

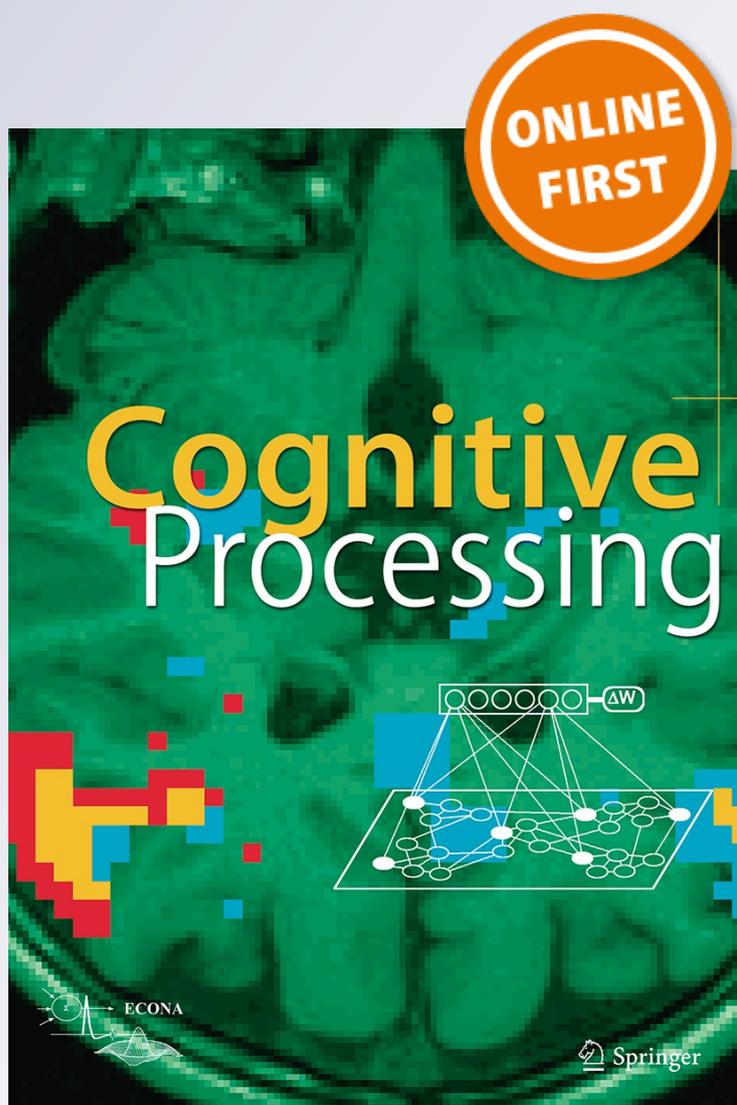
Why Saturday could be both green and red in synesthesia

Michele Miozzo & Bruno Laeng

Cognitive Processing
International Quarterly of Cognitive
Science

ISSN 1612-4782

Cogn Process
DOI 10.1007/s10339-016-0769-2



 Springer

Your article is protected by copyright and all rights are held exclusively by Marta Olivetti Belardinelli and Springer-Verlag Berlin Heidelberg. This e-offprint is for personal use only and shall not be self-archived in electronic repositories. If you wish to self-archive your article, please use the accepted manuscript version for posting on your own website. You may further deposit the accepted manuscript version in any repository, provided it is only made publicly available 12 months after official publication or later and provided acknowledgement is given to the original source of publication and a link is inserted to the published article on Springer's website. The link must be accompanied by the following text: "The final publication is available at link.springer.com".

RESEARCH REPORT

Why Saturday could be both green and red in synesthesia

Michele Miozzo^{1,2} · Bruno Laeng³Received: 16 July 2015 / Accepted: 31 May 2016
© Marta Olivetti Belardinelli and Springer-Verlag Berlin Heidelberg 2016

Abstract It has long been observed that certain words induce multiple synesthetic colors, a phenomenon that has remained largely unexplored. We report here on the distinct synesthetic colors two synesthetes experienced with closed sets of concepts (digits, weekdays, months). For example, *Saturday* was associated with green, like other word starting with *s*; however, *Saturday* also had its specific color (red). Auditory priming and Visual Color Stroop tasks were used to understand the cognitive mechanisms supporting the distinct synesthetic colors. Results revealed that processing of word segments and whole words was specifically involved in each type of synesthetic colors. However, these mechanisms differed between participants, as they could relate either to orthography (and written words) or phonology (and spoken words). Further differences concerned the word representations, which varied as to whether or not they encoded serial positions. In addition to clarifying the cognitive mechanisms underlying the distinct synesthetic colors, our results offer some clues for understanding the neurocognitive underpinnings of a rather common form of synesthesia.

Keywords Synesthesia · Color synesthesia · Word processing

In one of the very first detailed descriptions on synesthesia, published in 1812, Sachs noticed that both letters and words could generate color perceptions. This was probably not coincidental, as recent surveys have revealed that some of the most common forms of synesthesia are associated with both of these stimuli (Johnson et al. 2013; Rich et al. 2005; Simner et al. 2006; Simner and Haywood 2009). Strikingly, Sachs also reported that the same individual perceived distinct synesthetic colors for a word and its constituent letters, a form of multicolor synesthesia recorded in several other studies ever since (e.g., Bleuler and Lehmann 1881; Galton 1883; Holden 1885; Krohn 1892; Paulesu et al. 1995; Rich et al. 2005). This type of color synesthesia has been described anecdotally and remains relatively under-investigated, despite its frequency and—perhaps more importantly—the interesting questions it raises: Are there different underlying neurocognitive mechanisms for the distinct synesthetic colors induced by the word and its constituents? Do each of these distinct synesthetic colors emerge at different points in the development? And are these distinct synesthetic colors rooted in the same neurodevelopmental processes (e.g., incomplete neural pruning)? The present study represents the first systematic investigation of this peculiar form of color synesthesia and reports on two synesthetes (CB and VS).

Recent studies conducted on large groups of synesthetes have shown that inducers (i.e., the stimuli eliciting synesthetic colors) are less idiosyncratic than commonly assumed and recurring patterns are discernible across individuals. For example, synesthetes tend to associate higher frequency letters with higher frequency color terms

Handling editor: Marta Olivetti Belardinelli, Sapienza University of Rome.

Reviewers: Aurora Rizza, Sapienza University of Rome; Lutz Jaencke, University of Zurich.

✉ Michele Miozzo
mm1150@columbia.edu

¹ Department of Psychology, The New School, 80 Fifth Avenue, New York, NY 10011, USA

² Johns Hopkins University, Baltimore, MD, USA

³ University of Oslo, Oslo, Norway

(Rich et al. 2005; Simner et al. 2005), more frequent digits with more luminous colors (Beeli et al. 2007), and often the first letter of a color term reliably induces that color, as in the case of blue experienced for *b* or yellow for *y* (Day 2005; Rich et al. 2005; Simner et al. 2005). Furthermore, items at the beginning of a series (1 for digits, *Monday* for weekdays, *January* for months) tend to receive pale colors (Rich et al. 2005). Moreover, semantic associations can occasionally underlie color assignment, as when *D* is related to brown via *dog* (Hancock 2013; Rich et al. 2005). In light of these patterns, the distinct synesthetic colors associated with a word might depend on the different susceptibility to variables like the frequency of color names or semantic associations. Under this account, each of the distinct synesthetic colors related to an individual word could reflect the ontogenesis of color associations. But the reason for the distinct synesthetic colors could be related to differences in the neurocognitive mechanisms underlying each type of synesthetic colors. This is the hypothesis we tested in the present study.

As described in prior reports of color synesthesia, inducers vary in modality, corresponding to written letters and words or phonemes and spoken words (Rich et al. 2005; Simner 2006). We first determined whether the inducers of distinct synesthetic colors could also vary in modality (orthographic vs. phonological), if not within a synesthete, at least across individuals. To this end, we examined the effects of words presented auditorily and visually in two tasks—Auditory Priming and Visual Color Stroop—that have been extensively investigated in synesthesia research as they involve automatic and implicit word processing (Dixon et al. 2000; Gebius et al. 2009; Gray et al. 2006; Mattingley et al. 2001; Mills et al. 1999; Ward et al. 2006; Woolen and Ruggiero 1983). In the Auditory Priming Task, auditory words preceded the presentation of colored squares, whose colors the participants named. In the Visual Color Stroop Task, participants named the colors of visually presented words. Previous results have shown that color-naming latencies in both tasks depended on whether the inducers elicited the same colors named by the synesthetes. In the present study we examined whether similar effects would appear in these tasks with one or both of the distinct synesthetic colors induced by a word. Such effects would reveal the modality of the inducers: phonological, if effects appear in the Auditory Priming Task, orthographic if effects appear in the Visual Color Stroop Task. These effects would also inform us on the representations involved in the distinct synesthetic colors. Effects in the Auditory Priming Task would imply phonological representations implicated in speech recognition. However, it is more complicated to draw conclusions about the representations underlying synesthesia when inducers are written words. The reason is that

orthographic representations and phonological representations are both automatically accessed from written words, as shown by results from research on reading processing (Carreiras et al. 2005; Frost et al. 2003; Lukatela and Turvey 1990). Therefore, not only access to orthographic representations but also access to phonological representations could, at least in part, contribute to the appearance of synesthetic colors with written stimuli. As described in detail below, we conducted further tests to determine the engagement of orthographic and phonological representations with written words.

A distinction is typically made at the level of speech comprehension processing between representations encoding information about the whole word and the word constituents (e.g., phonemes) (McQueen 2007; Remez 2005). Parallel distinctions are made between lexical and sublexical representations at the level of orthographic processes (Coltheart et al. 2001; Grainger et al. 2008). In light of these distinctions, we can ask whether lexical and sublexical representations are differently involved in the multiple synesthetic colors elicited by an individual word. As a first step toward answering this question, we determined whether some of the synesthetic colors were related to the individual segments (phonemes or letters) of the words. A common finding in color synesthesia is that the color of the entire word depends on the initial word segment(s), as demonstrated by the very similar colors associated with onset-related words like *cat-cap-cab* or *tip-table-team* (e.g., Krohn 1892; Paulesu et al. 1995; Simner 2006; Ward et al. 2005). We tested this hypothesis by comparing the words associated with multiple colors and their onset-related words. Let us suppose that the word *Saturday* was associated with green and red. We compared *Saturday* with its onset-related word *satire* and examined whether the synesthetic color of *satire* was one of the synesthetic colors of *Saturday*, either green or red. We tested this hypothesis not only by determining the similarity of the colors assigned to *Saturday* and *satire*, but also by investigating whether *Saturday* and *satire* induced similar effects in Auditory Priming and Visual Color Stroop tasks. Similarities between *Saturday* and *satire* would establish that one synesthetic color of *Saturday* relates to the segments of *Saturday*. We refer to this shared synesthetic color as the *segment color*. The segments crucial for the appearance of segment colors could be either phonemes or graphemes, depending on whether speech processing or orthographic processing underlies color synesthesia. It should be noted that the term *segment color* is neutral with respect to the modality (phonological vs. orthographic) of the sublexical representation related to color synesthesia. In contrast, the term *word color* will be used to refer to synesthetic colors not shared by onset-related words. For example, the word color of *Saturday* is

the synesthetic color that differs from the synesthetic color of *satire*. Being related to entire words, word colors are, almost by definition, related to lexical representations. These representations can be either phonological or orthographic, depending on whether speech processing or orthographic processing is related to synesthesia. Like the term *segment color*, the term *word color* is also modality-neutral. Importantly, clear predictions follow from the hypothesis that different representations support the appearance of segment colors and word colors. In fact, this hypothesis anticipates differences between the effects induced by each type of synesthetic color in Auditory Priming and Visual Color Stroop Tasks.

