weiss et al. gave participants 8000ms to provide a word that completed the letter string, allowing more time for bidirectionality effects to arise. A final difference in the two studies is that Weiss et al. only allowed the letter to be added at the beginning of the string, while in the current study the coloured letter could appear at any point in the string.

In conclusion, the current study shows very little evidence of bidirectionality in either number-colour or letter-colour synaesthesia, but this lack could be due to several other attributes of the experimental procedures used. Therefore, the current methodologies can be used to mark an 'outer limit' of bidirectionality in synaesthesia in terms of task difficulty and location within a sum or a word of an incongruent stimulus. In the future, tasks intermediate in complexity between the current task and, for example, the mental dice task of Knoch et al. (2005) can be used to ascertain how far bidirectionality does extend. Similarly, systematic manipulation of the incongruent element in a stimulus can be used to determine which aspects of lexical and mathematical cognition are most important in synaesthesia.

Paper 5

The mental representation of number: insights from number-colour synaesthesia

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Abstract

Number-colour synaesthesia is a neurological condition in which seeing numbers gives rise to perceptions of colour. The debate as to whether these perceptions are the result of physical or conceptual aspects of number may be linked to ‘leakage’ of synaesthetic colours across different representations of number. Number-colour synaesthetes were presented with two Stroop-type tasks. In the first, based on Nikolić, Lichti and Singer’s (2007) opponent-colour task, synaesthetes were asked to name the colour of numbers presented in congruent, opponent or independent colours (the latter two at 180° and 90° respectively on the colour wheel, in relation to the congruent colour). No Stroop effect was found. In the second, a classic Stroop-type task, participants were asked to name the colour of numbers presented in various formats in their own colour or the colour of another number (e.g. 4 presented in the colour of 5). Congruency effects existed in both the number-word condition and the digit condition, and there was also an effect of priming in the digit condition. Implications for synaesthesia research and models of numerical cognition are discussed.

1 Introduction

In the Western world, the most common way of representing number is to use the digits, or Arabic numerals, 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9 (Dehaene, 1997). However, there are many other symbols that can be used, such as Roman numerals (I, II, II, IV, etc.), number-words (one, two, three, etc.) and the dot patterns commonly seen on dice. While it is possible to use these other symbols for the purposes of calculation, the quickest way to calculate with numbers is to use digits (Zhang & Norman, 1995), probably because digits access the mental representation of number more easily than other forms of number (Fias, 2001; Fias, Reynvoet, & Brysbaert, 2001). It has been suggested by Moyer and Landauer (1967) that digits are automatically converted to analogue magnitudes that can be compared against each other in a manner similar to physical properties such as length. Dehaene (1992) has suggested that for those whose written language runs left-to-right this representation takes the form of a left-to-right mental number line (MNL).

The mental representation of number has two distinct effects on number comparison: the distance effect and the size effect. The distance effect was first noted by Moyer and Landauer (1967), who found that participants took longer to decide which of two simultaneously presented, non-equal numbers was larger when they were numerically close than when they were numerically distant. The distance effect has been replicated by Parkman (1971), who was also the first to document the size effect – that the time to decide which of two numbers is larger also increases with the magnitude of the smallest number presented, and to a lesser extent with the sum of the two numbers presented. Both these effects are reliably present in number comparison tasks (see Brysbaert, 1995, for a summary). Other representations of number also show distance and size effects, but reaction times are slower, indicating slower access to the MNL (Buckley & Gillman, 1974; Dehaene & Akhavein, 1995). Symbolic and literal comparisons in several other sensory dimensions can also produce distance effects, indicating that conversion to analogue spatial terms is a key feature of comparison processes. (Bartlett & Dowling, 1980; Moyer & Bayer, 1976; Paivio & te Linde, 1979).

1.1 Higher, lower, and 'leaky' synaesthesia

For number-colour synaesthetes, digits are not just tied to magnitude, but also to certain colours. For example, the digit '1' may automatically induce a percept of the colour white, and the digit '4' may induce the colour green. Each synaesthete has a personal set of colours corresponding to the digits 0-9 (though some synaesthetes, for example LHM, LJM and RN in this study, do not report colours for all numbers). Beyond 9, unique colours for numbers are not usually seen (but see Gevers, Imbo, Cohen Kadosh, Fias, & Hartsuiker, 2010, for a counter-example); for example, 13 is likely to evoke the colours of 1 and 3 rather than have a specific colour of its own.

Some synaesthetes may literally see their colours, whether occupying the same space as or a different space from the digit itself, while others see the colour in their mind's eye, and some may have no visual experience but simply 'know' that the number is a certain colour (Ward, Li, Salih, & Sagiv, 2007). All, however, show a synaesthetic Stroop effect: it takes longer to name the colour of a digit when it is incongruent to synaesthesia than when it is congruent. For example, if 3 were presented in the colour of 5 it would take longer to name the colour than if 3 were presented in its own colour.

It is unclear whether number-colour synaesthetes tie colour to the perceptual aspects of the number (i.e. the shape of a digit) or its conceptual aspects (i.e. its magnitude, parity, etc.). Since numbers above nine usually do not evoke unique colours, it could be argued that percepts may be more important. However, the 2s of 26 and 216 also represent the concept ‘two’, it is simply that they are counted as ‘two tens’ or ‘two hundreds’ rather than ‘two units’.

Ramachandran and Hubbard (2001) suggested that there are two groups of number-colour synaesthetes, whom they termed ‘higher’ and ‘lower’ synaesthetes. For higher synaesthetes, colour is assumed to be elicited by number meaning. Given that different number formats have access to this meaning, colour experiences are elicited for more than one type of number representation. For lower synaesthetes colour is elicited by the structural representation of the digit and does not generalise to other number formats.

Higher and lower forms of synaesthesia may be related to the extent to which synaesthesia ‘leaks’ across systems of number representation. As stated above, if a synaesthete perceives the same colour for more than one representation of a number, she is clearly a higher synaesthete. It is harder to assess whether a synaesthete who responds only to the Arabic (digit) representation of a number is a lower synaesthete or a higher synaesthete who simply has a weak semantic link between non-digit representations of number and their associated concepts.

