NeuroImage 98 (2014) 416–424

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

Achromatic synesthesias — A functional magnetic resonance imaging study

H. Melero [a,b,*], M. Ríos-Lago [c,d,e], A. Peña-Melián [f], J. Álvarez-Linera [e,g]

[a] *Departamento de Psicobiología, Facultad de Psicología, Universidad Complutense de Madrid, 28223, Spain*
[b] *Departamento de Investigación, Desarrollo y Promoción, Fundación Internacional Artecittá, Spain*
[c] *Departamento de Psicología Básica II, UNED, Madrid 28040, Spain*
[d] *Unidad de daño Cerebral, Hospital Beata María Ana, Madríd 28007, Spain*
[e] *Laboratorio de Análisis de Imagen Médica, Fundación CIEN-Fundación Reina Sofía, Madrid 28031, Spain*
[f] *Departamento de Anatomía y Embriología Humana I, Facultad de Medicina, Universidad Complutense de Madrid, 28040, Spain*
[g] *Servicio de Neurorradiología, Hospital Ruber Internacional, Madrid 28034, Spain*

ARTICLE INFO

Article history:
Accepted 9 May 2014
Available online 16 May 2014

Keywords:
Achromatic synesthesias
The congruency effect
Emotional binding theory

ABSTRACT

Grapheme–color synesthetes experience consistent, automatic and idiosyncratic colors associated with specific letters and numbers. Frequently, these specific associations exhibit achromatic synesthetic qualities (e.g. white, black or gray). In this study, we have investigated for the first time the neural basis of achromatic synesthesias, their relationship to chromatic synesthesias and the achromatic congruency effect in order to understand not only synesthetic color but also other components of the synesthetic experience. To achieve this aim, functional magnetic resonance imaging experiments were performed in a group of *associator* grapheme–color synesthetes and matched controls who were stimulated with *real* chromatic and achromatic stimuli (Mondrians), and with letters and numbers that elicited different types of grapheme–color synesthesia (i.e. chromatic and achromatic *inducers* which elicited chromatic but also achromatic synesthesias, as well as congruent and incongruent ones). The information derived from the analysis of Mondrians and chromatic/achromatic synesthesias suggests that *real* and synesthetic colors/achromaticity do not fully share neural mechanisms. The whole-brain analysis of BOLD signals in response to the complete set of synesthetic *inducers* revealed that the functional peculiarities of the synesthetic brain are distributed, and reflect different components of the synesthetic experience: a perceptual component, an (attentional) feature binding component, and an emotional component. Additionally, the inclusion of achromatic experiences has provided new evidence in favor of the emotional binding theory, a line of interpretation which constitutes a bridge between grapheme–color synesthesia and other developmental modalities of the phenomenon.

Introduction

Synesthesia is a neural phenomenon in which sensory and/or conceptual stimuli elicit unusual perceptions. Grapheme–color synesthesia has been described as a phenomenon in which achromatic (white, black or gray) letters and/or numbers elicit the perception of colors (Dixon et al., 2004; Erskine et al., 2012; Hupé et al., 2011; Kim et al., 2006; Marks, 2011; Rich et al., 2006), i.e. achromatic graphemes (achromatic *inducers*) elicit synesthetic experiences of color (chromatic *concurrents*). Nevertheless, chromatic graphemes (e.g. labels, electric signs) also act like *inducers* and grapheme–color synesthetes self reports usually include one or more achromatic *concurrents* (e.g. X is black). Research on the prevalence of specific associations between graphemes and colors reports a generalized tendency to perceive some letters and numbers as non-hued: 78% of 172 grapheme–color synesthetes saw the letter I as achromatic and 75% the letter O as achromatic (Day, 2005); 56% of synesthetes experienced white for the letter O and 60% saw white for the number 1 while 20% saw it black (Rich et al., 2005; Simner et al., 2006). This tendency seems to appear in non-synesthetes as well, who chose black, gray and white for the letters X, Z and I, and white for the number 1 (Rich et al., 2005).

Given the high prevalence of color synesthesias (relative frequency of color *concurrents* = 87%: Hochel and Milán, 2008), functional magnetic resonance imaging (fMRI) studies on grapheme–color synesthesia have usually stimulated participants with achromatic graphemes that elicited color (Hubbard et al., 2005; Hupé et al., 2011) and, to our knowledge, only one study included graphemes that elicited achromatic

---

Abbreviations: ISEQ, Illustrated Synesthetic Experience Questionnaire; ANOVA, analysis of variance; ACE, alien-color-effect; ACG, anterior cingulate gyrus; MFG, middle frontal gyrus; SMA, supplementary motor area; ToM, theory of mind.

[*] Corresponding author at: Departamento de Psicobiología, Universidad Complutense de Madrid, Campus de Somosaguas, Pozuelo de Alarcón, Madrid 28223, Spain.
E-mail address: hmelero@ucm.es (H. Melero).

http://dx.doi.org/10.1016/j.neuroimage.2014.05.019
1053-8119/

synesthesias (Sperling et al., 2006). Additionally, the congruency and incongruency effects, which are the result of the match or mismatch between the physical nature of a stimulus and the synesthetic *photism* associated with it, have been investigated (Niccolai et al., 2012a; van Leeuwen et al., 2010; Weiss et al., 2005), but achromatic incongruency was not included. The results from research centered in color *concurrents* suggested that color areas (the V4 complex: Bartels and Zeki, 2000; V8: Hadjikhani et al., 1998; V4v: Sereno et al., 1995) could be at the root of grapheme–color synesthesia, probably due to the implication of higher order regions, such as the parietal cortex, which could bind color and form (Hubbard et al., 2011). Nonetheless, functional and anatomical evidence to this respect is not conclusive (see Hupé et al., 2011) and the nature of synesthetic color is still uncertain.

In recent years, the link between *real* and synesthetic colors has been studied from different perspectives. Experiments on brightness contrast and chromatic adaptation suggest that early visual mechanisms do not contribute to synesthetic color experiences (Hong and Blake, 2008). In 2010, a repetition suppression paradigm was applied in order to test the ability of synesthetic color to suppress BOLD effects for real color (van Leeuwen et al., 2010). The absence of the suppression effects led to the conclusion that the two types of colors do not fully share neural mechanisms. More recently, a behavioral experiment revealed that synesthetic colors are not affected by the mechanisms of color constancy (Erskine et al., 2012).

In this study, we investigated the neural basis of achromatic synesthesias and their link to chromatic ones, including the congruency effect. To achieve this aim, BOLD signals were measured while participants performed a *real* color task (i.e. Mondrians task) and a synesthetic color task consisting of a varied set of synesthetic *inducers*. These included chromatic and achromatic *inducers* that induce congruent synesthesias (real color/achromaticity matches the perceived synesthetic *photism* for each synesthete) and incongruent synesthesias (real color/achromaticity mismatches the perceived synesthetic *photism* for each synesthete), but also chromatic *inducers* that induce achromatic experiences (e.g. a real red letter O, which induces the synesthetic color white) and vice versa (e.g. a real gray letter A, which induces the synesthetic color red). This varied set of stimuli and a whole-brain analysis allowed us to investigate the neural basis of grapheme–color synesthesia considering, for the first time, all the different types of *inducer–concurrent* associations. This approach aimed to understand other essential aspects of the synesthetic experience (e.g. the emotional component) whose neural basis could lie outside color areas.