An opportunity to further clarify whether lexical or sublexical representations are related to word colors and segment colors, respectively, arises in speech recognition. Activation in speech recognition rises faster and decays more quickly with phonemes as compared to whole words. A host of data has demonstrated the different time-courses of phoneme versus word activation (for review see e.g., Poeppel and Monahan 2008; Remez 2005), a distinction incorporated in models of speech recognition (e.g., TRACE by McClelland and Elman 1986; the cohort model by Marslen-Wilson 1987). If lexical and sublexical levels of processing contribute separately to synesthetic colors, then segment colors should appear faster and fade earlier compared to word colors. These predictions were tested specifically in the Auditory Priming Task varying the prime–target interval, a procedure that allows tracking the time-course of activation.

Researchers have drawn attention to the fact that digits, weekdays and months, which are among the most common inducers of color synesthesia (Pariyadath et al. 2012; Sagiv et al. 2006; Shanon 1982), refer to sequences—a feature also shared by musical notes, another type of stimulus frequently associated with synesthesia (Day 2005; Marks 1975). The words that previous anecdotal reports indicated as eliciting multiple colors were typically digits, weekdays, and months (e.g., Galton 1883; Paulesu et al. 1995; Rich et al. 2005), all words related to sequences, either numerical or chronological. As described below, this was also true for our synesthete participants. The specificity of these words led us to investigate whether *word colors* could be related to representations encoding ordinal sequences. The relevance of sequences in synesthesia could reflect the involvement of parietal regions—especially the intraparietal sulcus—that have been implicated in the computation of sequences (e.g., numerical sequences; Hubbard et al. 2005) and are part of the neural network enabling some synesthetes to form mental images or spatial forms of the sequence of numbers (Jonas and Jarick 2013; Tang et al. 2008).

A few recent studies have started to unveil the neural fibers connecting regions processing linguistic stimuli to

regions processing colors (Dovern et al. 2012; Gray et al. 2006; Jäncke et al. 2009; Rouw and Scholte 2007; Tomson et al. 2013; van Leeuwen et al. 2011; for review, see Hupé and Doja 2015), a critical component of the neural system unique to synesthesia possibly resulting from incomplete neural pruning (Baron-Cohen et al. 1993; Cytowic and Wood 1982; Harrison 2001; Maurer 1997), atypical hyperconnectivity and/or disinhibition among these connections (Grossenbacher and Lovelace 2001; Hänggi et al. 2011; Rouw 2013; Smilek et al. 2001). Although our results aimed primarily to define the cognitive mechanisms underlying the multiple synesthetic colors elicited by individual words, they could constrain hypotheses about the neural mechanisms underpinning the experience of multiple synesthetic colors. A first contribution in this direction came from determining whether phonological and/or orthographic representations were involved in the multiple synesthetic colors. As partially distinct neural structures support phonological and orthographic processing (Dehaene and Cohen 2011; Price 2012; Vigneau et al. 2006), determining whether synesthesia depends on phonological or orthographic representations has clear implications for outlining the neural system of synesthesia. Determining whether lexical or sublexical representations are involved in forms of multicolor synesthesia would have further implications. For example, neuroimaging results have revealed a posterior–anterior organization in the fusiform areas implicated in reading and writing, with more posterior regions responding to graphemes and more anterior regions to entire words (Cohen et al. 2000; Vinckier et al. 2007). Synesthetic colors specifically related to graphemes or orthographic words might differently engage posterior and anterior regions in the fusiform gyrus. Finally, exploring whether some of the synesthetic colors are associated with sequences could give us some clues as to whether there is an involvement of parietal processing. As mentioned earlier, activation in parietal areas has been implicated in various forms of synesthesia related to sequences and numbers (Jonas and Jarick 2013; Tang et al. 2008).

The next sections are organized as follows. In the ‘[Case Description](#)’ section, we provide biographical information for each participant. In the following section—‘[Experimental Investigation](#)’—we report results informing on (a) what linguistic representations underlie the different types of synesthetic colors in CB in VS, (b) the time-course of their synesthetic colors, and (c) the role of serial positions.

Case Descriptions

Both synesthete participants (CB and VS) were female, right-handed English speakers, with post-graduate degrees, in their fifties at the time of their participation in the study.

CB was a university professor; VS a library director, with a previous occupation as a textile designer. Their medical history was uneventful for cognitive, neurological, and psychiatric episodes, and they reported having experienced synesthetic colors since early childhood. A sister is the only other member in both of their families believed to be a synesthete. The Farnsworth-Munsell 100 Hues Test revealed normal color sensitivity.

CB and VS reported perceiving synesthetic colors, both regularly and automatically, when reading and listening to words. As in previous studies (Baron-Cohen et al. 1987; Laeng et al. 2004; Johnson et al. 2013; but see also Binet and Philippe 1892), the genuineness of their synesthesia was assessed by examining the test–retest consistency of the colors assigned to letters ($N = 26$) and words ($N = 24$; words did not refer to objects with specific colors). Each stimulus was named by the experimenter as soon as it appeared in black on the computer screen. Stimuli remained in view until a color was selected from the pantone palette of Microsoft Word that displayed about 16.5 million colors. Color assignment was retested 4 months later with CB and VS, 1 week later with five age-matched non-synesthete participants. Euclidean distances were measured using the RGB values of the colors selected at test and retest. Distances were considerably shorter for CB (mean = 23.1) and VS (mean = 16.8) relative to controls (range 117–174), a result confirming the genuineness of the synesthetic colors perceived by CB and VS.

CB and VS both reported experiencing synesthetic colors in external space, the defining feature of projector synesthetes (Dixon et al. 2004). Like other projector synesthetes (Laeng et al. 2004; Smilek et al. 2001), CB showed a synesthetic color pop-out-like effect. An increase in distractor number did not result in longer search times with target and distractor (black) digits that CB associated with distinct synesthetic colors; such an increase appeared, however, with target and distractor digits that CB associated with the same synesthetic color. The lack of synesthetic color pop-out-like effect with VS suggests a more diffuse, less localized form of color projection than CB's.

Experimental investigation

Color assignments

A preliminary test was conducted to determine what kinds of synesthetic colors CB and VS would associate with different types of words. We used the color assignment procedure described earlier (see 'Case Description' section) that required the selection of the colors best corresponding to a certain word. The color selections obtained in this preliminary test were used in more rigorous tests of

color synesthesia presented below. Color assignments were obtained for three types of words. First, we obtained them for names of weekdays, months and digits, all words that, as reviewed in the Introduction, have been reported as eliciting distinct types of synesthetic colors in prior anecdotal descriptions (e.g., Galton 1883; Paulesu et al. 1995; Rich et al. 2005). Second, we obtained colors for a set of words that were onset-related to weekdays and months (e.g., *satire* for *Saturday*) to determine whether some of the synesthetic colors elicited by weekdays and months were actually related to segments in initial word positions, as reported in prior cases (e.g., Krohn 1892; Paulesu et al. 1995; Simmer 2006; Ward et al. 2005). We selected two onset-related words for each weekday and month, which were comparable to onset-related words for letter length (means: 6.5 vs. 6.0; $t < 1$) and phoneme length (means: 5.4 vs. 5.1; $t < 1$), and shared an average of 50 % of the letters and 59 % of the phonemes. Third, we obtained colors for a second set of onset-related words (e.g., *helmet-helicopter*) to determine whether similarities between the colors obtained with weekdays and months and their onset-related words generalized to other onset-related words. The onset-related words in this second set were similar for letter length (means: 6.0 vs. 5.5; $t < 1$) and phoneme length (means: 4.9 vs. 4.6; $t < 1$), and shared an average of 50 % of their letters and 57 % of their phonemes. Shared letters/phonemes were at the beginning of words. The two sets of onset-related words were matched by number ($N = 38$) as well as by letter/phoneme length and overlap ($ts < 1$).

CB and VS selected two colors for each of the weekdays, months and digits, and for each word, the colors differed greatly one from the other. For example, CB chose pink and red for *Monday*, and VS associated *Saturday* with green and red (see Table 1 for additional examples). By contrast, each of the other words was associated with a single synesthetic color; therefore, *mitten* was 'only' red for CB, 'only' pink for VS. Furthermore, onset-related words tended to have similar colors, as it was apparent not only with word pairs like *helmet-helicopter*, but also with weekdays and months and their onset-related words. For example, purple was one of the colors CB selected for *Friday* and her choice for *friend*, while green was one of the colors VS identified for *Saturday* and her choice for *satire*. Thus, CB and VS's color choices appeared to be determined by word onset, which was true also for some of the colors they selected for weekdays and months. Finally, as evident from the examples cited thus far, the colors selected for the same word differed greatly between participants—e.g., *Tuesday* was green and gray for CB, but blue and black for VS; *whistle* was brown for CB, but purple for VS.

The distinct colors CB and VS assigned to weekdays, months and digits were grouped into two sets. One set

Table 1 Examples of color assignments (based on basic color terms)

VS			CB		
Word	Segment colors	Word colors	Word	Segment colors	Word colors
<i>Monday</i>	Pink	White	<i>Monday</i>	Red	Pink
<i>Tuesday</i>	Black	Blue	<i>Tuesday</i>	Gray	Green
<i>Saturday</i>	Green	Red	<i>Wednesday</i>	Brown	Purple
<i>January</i>	Black	Gray	<i>Thursday</i>	Gray	Green
<i>June</i>	Black	Blue	<i>Friday</i>	Purple	Blue
1	Purple	Gray	2	Gray	Yellow
2	Black	Gray	4	Purple	Pink
3	Gray	Pink	5	Purple	Blue
<i>Money</i>	Pink		<i>Money</i>	Red	
<i>Tulip</i>	Black		<i>Tulip</i>	Gray	
<i>Satire</i>	Green		<i>Wench</i>	Brown	
<i>Janitor</i>	Black		<i>Thermos</i>	Gray	
<i>Junior</i>	Black		<i>Fried</i>	Purple	

Table 2 Mean Euclidean distances between synesthetic colors selected by VS and CB

Words/synesthetic colors	Examples	Euclidian distance (Mean)	
		VS	CB
Weekdays and months	<i>Saturday versus Saturday</i>	77.4	179.1
Segment colors versus word colors			
Word colors	<i>Saturday versus satire</i>	71.6	151.6
Weekdays and months versus onset-related words			
Segment colors	<i>Saturday versus satire</i>	16.8	66.5
Weekdays and months versus onset-related words			
Onset-related words	<i>Helicopter versus helmet</i>	17.0	62.8
segment colors			

included the colors that were similar to those that CB and VS assigned to onset-related words. For example, here the color of *Saturday* was green, the same color of the onset-related word *satire*. Hereof, we will refer to this set of synesthetic colors as *segment colors*, a term underscoring the relationship between these synesthetic colors and word segments. The colors in the other set were unique to weekdays, months and digits differing from those assigned to onset-related words. For example, here the color of *Saturday* was red, which differed from green, the color of *satire*. Hereof, we will refer to this set of synesthetic colors as *word colors*. The term *segment color* will be used in reference not only to weekdays, months and digits, but also to any other word. Thus, the green of *Saturday* and the green of *satire* will both be identified as *segment colors*. This contrasts with the term *word color*, which is used only in reference to weekdays, months and digits.