1.2 Bidirectionality in synaesthesia

Synaesthesia has classically been assumed to be unidirectional; that is, while a grapheme may consciously evoke a colour, the colour of a grapheme does not consciously evoke that grapheme (Mills, Boteler, & Oliver, 1999). It has been suggested that this might be because, when a number is seen, the colour can bind specifically to the shape of the number, whereas when a colour is seen there is no specific area for the number to bind to (Hubbard & Ramachandran, 2005). However, this does not fit with the subjective reports of some synaesthetes that the colour does not bind to the shape but rather exists in a non-physical form, in the mind's eye, or in physical space but unattached to the number (Ward et al., 2007). The number may provide a focal point for synaesthesia, but colour is not necessarily physically bound to it. The reverse, then, may also be true. Instead of evoking a symbolic representation of number, the colour may evoke a literal, unconscious representation of magnitude, rather than the percept of a digit. The presence of bidirectionality would indicate that the synaesthete in question has higher number-colour synaesthesia.

Conscious bidirectionality in number-colour synaesthesia exists in isolated cases such as synaesthete IS (Cohen Kadosh, Cohen Kadosh, & Henik, 2007; Cohen

Kadosh & Henik, 2006c; Cohen Kadosh, Tzelgov, & Henik, 2008), who reports that under some conditions colours spontaneously evoke a vague visual percept of their corresponding numbers.

However, number-colour synaesthetes without explicit bidirectionality show unconscious bidirectionality on a number of tasks, such as Cohen Kadosh and Henik's (2006b) number comparison task in which pairs of numbers were presented in congruent or reversed colours according to their participant's synaesthesia. She took much longer to identify which number was larger when colours were reversed and this effect was larger the smaller the distance between the two numbers, indicating a synaesthetic distance effect. Johnson, Jepma and de Jong (2007) also demonstrated a small tendency towards a congruency effect when synaesthetes were presented with coloured digits and asked to name the digit. Finally, a study by Knoch, Giannotti, Mohr and Brugger (2005) showed that synaesthetes, when randomly generating colours they associated with the numbers one to six, showed 'counting' behaviour in that they commonly chose consecutive colours belonging to adjacent numbers. Non-synaesthetes trained to make the same associations between number and colour (arguably simulating a very weak form of lower number-colour synaesthesia) did not show this tendency.

The overall conclusion that must be drawn from these studies of unconscious bidirectionality is that colour is bound to the concept of number. Without binding to number concept, bidirectionality effects could not appear. However, this does not necessarily imply that any synaesthete showing bidirectionality must be a higher synaesthete, as this effect could take place when colour activates the physical concept of a digit, which in turn activates magnitude. In this case, though, we would expect bidirectionality effects to be weaker as the link between colour and magnitude is not direct.

1.3 Models of numerical cognition

McCloskey, Caramazza and Basili (1985) proposed a model of numerical cognition with two input processes: Arabic and verbal. These are converted to an abstract internal representation which can be used for operations such as calculation. Subsequently, the abstract representation is converted to Arabic or verbal output. In this model, higher synaesthesia functions through the abstract internal representation and lower synaesthesia through the digital input (in which case one might expect bidirectionality) or though the digital output (in which case one would not expect bidirectionality).

The Clark and Campbell specific-integrated theory (e.g. Clark & Campbell, 1991) is counter to the McCloskey et al. model in two ways. Firstly, it is argued that the different input processes by which one can receive numerical knowledge do not become abstract but remain in their own format. Secondly, the McCloskey model assumes that the various operations that might be performed during number processing are modular, while the Clark and Campbell model indicates that the processes largely overlap. Here, then, higher synaesthesia would occur during number processing, while lower synaesthesia would occur before or after processing (with bidirectionality only being seen if lower synaesthesia occurs before processing).

Dehaene’s (1992) triple-code model divides numbers into three different mental representations: auditory, visual Arabic and analogue magnitude. Unlike the McCloskey et al. model, there is no abstract representation. Though the codes are interlinked, so that one representation can be converted to another, each deals with a specific operation. For example, the analogue magnitude representation is responsible for approximate calculations, and the digit representation is responsible for parity decisions. In this model, higher synaesthesia occurs only when a number is converted to its analogue magnitude form, while lower synaesthesia occurs in the visual Arabic form. Because of the ease of translation between the two forms, bidirectionality effects might appear in either higher or lower synaesthesia.

Number-colour synaesthesia can inform and be informed by these models. From the experiments on bidirectionality outlined above, it is assumed that colour is strongly bound to number, perhaps even processed as though it is number. Assessing differences between numbers and colours presented in different formats in classic Stroop-type tasks such as Experiment 2 may allow us to understand not only how colour is processed but also the ways in which it interacts with number in its different formats.

2 Experiment 1

In Experiment 1, we assessed differences between synaesthetes showing different extents of leakage across four systems of numerical using a paradigm similar to that created by Nikolić, Lichti and Singer (2007). Classically, grapheme-colour synaesthesia is tested using a simple Stroop-type task in which synaesthetes are presented with a single grapheme in its own colour or the colour of another grapheme and asked to name the colour presented as quickly and accurately as possible. However, Nikolić et al. (2007) modified this task so that, for incongruent trials, the grapheme was presented in a colour either the exact opposite hue (opponent colour) or a hue midway between the congruent and opponent colours (independent colour). In the current experiment, numbers (presented as digits, Roman numerals, number-words and dot patterns) were used as inducers.

We hypothesise that low-leakage synaesthetes respond at a low perceptual level to Arabic numerals alone – other representations of number should not produce a concurrent at all and therefore should not interfere with colour naming. As such, digit-only synaesthetes will show a pattern of responses identical to that found by Nikolić et al. for Arabic numerals only – that is, participants will show a significantly longer reaction time (RT) when naming opponent colours than when naming independent or congruent colours. Synaesthetes with high leakage, who perceive concurrents for all representations of number, are predicted to show the same pattern for each representation: a significantly shorter RT for congruent trials, but no difference in RTs between independent and opponent trials as this difference is perceptual in nature.