Additionally, given that one of the main debates about the neural basis of grapheme–color synesthesia revolves around the implication of the color centers, the differences between chromatic and achromatic synesthesias were investigated. Color areas show greater activation when participants are stimulated with chromatic stimuli (i.e. chromatic Mondrians) in contrast to achromatic ones, when luminance remains constant (Bartels and Zeki, 2000). Following this reasoning, if the color areas should participate in grapheme–color synesthesia, their activation would be less prominent when stimuli that elicit achromatic *concurrents* appear. This hypothesis was tested in order to understand if chromatic and achromatic synesthesias behave like real chromatic and achromatic stimuli. Finally, the neural basis of the congruency effect was analyzed including the neural responses to congruent and incongruent achromatic *inducers*.

Material and methods

Participants

Ten synesthetes and ten controls matched by age (synesthetes' mean age = 25.1 ± 5.46; controls' mean age = 26.4 ± 6.16), sex (synesthetes: 7 women and 3 man; controls: 7 women and 3 men), handedness (self-reported hand preference: right hand) and education (self-reported education level: higher education) participated in this study. All participants completed the Synesthesia Battery grapheme–color task (Eagleman et al., 2007). Every synesthete scored below 1 and every control participant scored well above 2. Only those subjects who affirmed that they never experienced any of the synesthesias described in the battery were selected for the control group. The Illustrated Synesthetic Experience Questionnaire (ISEQ) (Skelton et al., 2007) classified all synesthetes as *associators* (Dixon et al., 2004). The participants had no history of neurological, neurophysiological nor psychiatric illness and none of them reported drug abuse. They all had normal or corrected-to-normal visual acuity. Subjects were informed of the purpose of the investigation before the experimental session and signed a consent form according to the Declaration of Helsinki.

fMRI stimuli

fMRI data were recorded in a single session, in which participants performed two different tasks. Stimuli for each task were designed using Adobe Photoshop 8.0 software and presented in different series, as described below.

In the first series (second series for half of the subjects and their matched controls), participants viewed chromatic and grayscale luminance-matched Mondrians (Figs. 1A and B) similar to those used in

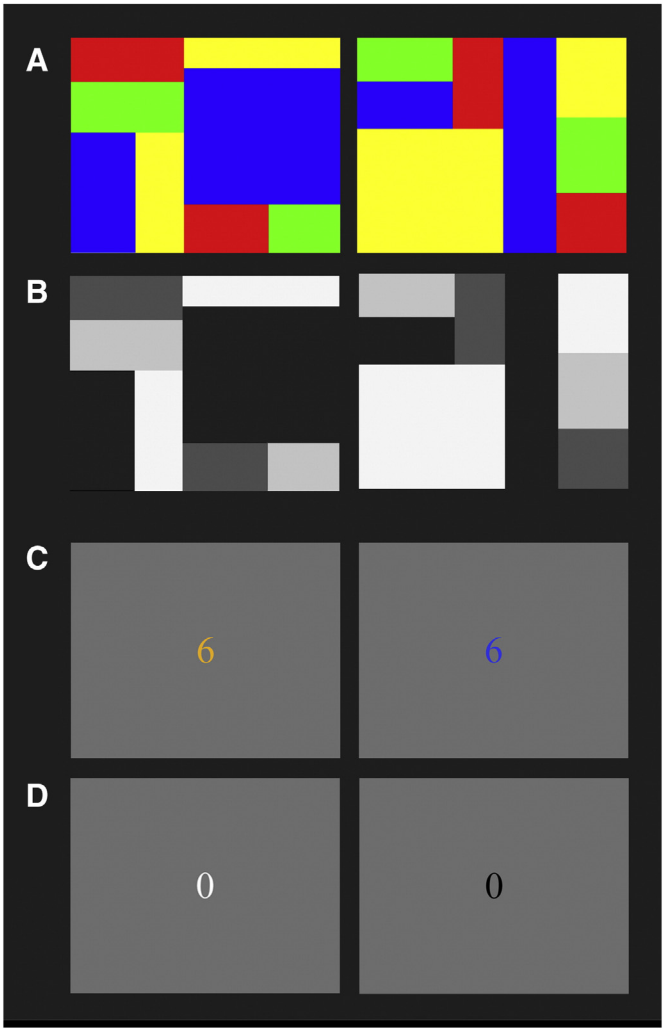

Fig. 1. Examples of stimuli. A: color Mondrians; B: grayscale luminance-matched Mondrians; C: chromatic alphanumeric stimuli in their congruent and incongruent versions; D: achromatic alphanumeric stimuli in their congruent and incongruent versions.

previous synesthesia research (Nunn et al., 2002; Rich et al., 2006; Sperling et al., 2006). In the present study, this task was administered in order to investigate intergroup differences in color processing, given the behavioral evidence about enhanced color sensitivity in synesthetes (Banissy et al., 2009). To create the total set of Mondrians, four models were drawn using colored squares and rectangles in red, green, blue or yellow (RGB values: a) red: 255, 0, 0, b) green: 0, 255, 0, c) blue: 0, 0, 255 and d) yellow: 255, 255, 0). These four original models were rotated to create 16 color models that were subsequently transformed to grayscale to obtain their achromatic versions (32 stimuli in total = 16 chromatic Mondrians and 16 achromatic Mondrians). Mondrians were presented to participants in an AB boxcar design (blocks of each type = 9; stimuli per block = 16; block duration = 24.4 s; stimuli duration = 1000 ms; interstimuli interval (ISI) = 450/500/550/600 ms; total run time = 7 min and 19.2 s). A gray interstimuli screen (RGB values: 128, 128, 128) was used to avoid motion cues at transitions to new spatial patterns.

In the second series, synesthetes and their matched controls viewed alphanumeric stimuli (Figs. 1C and D) that elicited different grapheme–color synesthetic experiences (chromatic/achromatic, congruent/incongruent) in order to investigate the neural network that underlies grapheme–color synesthesia. The alphanumeric stimuli were designed specifically for each synesthete (and matched control) and divided into six experimental conditions that differ in: a) real chromaticity and b) nature of the synesthetic *photism* associated with each letter/number (Table 1 shows the defining characteristics of each condition and examples of each one). Congruent stimuli (experimental conditions 1 and 5) were designed using the color chosen for each grapheme by each synesthete in the Synesthesia Battery (Eagleman et al., 2007). For this purpose, only the 8 alphanumeric stimuli with the highest consistency value in the results (the Synesthesia Battery) of each synesthete were chosen, in order to maximize the congruency effect. The stimuli were chosen taking into account the color they elicited, so that the synesthetic colors that each synesthete would experience during the task were as varied as possible (e.g. red, green, blue, yellow…). Given that the number of alphanumeric stimuli which elicited achromatic synesthesias was small, only 4 achromatic stimuli were selected. Nevertheless, they appeared twice in the proper experimental condition in order to guarantee that every block included the same number of stimuli. Inverse colored versions of the congruent-color graphemes and the congruent-achromatic graphemes were created for experimental conditions 2 and 6. The inverse color transformation was aimed at maximizing the incongruency effect, given that real color produces the highest interference in behavioral tasks when it is opponent to synesthetic color (Nikolic et al., 2007). Achromatic versions of the congruent-color graphemes were created for experimental condition 3. Graphemes that elicited achromatic synesthesias were also presented in the four colors that were used to create the Mondrians (experimental condition 4). Whereas inverse-color or inverse-achromatic stimuli were considered incongruent, color stimuli that elicited achromatic synesthesias and conversely achromatic stimuli that elicited colors were considered undefined in regard to congruency.