The RGB values of segment and word colors were analyzed to characterize similarities and differences

between the two types of synesthetic colors. As shown by the data in Table 2, weekdays and months had segment colors that were more distant from their word colors than from the segment colors of their onset-related words [CB: means = 179.1 vs. 66.5, $F(1, 36) = 40.15$, $p < .0001$; $\eta^2 = .64$; VS: means = 77.4 vs. 16.8, $F(1, 36) = 33.99$, $p < .0001$; $\eta^2 = .53$]. Furthermore, the segment colors of weekdays and months (e.g., *Saturday*) were as close to the synesthetic colors of their onset-related words (e.g., *satire*) as the synesthetic colors of other pairs of onset-related words (*helmet-helicopter*; means: CB = 66.5 vs. 62.8, VS = 16.8 vs. 17.0; $F_s < 1$). Altogether, these data confirmed that a word elicited a segment color that differed from its word color. CB and VS's color selections provided the first indication that at least some of the word stimuli generated different synesthetic colors. In addition, these color selections confirmed that onset-related words elicited very similar synesthetic colors (e.g., *helmet* and *helicopter* were both associated by VS with green). These

similarities extended to weekdays and months and their onset-related words (*Saturday* and *satire*), a finding suggesting that one of the two synesthetic colors elicited by weekdays and months was related to word segments.

Auditory priming tasks

A first test of the distinct but seemingly overlapping appearance of segment and word colors was undertaken using the auditory priming paradigm. Auditory words presented as primes were immediately followed by a colored square whose color was named by CB and VS. We varied whether or not color targets matched the synesthetic colors CB and VS assigned to the word primes, anticipating faster color naming responses with color-congruent prime–target pairs. As priming effects involve automatic and implicit mechanisms (Anderson and Holcomb 1995; McNamara 2005), the appearance of priming with segment colors and word colors would represent strong evidence of the genuineness of the synesthetic colors experienced by CB and VS. The auditory nature of the primes provided an additional reason for investigating the auditory priming paradigm, specifically to determine whether or not speech recognition mechanisms were involved in both types of synesthetic colors and with both participants. These questions were addressed with all types of words CB and VS reported as inducing segment and word colors (weekdays, months and digits). Additional questions were investigated using words that were onset-related to weekdays and months (e.g., *satire* for *Saturday*) as primes. Onset-related primes were shown either with the segment colors or the word colors of their related words—e.g., *satire* was paired with green, the segment color of *Saturday*, and red, the word color of *Saturday*. Onset-related primes were first tested to determine whether word colors were elicited exclusively by certain words (e.g., weekdays and months). Under this hypothesis, words onset-related to weekdays and months should not induce word colors; therefore, priming effects should not appear with these onset-related words—they should be found only with weekdays and months. For instance, *satire* was not expected to affect responses to red, the word color of *Saturday*. Onset-related primes were also tested to determine whether segment colors were associated with sublexical features. This hypothesis predicts that any word prime bearing the critical segments would elicit segment colors, therefore anticipating comparable priming effects between weekdays and months and their onset-related words. For example, the segment color of *Saturday* (green) should be similarly affected by *Saturday* and *satire*.

Methods

There were different versions of the Auditory Priming Task, varying either in their primes or targets. By necessity, different word primes and color targets were tested with CB and VS, reflecting their distinct color choices. Four versions of the task were created by crossing the variables ‘synesthetic color’ (segment vs. word colors) and ‘word primes’ (weekdays, months or their onset-related words). Five words were tested in each task version of the Auditory Priming Task with CB, 6 with VS. The weekdays and the months shown in the Auditory Priming Task had to meet two criteria. First, their segment colors had to differ from their word colors (e.g., *Saturday* was paired by VS with the segment color green and the word color red). Second, their segment and word colors had to be identifiable by basic color terms (e.g., *red*, *yellow*). Since participants named the segment and word colors, it was necessary that these colors could be easily identified. In one version of the task, weekdays and months were paired with their segment colors in congruent trials, and with the segment color of another tested word in incongruent trials; however, word primes were never paired with their word colors—in this way, we specifically investigated the effects of segment colors. For example, with VS *Saturday* primed green, the segment color of *Saturday*, or pink, the segment color of *Monday*, another word prime tested in that condition; however, *Saturday* was never presented with red, the word color of *Saturday*. A similar design was used in the task version in which weekdays and months were paired with their word colors. In other two task versions, weekdays and months were substituted by onset-related words (e.g., *Saturday* by *satire*). Therefore, in different task versions, the onset-related words were paired either with the segment colors or the word colors of their corresponding weekdays and months. Weekdays and months and their onset-related words were similar in phoneme length (means: CB = 4.4 vs. 5.2, VS = 5.1 vs. 5.5), and shared 54 % of their phonemes with CB, and 60 % with VS. In each of the four task versions, congruent and incongruent prime–target pairs were presented an equal number of times (80 with CB, 96 with VS). Furthermore, individual words and colors appeared an equal number of times in congruent and incongruent word–color pairs (16 times for both participants). Primes were named by a female speaker, and the digital recordings had a mean duration of 513 ms, ranging from 406 ms (*June*) to 644 ms (*September*).

An additional version was added to test digits and the word colors of digits in order to replicate the effects of word colors with a second word set. In congruent trials, colored squares matched the word colors that CB and VS

had previously selected for the digit primes, while in incongruent trials color squares corresponded to the word colors of one of the other digits. Eight digit words (from *two* to *nine*) were used as primes with CB, seven digit words with VS. Each digit word was shown an equal number of times (eight with both participants) in congruent and incongruent trials. The digit words presented as auditory primes had an average duration of 436 ms, ranging from 325 ms (*eight*) to 532 ms (*five*).

In all conditions tested in the Auditory Priming Task, targets were colored squares with 4 cm edges that appeared centered at fixation. The colors of these squares had the same RGB specifications as either the segment colors or the word colors chosen by the participants for the weekdays, months and digits.

The procedure was the same across conditions. An auditory cue signaled the beginning of a new trial and was followed 800 ms later by the fixation point that stayed on view for the entire duration of the auditory prime. The fixation point was immediately replaced by the target that remained on screen until the naming response started. The inter-trial interval was set at 4 s. Words and colors were presented pseudo-randomly, preventing the same word or color from appearing in consecutive trials. Instructions required participants to verbally name the color in which the squares appeared on the computer screen as fast and accurately as possible. Naming latencies corresponded to the time elapsed from the appearance of the target square to the beginning of the naming response. Each task version was tested separately, at least a week apart one from the other. Stimuli presentation and the recording of response latencies were controlled by PsychScope. Responses that were fast (<300 ms) or 3 SDs above a participant's mean for that task condition were treated as outliers and excluded from analyses. Responses scored as errors included incorrect color naming, hesitations and self-corrections. Error rates were consistently low across task variants (<5%), which prevented us from carrying out reliable error analyses (as error rates were similarly low in all of the other tasks included in the present investigation, results of error analyses are not reported for the other tasks either.)

Results

As illustrated by the results in Table 3, similar response patterns were observed between participants. For both participants, color naming was faster when the weekdays and months matched the segment colors [CB: 246 ms, $F(1, 158) = 80.18$, $p < .0001$, $\eta^2 = .34$; VS: 58 ms, $F(1, 190) = 31.65$, $p < .0001$, $\eta^2 = .14$] or the word colors [CB: 363 ms, $F(1, 158) = 175.26$, $p < .0001$, $\eta^2 = .52$; VS: 73 ms, $F(1, 190) = 122.63$, $p < .0001$, $\eta^2 = .39$], when onset-related words matched segment colors [CB:

214 ms, $F(1, 158) = 117.94$, $p < .0001$, $\eta^2 = .43$; VS: 105 ms, $F(1, 190) = 180.25$, $p < .0001$, $\eta^2 = .49$], and when digit words matched word colors [207 ms, $F(1, 126) = 86.60$, $p < .0001$, $\eta^2 = .41$; VS: 35 ms, $F(1, 110) = 17.26$, $p < .0001$, $\eta^2 = .16$]. A final common result concerned onset-related words, which failed to prime word colors ($F_s < 1$).

The auditory priming effects observed with CB and VS provided clear responses to two of the questions that had motivated the investigation of these effects—one concerning the genuineness of the synesthetic experiences, the other related to the involvement of speech recognition mechanisms in the appearance of synesthetic colors. The robust priming effects found with the segment colors and the word colors of weekdays, months and digits indicated that both types of synesthetic colors were genuine and related to speech recognition mechanisms. Further conclusions can be drawn from the contrasting effects found with word primes that were onset-related to weekdays and months (e.g., *satire-Saturday*). Significant effects appeared with segment colors but not with word colors. As distinct effects were expected if word colors differed from segment colors, the contrasting results demonstrated the different nature of these synesthetic colors. Furthermore, the lack of an effect with word colors confirmed that this type of synesthetic color was exclusively associated with certain words. However, the similar priming effects found with segment colors with weekdays and months (e.g., *Saturday*) and their onset-related words (e.g., *satire*) revealed that segment colors were more pervasive and likely related to the sublexical features of the inducers. That these effects were elicited by auditory primes further implied that segment colors were related to phonemes.

Visual Color Stroop Task

Stroop-like effects have been demonstrated with synthetic colors (Dixon et al. 2000, 2006; Laeng et al. 2011; Mattingley et al. 2001; Mills et al. 1999; Myles et al. 2003) and have taken the form of fast color naming responses when colors matched the synesthetic colors induced by visually presented words. Whether similar Stroop-like effects could be observed with segment colors and word colors was examined by asking CB and VS to name the colors with which weekdays, months and onset-related words were shown, and varying whether or not these words were colored in their segment colors or their word colors. Using the Visual Color Stroop Task, we could extend to visual and orthographic domains questions we previously addressed in the speech domain, questions that were related to the genuineness of segment and word colors, the specificity of word colors, and the role of sublexical features in segment colors.