2.1 Methods

2.1.1 Participants

Twelve number-colour synaesthetes (mean age = 26.75 years; *S.D.* = 9.26; range 17-46; 9 female) took part in this experiment. All synaesthetes gained a score of under 1.00 on the consistency subtest, and/or over 85% accuracy on the Stroop subtest of the Eagleman battery at www.synesthete. org (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007)[19]. All but one were native English speakers (AP's first language is Bulgarian, but she learned English at age six and speaks it fluently). One synaesthete was later excluded from analysis, due to a technical error during the experiment.

2.1.2 Materials and procedure

Before taking part in the main experiment, participants were asked to provide colours for the numbers 0-9 in the form of RGB values, by altering the colour of the numbers from black to the perceived colour in a Microsoft Word document, or by completing the synaesthesia battery at www.synesthete.org (Eagleman et al., 2007). If

[19] Two synaesthetes who did not meet either of these criteria, SK and SS, were included on the basis that their consistency scores, when asked to provide verbal labels for number concurrents, were very high (100% over 3 months and 30 months, respectively). They provided colours by using the colour picker in Microsoft Word to alter the colours of numbers 0-9 from black to their concurrent colours.

synaesthetes used the latter method, a mean RGB value was calculated for each number from the three repetitions of that number during the battery.

In addition, synaesthetes were asked whether their experiences of colour with Arabic numerals were similar to those they had with number-words, dot patterns, and (in Experiments 1 and 2) Roman numerals (see Table 1). Any synaesthete not reporting colours for all number representations was classed as ‘low-leakage’ (marked with a star in Table 2), since in cases where some number representations have colour and others do not, it is likely that transferences to other number representations are due to learned associations between a particular number representation and its corresponding synaesthetic colour. Eleven out of twenty-four synaesthetes (46%) report conflicting colours for different representations of number due to letter-colour synaesthesia. This is higher than the proportion of 30% reported by Rich, Bradshaw and Mattingley (2005).

Table 1: Self-reports of experience of colour in response to digits, Roman numerals, number-words and dice patterns among participants in Experiments 1, 2 and 3. Conflict indicates that the synaesthete has letter-colour synaesthesia which determines the colour of the number-word as opposed to number colour synaesthesia. Asterisks indicate those classed as low-leakage synaesthetes. Dashes indicate synaesthetes who took part in Experiment 3 only and did not provide data on their experiences for Roman numerals.

Synaesthete	**Reports same colour for:**			
	Digits	**Roman numerals**	**Number words**	**Dice patterns**
AG*	Yes	-	Yes	No
AP	Yes	Yes	Yes	Yes
EF*	Yes	Conflict	Conflict	No
HGT*	Yes	-	Conflict	No
HM*	Yes	-	Conflict	No
HO*	Yes	No	No	No
JD	Yes	Yes	Yes	Yes
KB*	Yes	-	Conflict	No
LD*	Yes	-	Yes	No
LM	Yes	Yes	Yes	Yes
MA*	Yes	-	Conflict	No
MH*	Yes	-	Conflict	No
MC*	Yes	Yes	No	Yes
MV*	Yes	Yes	No	No
RN*	Yes	No	No	No
SAR	Yes	Yes	Yes	Yes
SD	Yes	-	Yes	Yes
SH*	Yes	Conflict	Conflict	Yes
SK*	Yes	Yes	Conflict	Yes
SR*	Yes	-	No	Yes
SS*	Yes	Conflict	Yes	No
TA*	Yes	-	Conflict	Yes
TW*	Yes	-	Yes	No
YR*	Yes	-	Conflict	No

A modified form of the Nikolić et al. (2007) Stroop test was used to assess reactions to numbers presented in congruent, incongruent and opponent colours. Participants were presented with four numbers in four forms (digit, Roman numeral, number-word or dot pattern). Using E-Prime 2.0, synaesthetes saw a white fixation cross on a black screen for 1000ms, followed by the stimulus, until a response was made. Synaesthetes were asked to name the colour of each stimulus presented into a microphone as quickly and accurately as possible, for a total of 480 trials. All synaesthetes gave their answers in English. Due to the constraints of E-Prime 2.0, dot pattern trials were presented as a separate block, while the other trial types were mixed together randomly.

Before statistical analysis, errors and trials in which the microphone failed to pick up a response were excluded, along with any trial with an RT of less than 300ms. Finally, trials with an RT of more than three standard deviations above or below the mean were removed. The last data cleaning exercise was continued until no outliers remained. In total, 9.2% of the data was lost.

2.2 Results

A 2x3x4 mixed ANOVA was used to analyse RT data of synaesthete type (high-leakage or low-leakage) by colour presented (congruent, incongruent or opponent) by number notation (digit, Roman, word or dice). There were no significant main effects or interactions (all *p*s > .11). Means and standard errors for each notation are summarised in Figure 1.