Alphanumeric stimuli were presented in a block design (blocks of each type = 5; stimuli per block = 16; block duration = 25 s; stimuli duration = 1000 ms; interstimuli interval (ISI) = 450/525/600/675 ms; total run time = 14 min and 34.8 s). In each stimulus, a 200-point letter or number appeared over a middle gray background (RGB values: 128, 128, 128). Middle gray was chosen for the background as it provided enough contrast for all the stimuli presented, both chromatic and achromatic (i.e. black, white, red…). In the alphanumeric part of the study subjects were instructed to press a button on a device held in their right hand whenever a number appeared, and a button in their left hand whenever a letter appeared (half of the synesthetes and their matched controls did it conversely to control for handedness effects). This task had a twofold aim: first of all, it was designed to help maintain the level of attention necessary to elicit a synesthetic experience (Mattingley et al., 2006); secondly, this specific task was chosen because its nature exhibits a superordinate level (Gauthier et al., 2010) (i.e. stimuli reach categorization stages: letter vs. number) and thus, it resembles everyday experience of perceiving letters and numbers, i.e. the context in which synesthesia usually occurs.

fMRI study

The fMRI data were acquired on a 3.0 T Signa HDx MR scanner (GE Healthcare, Waukesha, WI, USA) with an eight-channel head coil (GE Coils, Cleveland, OH). Head motion was minimized with a vacuum-pack system molded to fit each subject. The SuperLab 4.0 software package (Cedrus Corporation, www.cedrus.com) was used for stimuli presentation. Stimuli were presented to participants in two different series through optic-fiber-based glasses (MRVision 2000 ultra, Resonance Technology, Inc., Northridge, USA) connected to the stimulation computer. Responses to the second series were registered with Lumina LP400 response pads for fMRI.

Functional images were obtained using a T2* weighted echo-planar imaging (EPI) sequence (echo time = 34 ms; flip angle = 90°; matrix size = 128 × 128; field of view = 24 × 24 cm; repetition time = 3 s). Thirty-nine contiguous axial slices (3 mm thickness) covering the whole brain were acquired. A total of 165 scans in the Mondrians series and 325 scans in the alphanumeric series were recorded for each participant in a single session, with the first five volumes of each series subsequently discarded to allow for T1 equilibration effects. The data were analyzed using a general linear model in SPM8 (*Statistical Parametric Mapping*, *Wellcome Department of Imaging Neuroscience*, *London*; www.fil.ion.ucl.ac.uk/spm) implemented in MATLAB 7 (Mathworks, Inc.). Individual scans were i) spatially realigned and unwarped to compensate for head-movement; ii) corrected for differences in slice acquisition time (number of slices = 39, TR = 3 s); iii) spatially normalized to the EPI template supplied with SPM8, based upon the Montreal Neurological Institute (MNI) reference brain (Evans et al., 1993) and iv)

Table 1
Characteristics of the stimuli presented in each condition of the alphanumeric task, regarding real chromaticity (achromatic and chromatic), the nature of the synesthetic photism associated with each letter/number (achromatic and chromatic), and the congruency between them (congruent, incongruent and neutral). Last column shows examples of alphanumeric stimuli in each experimental condition.

Condition	Real appearance		Synesthetic photism		Stimuli-photism congruency			Examples
	Chromaticity		Chromaticity					
	Achromatic	Chromatic	Achromatic	Chromatic	Congruent	Incongruent	Undefined	
01	✓		✓		✓			0
02	✓		✓			✓		0
03	✓			✓			✓	2
04		✓	✓				✓	0
05		✓		✓	✓			2
06		✓		✓		✓		2

spatially smoothed to reduce noise and to compensate for anatomical inter-subject variability (Gaussian filter of 8 mm FWHM), using standard SPM methods.

Population inference was done in a two-stage procedure. In the first stage, a subject-specific analysis was carried out where the BOLD response for each voxel and experimental condition was modeled by a boxcar waveform convolved with a canonical hemodynamic response function plus temporal and dispersion derivatives. Statistical parametric maps of the t-statistic (SPMt) were generated for each subject and experimental condition, and the contrast images were stored. In the second stage, a 2 × 2 (Group × Mondrians) ANOVA was used to analyze data from task 1. Post hoc contrasts (t-statistic maps within the ANOVA model; $p_{FWE} < 0.05$) were carried out in order to specify which of the two levels of each factor accounted for the effects detected by the F contrasts. Data from task 2 were analyzed using *t*-tests ($p_{FWE} < 0.05$), aiming at identifying the regions of the brain that contribute to synesthesia. Two sample *t*-tests were used to compare groups (synesthetes and controls) and one sample *t*-tests were used for intragroup analyses. Additionally, the regions of activation common to both tasks (inclusive mask analysis) were investigated. Anatomical identification was performed via XjView 8 (http://www.alivelearn.net/xjview8/). In addition, the neuroanatomy atlases by Haines (2011) and Nolte and Angevine (2007) were consulted.

Results

Task 1: Mondrians

ANOVA was performed in order to test the differential sensitivity of color areas to *real* chromatic and achromatic stimuli in our sample. This analysis (Factor 1 = Group; two levels = controls and synesthetes; Factor 2 = Mondrians; two levels: chromatic and achromatic) resulted in a significant main effect of Mondrians ($F_{1,36} = 30{,}83$, $p_{FWE} < 0.05$). A post-hoc *t*-test ($p_{FWE} < 0.05$) revealed differential activity (chromatic Mondrians > achromatic Mondrians) in the bilateral fusiform gyrus (right local maxima at $x = 46$; $y = -32$; $z = 36$; $t = 7.53$; left local maxima at $x = -32$; $y = -54$; $z = -20$; $t = 9.27$). ANOVA yielded no significant main effect of the factor Group and no interaction. Therefore, we assume that *real* chromaticity and *real* achromaticity per se do not elicit significantly different activations in the synesthetic brain.

Task 2: Alphanumeric stimuli

In order to investigate the neural basis of grapheme–color synesthesia, brain activation was analyzed including all the experimental conditions of the alphanumeric task (Table 1). This analysis maximized the amount of data available and guaranteed that the functional model derived from the data could account for grapheme–color synesthesia as it occurs in everyday life (i.e. including all types of *inducer–concurrent* associations: chromatic and achromatic, congruent and incongruent ones). The synesthetic brain exhibited a distributed pattern of differential activation (whole-brain; synesthetes > controls; $p_{FWE} < 0.05$ at the cluster level) in several regions of the brain (Table 2 and Fig. 2). The greatest clusters (>200 vx) appeared in the parietal lobe, the supplementary motor area, the middle frontal gyrus and the inferior temporal cortex. These results were compared with the clusters found in the bilateral fusiform gyrus in response to chromatic Mondrians in our sample. The t-map obtained in the Mondrians analysis (chromatic Mondrians > achromatic Mondrians contrast) was used to create a mask image that was applied to the analysis of the second task (inclusive

Table 2
Fmri activations for the synesthetic task (whole-brain; synesthetes > controls; $p_{FWE} < 0.05$ at the cluster level). In columns: Region (derived from XjView 8 software: http://www.alivelearn.net/xjview8/), brain hemisphere (left or right), cluster size in voxels, MN I coordinates, t value and p value (corrected for multiple comparisons).