Table 3 Color-naming latencies (ms) in Auditory Priming Task (0 SOA)

Prime–target pairs	Weekdays and months (<i>Saturday</i>)		Onset-related words (<i>satire</i>)		Digit words (<i>eight</i>)
	Segment colors	Word colors	Segment colors	Word colors	Word colors
CB					
Incongruent pairs	1060	947	782	754	834
Congruent pairs	814	584	568	769	627
<i>Difference</i>	246**	363**	214**	–15	207**
VS					
Incongruent pairs	549	533	522	536	541
Congruent pairs	491	460	417	528	506
<i>Difference</i>	58**	73**	105**	8	35**

** $p < .0001$

Methods

The words and colors tested in the Visual Color Stroop Task were the same used previously in four of the versions of the Auditory Priming Task, which were created by crossing the variables ‘synesthetic color’ (segment and word colors) and ‘word distractors’ (weekdays and months and their onset-related words). Weekdays and months were similar in letter length to the corresponding onset-related words (mean: CB = 5.8 vs. 7, VS = 6 vs. 6.5) and shared 41 % of their letters with CB, and 52 % with VS. Words were shown in their corresponding segment colors (or word colors) in congruent trials, or in the segment colors (or word colors) associated with one of the other words tested in the same condition of the Visual Color Stroop Task in the incongruent trials. Word–color pairs were the same as those used in the Auditory Priming Task. Across task versions, the same number of word pairs was presented in congruent and incongruent conditions (80 with CB, 48 with VS), and individual words and colors were equally represented in each condition (16 times with CB, 8 times with VS). Words were shown in uppercase letters (font Geneva, size 36) on a white 15 × 10 cm background surrounded by a black frame. A trial started with an auditory cue, followed 800 ms later by the fixation point shown for 800 ms. The colored word immediately replaced the fixation point and stayed on view until the response began. The inter-trial interval was 4 s. Participants were instructed to verbally name the color of the displayed words, and both speed and accuracy were emphasized. Naming latencies corresponded to the time elapsed from the appearance of the target to the beginning of the verbal response. All other aspects of the procedure were as in the Auditory Priming Task.

Results

Naming responses differed greatly between participants, as shown by the results in Table 4. Naming latencies were significantly shorter with CB when weekdays and months were shown in their segment colors [100 ms; $F(1, 158) = 14.72$, $p < .0001$, $\eta^2 = .08$] or their word colors [277 ms; $F(1, 158) = 59.38$, $p < .0001$, $\eta^2 = .27$], and when onset-related words appeared in the segment colors of their corresponding weekdays and months [246 ms; $F(1, 158) = 55.46$, $p < .0001$, $\eta^2 = .26$]. By contrast, no advantages were found for VS in congruent trials ($F_s < 1$). These discrepancies in the results demonstrated clear differences in the way in which visually presented words induce synesthetic colors in each participant. Together with the results from the Auditory Priming Task, these results from the Visual Color Stroop Task provided a comprehensive picture of the variety of synesthetic colors our participants perceived. The co-occurrence with CB of synesthetic effects in the Auditory Priming Task and the Visual Color Stroop Task revealed a multimodality that was not apparent with VS, whose synesthetic effects were restricted to auditory priming. In the case of CB, we also found that onset-related words affected the naming of segment colors but not of word colors ($F < 1$). This finding confirmed that segment and word colors were different in type. Finally, with CB the Stroop-like effects of weekdays and months on segment colors were replicated with onset-related words. The similarities of the effects with segment colors indicated that sublexical features were indeed implicated in segment colors. That Stroop-like effects were elicited by specific categories of written words implied that graphemes were involved in the segment and word colors experienced by CB.

Table 4 Color-naming latencies (ms) in Visual Color Stroop Task (0 SOA)

Prime–target pairs	Weekdays and months (<i>Saturday</i>)		Onset-related words (<i>satire</i>)	
	Segment colors	Word colors	Segment colors	Word colors
CB				
Incongruent pairs	952	1091	1152	1087
Congruent pairs	852	814	906	1076
<i>Difference</i>	100**	277**	246**	11
VS				
Incongruent pairs	651	646	684	679
Congruent pairs	648	651	684	675
<i>Difference</i>	3	–5	0	5

** $p < .0001$

Print-to-sound transcoding?

The lack of Stroop-like effects observed with VS was apparently inconsistent with VS's subjective perception of segment and word colors in reading. This negative finding might reflect specific task characteristics rather than an absence of synesthesia in reading. Evidence from auditory priming that spoken words induced VS's synesthesia suggested that in reading VS's synesthesia could be based on phonology. Current models propose that multiple mechanisms contribute to reading, with some mechanisms being responsible for transcoding individual letters or letter clusters into their corresponding sounds (e.g., $f \rightarrow /f/$, $ph \rightarrow /f/$) (Coltheart et al. 2001; Jobard et al. 2003; Plaut et al. 1996; Zorzi et al. 1998). In normal circumstances print-to-sound transcoding mechanisms lead to retrieving the phonology of printed words (e.g., that *cat* sounds/ $kæt/$); however, in case of VS, phonology activation would further trigger a synesthetic color. As a result, VS would experience synesthesia in reading, but only through the activation of phonology. VS's synesthesia would not depend as crucially on another path described in models of readings, which is assumed to involve the retrieval of word orthography. A key feature of print-to-sound transcoding is that it unfolds incrementally, yielding a progressive retrieval of word sounds starting from word onset (Coltheart et al. 2001; Grainger et al. 2006). This feature provides an opportunity to test the hypothesis that VS's synesthesia in reading depends on phonology. As it takes some time to gradually retrieve the phonology of the word from print, Stroop-like effects might appear when more time is allowed for word recognition. A condition of this kind can be created in the Visual Color Stroop Task increasing stimulus-onset-asynchrony (SOA)—that is, by presenting the word distractor first in black and then, after a short interval, in color. At longer SOAs there would be enough time for recovering the phonology from print and,

therefore, for synesthetic colors to appear and affect color naming. Interestingly, this hypothesis also anticipated that we should observe differences in the time-courses of effects induced by segment versus word colors. As our previous data showed how segment colors are associated with word onsets, segment colors would appear as soon as the phonology of word onsets is retrieved. Differing in this respect from word colors, for which the phonology of the entire word needs to be available, effects of segment colors should appear earlier than effects of word colors. This prediction was tested by comparing effects of word colors and segment colors at 200 and 400 SOAs.

Methods

This was an almost complete replication of the Visual Color Stroop Task described above, which comprised four conditions varying for 'synesthetic colors' (segment and word colors) and 'word distractors' (weekdays and months and their onset-related words). The only change introduced in each condition concerned SOA: words first appeared in black for 200 ms (at 200 SOA) or 400 ms (at 400 SOA) before changing to color. This contrasted with the 0 SOA tested earlier, where words were immediately displayed as colored stimuli. Naming latencies were recorded from color appearance. Each condition and SOA was tested separately.

Results

Widespread Stroop-like effects appeared with segment colors, as demonstrated by the shorter color-naming latencies when words were shown in their segment colors (see Table 5; Fig. 1). For weekdays and months, the Stroop-like effect with segment colors was equal to 48 ms at 200 SOA [$F(1, 94) = 10.71$, $p = .001$, $\eta^2 = .10$ and 70 ms at 400 SOA [$F(1, 94) = 22.98$, $p < .0001$,

Table 5 VS's color-naming latencies (ms) in Visual Color Stroop Task (200 and 400 SOA)

Words/colors	Prime–target pairs	200 SOA	400 SOA
Weekdays and months (<i>Sunday</i>)			
Segment colors	Incongruent pairs	666	686
	Congruent pairs	618	616
	<i>Difference</i>	48**	70**
Weekdays and months (<i>Sunday</i>)			
Word colors	Incongruent pairs	631	688
	Congruent pairs	616	617
	<i>Difference</i>	15	71**
Onset-related words (<i>satire</i>)			
Segment colors	Incongruent pairs	673	661
	Congruent pairs	624	615
	<i>Difference</i>	49**	46**

** $p < .0001$

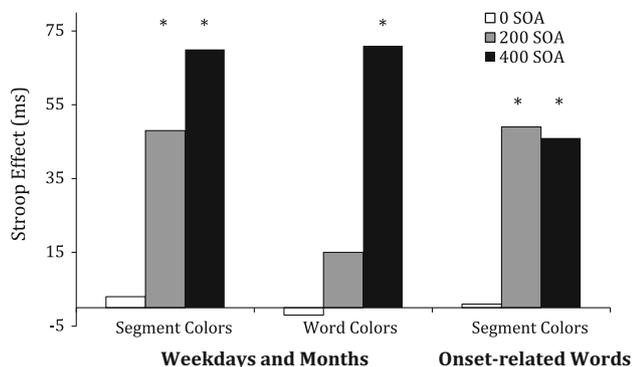


Fig. 1 Stroop-like effects (shown as differences between incongruent and congruent word–color pairs) found with VS across different SOAs (0, 200 and 400 ms), with different words (weekdays and months, onset-related words), and different synesthetic colors (segment and word colors). *Asterisk* indicates significantly shorter ($p < .0001$) color-naming latencies when target colors matched the synesthetic colors associated with word distractors (congruent word–color pairs)

$\eta^2 = .20$]. Furthermore, for words onset-related to weekdays and months, the Stroop-like effect with segment colors was equal to 49 ms at 200 SOA [$F(1, 94) = 30.94, p < .0001, \eta^2 = .25$] and 46 ms at 400 SOA [$F(1, 94) = 23.06, p < .0001, \eta^2 = .19$]. The results with word colors contrasted sharply, as a significant Stroop-like effect appeared with weekdays and months only at 400 SOA [71 ms; $F(1, 94) = 22.95, p < .0001, \eta^2 = .20$]—at 200 SOA, $F_s < 1$. As Stroop-like effects were expected at longer SOAs under the hypothesis that printed words induced synesthetic colors in conditions allowing print-to-sound transcoding, results from longer SOAs provided strong support to the hypothesis. These results converged with findings from auditory priming, as both demonstrated

an involvement of phonology in the segment colors and the word colors experienced by VS. Interestingly, the results also brought to light differences between segment colors and word colors, with the former showing effects at 200 and 400 SOAs, the latter only at 400 SOA. These differences in the time-courses of word colors and sound colors were anticipated under the hypothesis that the appearance, in reading, of synesthetic colors depends on print-to-sound transcoding mechanisms. Differences in the time-course of segment colors and word colors were also the focus of the tasks we present next.

Which synesthetic colors arise first?