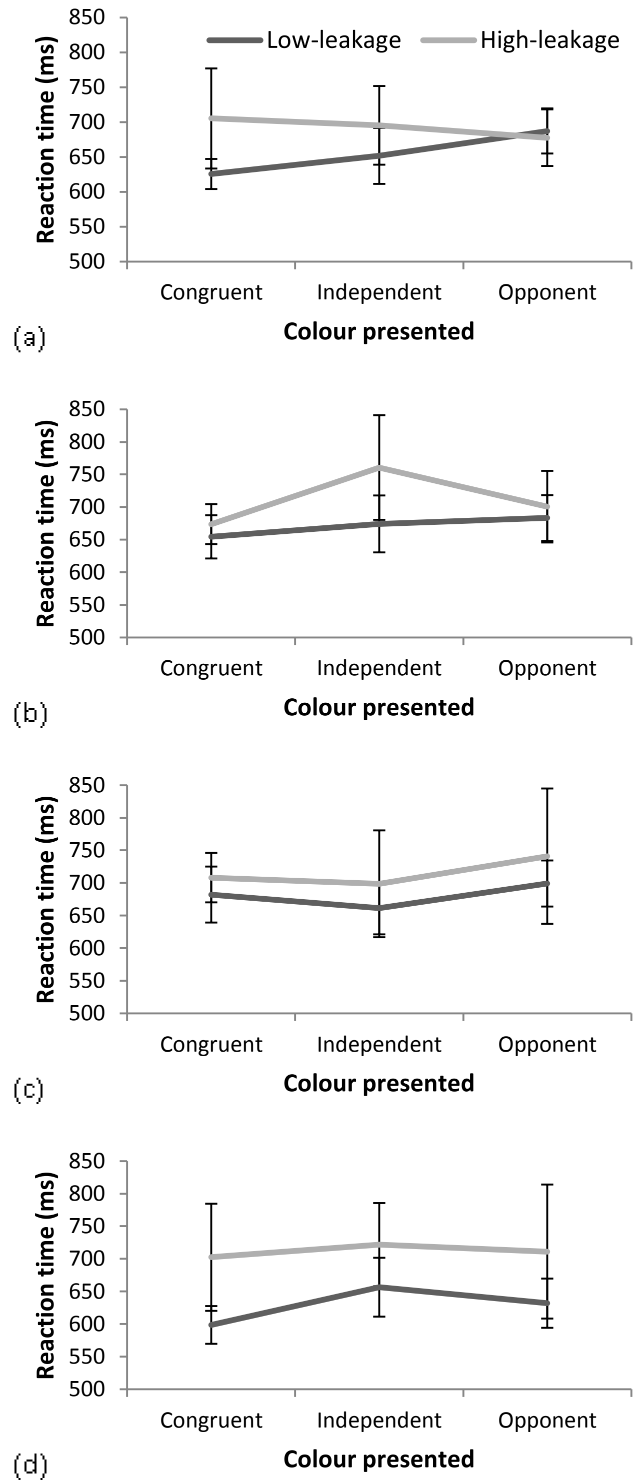

Figure 1: Mean RTs in congruent, incongruent and opponent conditions for low-leakage and high-leakage synaesthetes in (a) digit, (b) Roman numeral, (c) number-word and (d) dot pattern trials. Error bars show ± 1 S.E.M.

Given that there was no clear-cut distinction between low-leakage and high-leakage synaesthetes, the data for non-digit notations was reanalysed using a 2x3 mixed ANOVA in the dot condition, and 3x3 mixed ANOVAs in the Roman and word conditions, to analyse reported experience (concurrent, no concurrent, and in the Roman and word conditions, conflicting concurrent) by colour presented (congruent, incongruent or opponent).

In the dot condition, the only significant main effect was of reported experience ($F(1,9) = 5.76$; $p < .05$), caused by participants who reported concurrents for this notation taking longer to name the colour of a stimulus ($M = 704$ms) than those who did not report concurrents ($M = 560$ms). Interestingly, this did not interact with congruency, suggesting a generally cautious response strategy. A similar main effect was seen in the Roman numeral condition ($F(2,8) = 5.07$; $p < .05$), where a Bonferroni post-hoc test showed that those who experienced colours in line with their digit-colour synaesthesia ($M = 741$ms), or conflicting concurrents ($M = 731$ms), showed a tendency to be slower than those without concurrents ($M = 586$ms). However, no main effects or interactions were found in the word condition, though again, there is a trend for those reporting concurrents of any kind (digit colour $M = 693$ms, conflicting colour $M = 739$ms) to take longer than those without concurrents ($M = 638$ms). These findings are summarised in Figure 2.

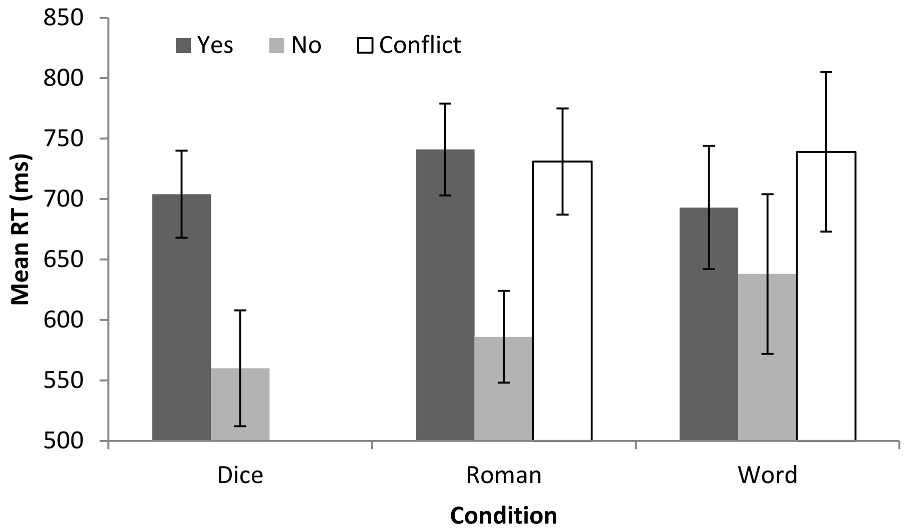

Figure 2: Mean RTs in dice, Roman numeral and word conditions, divided by subjective report of synaesthetic experience. Error bars show ± 1 S.E.M.

2.3 Discussion

There is no significant effect of congruency or extent of leakage on reaction time in this task. This non-significant result is not in line with the work of Nikolić et al. (2007) on graphemes. Since it was predicted that high-leakage synaesthetes would show a congruency effect on all number representations, and low-leakage synaesthetes an opponency effect on Arabic numerals alone, the most obvious interpretation is that all synaesthetic concurrents (for numbers) arise at a higher perceptual level than Nikolić et al. have suggested. However, their finding of an opponency effect must still be explained. Since the opponency Stroop is a new type of test for synaesthesia, it is possible that either the Nikolić et al. (2007) result is merely chance, or that the larger presence of letters (60% of trials) in their version of the test is the root cause of their Stroop effect.