Region	Hemisphere	Cluster size (vx)	MNI coordinates x y z	t value	p value (corrected)
Occipital					
Calcarine sulcus	L	26	−4 −94 −10	5.32	0.012
Cuneus BA19	L	29	−16 −88 26	5.09	0.011
Temporal					
Inferior temporal gyrus BA37	L	242	−58 −54 −14	6.59	<0.001
Lingual gyrus	R	44	−18 −82 −12	6.06	0.007
Superior temporal gyrus	L	30	−52 −4 −2	5.35	0.010
Parietal					
Inferior/superior parietal lobe	L	1896	−42 −36 34	7.67	<0.001
Superior parietal lobe	R	9	32 −66 64	5.38	0.025
Supramarginal gyrus	R	136	68 −32 22	7.44	0.001
Precuneus BA7	L	301	−22 −72 42	6.68	<0.001
	R	15	10 −64 50	5.08	0.019
Frontal					
Supplementary motor area	L	372	−12 −4 64	7.78	<0.001
	R	12	8 24 48	4.90	0.021
Anterior cingulate gyrus BA24	R	18	10 −2 48	5.36	0.016
Middle frontal gyrus BA9	R	339	46 32 38	6.82	<0.001
	R	146	38 56 2	6.19	0.001
	L	91	−46 24 34	5.66	0.002
Precentral gyrus BA6	R	84	12 −22 72	5.91	0.002
	L	20	−56 −8 40	4.99	0.015
Dorsolateral prefrontal cortex BA46	R	21	42 46 16	5.01	0.014
Orbitofrontal cortex BA10	L	8	−36 56 0	5.02	0.026
	R	5	28 50 −6	4.87	0.031
Insula					
Insula/ inferior frontal gyrus BA 47	R	15	32 20 −4	4.96	0.019
Insula BA13	L	14	−56 −38 20	4.85	0.019
Cerebellum					
Anterior cerebellum	R	117	36 −60 −32	5.95	0.001
	L	2	−32 −42 −28	4.70	0.039
Posterior cerebellum	R	27	24 −76 −28	5.21	0.012
	L	9	−38 −72 −30	4.82	0.026

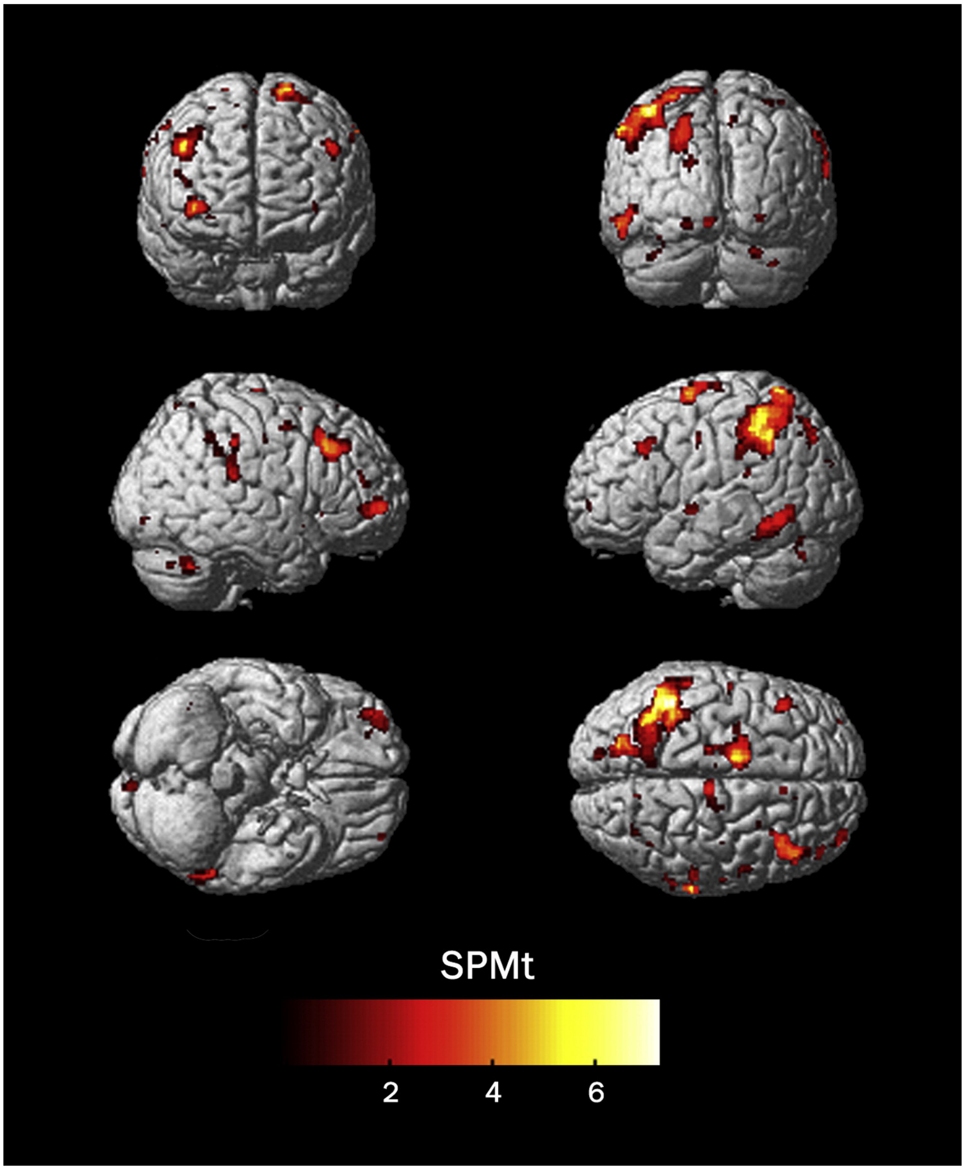

Fig. 2. Areas of the synesthetic brain which participate in grapheme–color synesthesia (whole-brain; synesthetes > controls; $p_{FWE} < 0.05$ at the cluster level). First row: anterior and posterior views; second row: right and left views; third row: inferior and superior views.

mask analysis) in SPM ($p_{FWE} < 0.05$). This analysis revealed no overlapping of results.

Real and synesthetic relations between chromatic and achromatic stimuli

Intra- and intergroup analyses were performed in order to test the functional differences between chromatic and achromatic synesthesias. Intragroup analysis (one sample *t*-test; synesthetes: achromatic stimuli inducing colors > achromatic stimuli inducing congruent achromatic synesthesias: whole brain analysis; $p_{FWE} < 0.05$ at the cluster level) and intergroup analysis (two sample *t*-test; synesthetes > controls: achromatic stimuli inducing colors > achromatic stimuli inducing congruent achromatic synesthesias; whole brain analysis; $p_{FWE} < 0.05$ at the cluster level) revealed no significant differences.

Synesthetic incongruency

Inter- and intragroup comparisons of incongruency (whole-brain analysis; congruent stimuli (experimental condition 1 + experimental condition 5) > incongruent stimuli (experimental condition 2 + experimental condition 6) and vice versa; $p_{FWE} < 0.05$ at the cluster level) did not reveal any significant clusters.

