

Research report

# Dissociating semantic and perceptual components of synaesthesia: behavioural and functional neuroanatomical investigations

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## Abstract

Colour digit synaesthetes experience atypical dual perceptions wherein achromatic digits are perceived along with coloured photisms. Recent studies have employed Stroop or priming tasks and exhibited interference or facilitation in synaesthesia [Nature 410 (2001) 580–582; Perception 28 (1999) 651–664]. We compared a synaesthete to a semantic control with arbitrary colour–number associations and demonstrated that these tasks do not elicit effects unique to synaesthesia. In contrast, we present functional neuroimaging data that clearly differentiates between these two conditions.

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## 1. Introduction

Synaesthesia is a rare condition wherein individuals consciously experience dual perceptions: A stimulus is perceived along with a perception in another modality, dimension, or attribute not normally associated with the stimulus [3,14]. These perceptions can involve associations between two modalities. For example, hearing a musical sound might trigger the perception of colours or shapes (known as photisms) [9,11]. To date, synaesthetic percepts have been reported for almost all possible intermodal combinations. However, synaesthesia usually occurs within one modality [1]. One common form is colour–grapheme synaesthesia wherein individuals perceive colours when presented with achromatic digits or letters.

Synaesthesia does not appear to be a deliberate cognitive strategy. Instead, it is an involuntary and concrete type of sensory experience that normally becomes apparent in early childhood [2]. One line of evidence for the auto-

maticity of synaesthesia employs an approach based on the Stroop effect [16]. When individuals are asked to name the print colour of an incongruent colour word (such as the word ‘RED’ printed in green), reaction times are much faster than those for naming congruent stimuli (such as ‘GREEN’ printed in green) [8]. Similarly, when colour–grapheme synaesthetes are presented with numbers or letters in colours congruent or incongruent with their photisms and are asked to name the colour of the grapheme, they exhibit faster reaction times for the congruent stimuli [6,10,12,14,19]. Some have suggested that these Stroop tasks can serve as an objective cognitive marker for synaesthesia [14].

It appears that synaesthesia does not require the physical presentation of the grapheme, and that these interference effects can be observed when only the concept associated with the grapheme is consciously evoked. For example, a ‘mathematical’ Stroop paradigm also produces interference in synaesthetes. Dixon et al. [6] presented mathematical problems with a colour patch in the location of the answer. When the answer to the problem (ex. 7) was congruent with the photism for the colour patch (ex. yellow), the synaesthete named the colour patch more quickly than when the colour patch was incongruent with the photism

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for the answer. These results suggest that photisms in synaesthesia are involuntary, conceptually driven and that they do not require an inducing stimulus [6].

Although the photisms are involuntary, it appears that the inducing stimulus must be consciously perceived [10]. When an alphanumeric prime was presented slowly enough to be consciously perceived (500 ms), synaesthetes were faster to name the colour patches when they were congruent with the primes. When the primes were presented too quickly for conscious recognition, there was no difference between the congruent and incongruent conditions. However, the same group demonstrated priming at durations too short for conscious perception when performing a letter–letter priming task. As such, Stroop effects observed in synaesthetes appear to require conscious processing.

In addition to the studies employing simple reaction-time measures, there have also been functional neuroimaging studies of synaesthetes [5,13,15]. Using PET imaging, Paulesu et al. [15] observed that while listening to words, the synaesthetes displayed more activation than the controls in some extrastriate visual cortical areas and less activation in the left lingual gyrus. Similarly, using fMRI, Nunn et al. [13] found V4/V8 activation in a group of colour–word synaesthetes while listening to spoken words. Therefore, the neural activity accompanying coloured-hearing suggests a partial activation of some higher-order visual cortical areas. In an investigation of taste–shape synaesthesia, Cytowic [5] used a xenon inhalation technique and found widespread decreases in cerebral blood flow (particularly in the left hemisphere) during synaesthesia.

This paper investigates synaesthesia through the use of both behavioural tasks and functional neuroimaging. However, we also employ a semantic-control wherein synaesthesia is compared to colour–number associations that are not due to synaesthesia.