We suggest that number-colour synaesthesia may produce weak effects on the Nikolić et al. Stroop test but strong effects on the classic Stroop test for synaesthesia (i.e. for a Stroop effect to appear in number-colour synaesthesia, incongruent stimuli must not only be in the wrong colour but that colour must belong to another number), while letters produce Stroop effects on either task. Consequently, concurrents for number-colour synaesthesia arise later in processing than concurrents for letter-colour synaesthesia.

3 Experiment 2

Experiment 2 is a slightly altered version of Experiment 1: all synaesthetes were presented with numbers 1-6 in digit, dice pattern and number-word formats, and the different number formats were presented in individual blocks. In this experiment, we also looked for synaesthetic distance and size effects. In a classic Stroop-type test, there are effectively two numbers present during a trial: the written number and the number implied by the colour of the stimulus. If colour acts as a number notation for synaesthetes, we would expect to find that synaesthetes take longer to name (incongruent) stimuli the closer the magnitude of the written and implied numbers (synaesthetic distance effect). Similarly, RT should increase with the magnitude of the lowest number presented, whether written or implied (synaesthetic size effect).

3.1 Methods

3.1.1 Participants

Eighteen number-colour synaesthetes (mean age = 28.11 years; S.D. = 11.23; range 18-49; 14 female). Six had previously taken part in Experiment 1. Again, all (aside from SS and SK; see Experiment 1) gained a score of under 1.00 on the consistency subtest, and/or over 85% accuracy on the Stroop subtest of the test battery at www.synesthete.org (Eagleman et al., 2007).

All participants saw number-word stimuli and gave all responses in their mother tongue[20]. Their self-reports regarding which number forms elicit colours are presented in Table 1.

One synaesthete was removed prior to analysis as she reported ordinal linguistic personification (Simner & Holenstein, 2007) had an influence on her number-colour synaesthesia. For example, 3 occasionally took on the colour of 5 or 8 as these numbers 'belonged together'.

3.1.2 Materials and procedure

New synaesthetes provided colours for their numbers in the same ways as those taking part in Experiment 1.

[20] AG saw number-words and gave responses in French, SR in German, YR in Swiss German, and all others in English.

During the main experiment, E-Prime 2.0 was used to present digits 1 to 6 in congruent or incongruent colours, tailored to each participant's synaesthesia. Incongruent colours were simply colours that belonged to other numbers. Each number was presented in each colour five times in a randomised order, for a total of 180 trials, plus six practice trials at the beginning (therefore, there were five incongruent trials for every congruent trial). Participants followed the same response instructions as in Experiment 1. The experimenter recorded any microphone or participant errors for later deletion.

E-Prime 2.0 was also used to present dice patterns and number-words. The same colour and number combinations were presented for the same number of trials as in the digit condition and required the same response from the participant. The order of conditions was counterbalanced across participants.

3.2 Results

The same data cleaning procedures were used as in Experiment 1.

3.2.1 Congruency effects

Mean reaction times for the congruent and incongruent trials were calculated for each participant. A 2x3 within-subjects ANOVA was used to compare congruent and incongruent means in each notation (Figure 3). There was a significant main effect of congruency (F (1,16) = 15.03; p < .01; congruent M = 690ms, incongruent M = 722ms) and of notation (F (2,32) = 7.07; p < .01; digit M = 735ms, dice M = 662ms;

word *M* = 721ms; Bonferroni post-hoc tests showed that this was due to participants taking longer in the digit than in the dice condition). There was also a significant interaction between congruency and notation (F (2,32) = 4.67; p < .05). Paired t-tests with a Bonferroni correction (α of .05/15 = .003) were used to determine that this interaction was caused by significant differences between the digit incongruent (*M* = 758ms) condition and three other conditions: digit congruent (*M* = 711ms), dice congruent (*M* = 657ms) and dice incongruent (*M* = 667ms).

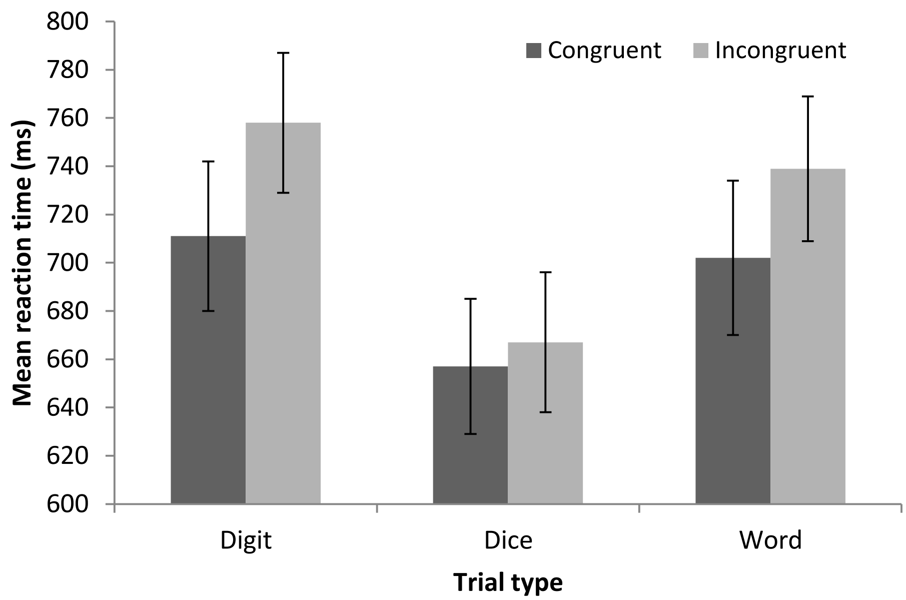

Figure 3: Mean reaction times to incongruent and congruent trials in the digit, dice and word conditions. Error bars show ± 1 S.E.M.

Subsequently, participants were divided into groups according to their subjective reports of concurrents for dice patterns (yes or no) and number-words (yes, no or conflict with letter-colour synaesthesia; the last two were collapsed as only two participants reported no concurrents). Two 2x2 mixed ANOVAs were used to compare RTs by subjective report and congruency for the dice and word conditions. There were no significant main effects or interactions in the dice data (all *p*s > .15). In the word condition, there was a significant main effect of congruency (F (1,15) = 8.62; $p < .05$) but no other significant main effect or interaction (*p*s > .28).