Discussion

Grapheme–color synesthesia is a complex phenomenon that exhibits a neuroanatomical and functional basis. The anatomical investigation of the phenomenon has provided evidence of distributed structural peculiarities, both at the cortical and subcortical levels (Hänggi et al., 2011; Hupé et al., 2011; Jäncke et al., 2009; Melero et al., 2013; Rouw and Scholte, 2007, 2010; Weiss and Fink, 2009). Functional experiments opened a debate on the role of color areas and binding systems, which helped define explanatory neurocognitive models. At this point, the functional analysis of other grapheme–color experiences (i.e. achromatic synesthesias) has provided new insight into the role of color areas and the nature of synesthetic color. *Real* color processing exhibits the same neural mechanisms in synesthetes and controls whereas synesthetic color recruits a differential distributed network which includes neural components related to different dimensions of the synesthetic experience. This analysis has reinforced the idea that *real* color and synesthetic color do not fully share neural mechanisms and that more extensive networks underlie the dynamics of the synesthetic brain.

Real chromatic and achromatic perceptions

The analysis of BOLD signals in response to *real* color stimuli (i.e. color Mondrians) revealed the expected pattern of activation in the bilateral fusiform gyrus of our participants, consistently with the literature about color vision (Bartels and Zeki, 2000; Hadjikhani et al., 1998; Sereno et al., 1995) and the results obtained in the Mondrians task in synesthesia research (Gray et al., 2006; Nunn et al., 2002; Rich et al., 2006). It is noteworthy that, in the present data, the cluster in the left is more significant. Left lateralization in this same task was found in alien-color-effect (ACE) synesthetes (Gray et al., 2006) and in non-synesthetic populations which exhibit bilateral activation of fusiform and lingual gyrus, but more prominently on the left side (Gray et al., 2006; Lueck et al., 1989; Zeki et al., 1991). Nonetheless, caution must be taken when interpreting lateralized results, given that the inverse tendency has also been described. For example, there exists empirical evidence of right lateralization in tasks of color perception in non-synesthetic populations, especially when the stimuli are primary colors (i.e. red, green, blue and yellow) (Njemanze et al., 1992; Trkanjec and Demarin, 2007). Likewise, grapheme–color synesthetes (Rich et al., 2006), colored-hearing synesthetes (Nunn et al., 2002) and non-ACE synesthetes (Gray et al., 2006) exhibited right lateralization in the Mondrians task.

Given that grapheme–color synesthesia research has focused on achromatic graphemes that elicited color (Hubbard et al., 2005; Hupé et al., 2011), we considered it important to investigate if *real* achromaticity elicited a differential response in the synesthetic brain, i.e. if the achromatic nature of graphemes elicited differential activation in the absence of symbolic (graphemic) content. ANOVA (task 1) revealed that chromatic and achromatic stimuli do not elicit differential activation in the synesthetic brain per se, failing to provide functional evidence for the enhanced color sensitivity of synesthetes reported in behavioral studies (Banissy et al., 2009). Additionally, these data do not support the existence of a bidirectional experience (e.g. achromatic stimuli-grapheme), an idea that agrees with the different qualitative nature of *real* and synesthetic colors and with the subjective reports of our participants about the unidirectionality of their synesthesia.

The synesthetic network

The inclusion of different grapheme–color modalities in the functional analysis of the synesthetic brain has provided significant data in a wide variety of areas. Consequently, the patterns of activation related to synesthesia seem distributed rather than confined to specific sensory areas. These data are consistent with previous functional (Sinke et al., 2012) and anatomical data (Hänggi et al., 2011) and also with the idea that different cognitive functions configure the unified synesthetic experience. These functions include: sensory processes, (attentional) feature binding processes and cognitive control processes (Dovern et al., 2012; Rouw et al., 2011).

Sensory processes

In the case of grapheme–color synesthesia, both the *inducer* and the *concurrent* belong to the visual domain, so activation specific to sensory processes is expected in visual areas. Both striate and extrastriate areas showed differential activation in our sample. The calcarine sulcus has shown anatomical variations (Hänggi et al., 2008; Jäncke et al., 2009) and differential activation in *projector* synesthetes (Rouw and Scholte, 2010) previously. In the present study, only *associators* were investigated, and thus this activation cannot be attributed to the projected nature of the synesthetic *concurrents* (bound to an object –grapheme – in external space: Rouw and Scholte, 2010). Recent empirical evidence confirms the role of V1 in color processing and defies the modular view, pointing out the inextricable link between color and form in visual cortical processing (Shapley and Hawken, 2011). In line with this approach, unusual activations in the calcarine sulcus may be related to synesthetic binding itself, independently of its spatial location (i.e. even if the binding of color and form occurs in the *mind's eye*). Additionally, this activation may be interpreted as the result of the influence that the whole network exerts on the visual process itself (i.e. homomodal – visual to visual – synesthesia). This is coherent with EEG data, which suggested that early cognitive processes distinguish cross-modal synesthetic perceptions from acquired associations (Niccolai et al., 2012a).

The implication of V4 in synesthesia has been discussed recently on the basis of essential methodological suggestions (Hupé et al., 2011). These suggestions include the recommendation of the use of correction for multiple comparisons. In the present study, despite the small size of the sample (N = 20), fusiform differential activations in synesthetes overcome correction for multiple comparisons ($p_{FWE} < 0.05$ at the cluster level). It is important to stress that inclusive mask analysis revealed no overlapping between the inferior temporal clusters reported in the synesthetic task and those that showed specific color activations in the Mondrians task. This constitutes additional evidence that the neural mechanisms that underlie *real* and synesthetic colors are not identical (Hupé et al., 2011; van Leeuwen et al., 2010). In order to differentiate the purely sensory components of the phenomenon (e.g. line orientation processing and/or *real* ink color processing) from the complex experience of synesthetic *concurrents*, hereinafter we will use the term *perceptual process* to describe this component.

(Attentional) feature binding processes

There is consistent functional and anatomical evidence on the implication of the parietal lobe in grapheme–color synesthesia and its role in *hyperbinding* (Rouw et al., 2011). Likewise, in the present data, the left superior parietal lobe is one of the differentially activated areas during the synesthetic task. Interestingly, the inferior parietal lobe (BA7) has shown differential activation and increased functional connectivity (between the parietal and primary visual cortices) in grapheme–color synesthetes (Sinke et al., 2012). Additionally, the supramarginal gyrus has been described as part of the lateral parietal network which differentiated synesthetes and controls (Dovern et al., 2012). These results reinforce the idea that, in grapheme–color synesthesia, perceptual processes are linked to higher order networks that contribute to the qualitative experience of color/achromaticity. The parietal clusters reported here may be part of one of these networks, reflecting the attentional component that, according to behavioral (Mattingley et al., 2006) and neuroimaging studies (Sinke et al., 2012), is crucial in the eliciting of synesthetic *concurrents*.