## 2. Materials and methods

### 2.1. Participants

Three types of participants were recruited for the experiments described below: (1) a colour–grapheme synaesthete; (2) a semantic-control individual with well learned semantic colour–digit associations (semantic control) from using cross-stitch patterns over a period of 8 years (for example, in one cross-stitching system the number 3 indicates the use of red thread and 7 indicates the use of yellow thread); (3) four untrained controls with no synaesthetic or learned colour–digit associations.

### 2.2. Behavioural assessments

To assess the reliability of the colour–number associa-

tions of both the synaesthete and semantic-control, the digits 0–9 were presented 10 times each in randomized order and the participant was asked to name the colour associated with that digit. The semantic-control offered responses that were 100% consistent whereas the synaesthete's responses were 98% consistent. The colour–number associations for the semantic-control did not overlap (i.e. there were 10 different colour–digit mappings for the digits 0–9). For the synaesthete, six of the 10 digits were associated with unique colours. Those digits not associated with unique colours were not employed for the reaction time tests. To assess the automaticity of the colour–digit associations, three behavioural tasks were performed: a colour-naming Stroop task [12]; a mathematical Stroop task [6]; and a priming task [10]. For the three tasks, the vocal reaction times (RTs) were recorded.

The colour naming Stroop task consisted of four digits displayed in colours congruent or incongruent with the synaesthete's or semantic-control's associations ( $n=192$  trials; 48 congruent). Participants were required to state the colour of the typeface. Pilot data from normal control participants suggested that equal proportions of congruent and incongruent trials resulted in weak interference. As such, we used a fully randomized design wherein four numbers were presented in one of four colours. The mathematical Stroop task consisted of a digit (ex. 5), an operator (ex. +), and a second digit (ex. 2), followed by a colour patch [6]. Participants were instructed to name the colour patch as quickly as possible, followed by answering the mathematical problem ( $n=256$  trials, 64 congruent). The priming task was a variant of the Stroop task, wherein a priming alphanumeric character was briefly presented prior to a colour patch [10]. Congruent and incongruent primes were presented either slowly enough to be consciously perceived (500 ms; 96 trials, 24 congruent), or too quickly for conscious recognition (24 or 48 ms; 192 trials, 48 congruent).

### 2.3. fMRI assessments

Within the fMRI environment (1.5-T Siemens Symphony Magnetom imager), we administered three tasks requiring the processing of numeric information: the colour–number Stroop task (see above); a dice calculation task; and an eyes-closed addition task. The latter two tasks did not require visual presentation of arabic numerals. For the dice calculation task, participants viewed two achromatic die faces and were asked to calculate the sum of the two dice. For the eyes-closed addition task, participants were asked to close their eyes and simple addition problems (identical to those employed in the dice task) were presented auditorily. For these tasks, participants answered silently. All participants also completed a task that did not require numerical processing. A nonsense symbol discrimination task was administered wherein two identical (50% of the time) or different non-linguistic symbols were

presented. Participants were asked to silently indicate whether the symbols were the same or different.