3.2.2 Distance effects

The 'distance' between the number presented and the number implied by the presented colour was calculated as follows. The digit 2 in the colour of 3 would receive a distance of +1, while 3 in the colour of 2 would receive a distance of -1. Congruent trials, which have a distance of 0, were not included.

A 2x5 (positive or negative direction by distance of 1-5) within-subjects ANOVA was conducted on data in the digit condition (Figure 4). There was found to be a significant interaction of distance with direction (F (2.70, 43.17) = 3.07; $p < .05$ with Greenhouse-Geisser correction), but no significant main effects of direction ($p = .44$) or distance ($p = .12$). Paired t-tests were used to investigate this interaction, summarized in Table 2.

Table 2: Significant (p < .05) differences between mean RT for stimuli at different distances in positive and negative directions in the digit condition.

Significant interaction (higher RT/lower RT)	Higher mean RT (ms)	Lower mean RT (ms)
-2/+2	753	721
+3/+2	747	721
+5/-5	800	745
+5/-1	800	727
+5/-4	800	436
+5/+2	800	721

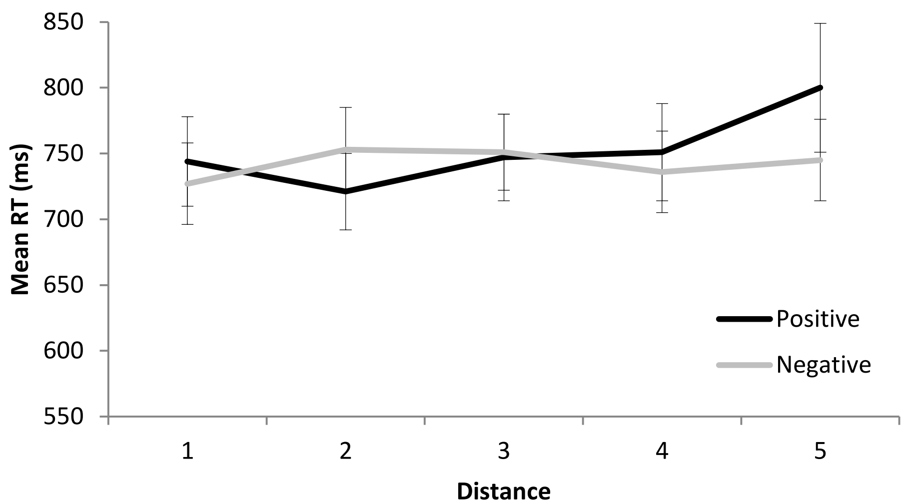

Figure 4: Reaction times to stimuli at different distances in positive and negative directions in the digit condition. Error bars show ± 1 S.E.M.

In the dice condition, a 2x5 (direction by distance) mixed ANOVA was conducted. There were no significant main effects or interactions (all *p*s > .08).

Finally, in the word condition, a 2x5 (direction by distance) mixed ANOVA was conducted (Figure 5). There was a significant main effect of distance (F (1,16) = 5.01; p

< .01), caused by participants having shorter RTs to stimuli at a distance of 5 than at distances of 2 and 4. There were no other significant main effects or interactions (all *p*s > .17).

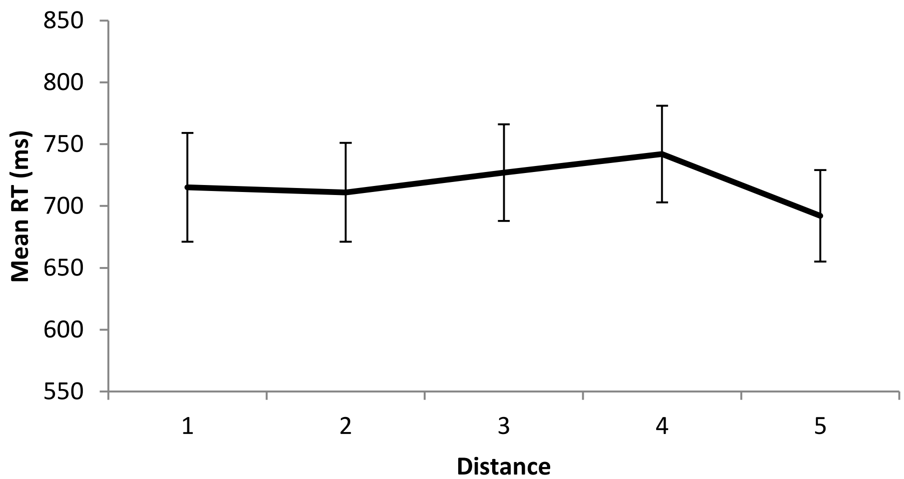

Figure 5: Reaction times to stimuli at different distances in the word condition.

There is no obvious support for the synaesthetic distance effect in any of the conditions, but this may not be due to the absence of a distance effect *per se*. In number-colour synaesthesia, luminance tends to decrease as magnitude increases (Cohen Kadosh, Henik, & Walsh, 2007). Since increasing distances allow fewer and fewer pairs of colours (e.g. a distance of -1 is present in trials with 6 in the colour of 5, 5 in the colour of 4, 4 in the colour of 3, 3 in the colour of 2 and 2 in the colour of 1, while a distance of -5 is only present in trials with 6 in the colour of 1), it is possible that a synaesthetic distance effect could be obscured by an interaction with luminance (see *Size effects* below). To assess this possibility, data from trials featuring the colour of 6 only were subjected to a one-way within-subjects ANOVA in the digit condition, and 2x5 (report by distance) mixed ANOVAs in the dot and word conditions. Data are presented in Figure 6.