Cognitive control processes

Differential activity in the frontal and parietal cortices of synesthetes has been interpreted as a component of cognitive control (Rouw et al., 2011; Specht and Laeng, 2011), which reflects the conflict between physically evoked and synesthetic color. Nonetheless, recent empirical evidence does not allow establishing a relation between executive functions and synesthesia (Rouw et al., 2013), which suggests that the findings which were interpreted from this perspective may be reflecting other components of the synesthetic experience, or alternatively, other cognitive domains not directly related to synesthesia. This is the case of the anterior cingulate gyrus (ACG), which was said to mediate conflict monitoring (Specht and Laeng, 2011), but whose role in synesthesia has been reinterpreted recently from the perspective of the emotional binding theory (Melero et al., 2013). Likewise, insula activations were considered relevant to the conversion process of a given external stimulus to a different internal stimulus (Paulesu et al., 1995) and to audiovisual integration (Niccolai et al., 2012b). In the light of anatomical

(Jäncke et al., 2009; Melero et al., 2013) and functional data (Niccolai et al., 2012b; Specht and Laeng, 2011; Sperling et al., 2006), several authors have emphasized its relation to the emotional quality of synesthetic experiences (Melero et al., 2013; Rouw et al., 2011). Other clusters reported here may contribute to this emotional component. This is the case of the orbitofrontal cortex which is functionally connected to the insula (Cavada et al., 2000) and the amygdala (Barbas, 2007) and which plays a role in the mediation of hedonic experience (Kringelbach, 2005). Interestingly, not only the orbitofrontal cortex, but also the cingulate and insular cortices have been described as hedonic hotspots (Kringelbach and Berridge, 2010).

The authors of the hypothesis of the three processes (i.e. sensory, binding and cognitive control) described the emotional component as a feature of the sensory processes (e.g. insula activation reflecting emotional quality, instead of gustatory experiences of a given *inducer*) which reflects "the richness of the synesthetic experience" (Rouw et al., 2011). In the light of previous research (Calkins, 1895; Callejas et al., 2007; Cytowic, 1989; Cytowic and Eagleman, 2009; Hupé et al., 2011; Melero et al., 2013; Perry and Henik, 2013; Ramachandran and Hubbard, 2001; Ward, 2004) and the data presented here, we suggest that the emotional component is relevant enough to reconsider it as an inherent process of the synesthetic experience. This emotional component is understood here from the perspective of radical embodiment, that is, as the inherent affective tonality which contributes to the development of cognition and conscious experiences (Rudrauf et al., 2003).

Whereas the contribution of some of the reported clusters can be attributed to one of the three components of the synesthetic experience, other results are more difficult to interpret. This is the case of the supplementary motor area (SMA), which has shown a differential activation not only in our synesthetic task but also in previous research (Gray et al., 2006; Rouw and Scholte, 2010). Other authors have explained its activation in terms of the need of ACE synesthetes to inhibit automatic responses in Stroop tasks (Gray et al., 2006). Following the emotional binding theory (Melero et al., 2013) we can hypothesize about its role in the synesthetic experience. A recent study investigating the differential neural basis of the affective and cognitive theory of mind (ToM) found that the SMA belongs to a functional network that helps differentiate both processes (Bodden et al., 2013). Given the role of the SMA in the process of recognizing the feelings of another person (Bodden et al., 2013), its contribution to the emotional component of grapheme–color synesthesia is not implausible. Moreover, the involvement of the fusiform gyrus, the superior temporal sulcus and the precuneus in the affective ToM opens a new road for interpretation of the canonical regions of interest described in empirical studies and explanatory models of synesthesia. This line of interpretation constitutes a bridge between grapheme–color synesthesia and other modalities of the phenomenon whose neural basis has been explained in terms of heightened emphatic ability (e.g. *mirror touch* synesthesia: Banissy and Ward, 2007).

Achromatic and chromatic synesthesias

In order to understand the role of the color centers in grapheme–color synesthesia, we looked for areas of the brain whose activation could help differentiate chromatic and achromatic synesthesias. As observed from the results of the Mondrians task, fusiform areas show enhanced bilateral activity in response to chromatic Mondrians in comparison to achromatic Mondrians. Therefore, if these areas participate in synesthesias as they do in *real* color perception one may expect them to be more active when *inducers* that elicit color (in contrast to those which elicit achromatic synesthesias) appear. Nonetheless, in the present synesthetic sample, no differences are observed when participants visualize achromatic stimuli that elicit color *photisms* in contrast to those that elicit achromatic experiences. This suggests that the neural mechanisms that help differentiate chromatic and achromatic perceptions are not shared by *real* and synesthetic chromaticity.

Thus, regarding the contribution of V4 to grapheme–color synesthesia in our sample of *associator* synesthetes, the inferior temporal cortex seems to contribute to the experience but not in the way it does for *real* color perception. This can explain why synesthetic and *real* colors can be perceived simultaneously without being mixed and why they belong, in some cases, to different "spaces" (i.e. external space vs. mind's eye) (Dixon et al., 2004). This evidence is also coherent with works that reported that synesthetic color signals are not impacted by the processes responsible for perceptual constancy (Erskine et al., 2012) and those which discarded the contribution of early visual mechanisms to synesthesia (Hong and Blake, 2008). Again, the different qualitative nature of *real* chromatic and achromatic stimuli do not support bidirectionality, as the complex experience of color/achromaticity linked to any given graphemic *inducer* is not present in the external world to act as an (implicit/explicit) *inducer*. As mentioned above, this could explain why synesthetes do not usually report conscious bidirectional experiences.

The congruency effect

In previous fMRI research, the dorsolateral prefrontal cortex showed an unusual activation in grapheme–color synesthetes who experienced incongruent stimuli (Weiss et al., 2005). In our sample, the incongruency effect (incongruent stimuli > congruent stimuli) did not reveal significant results. This may be due to the fact that our analysis compares incongruent vs. congruent stimuli, instead of incongruent vs. undefined (i.e. light gray stimuli which elicited color synesthesias: Weiss et al., 2005). To our knowledge, there is no empirical evidence of the neutrality of the color stimuli that elicit achromatic synesthesias and/or the achromatic stimuli that elicit colors. With this in mind, describing the neural correlates of incongruency on that basis (i.e. incongruent > undefined) may be misleading.

It is important to note that recent behavioral studies have observed the Stroop effect in non-synesthetes who learned grapheme–color associations (Colizoli et al., 2012; Meier and Rothen, 2009), an effect which prompted studies of the neural basis of the congruency effect (Weiss et al., 2005). Therefore, caution must be taken when considering the congruency effect as an intrinsic characteristic of the synesthetic experience. Additionally, this effect is idiosyncratic of the grapheme–color modality, i.e. only in homomodal synesthesias a *concurrent-like attribute* can be attached to the *inducer* creating an artificial incongruency between them. Thus, the investigation of the congruency effect allows restricted inference about the neural basis of other modalities of synesthesia.

In the present study, only *associator* synesthetes were investigated. *Projector* synesthetes may show a different pattern of activation in response to *inducers* which elicit achromatic synesthesias. Nonetheless, given the higher prevalence of *associators* among synesthetes (Niccolai et al., 2012c) these results largely contribute to the understanding of the neural mechanisms of the phenomenon. These data fit not only with previous anatomical and functional evidence, but also with phenomenological reports. For example, the absence of functional alterations in response to incongruency is coherent with the existence of an emotional component that does not interfere with the everyday experience of reading for grapheme–color synesthetes. Nonetheless, this empirical evidence is not sufficient to establish a relation between emotion and synesthesia. Direct measures of the neural basis of the emotional quality of synesthetic experiences are still needed to fully understand the unified conscious experience of synesthesia.