Images were acquired using a gradient echo, single-shot echo planar imaging sequence with fat saturation, an echo time  $T_E$  of 55 ms and a flip angle of  $90^\circ$ . The 143 volumes were obtained with a  $T_R$  of 1600 ms. The first five were used for stabilizing the MRI signal (and were discarded). These were followed by six blocks of trials, each of which were 23 volumes in length (the first six volumes in each block were in sync with presentations of the stimulus, the remaining volumes were ‘rest’). Ten slices per volume (with a slice thickness of 8 mm, 10 mm between slice centre lines and a field of view of 250 mm), were taken with a repeat time of 1600 ms sync with the trials (synchrony between the MRI and stimulus computer was maintained by triggering image acquisition with the stimulus computer). The fourth most inferior slice was centred on the posterior commissure and oriented in the axial plane. Acquisition matrix size was  $64 \times 64$  and the data were reconstructed to  $128^2$  size. The activation maps were computed using a general linear model that corrected for linear baseline drift and produced a parametric estimate for the mean Blood Oxygenation Level Dependent (BOLD) time course over the six blocks. A correlation statistic,  $r^2$ , was computed that represented the goodness of fit of the mean BOLD function to the observed BOLD data in terms of variance accounted for in the data by the mean response. This method of fMRI data analysis is similar to that proposed by Clare et al. [4] and was implemented using locally written software. Pixels with a resulting correlation coefficient  $r > 0.65$  and a maximum intensity change in the mean BOLD function of more than five grey-scale units were considered activated. False activations in regions of interest were eliminated by visually examining the pixel signal time course to verify that it represented a smoothly varying hemodynamic response. Voxel size was  $1.95 \times 1.95 \times 8$  mm and the Talairach coordinates were identified with a standard software package [17].

### 3. Results

#### 3.1. Behavioural assessments

For the colour–number Stroop task, both the synaesthete and semantic-control took more time to name the colours of digits that were incongruent with their associations,  $t(186)=2.07$ ,  $P=0.02$  and  $t(186)=1.96$ ,  $P=0.03$  (see Fig. 1a). For the mathematical Stroop task, both the synaesthete and semantic-control were slower to name the colour patches when the colour was incongruent with their colour–digit associations,  $t(237)=2.70$ ,  $P<0.01$  and  $t(241)=4.37$ ,  $P<0.01$  (Fig. 1b). For the priming task, both the synaesthete and the semantic-control were slower to name the colour patches when the colour was incongruent with the priming stimulus,  $t(92)=2.10$ ,  $P=0.02$  and  $t(92)=2.21$ ,  $P=0.01$  (Fig. 1c). When the primes were presented too quickly for conscious perception, the priming effect disappeared. For all of these three tasks, the untrained control group did not exhibit any difference between the congruent and incongruent conditions.

#### 3.2. fMRI assessments

For the colour–number Stroop task, both the synaesthete and semantic control exhibited similar activations in the congruent and incongruent conditions. However, for the dice arithmetic task and the eyes-closed addition task, the synaesthete demonstrated significant activation along the left dorsal visual stream (including Brodmann’s A—19, 7, 39, and 40), but there was *no such increase in activity* for the semantic-control or untrained controls (Fig. 2).

##### 3.2.1. Dice arithmetic task

The synaesthete exhibited activation in extrastriate cortex (corresponding to Talairach [18] cG-3 and bH-4, comprised of 35 voxels activated in these regions). The semantic-control failed to exhibit similar activation (0