As discussed in the Introduction, the time-course of the synesthetic experience may provide evidence for understanding whether access to segmental and/or lexical representations is responsible for the appearance of segment colors and word colors with spoken words. Consistent with the idea that a word's segments are activated before its lexical content (McClelland and Elman 1986; Poeppel et al. 2008; Remez 2005), we expected segment colors to be perceived slightly ahead of word colors when synesthesia was induced by spoken words. We tested this prediction with VS, whose seemingly 'pure auditory synesthesia' provided a better opportunity to test it than CB's multimodal synesthesia. The prediction was first tested by varying SOA in the Auditory Priming Task, specifically to determine whether effects induced by segment colors would reach their peak earlier than effects associated with word colors. 0 SOA was tested earlier, and in this condition word primes were immediately followed by color targets. Data from 0 SOA were integrated with additional data from 200 and 400 SOAs.

Methods

Four versions of the Auditory Priming Task conducted at 0 SOA were replicated at 200 and 400 SOAs. In two versions, weekdays and months were shown as primes and we varied either segment colors or word colors. In the two other versions, we either presented primes that were onset-related to weekdays and months and varied segment colors, or showed digit words as primes and varied word colors. Colored squares (targets) were presented 200 ms or 400 ms after the presentation of auditory primes was completed. This differed from the 0 SOA condition, where the appearance of colored squares coincided with the end of the presentation of auditory primes. Like at 0 SOA, the fixation point was shown simultaneously with the presentation of auditory primes, although it stayed on view longer at 200 and 400 SOAs (200 and 400 ms, respectively). Naming latencies were recorded from color appearance. Synesthetic colors (segment and word colors) and SOAs (200 and 400) were tested in different sessions.

Results

Table 6 shows the results from 200 and 400 SOAs. VS's responses from 0, 200 and 400 SOAs were entered in 2 (congruent, incongruent colors) × 3 (SOA) ANOVAs, and distinct analyses were conducted for each condition. Significant interactions ($p < .05$) were found for each condition (weekdays and months and segment colors; weekdays and months and word colors; onset-related words and segment colors; digit words and word colors), a result

indicating that priming effects varied consistently across SOAs. As shown in Fig. 2, the priming effects differed in their time-courses, peaking at 0 SOA with segment colors, but later—at 200 SOA—with word colors. Comparisons of the priming effects between 0 and 200 SOAs confirmed that with weekdays and months segment colors induced larger effects at 0 SOA [$F(1, 190) = 10.81, p = .001, \eta^2 = .05$], whereas word colors peaked at 200 SOA [$F(1, 190) = 21.04, p < .0001, \eta^2 = .10$]. The larger effect of segment colors at 0 SOA than 200 SOA was replicated with onset-related words [$F(1, 190) = 6.74, p = .01,$

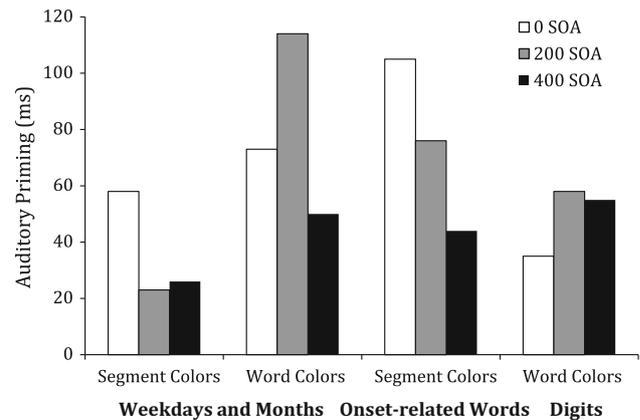


Fig. 2 Auditory priming found with VS across different SOAs (0, 200 and 400 ms), with different words (weekdays and months, onset-related words, digits), and different synesthetic colors (segment and word colors). Segment and word colors had distinct time-courses, as shown by the larger priming effects found at 0 SOA with segment colors and at 200 SOA with word colors

Table 6 VS's color-naming latencies (ms) in Auditory Priming Task (200 and 400 SOA)

Words/colors	Prime–target pairs	200 SOA	400 SOA
Weekdays and months (<i>Sunday</i>)			
Segment colors	Incongruent pairs	546	546
	Congruent pairs	523	572
	<i>Difference</i>	23*	26**
Weekdays and months (<i>Sunday</i>)			
Word colors	Incongruent pairs	538	571
	Congruent pairs	424	521
	<i>Difference</i>	114**	50**
Onset-related words (<i>satire</i>)			
Segment colors	Incongruent pairs	530	532
	Congruent pairs	454	488
	<i>Difference</i>	76**	44**
Digit words (<i>eight</i>)			
Word colors	Incongruent pairs	540	532
	Congruent pairs	482	477
	<i>Difference</i>	58**	55**

* $p = 01$; ** $p < .0001$

$\eta^2 = .03$]. In addition, the larger effect of word colors at 200 SOA than 0 SOA was also replicated with digit words [$F(2, 110) = 6.71, p = .01, \eta^2 = .01$]. These results demonstrated that segment colors rose faster than word colors, as anticipated by the hypothesis that different representations (lexical and phonemic) elicited the word and segment colors of weekdays and months.

Which synesthetic colors last longer?

The hypothesis that phonemic and lexical representations are differently involved in segment and word colors makes a second prediction concerning the duration of these synesthetic colors. As we reasoned in the Introduction, the hypothesis anticipates the longer duration of word colors. This prediction was tested in the Auditory Priming Task, again with VS, presenting the segment and word colors of weekdays and months at 200, 400, 600, 800 and SOAs.

Methods

To make segment colors and word colors maximally comparable, the same seven weekdays and months were used to prime both types of synesthetic colors. For example, *Sunday* was paired with its word color yellow, its sound color green, and the unrelated color brown. The design varied from the one used in the previous experiments, in which segment and word colors were tested with different words. As in previous experiments, however, the colors assigned to the words could be named with basic color terms. At each SOA (200, 400, 600, 800), 189 prime–target pairs were tested, while a word prime or a target color was presented 27 times. As in previous experiments, each SOA was tested separately.

Results

As shown in Table 7, color naming was faster with primes associated with word colors than with unrelated colors [$F(1, 502) = 252.01, p < .0001, \eta^2 = .33$], with a robust priming effect at each SOA ($ps < .0001$). The widespread priming effect of word colors contrasted sharply with the lack of priming with segment colors at each SOA ($ps > .18$). In short, these data revealed differences in duration between segment colors and word colors, with the latter engendering synesthetic color perceptions lasting longer, as anticipated by the hypothesis that lexical representations underlie word colors. It also worth noting that the priming effect was greater with word colors at 200 SOA than 400 SOA [$F(1, 124) = 3.80, p = .05; \eta_p^2 = .03$], which is the same exact difference found in the Auditory Priming Task described in the previous section [$F(1, 190) = 29.31, p < .0001; \eta_p^2 = .13$]. This difference

Table 7 VS's color-naming latencies (ms) in Auditory Priming Task—weekdays and months (200–800 SOA)

	200 SOA	400 SOA	600 SOA	800 SOA
<i>Synesthetic colors</i>				
Segment colors	532	535	526	528
Word colors	440	463	447	435
Unrelated colors	520	524	512	531
<i>Priming effect</i>				
Segment colors	12	11	14	3
Word colors	80**	61**	65**	96**

** $p < .0001$

suggests that activation of word colors declines slightly after an initial peak.

Ordinal effects?

The idea that activation spreads more to items close versus distant in the sequence has been embodied in theories on different cognitive processes—from number representation (Hubbard et al. 2005), to serial encoding (Lewandowsky and Murdock 1989), to word–letter positions (Davis 2010). This idea has also proved useful in explaining a variety of findings. An example is the finding that 4 appeared to be more activated by 5 than 1 in a magnitude judgment task (Moyer and Landauer 1967). We explored whether similar effects of serial position could be observed with word colors induced by weekdays and months or digits. We reasoned that if *Tuesday* is more activated than *Friday* by the presentation of *Monday*, then blue, the word color of *Tuesday*, is more likely to be elicited as compared to green, the word color of *Friday*. Similar predictions can be drawn with digits, so that *one* should activate the word color of *two* more strongly than the word colors of *seven*. This idea was tested in the Auditory Priming Task as effects of word colors were found in this task with both participants. Prior color assignments made weekdays stimuli more suited for VS, digits for CB. Thus, with VS the prime *Monday* was paired either with the target color blue (the word color of *Tuesday*) or the target color green (the word color of *Friday*). With CB the prime *two* preceded either the target color red (associated with *three*) or the target color purple (associated with *nine*). We anticipated priming effects to be inhibitory. This is because it should be quite difficult to select the target color name ('blue') when multiple color names are strongly activated by the prime, as when *Monday* activates its word color (white) and the word color of *Tuesday* (blue). It should be comparatively easier to name the word color of *Friday* (green) if *Monday* only activated its word color.

Methods

Word primes and color targets differed between participants. With VS, word primes were six weekdays that were paired eight times either with the word color of the next weekday or the word color of a more distant weekday. With CB, word primes were the digits from *two* to *nine*, which were paired four times either with the word color associated with the next digit or the word color of a more distant digit. The procedure of the Auditory Priming Task was the same as described earlier.

Results

With VS, naming latencies were significantly slower for colors associated with close than distant weekdays [means: 562 vs. 531; $F(1, 94) = 5.45$, $p = .02$, $\eta^2 = .05$]. However, with CB no evidence was found that a digit (*two*) activated the color of the digit close in the sequence (*three*). In fact, a color (*red*, associated with *three*) was named very similarly when primed by a close digit (*two*) or a distant digit (*nine*) (mean response latencies: 838 vs. 834 ms; $F < 1$). The inhibitory priming effect observed with VS lends support to the hypothesis of a linkage between word colors and sequences. By contrast, CB's results indicated that serial information was not critically involved in the word colors that this participant experienced.

General discussion

This first systematic investigation of the multiple colors that synesthetes can associate with some words not only has confirmed the genuineness of this particular form of synesthesia, but it has also illustrated its richness. The implications of the results from the synesthete participants of our study (CB and VS) are discussed below. First, their results shed light on the cognitive mechanisms underlying their distinct synesthetic colors. Second, the characterization of such cognitive mechanisms helps us to understand the neural mechanisms involved in both types of colors. Finally, we consider the implications that cases of synesthetes 'seeing' distinct colors with single words have for studies of synesthesia.