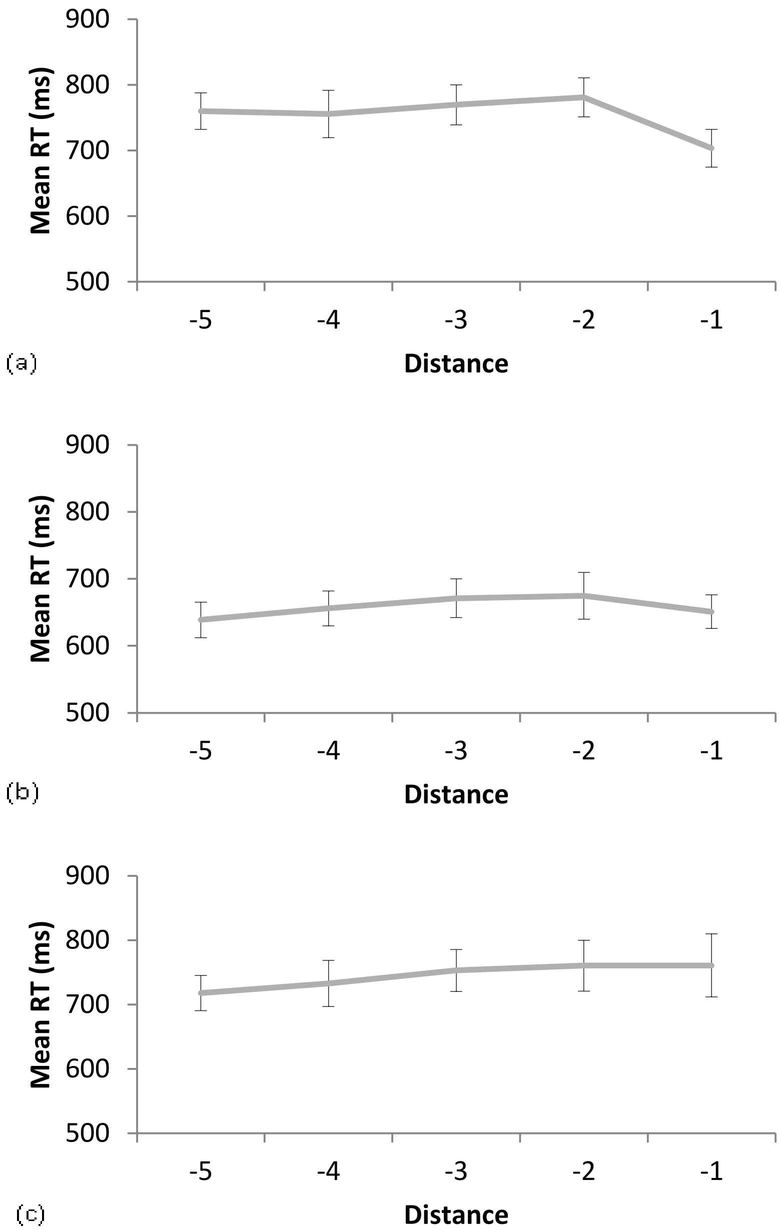

Figure 6: Reaction times to stimuli at different distances from 6 in (a) digit, (b) dot and (c) word conditions. Error bars show ± 1 S.E.M.

There was a significant main effect of distance in the digit ANOVA (F (2.52, 40.37) = 4.56, $p < .01$ with Greenhouse-Geisser correction), as participants' mean RT was lower for distances of -1 (M = 704ms) than for distances of -2 (M = 781ms) and -5 (M = 760ms). The dot data produced no significant main effects or interactions (all ps > .34); the same was true of the word data (all *ps* > .08).

3.2.3 Size effects

For all synaesthetes' incongruent trials, a grand mean RT was taken for each sum of the number presented and the number implied (e.g. 3 in the colour of 2 would give a sum of 5). A grand mean RT was also taken for all trials (congruent and incongruent) in each colour. Sum and grand mean RT for each colour were entered as predictors in a simultaneous multiple regression for RT at each sum.

For the digit data, the regression model was marginally significant (F (2,29) = 3.05; $p = .06$, $R^2 = .18$). The colour of the stimulus played a larger and more significant role in the model ($B = .74$, *S.E.* $B = .42$, $\beta = .34$, $p = .09$) than the sum of the stimulus ($B = -1.79$, *S.E.* $B = 2.32$, $\beta = -.15$, $p = .45$). For the word data, the regression model was significant (F (2,29) = 5.28; $p < .05$, $R^2 = .28$). Again, the colour of the stimulus played a larger, significant role in the model ($B = 1.08$, *S.E.* $B = .36$, $\beta = .49$, $p < .01$), while the sum of the stimulus was non-significant as a predictor ($B = 3.02$, *S.E.* $B = 2.0$, $\beta = .23$, $p = .16$).

3.3 Discussion

In this experiment, synaesthetes performed a classic Stroop-type task on digits, number-words and dice patterns.

An effect of congruency was found in the digit and word conditions, but not in the dice condition. This suggests that participants may be reading digits and words to themselves and that the congruency effect is due to an auditory/verbal link between number and colour. This is supported by the fact that participants show a congruency effect in the word condition regardless of their subjective experience (i.e. the same colour as for digits, no colour or colours based on letter-colour synaesthesia).

No distance effect was found in any of the conditions, though when data from trials featuring the colour of 6 were analysed alone, participants were quicker to respond to distances of -1 than distances of -2 and -5. This may be a priming effect – i.e. for numbers presented in colours belonging to nearby numbers, reaction times are small because of partial activation of the nearby number and consequently its colour (e.g. 4 in the colour of 5 is responded to quickly because participants are partially primed for 5 and its colour by the appearance of 4). Our results show that this effect is restricted to numbers and colours that are neighbours (e.g. 5 is the neighbor of 4 and 6) and are in line with Den Heyer and Briand’s (1986) finding that numbers are more strongly primed by their neighbours than by more distant numbers.

The priming effect is likely to be stronger than a putative distance effect because it works in the usual, conscious direction of synaesthesia rather than in the opposite direction, and would work in approximately this manner: on seeing a number, neighbouring numbers are partially activated and in turn, their colours are partially activated. Consequently, the colour of a stimulus is indirectly primed by the appearance of a near number. Note that this effect relies on the number presented being processed more quickly than the colour can be named.

One other aspect of this study that should be addressed is the high ratio of congruent to incongruent trials. This may have lead to overly-cautious responses from participants and consequently masked or altered some other features of their responses.