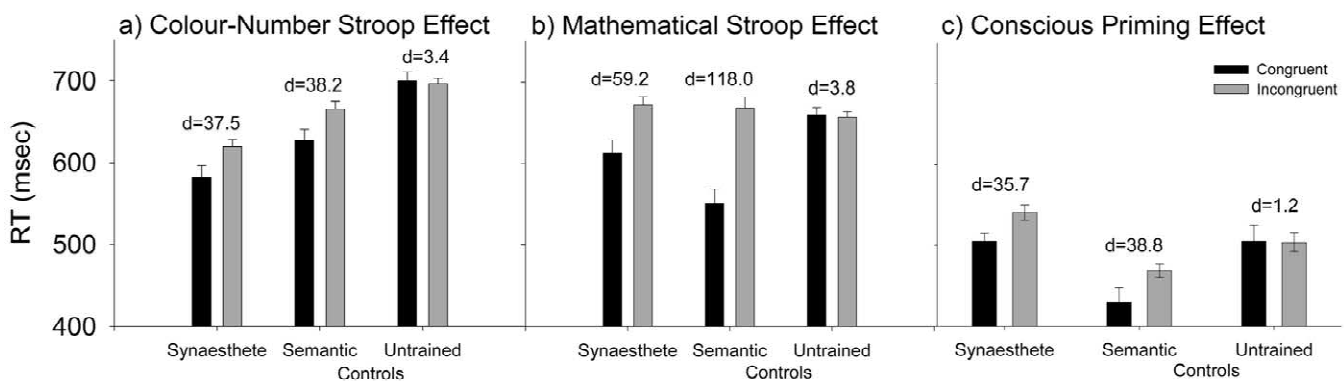


Fig. 1. (A) Reaction times (RTs) for a synaesthete, semantic control, and untrained controls on a colour–number Stroop task. (B) RTs for the same group given the mathematical Stroop task. (C) RTs for the same group given the conscious/unconscious priming task. All values are means  $\pm$  S.E.M. \* Indicates significant differences,  $P < 0.05$ .