An orthographic versus phonological representations

A primary question that our data enabled us to clarify concerned the type of linguistic representations underlying the distinct synesthetic colors experienced by CB and VS. On one hand, the auditory priming effects we found with

CB and VS provided strong evidence that access to phonological representations in auditory speech comprehension elicited synesthetic colors in both participants. On the other hand, Stroop-like effects would indicate that access to orthography induces synesthetic colors. The finding that Stroop-like effects appeared at 0 SOA only with CB revealed the orthographic basis of CB's synesthesia not VS's. However, the lack of Stroop effects at 0 SOA does not imply that VS would not experience synesthetic colors with written words in reading. Robust Stroop-like effects appeared at later SOAs, conditions that allowed written words to activate phonology, which in turn would have triggered the synesthetic colors. The contrasting Stroop-like effects demonstrated by CB and VS can be explained under current models of reading that propose different processing pathways, one based on word orthography and relatively faster, the other based on phonology and relatively slower (Coltheart et al. 2001; Grainger et al. 2006; Jobard, et al. 2003; Zorzi et al. 1998). With CB's orthographically based synesthesia, the fast access to orthography through the 'orthographic' pathway enabled synesthetic colors to appear rather quickly and this affected the color naming task giving rise to Stroop-like effects. The slower 'phonological' pathway would not induce a similarly fast activation of synesthetic colors—hence, the lack of Stroop-like effects with VS at 0 SOA. Nevertheless, there would be enough time for the 'phonological' pathway to activate the synesthetic colors at later SOAs, as demonstrated by the Stroop-like effects found with VS at these SOAs. Crucially, the hypothesis of a phonologically based synesthesia also predicted earlier effects of segment colors than word colors, and VS's results conformed to this prediction.¹

If correct, our explanation would imply that stimulus modality is not critical in forms of synesthesia as those described with VS, the determining factor being rather

¹ The hypothesis that VS's synesthesia involved print-to-sound transcoding mechanisms could also be tested with letter clusters mapping onto single phonemes (*wr* → /r/ as in *wrinkle*; *ph* → /f/ as in *photo*). Because these mechanisms operate without lexical support, the sounds of individual letters (*/w* and */r* with *wrinkle*; */p* and */f* with *photo*) are derived in addition to the correct sounds corresponding to letter clusters. Consequently, letters and letter clusters would both contribute to the synesthetic colors. Results from VS's color assignment were consistent with this prediction. We selected 13 word triplets like *wrinkle-ringlet-welcome*, for which we obtained synesthetic colors following the procedure described in the Case Description section. Synesthetic colors were also obtained for pairs of randomly selected words sharing no common letters in initial positions (e.g., *crumble-studio*). As shown by Euclidean distances, synesthetic colors were more similar between *wrinkle-ringlet* (56.6) and between *wrinkle-welcome* (22.1) than between *crumble-studio* (78.9; $ps > .0001$). These results suggest that letter clusters and individual letters could both affect synesthetic colors, as anticipated by the hypothesis that sound-to-print transcoding mechanisms were at play in VS's synesthesia.

whether specific representations are activated. In the case of VS, synesthesia depends on the activation of phonological representations, which can be induced by stimuli differing in modality (spoken or written). This modality independence may naturally occur in forms of synesthesia related to phonological representations that are an inherent component of the reading system. It is probably less likely in forms of synesthesia depending on orthographic representations that are typically activated by written stimuli (although there is evidence in non-synesthetes of activation of orthography from speech; Damian and Bowers 2003a).

In general, comparable effects appeared with segment colors and word colors in both of our participants. This finding indicates that the same types of representations (phonological and/or orthographic) were implicated with both types of synesthetic colors. However, the many discrepancies we observed between segment colors and word colors imply differences in the phonological and orthographic representations underlying these distinct synesthetic colors, as we discuss in detail in the next section.

Lexical versus sublexical representations

As reported in a number of prior studies, synesthetic colors could depend on word initial letters or phonemes, as evidenced by the very similar synesthetic colors induced by onset-related words (Krohn 1892; Paulesu et al. 1995; Simner 2006; Ward et al. 2005). Some of the synesthetic colors experienced by CB and VS with weekdays, months and digits—which were referred to as *segment colors*—appeared to be of this kind. The segment colors CB and VS assigned to weekdays and months were impressively similar to those they chose for words onset-related to weekdays and months. For example, *Friday* and *fried* were both purple for CB, *Saturday* and *satire* were both green for VS. Importantly, the similarities between weekdays and months were consistently confirmed by any of the experimental results obtained with our participants in the Auditory Priming Task and the Visual Color Stroop Task. While collectively our results make a strong case that segment colors are associated with word onsets, the findings reviewed in the previous section clarified that phonemes are involved in the segment colors experienced by VS, graphemes and phonemes in those experienced by CB.

Another recurrent result in our study related to the different effects of segment colors and word colors, as we referred to the other type of synesthetic colors CB and VS assigned to weekdays, months and digits. Especially revealing was that the segment colors of weekdays and months (e.g., *Saturday*) invariably affected words onset-related to weekdays and months (*satire*), a reciprocity never found with the word colors of weekdays and months and their onset-related words. These contrasting findings

revealed the uniqueness of word colors, which were associated with specific words and differed in this respect from segment colors lacking specific lexical associations. In essence, word colors and segment colors appeared to be related to lexical and sublexical representations, respectively, a distinction that holds in phonology (with CB and VS) as well as in orthography (with CB). This characterization of segment and word colors led to specific predictions about the time-course of each of these synesthetic colors that were tested with VS. As activation raises and decays faster with phonemes relative to lexical representations in speech perception (Marslen-Wilson 1987; McClelland and Elman 1986; Remez 2005), earlier auditory priming effects were expected with segment colors than word colors, a prediction confirmed by VS's results. Converging results were found with Stroop-like effects that, as described earlier, depended in VS on phonological activation. As anticipated, Stroop-like effects appeared earlier with segment colors than word colors.

Presenting VS with a weekday (*Tuesday*) elicited the synesthetic color of a weekday close in the sequence (*Wednesday*). Similar position effects were not replicated with CB using digits. This difference suggested that word colors implicated distinct representations in each participant. While VS's word colors involved representations encoding the position taken in the sequence by digits, weekdays and months, CB's word colors relied on representations encoding serial positions less precisely and/or less strongly, or lacking any specification of serial position.

Two negative findings from VS are worth considering. The first finding related to the Visual Color Stroop Task, where no effects of color words appeared at short SOAs (0 and 200 ms). Various kinds of semantic effects have been observed at 0 SOA, including the classic Stroop-color effect and the effect of color-associated words (*sky-blue*; MacLeod 1991). To the extent that these effects have been interpreted as involving the selection of word meanings (Damian and Bowers 2003b; Levelt et al. 1999; Miozzo and Caramazza 2003), the lack of word color effects at 0 SOA appeared to rule out a critical contribution of semantics in VS's colors.² The second negative finding concerned words onset-related to weekdays and months (*satire-Saturday*, *money-Monday*). No word color effects were found with these onset-related words. Thus, there was

² We controlled the effect of color-associated *printed* words to ensure that VB was sensitive to semantic effects in the Visual Color Stroop Task at 0 SOA. We tested seven words strongly associated with a color (*ash-gray*, *blood-red*, *chocolate-brown*, *grass-green*, *lemon-yellow*, *sky-blue*, and *tar-black*). Each word was paired seven times with its associated color (*sky-blue*) and 7 times with another color (*sky-green*). The finding of a sizable facilitation of 39 ms (648 vs. 687 ms; $F(1, 82) = 4.6$, $p < .05$, $\eta^2 = .04$) showed that VS could access aspects of the meaning related to colors with written words at 0 SOA.

no evidence that *satire* activated *red*, the word color of *Saturday*. Given the extent to which co-activation of onset-related words is so pervasive in auditory word recognition (Vitevitch and Luce 1999) and reading (Grainger 1990; Perea and Pollatsek 1998), one would have anticipated effects of word colors to extend to onset-related words. Findings from VS suggested instead that word colors were specifically associated with certain words. Altogether, the two negative findings—one concerning Stroop-like effects, the other onset-related words—indicated that lexical-semantic representations were not associated with VS's word colors, a conclusion fitting our hypothesis that VS's color words depended instead on representations encoding serial positions.

The neural underpinnings of segment and word colors

The characterization of the cognitive mechanisms involved in segment and word colors provides the basis for outlining the corresponding brain mechanisms. Of particular relevance is the finding that word colors and segment colors involved orthographic or phonological representations. Regions in the fusiform gyrus, especially in the left hemisphere, respond specifically to visually presented letters in reading and appeared to support access to word orthography (Dehaene and Cohen 2011; Jobard et al. 2003; Kronbichler et al. 2008; Rapp and Lipka 2011; Vinckier et al. 2007). These regions are plausible candidate structures for the processing of orthographic information crucial for synesthetic colors. As the fusiform gyrus shows some degree of functional specialization, with distinct subregions processing graphemes and orthographic words (Cohen et al. 2000; Vinckier et al. 2007), each of these subregions could be especially engaged in the processing of segment colors and word colors, respectively. Activation of each of these subregions from visually presented letters would propagate to nearby anterior-occipital and posterior-temporal regions processing colors, thus giving rise to synesthetic perception in reading (Dovern et al. 2012; Gray et al. 2006; Jäncke et al. 2009; Rouw and Scholte 2007; Tomson et al. 2013; van Leeuwen et al. 2011). Although the type of lexical information encoded at the level of the fusiform gyrus remains a matter of debate (Hillis et al. 2005; Price and Devlin 2011), most of the results do not suggest an encoding of semantic information, for which a variety of results indicate that processing takes place in temporal areas localized more anteriorly than the fusiform gyrus (Binder et al. 2009; Martin 2007; Miozzo et al. 2014). If semantic representations are involved in word colors, temporal areas are likely candidate structures for word colors that, like in CB, have an orthographic basis.

VS's word colors were related to serial position, as revealed by the finding that a word (*Monday*) also activated the word colors of words next in the sequence (*Tuesday*, *Wednesday*).³ Similar position effects have been documented in synesthetes who perceived digits forming a line or a circle (Jonas and Jarick 2013). Neuroimaging results have further revealed that these synesthetic responses involved parietal regions that in non-synesthetes are associated with the number line, an analogical type of numerical representation (Pinel et al. 2004). This neuroimaging evidence makes it plausible that the same parietal regions were engaged in VS's word colors. The phonological nature of VS's synesthesia further constrained hypotheses about the neural system determining word colors. It likely depended on the co-activation of inferior-parietal, superior-temporal regions responsible for the recognition of auditory words, and parietal regions encoding serial positions.