4 General discussion

4.1 Nikolić et al. Stroop-type task

The lack of opponency effects for Roman numerals, number-words and dot patterns is consistent with the elicitation of a concurrent at a late stage in processing in number-colour synaesthesia. Additionally, the extent to which the synaesthete perceives different systems of number representations as having colour does not appear to be indicative of the level at which the inducer is processed.

Some of our synaesthetes reported that they saw or thought of colour for all four number forms tested in Experiment 1, but a much more common response pattern is that some forms elicit colour while others do not. The lack of consistency in reported colour experiences indicates that the links between number and colour in forms other than Arabic numerals are likely to be semantic rather than synaesthetic, and thus reliant on the level of familiarity with other forms of number.

4.2 Congruency effects in different forms of number

Effects of congruency are seen for digits and words, but not dot patterns, in Experiment 2. It could be argued that because dice patterns literally represent quantity (i.e. the number of dots *is* the quantity), this result is incompatible with higher synaesthesia. However, dice patterns are over-learned by comparison to random dot patterns of the same quantity and it is likely that a heuristic which does not involve counting is in place.

Unusually, congruency effects are present in the word condition even when synaesthetes report subjectively different colours for number-words and digits, which suggests a role of phonology in the Stroop-type effect, or perhaps pseudosynaesthesia (Berteletti et al., 2010). One way to test this is to disable the phonological loop during the experimental task. Because of the use of vocal responses to complete the task, this would have to be a task that could be performed silently while carrying out the task itself; for example, synaesthetes could be asked to remember a nonsense sequence of syllables immediately before a trial and to report them immediately after a trial.

4.3 Distance, priming and size effects

In Experiment 2, the relationship of RT with distance in the digit condition is not linear. This is seen in both positive (i.e. colour larger than number) and negative (i.e. number larger than colour) distances. We hypothesise that the distance effect is not taking place for the digit condition because it is not present or is overcome by a second effect – priming. Priming effects (Reynvoet, Brysbaert, & Fias, 2002) can be seen in number-naming tasks when a masked prime is presented before the target number; naming is facilitated only when the prime and target numbers are neighbours. In our task, the prime (the stimulus number) and the target (the colour) are simultaneously presented, but the task can be completed without consciously noting the stimulus number. However, the colour in question is also tied to a specific number, and as such may offer a second route to arrive at the colour name that is not available to non-synaesthetes. For example, if 6 is presented in the colour of 5, then not only is the target colour physically present but it is also primed: the number 6 primes (i.e. partially activates) the number 5, which in turn primes the colour of 5. Priming may overcome the distance effect at short distances because it relies on the conscious direction of synaesthesia – from number to colour. The distance effect, on the other hand, relies on unconscious links from colour to number. However, the lack of size effects in both the digit and the word conditions argues against there being a masked distance effect in the digit condition: bidirectionality for digit-colour synaesthesia is not indicated by our findings.

In the dice and word conditions, distance effects are not present. This result is compatible with the view that notations of number other than digits have only semantic access to colour; a priming effect would be much weaker for non-digit notations as they would only become activated once a particular representation of number is learned.

4.4 Consequences for models of numerical cognition

The results of these experiments strongly suggest that in synaesthesia, digits, number-words and dice patterns are processed in different ways. This is completely incompatible with the McCloskey et al. (1985) model, where all forms of number are converted to an abstract code in order to be processed. However, this conclusion is neutral with regards to the specific-integrated (Clark & Campbell, 1991) and triple-code (Dehaene, 1992) models, both of which specify that numbers remain in their original format during processing.

The triple code model may also inform synaesthesia. Since distance and size effects are posited to take place in the analogue magnitude representation of the triple-code model (Dehaene & Cohen, 1995), the results gained in this study indicate that number-colour synaesthesia is not taking place at this level, but in the visual Arabic system (digit-colour) and the auditory system (number word-colour). Because of the strong links between the different codes in Dehaene's model, however, the effects of synaesthesia may filter through to the analogue format in a weaker format. Thus, we would perhaps expect distance and size effects (given the strong influence of priming) to appear only in a much larger sample of number-colour synaesthetes.

4.5 Conclusions

The results from these experiments indicate that number-colour synaesthetes tie number to colour, but do not do so strongly enough that colours imply magnitude when their associated numbers are not present. When synaesthetes are presented with congruent, independent and opponent colours (as in Experiment 1), no congruency effects are seen. In Experiment 2, congruency effects are seen in the digit and word conditions (but not the dot condition), suggesting that the number-colour synaesthetes we have tested are responsive to words because of their strong auditory link with digits (a factor that dot patterns do not share). In addition, there is an effect of priming in the digit condition which may or may not be masking a distance effect. The lack of a size effect supports the latter interpretation. Overall, our results suggest that lower number-colour synaesthesia or a form that produces lower-like synaesthesia is the dominant, if not the only, form in the synaesthetic population.

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Appendix

Stimuli used in Paper 5, Experiment 2

Word 1	Word 2	Non-word 1	Non-word 2
BOLD	FOLD	VOLD	NOLD
GOAT	COAT	YOAT	POAT
ZONE	CONE	SONE	JONE
MICE	DICE	HICE	SICE
SEED	WEED	GEED	JEED
BATH	PATH	FATH	RATH
SEAM	SWAM	SOAM	STAM
TYPE	TAPE	TEPE	TUPE
SCAR	STAR	SHAR	SMAR
CHIN	COIN	CLIN	CRIN
TEEN	THEN	TWEN	TIEN
WALL	WILL	WULL	WOLL
FIRE	FINE	FIGE	FIME
CAVE	CAKE	CADE	CAZE
SOCK	SOAK	SOLK	SONK
NOSE	NOTE	NOGE	NOVE
NEWT	NEST	NENT	NERT
RISE	RIPE	RINE	RIKE
TREE	TREK	TREP	TREB
BAND	BANK	BANT	BANY
YARD	YARN	YARE	YARM
WORK	WORD	WORC	WORG
HERO	HERB	HERL	HERM
MAIL	MAID	MAIF	MAIP