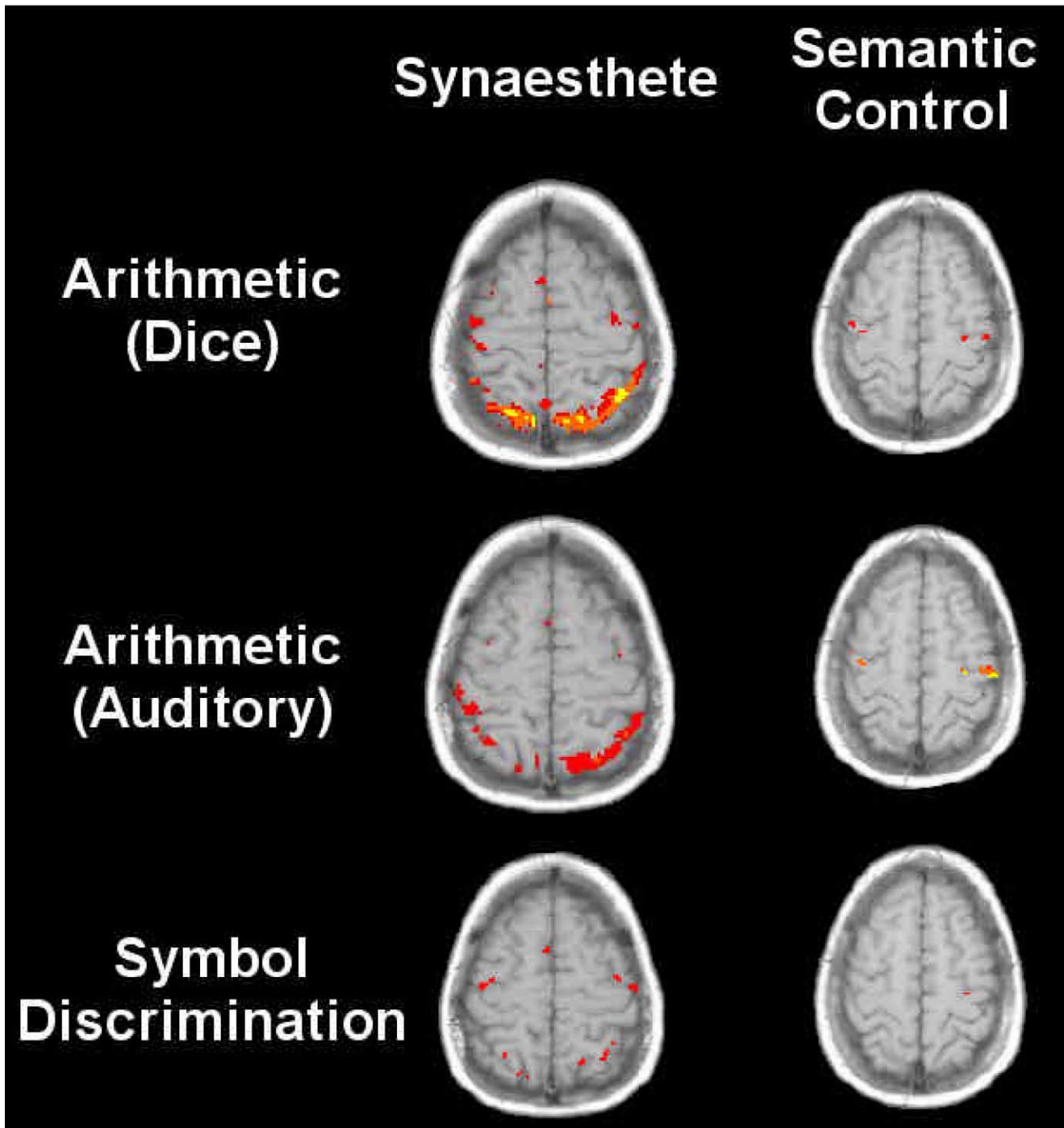


Fig. 2. Functional magnetic resonance imaging (fMRI) activation maps from the synaesthete and semantic control on three tasks. (A) Dice arithmetic task, (B) auditory arithmetic task, and (C) nonsense symbol discrimination task. The slices shown are at a depth of +50 mm above the AC–PC line.

voxels in cG-3 and bH-4), as did the four untrained controls (cG-3  $\bar{x}$ =1.5, S.D.=3; bH-4  $\bar{x}$ =0, S.D.=0).

### 3.2.2. Auditory arithmetic task

The synaesthete exhibited activation in cG-3 and bH-4, comprised of 37 voxels activated in these regions). The semantic-control failed to exhibit similar activation (0

voxels in cG-3 and bH-4), as did the four untrained controls (0 voxels in cG-3 and bH-4).

### 3.2.3. Nonsense symbol discrimination task

The synaesthete exhibited marked reduction in cG-3 (14 voxels) and bH-4 (0 voxels). These results are summarized in Fig. 2. The maps displayed are visibility maps wherein red represents visibilities between five and 10 grey scale

units, yellow, visibilities between 10 and 15 grey scale units and yellow, visibilities greater than 15 grey scale units. The visibilities represent the intensity (amplitude) of the hemodynamic response.

#### 4. Discussion

When employing simple reaction time measures to study the semantic links in colour–grapheme synaesthesia, individuals with explicitly learned associations cannot be reliably distinguished from those with synaesthesia. The consistency of these congruent/incongruent differences between the synaesthete and the semantic-control demonstrate that the semantic interference/facilitation recently reported in synaesthetes is *not* a phenomenon unique to synaesthesia. Individuals with well-learned colour–digit associations can behave similarly given the same task. Therefore, such tasks can not be used as objective cognitive markers for synaesthesia.

However, colour–grapheme synaesthetes and individuals with well learned colour–grapheme associations differ in a number of important ways. Synaesthetes usually cannot report the origin of their colour–grapheme associations and the presentation of graphemes elicits involuntary photisms. Furthermore, many colour–grapheme synaesthetes also report rich spatial associations with graphemes (such as imagining a number-line or circular arrangement of numbers) [7]. Individuals with arbitrarily learned colour–grapheme associations do not normally develop similar experiences. However, when the Stroop tasks described above are administered to these two types of individuals, their behaviour is indistinguishable. These tasks appear to tap the semantic associations between the colour and the grapheme, but fail to assess what is unique in synaesthesia—the triggering of photisms.

When a synaesthete demonstrates interference/facilitation on a Stroop or priming task, this effect could be due to either the semantic component of the synaesthesia, the unique perceptual phenomena that accompany synaesthesia, or a combination of the two. Given that the behaviour of individuals with explicitly learned associations is virtually identical to that seen in synaesthesia on these tasks, it appears that they fail to assess the perceptual phenomena that are unique to synaesthesia. Further evidence for their specificity to the semantic links between colours and digits is found in our neuroimaging data. When performing a Stroop task, the semantic control and the synaesthete did not differ in their patterns of activation. Therefore, such tasks can not be used as objective cognitive markers for synaesthesia. Instead, they are simply a means to assess semantic associations between colours and numbers. This does not imply that synaesthetes are qualitatively similar to individuals with arbitrary colour–digit associations. Both conditions appear to rely on similar

semantic mechanisms, but they are accompanied by very different perceptual phenomena.

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