The distinct nature of segment colors and word colors might constrain theories that explain synesthesia as resulting from neural pruning, which is either lacking or incomplete in synesthesia (Baron-Cohen et al. 1993; Cytowic and Wood 1982; Harrison 2001; Maurer 1997). These theories implicitly assume that neural connections determining synesthesia are part of the non-synesthete brain, although they would exist here only temporarily and would be subjected to neural pruning. Accordingly, neural connections would exist at one point in the non-synesthete brain between neural structures supporting the processing of segment colors and word colors. For example, neural connections linking brain regions engaged in the processing of sublexical features and colors should pre-exist segment colors. Evidence that distinct lexical and sublexical mechanisms, both in orthography and phonology, underlie segment colors and word colors raise an important test for theories assuming neural pruning. In fact, pre-existing neural connections should be present for each of these types of synesthetic colors. A second implication of our results relates to the age at which neural pruning should be completed. Some forms of synesthesia may depend on representations that are acquired relatively late in development, possibly past the age at which neural pruning has been completed. It is the most likely that children acquire phonemes before the words inducing word colors (e.g., *Saturday*, *May*, *nine*), and similar delays would occur in

³ In this respect, it was indicative that pale colors were chosen for items at the beginning of sequences (*I*, *Monday*, *January*) when VS selected word colors. This pattern, also observed with other synesthetes (Mills et al., 1999), might appear especially with word colors that, as we found with VS, were associated with sequences. Furthermore, it is perhaps not coincidental that associations with color names (*B* → blue) and associations found early in childhood (*I*, *O* → white; Spector and Maurer 2011) appeared when VS assigned segment colors. It is in fact segment colors that should be related to phonemes and the earliest multimodal associations.

orthography between letters and word spelling (Baron-Cohen et al. 1987; Rich et al. 2005; Simner and Bain 2013). Neural pruning would not be completed at least until the age at which the specific words inducing word colors have been acquired.

Phonemes, graphemes, and words induced effects at the earliest SOA we tested, suggesting a quick activation of each type of synesthetic colors. These findings echoed recent ERPs and MEG results that showed early modulations of ERPs or MEG components starting at about ~ 150 ms from stimulus presentation, which likely arose from cortical regions underlying perceptual processing (Beeli et al. 2008; Brang et al. 2010, 2011; Gebius et al. 2009; Goller et al. 2008; Jäncke 2013). It should be emphasized that our estimates of the time-course of activation of segment colors and word colors were based on inferences derived from SOAs. More direct measurements of the brain activation associated with the distinct synesthetic colors—e.g., by ERPs—would provide more precise tests of the hypothesis that there are distinct contributions of lexical and sublexical processes.

Implications for studies on synesthesia

The perception of distinct synesthetic colors when a word is heard or read is a curious phenomenon prompting questions on how exactly synesthetes could ‘see’ these colors. Our results shed some light on the phenomenology of this multiple color perception. The longer duration of word colors demonstrated with VS might translate into the subjective perception of word colors more intense and vivid than segment colors. These differences in intensity and vividness could also have consequences for cognitive tasks affected by synesthesia (e.g., memory; Gross et al. 2011; Radvansky et al. 2011; Rothen and Meier 2010). It is possible that such effects become visible prevalently, if not exclusively, with word colors, a question we leave to future research to investigate.

VS claimed to perceive segment colors and word colors when hearing or reading words. VS’s subjective report was confirmed by experimental data, which further revealed, however, that synesthetic colors were elicited by printed words indirectly, through print-to-sound mapping mechanisms enabling the activation of word sounds. Specifically, printed words induced effects of synesthetic colors in the Visual Color Stroop Task only when there was sufficient time for print-to-sound mapping. This result suggests that forms of synesthesia related to phonology might be more common than what gets self-reported by synesthetes, who would correctly indicate that their synesthetic colors are triggered by printed stimuli but would not be aware of the phonological basis of their synesthetic colors. More generally, VS’s results indicate that self-reports could be

misleading as they might under-estimate the incidence of synesthesia related to phonology and over-estimate the incidence of synesthesia related to orthography. However, determining that synesthesia in reading has a phonological basis could have important implications for developmental accounts of synesthesia. The association with printed stimuli has been considered by many (e.g., Baron-Cohen et al. 1987; Rich et al. 2005; Simner and Bain 2013; Simner et al. 2009) a clue that synesthesia may appear relatively ‘late’ during development, not sooner than print letters and words have been acquired and corresponding graphemic representations established in the child’s brain. Rather, cases like VS would suggest that when synesthesia predates reading and involves phonological processing maturing at earlier stages of development. Such cases would further predict that, in children, the association between synesthesia and reading would follow the acquisition of print-to-sound mapping.

Conclusions

Confirming the genuineness of simultaneous synesthetic colors and demonstrating their intrinsic differences, our findings made it clear that the synesthetic colors experienced by an individual can be remarkably complex. Such a complexity is bound to complicate research on synesthesia, especially if coexisting synesthetic colors are common among synesthetes. Group studies aimed at uncovering recurrent patterns could be particularly affected. Self-reported data might reflect multiple types of synesthetic colors—related to segments, words, phonology or orthography—a circumstance weakening the possibility of finding underlying trends. On the other hand, different patterns could emerge with each type of synesthetic colors. To the extent that cases like CB and VS make us to realize the complexity of synesthetic experiences, they hopefully also lead us to make progress in understanding the neurocognitive underpinning of synesthesia.

Acknowledgments We would like to thank Robert Remez and Torstein Låg for having discussed some aspects of this project with us. Most of all, our thanks go to the participants: their curiosity has really been contagious, and their insights have taught us a great deal about synesthesia.

References

- Anderson JE, Holcomb PJ (1995) Auditory and visual semantic priming using different stimulus onset asynchronies: an event-related brain potential study. *Psychophysiology* 32:177–190
- Baron-Cohen S, Wyke MA, Binnie C (1987) Hearing words and seeing colours: an experimental investigation of a case of synaesthesia. *Perception* 16:761

- Baron-Cohen S, Harrison J, Goldstein LH, Wyke MA (1993) Coloured speech perception: is synaesthesia what happens when modularity breaks down? *Perception* 22:419–426
- Beeli G, Esslen M, Jäncke L (2007) Frequency correlates in grapheme-color synaesthesia. *Psychol Sci* 18:788–792
- Beeli G, Esslen M, Jäncke L (2008) Time course of neural activity correlated with colored-hearing synesthesia. *Cereb Cortex* 35:379–385
- Binder JR, Desai RH, Graves WW, Conant LL (2009) Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cereb Cortex* 19:2767–2796
- Binet A, Philippe J (1892) Étude sur un nouveau cas d'audition colorée. *Revue Philosophique* 33:461–464
- Bleuler E, Lehmann K (1881) Zwangmässige Lichtempfindungen durch Schall und verwandte Erscheinungen. *Fuesverlag, Leipzig*
- Brang D, Hubbard EM, Huang M, Ramachandran VS (2010) Magnetoencephalography reveals early activation of V4 in grapheme-color synesthesia. *NeuroImage* 53:268–274
- Brang D, Kanai S, Ramachandran VS, Coulson S (2011) Contextual priming in grapheme-color synesthetes and yoked controls: 400 ms in the life of a synesthete. *J Cogn Neurosci* 23:1681–1696
- Carreiras M, Ferrand L, Grainger J, Perea M (2005) Sequential effects of masked phonological priming. *Psychol Sci* 16:585–589
- Cohen L, Dehaene S, Naccache L, Lehéricy S, Dehaene-Lambertz G, Hénaff M, Michel F (2000) The visual word form area: spatial and temporal characterization of an initial stage of reading in normal and posterior split-brain patients. *Brain* 123:291–307
- Coltheart M, Rastle K, Perry C, Langdon R, Ziegler J (2001) DRC: a dual route cascaded model of visual word recognition and reading aloud. *Psychol Rev* 108:204–256
- Cytowic RE, Wood FB (1982) Synaesthesia I: a review of major theories and their brain basis. *Brain Cogn* 1:23–35
- Damian MF, Bowers JS (2003a) Effects of orthography on speech production in a form-preparation paradigm. *J Mem Lang* 49:119–132
- Damian MF, Bowers JS (2003b) Locus of semantic interference in picture-word interference tasks. *Psychon Bull Rev* 10:111–117
- Davis CJ (2010) The spatial coding model of visual word identification. *Psychol Rev* 117:713–758
- Day S (2005) Some demographic and socio-cultural aspects of synesthesia. In: Robertson LC, Sagiv N (eds) *Synesthesia: Perspectives from cognitive neuroscience*. Oxford University Press, New York (NY), pp 3–10
- Dehaene S, Cohen L (2011) The unique role of the visual word form in reading. *Trends Cogn Sci* 15:254–262
- Dixon MJ, Smilek D, Cudahy C, Merikle PM (2000) Five plus two equals yellow. *Nature* 406:365
- Dixon MJ, Smilek D, Merikle PM (2004) Not all synaesthetes are created equal: projector versus associator synaesthetes. *Cogn Affect Behav Neurosci* 4:335–343
- Dixon MJ, Smilek D, Duffy PL, Zanna MP, Merikle PM (2006) The role of meaning in grapheme-colour synaesthesia. *Cortex* 42:243–252
- Dovern A, Fink GR, Fromme ACB, Wohlschlagel AM, Weiss PH, Riedel V (2012) Intrinsic network connectivity reflects consistency of synesthetic experiences. *J Neurosci* 32:7614–7621
- Frost R, Ahissar M, Gottesman R, Tayeb S (2003) Are phonological effects fragile? The effect of luminance and exposure duration on form priming and phonological priming. *J Mem Lang* 48:346–378
- Galton F (1883) *Inquiries into human faculty and its development*. Macmillan, London
- Gebius T, Nijboer TCW, Van der Smagt MJ (2009) Multiple dimensions in bi-directional synesthesia. *Eur J Neurosci* 29:1703–1710
- Goller AI, Otten LJ, Ward J (2008) Seeing sounds and hearing words: an event-related potential study of auditory-visual synesthesia. *J Cogn Neurosci* 21:1869–1881
- Grainger J (1990) Word frequency and neighborhood frequency effects in lexical decision and naming. *J Mem Lang* 29:228–244
- Grainger J, Kiyonaga K, Holcomb PJ (2006) The time course of orthographic and phonological code activation. *Psychol Sci* 17:1021–1026
- Grainger J, Rey A, Dufau S (2008) Letter perception: from pixel to pandemonium. *Trends Cogn Sci* 12:381–387
- Gray JA, Parslow DM, Brammer MJ, Chopping S, Vythelingum GN, Fytche DH (2006) Evidence against functionalism from neuroimaging of the alien colour effect in synaesthesia. *Cortex* 42:309–318
- Gross VC, Nearing S, Caldwell-Harris CL, Cronin-Golomb A (2011) Superior encoding enhances recall in color-graphemic synesthesia. *Perception* 40:196–208
- Grossenbacher PG, Lovelace CT (2001) Mechanisms of synesthesia: cognitive and physiological constraints. *Trends Cogn Sci* 5:36–41
- Hancock P (2013) Synesthesia, alphabet books, and fridge magnets. In: Simner J, Hubbard EM (eds) *The Oxford handbook of synesthesia*. Oxford University Press, Oxford
- Hänggi J, Wotruba D, Jäncke L (2011) Globally altered structural brain network topology in grapheme-color synesthesia. *J Neurosci* 31(15):5816–5828
- Harrison J (2001) *Synesthesia: the strangest thing*. Oxford University Press, Oxford
- Hillis AE, Newhart M, Heidler J, Barker P, Herskovits E, Degaonkar M (2005) The roles of the 'visual word form area' in reading. *Neuroimage* 24:548–559
- Holden ES (1885) Color and other associations. *Science* 6:242–243
- Hubbard EM, Piazza M, Pinel P, Dehaene S (2005) Interactions between number and space in parietal cortex. *Nat Rev Neurosci* 6:435–448
- Hupé JM, Doja M (2015) A critical review of the neuroimaging literature on synesthesia. *Front Hum Neurosci* 9:103
- Jäncke L (2013) The timing of neurophysiological events in synesthesia. In: Simner J, Hubbard E (eds) *The Oxford handbook of synesthesia*. Oxford University Press, Oxford
- Jäncke L, Beeli G, Eulig C, Hänggi J (2009) The neuroanatomy of grapheme-color synesthesia. *Eur J Neurosci* 29:1287–1293
- Jobard G, Crivello F, Tzourio-Mazoyer N (2003) Evaluation of the dual route theory of reading: a meta-analysis of 35 neuroimaging studies. *Neuroimage* 20:693–712
- Johnson D, Allison C, Baron-Cohen S (2013) The prevalence of synesthesia: the consistency revolution. In: Simner J, Hubbard E (eds) *The Oxford handbook of synesthesia*. Oxford University Press, Oxford
- Jonas C, Jarick M (2013) Synesthesia, sequences, and space. In: Simner J, Hubbard EM (eds) *The Oxford handbook of synesthesia*. Oxford University Press, Oxford
- Krohn WO (1892) Pseudo-chromesthesia, or the association of colors with words, letters and sounds. *Am J Psychol* 5:20–41
- Kronbichler M, Klackl J, Richlan F, Schurz M, Staffen W, Ladurner G, Wimmer H (2008) On the functional neuroanatomy of visual word processing: effects of case and letter deviance. *J Cogn Neurosci* 21:222–229
- Laeng B, Svartdal F, Oelmann H (2004) Does color synesthesia pose a paradox for early-selection theories of attention? *Psychol Sci* 15:277–281