Conclusions

The analysis of brain activation in response to *real* chromatic/achromatic stimuli has revealed no differences between synesthetes and controls and has failed to provide proof for bidirectionality. This together with the differences found in the neural mechanisms which underlie *real* and synesthetic perceptions of chromaticity and achromaticity, constitutes additional evidence about the different qualitative nature of *real* and synesthetic colors. The inclusion, for the first time, of achromatic *inducers* and *concurrents* in the fMRI investigation of the phenomenon has provided new data about the neural basis of synesthesia. The functional peculiarities of the synesthetic brain are distributed, reflecting different components of the synesthetic experience: a perceptual component, an (attentional) feature binding component and an emotional component. These three components are interrelated, and help explain the richness of synesthetic chromatic/achromatic experiences in response to graphemic *inducers*. Additionally, the inclusion of achromatic experiences has provided new evidence in favor of the emotional binding theory, a line of interpretation which constitutes a bridge between grapheme–color synesthesia and other developmental modalities of the phenomenon.

Acknowledgments

We thank the participants and the technical staff at the 3 T scanner facility of Fundación Centro de Investigación de Enfermedades Neurológicas for their essential collaboration in this study. Financial support was provided by the Universidad Complutense de Madrid, Fundación Centro de Investigación de Enfermedades Neurológicas and Ministerio de Ciencia e Innovación PSI2009-14415-C03-03.

Conflict of interest

The authors declare that they have no competing interests. This work conforms to Standard 8 of the American Psychological Association's Ethical Principles of Psychologist and Code of Conduct.

References

Banissy, M.J., Ward, J., 2007. Mirror-touch synesthesia is linked with empathy. Nat. Neurosci. 10, 815–816.

Banissy, M.J., Walsh, V., Ward, J., 2009. Enhanced sensory perception in synaesthesia. Exp. Brain Res. 196, 565–571.

Barbas, H., 2007. Flow of information for emotions through temporal and orbitofrontal pathways. J. Anat. 211 (2), 237–249.

Bartels, A., Zeki, S., 2000. The architecture of the colour centre in the human visual brain: new results and a review. Eur. J. Neurosci. 12, 172–193.

Bodden, M.E., Kubler, D., Knake, S., Menzler, K., Heverhagen, J.T., Sommer, J., Kalbe, E., Krach, S., Dodel, R., 2013. Comparing the neural correlates of affective and cognitive theory of mind using fMRI: involvement of the basal ganglia in affective theory of mind. Adv. Cogn. Psychol. 9, 32–43.

Calkins, M.W., 1895. Synaesthesia (minor studies from Wellesley College). Am. J. Psychol. 7, 90–107.

Callejas, A., Acosta, A., Lupianez, J., 2007. Green love is ugly: emotions elicited by synesthetic grapheme–color perceptions. Brain Res. 1127, 99–107.

Cavada, C., Company, T., Tejedor, J., Cruz-Rizzolo, R.J., Reinoso-Suarez, F., 2000. The anatomical connections of the macaque monkey orbitofrontal cortex. A review. Cereb. Cortex 10 (3), 220–242.

Colizoli, O., Murre, J.M., Rouw, R., 2012. Pseudo-synesthesia through reading books with colored letters. PLoS ONE 7 (6), e39799.

Cytowic, R.E., 1989. Synesthesia: A Union of the Senses. Springer, New York.

Cytowic, E.R., Eagleman, D.M., 2009. Wednesday Is Indigo Blue: Discovering the Brain of Synesthesia. MIT Press, Cambridge.

Day, S., 2005. Some demographic and socio-cultural aspects of synesthesia. In: Robertson, C.L., Sagiv, N. (Eds.), Synesthesia: Perspectives From Cognitive Neuroscience. Oxford University Press.

Dixon, M., Smilek, D., Merikle, P., 2004. Not all synaesthetes are created equal: projector versus associator synaesthetes. Cogn. Affect. Behav. Neurosci. 4, 335–343.

Dovern, A., Fink, G.R., Fromme, A.C., Wohlschlager, A.M., Weiss, P.H., Riedl, V., 2012. Intrinsic network connectivity reflects consistency of synesthetic experiences. J. Neurosci. 32, 7614–7621.

Eagleman, D.M., Kagan, A.D., Nelson, S.S., Sagaram, D., Sarma, A.K., 2007. A standardized test battery for the study of synesthesia. J Neurosci Meth. 159, 139–145.

Erskine, H., Mattingley, J.B., Arnold, D.H., 2012. Synaesthesia and colour constancy. Cortex 49, 1082–1088.

Evans, A.C., Collins, D.L., Mills, S.R., Brown, E.D., Kelly, R.L., Peters, T.M., 1993. 3D statistical neuroanatomical models from 305 MRI volumes. Paper presented at: Nuclear Science Symposium and Medical Imaging Conference, IEEE Conference Record. CA, San Francisco.

Gauthier, I., Tarr, M.J., Bub, D., 2010. Perceptual expertise: bridging brain and behavior. Oxford University Press, Oxford.

Gray, J.A., Parslow, D.M., Brammer, M.J., Chopping, S., Vythelingum, G.N., ffytche, D.H., 2006. Evidence against functionalism from neuroimaging of the alien colour effect in synaesthesia. Cortex 42, 309–318.

Hadjikhani, N., Liu, A.K., Dale, A.M., Cavanagh, P., Tootell, R.B., 1998. Retinotopy and color sensitivity in human visual cortical area V8. Nat. Neurosci. 1, 235–241.

Haines, D., 2011. Neuroanatomy: an atlas of structures, sections and systems, 8th edn. Wolters Kluwer (Health)/Lippincott Williams & Wilkins, Philadelphia.

Hänggi, J., Beeli, G., Oechslin, M.S., Jäncke, L., 2008. The multiple synaesthete E.S.: neuroanatomical basis of interval-taste and tone-colour synaesthesia. NeuroImage 43 (2), 192–203.

Hänggi, J., Wotruba, D., Jancke, L., 2011. Globally altered structural brain network topology in grapheme–color synesthesia. J. Neurosci. 31, 5816–5828.

Hochel, M., Milán, E., 2008. Synaesthesia: the existing state of affairs. Cogn. Neuropsychol. 25, 93–117.

Hong, S.W., Blake, R., 2008. Early visual mechanisms do not contribute to synesthetic color experience. Vision Res. 48, 1018–1026.

Hubbard, E.M., Arman, A.C., Ramachandran, V.S., Boynton, G.M., 2005. Individual differences among grapheme–color synesthetes: brain–behavior correlations. Neuron 45, 975–985.

Hubbard, E.M., Brang, D., Ramachandran, V.S., 2011. The cross-activation theory at 10. J. Neuropsychol. 5, 152–177.

Hupé, J.M., Bordier, C., Dojat, M., 2011. The neural bases of grapheme–color synesthesia are not localized in real color-sensitive areas. Cereb. Cortex 22, 1622–1633.

Jäncke, L., Beeli, G., Eulig, C., Hänggi, J., 2009. The neuroanatomy of grapheme–color synesthesia. Eur. J. Neurosci. 29, 1287–1293.

Kim, C., Blake, R., Palmeri, T., 2006. Perceptual interaction between real and synesthetic colors. Cortex 42, 195–203.