- Laeng B, Hugdahl K, Specht K (2011) The neural correlate of colour distances revealed with competing synaesthetic and real colours. *Cortex* 47:320–331
- Levelt WJM, Roelofs A, Meyer AS (1999) A theory of lexical access in speech production. *Behav Brain Sci* 22:1–75
- Lewandowsky S, Murdock BB Jr (1989) Memory for serial order. *Psychol Rev* 96:25–57
- Lukatela G, Turvey MT (1990) Automatic and pre-lexical computation of phonology in visual word identification. *Eur J Cogn Psychol* 2:325–344
- MacLeod CM (1991) Half a century of research on the Stroop effect: an integrative review. *Psychol Bull* 109:163–203
- Marks LE (1975) On coloured-hearing synesthesia: cross-modal translations of sensory dimensions. *Psychol Bull* 82:303–331
- Marslen-Wilson WD (1987) Functional parallelism in spoken word recognition. *Cognition* 25:71–102
- Martin A (2007) The representation of object concepts in the brain. *Annu Rev Psychol* 58:25–45
- Mattingley JB, Rich AN, Bradshaw JL (2001) Unconscious priming eliminates automatic binding of colour and alphanumeric form in synaesthesia. *Nature* 410:580–582
- Maurer D (1997) Neonatal synesthesia: implications for the processing of speech and faces. In: Baron-Cohen S, Harrison JE (eds) *Synaesthesia: classic and contemporary readings*. Blackwell, Oxford
- McClelland JL, Elman JL (1986) The TRACE model of speech perception. *Cogn Psychol* 18:1–86
- McNamara TP (2005) *Semantic priming: perspectives from memory and word recognition*. Psychology Press, New York
- McQueen I (2007) Eight questions about spoken word recognition. In: Gaskell GM (ed) *The Oxford handbook of psycholinguistics*. Oxford University Press, New York (NY)
- Mills CB, Boteler EH, Oliver GK (1999) Digit synaesthesia: a case study using a Stroop-type test. *Cogn Neuropsychol* 16:181–191
- Miozzo M, Caramazza A (2003) When more is less: a counterintuitive effect of distractor frequency in the picture-word interference paradigm. *J Exp Psychol Gen* 132:228–252
- Miozzo M, Hauk O, Pulvermüller F (2014) Early parallel activation of semantics and phonology in picture naming: evidence from a multiple-linear-regression MEG Study. *Cereb Cortex* (25):3343–3355
- Moyer RS, Landauer TK (1967) Time required for judgments of numerical inequality. *Nature* 215:1519–1520
- Myles KM, Dixon MJ, Smilek D, Merikle PM (2003) Seeing double: the role of meaning in alphanumeric-colour synaesthesia. *Brain Cogn* 53:342–345
- Pariyadath V, Plitt MH, Churchill SJ, Eagleman DM (2012) Why overlearned sequences are special: distinct neural networks for ordinal sequences. *Front Hum Neurosci*. doi:10.3389/fnhum.2012.00328
- Paulesu E, Harrison J, Baron-Cohen S, Watson JDG, Goldstein L, Heather J, Frackowiak RSJ, Frith CD (1995) The physiology of coloured hearing: a PET activation study of colour-word synaesthesia. *Brain* 118:661–676
- Perea M, Pollatsek A (1998) The effects of neighborhood frequency in reading and lexical decision. *J Exp Psychol Hum Percept Perform* 24:767–779
- Pinel P, Piazza M, Le Bihan S, Dehaene S (2004) Distributed and overlapping cerebral representations of number, size, and luminance during comparative judgments. *Neuron* 41:983–993
- Plaut DC, McClelland JL, Seidenberg MS, Patterson K (1996) Understanding normal and impaired word reading: computational principles in quasi-regular domains. *Psychol Rev* 103:56
- Poeppl D, Monahan PJ (2008) Speech perception: cognitive foundations and cortical implementation. *Curr Dir Psychol Sci* 17:80–85
- Poeppl D, Idsardi WJ, van Wassenhove V (2008) Speech perception at the interface of neurobiology and linguistics. *Philos Trans R Soc Lond B Biol Sci* 363:1071–1086
- Price CJ (2012) A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading. *NeuroImage* 62:816–847
- Price CJ, Devlin JT (2011) The interactive account of ventral occipitotemporal contributions to reading. *Trends Cogn Sci* 15:246–253
- Radvansky G, Gibson BS, McNerney MW (2011) Synesthesia and memory: color congruency, von Restorff, and false memory effects. *J Exp Psychol Learn Mem Cogn* 37:219–229
- Rapp B, Lipka K (2011) The literate brain: the relationship between spelling and reading. *J Cogn Neurosci* 23:1180–1197
- Remez RE (2005) Perceptual organization of speech. In: Pisoni DB, Remez RE (eds) *The handbook of speech perception*. Basil Blackwell, Oxford
- Rich AN, Bradshaw JL, Mattingley JB (2005) A systematic, large-scale study of synaesthesia: implications for the role of early experience in lexical-colour associations. *Cognition* 98:53–84
- Rothen N, Meier B (2010) Grapheme-colour synaesthesia yields ordinary rather than extraordinary memory advantage: evidence from a group study. *Memory* 18:258–264
- Rouw R (2013) Synesthesia, hyperconnectivity, and diffusion tensor imaging. In: Simner J, Hubbard E (eds) *The Oxford handbook of synesthesia*. Oxford University Press, Oxford
- Rouw R, Scholte HS (2007) Increased structural connectivity in grapheme-color synesthesia. *Nat Neurosci* 10:792–797
- Sachs GTL (1812) *Historiae naturalis duorum leucaetiopum: auctoris ipsius et sororis eius*. Sumptibus Bibliopolii Seideliani, Solisbaci
- Sagiv N, Simner J, Collins J, Butterworth B, Ward J (2006) What is the relationship between synaesthesia and visuo-spatial number forms? *Cognition* 101:114–128
- Shanon B (1982) Colour associates to semantic linear orders. *Psychol Res* 44:75–83
- Simner J (2006) Beyond perception: synaesthesia as a psycholinguistic phenomenon. *Trends Cogn Sci* 11:24–29
- Simner J, Bain AE (2013) A longitudinal study of grapheme-color synesthesia in childhood: 6/7 years to 10/11 years. *Front Hum Neurosci* 7:603
- Simner J, Haywood SL (2009) Tasty non-words and neighbours: the cognitive roots of lexical-gustatory synaesthesia. *Cognition* 110:171–181
- Simner J, Ward J, Lanz M, Jansari A, Noonan K, Glover L, Oakley DA (2005) Non-random associations of graphemes to colours in synaesthetic and non-synaesthetic populations. *Cogn Neuropsychol* 22:1069–1085
- Simner J, Glover L, Mowat A (2006) Linguistic determinants of word colouring in grapheme-colour synaesthesia. *Cortex* 42:281–289
- Simner J, Harrold J, Creed H, Monro L, Foulkes L (2009) Early detection of markers for synaesthesia in childhood populations. *Brain* 132:57–64
- Smilek D, Dixon MJ, Merikle PM (2001) Synaesthetic photisms influence visual perception. *J Cogn Neurosci* 13:930–936
- Spector F, Maurer D (2011) The colors of the alphabet: naturally-biased associations between shape and color. *J Exp Psychol Hum Percept Perform* 37:484–495
- Tang J, Ward J, Butterworth B (2008) Number forms in the brain. *J Cogn Neurosci* 20:1547–1556
- Tomson SN, Narayan M, Allen GI, Eagleman DM (2013) Neural networks of colored sequence synesthesia. *J Neurosci* 33:1498–14106
- van Leeuwen TM, den Ouden HEN, Haagort P (2011) Effective connectivity determines the nature of subjective experiences in grapheme-color synesthesia. *J Neurosci* 31:9879–9884

- Vigneau M, Beaucousin V, Herve PY, Duffau H, Crivello F, Houde O et al (2006) Meta-analyzing left hemisphere language areas: phonology, semantics, and sentence processing. *Neuroimage* 30:1414–1432
- Vinckier F, Dehaene S, Jobert A, Dubus JP, Sigman M, Cohen L (2007) Hierarchical coding of letter strings in the ventral stream: dissecting the inner organization of the visual word-form system. *Neuron* 55:143–156
- Vitevitch MS, Luce PA (1999) Probabilistic phonotactics and neighborhood activation in spoken recognition. *J Mem Lang* 40:374–408
- Ward J, Simner J, Auyeung V (2005) A comparison of lexical-gustatory and grapheme-colour synaesthesia. *Cogn Neuropsychol* 22:28–41
- Ward J, Huckstep B, Tsakanikos E (2006) Sound-color synaesthesia: to what extent does it use cross-modal mechanisms common to us all? *Cortex* 42:264–280
- Woolen KA, Ruggiero FT (1983) Coloured-letter synaesthesia. *J Ment Imag* 7:83–86
- Zorzi M, Houghton G, Butterworth B (1998) Two routes or one in reading aloud? A connectionist dual-process model. *J Exp Psychol Hum Percept Perform* 24(4):1131