Kringelbach, M.L., 2005. The human orbitofrontal cortex: linking reward to hedonic experience. Nat. Rev. Neurosci. 6 (9), 691–702.

Kringelbach, M.L., Berridge, K.C., 2010. The functional neuroanatomy of pleasure and happiness. Discov. Med. 9 (49), 579–587.

Lueck, C.J., Zeki, S., Friston, K.J., Deiber, M.P., Cope, P., Cunningham, V.J., Lammertsma, A.A., Kennard, C., Frackowiak, R.S., 1989. The colour centre in the cerebral cortex of man. Nature 340, 386–389.

Marks, L.E., 2011. Synesthesia, then and now. Intellectica 1, 47–80.

Mattingley, J.B., Payne, J.M., Rich, A.N., 2006. Attentional load attenuates synaesthetic priming effects in grapheme-colour synaesthesia. Cortex 42, 213–221.

Meier, B., Rothen, N., 2009. Training grapheme-colour associations produces a synaesthetic Stroop effect, but not a conditioned synaesthetic response. Neuropsychologia 47 (4), 1208–1211.

Melero, H., Pena-Melian, A., Rios-Lago, M., Pajares, G., Hernandez-Tamames, J.A., Alvarez-Linera, J., 2013. Grapheme–color synesthetes show peculiarities in their emotional brain: cortical and subcortical evidence from VBM analysis of 3D-T1 and DTI data. Exp. Brain Res. 227, 343–353.

Niccolai, V., Wascher, E., Stoerig, P., 2012a. Distinct neural processes in grapheme-colour synaesthetes and semantic controls. Eur. J. Neurosci. 36, 3593–3601.

Niccolai, V., van Leeuwen, T.M., Blakemore, C., Stoerig, P., 2012b. Synaesthetic perception of colour and visual space in a blind subject: an fMRI case study. Conscious. Cogn. 21, 889–899.

Niccolai, V., Jennes, J., Stoerig, P., Van Leeuwen, T.M., 2012c. Modality and variability of synesthetic experience. Am. J. Psychol. 125, 81–94.

Nikolic, D., Lichti, P., Singer, W., 2007. Color opponency in synaesthetic experiences. Psychol Sci. 18, 481–486.

Njemanze, P.C., Gomez, C.R., Horenstein, S., 1992. Cerebral lateralization and color perception: a transcranial Doppler study. Cortex 28, 69–75.

Nolte, J., Angevine, J., 2007. The human brain in photographs and diagrams, 3rd edn. Mosby Elsevier, Philadelphia.

Nunn, J.A., Gregory, L.J., Brammer, M., Williams, S.C.R., Parslow, D.M., Morgan, M.J., Morris, R.G., Bullmore, E.T., Baron-Cohen, S., Gray, J.A., 2002. Functional magnetic resonance imaging of synesthesia: activation of V4/V8 by spoken words. Nat. Neurosci. 5, 371–375.

Paulesu, E., Harrison, J., Baron-Cohen, S., Watson, J.D., Goldstein, L., Heather, J., Frackowiak, R.S., Frith, C.D., 1995. The physiology of coloured hearing. A PET activation study of colour-word synaesthesia. Brain 118 (3), 661–676.

Perry, A., Henik, A., 2013. The emotional valence of a conflict: implications from synesthesia. Front. Psychol. 4, 978.

Ramachandran, V.S., Hubbard, E.M., 2001. Psychophysical investigations into the neural basis of synaesthesia. Proc. R. Soc. Lond. 268, 979–983.

Rich, A., Bradshaw, J., Mattingley, J., 2005. A systematic, large-scale study of synaesthesia: implications for the role of early experience in lexical-colour associations. Cognition 98, 53–84.

Rich, A., Williams, M., Puce, A., Syngeniotis, A., Howard, M., McGlone, F., Mattingley, J., 2006. Neural correlates of imagined and synaesthetic colours. Neuropsychologia 44, 2918–2925.

Rouw, R., Scholte, H.S., 2007. Increased structural connectivity in grapheme–color synesthesia. Nat. Neurosci. 10, 792–797.

Rouw, R., Scholte, H.S., 2010. Neural basis of individual differences in synesthetic experiences. J. Neurosci. 30, 6205–6213.

Rouw, R., Scholte, H.S., Colizoli, O., 2011. Brain areas involved in synaesthesia: a review. J. Neuropsychol. 5, 214–242.

Rouw, R., van Driel, J., Knip, K., Richard Ridderinkhof, K., 2013. Executive functions in synesthesia. Conscious. Cogn. 22, 184–202.

Rudrauf, D., Lutz, A., Cosmelli, D., Lachaux, J.P., Le Van Quyen, M., 2003. From autopoiesis to neurophenomenology: Francisco Varela's exploration of the biophysics of being. Biol. Res. 36, 27–65.

Sereno, M.I., Dale, A.M., Reppas, J.B., Kwong, K.K., Belliveau, J.W., Brady, T.J., Rosen, B. R., Tootell, R.B., 1995. Borders of multiple visual areas in humans revealed by functional magnetic resonance imaging. Science 268, 889–893.

Shapley, R., Hawken, M.J., 2011. Color in the cortex: single- and double-opponent cells. Vision Res. 51 (7), 701–717.

Simner, J., Mulvenna, C., Sagiv, N., Tsakanikos, E., Witherby, S.A., Fraser, C., Scott, K., Ward, J., 2006. Synaesthesia: the prevalence of atypical cross-modal experiences. Perception 35, 1024–1033.

Sinke, C., Neufeld, J., Emrich, H.M., Dillo, W., Bleich, S., Zedler, M., Szycik, G.R., 2012. Inside a synesthete's head: a functional connectivity analysis with grapheme–color synesthetes. Neuropsychologia 50, 3363–3369.

Skelton, R., Ludwig, C., Mohr, C., 2007. A novel, illustrated questionnaire to distinguish projector and associator synaesthetes. Cortex 45, 721–729.

Specht, K., Laeng, B., 2011. An independent component analysis of fMRI data of grapheme-colour synaesthesia. J. Neuropsychol. 5, 203–213.

Sperling, J.M., Prvulovic, D., Linden, D.E., Singer, W., Stirn, A., 2006. Neuronal correlates of colour-graphemic synaesthesia: a fMRI study. Cortex 42, 295–303.

Trkanjec, Z., Demarin, V., 2007. Hemispheric asymmetries in blood flow during color stimulation. J. Neurol. 254, 861–865.

van Leeuwen, T.M., Petersson, K.M., Hagoort, P., 2010. Synaesthetic colour in the brain: beyond colour areas. A functional magnetic resonance imaging study of synaesthetes and matched controls. PLoS ONE 5 (8), e12074.

Ward, J., 2004. Emotionally mediated synaesthesia. Cogn. Neuropsychol. 21, 761–772.

Weiss, P.H., Fink, G.R., 2009. Grapheme-colour synaesthetes show increased grey matter volumes of parietal and fusiform cortex. Brain 132, 65–70.

Weiss, P.H., Zilles, K., Fink, G.R., 2005. When visual perception causes feeling: enhanced cross-modal processing in grapheme–color synesthesia. NeuroImage 28, 859–868.

Zeki, S., Watson, J.D., Lueck, C.J., Friston, K.J., Kennard, C., Frackowiak, R.S., 1991. A direct demonstration of functional specialization in human visual cortex. J. Neurosci. 11, 641–649.