DOES BINDING OF SYNESTHETIC COLOR TO THE EVOKING GRAPHEME REQUIRE ATTENTION?

Noam Sagiv[1,2]**, Jeffrey Heer**[3] **and Lynn Robertson**[1,4]

([1]Department of Psychology, University of California, Berkeley, CA, USA; [2]Department of Psychology, University College London, London, UK; [3]Computer Science Department, University of California, Berkeley, CA, USA; [4]Neurology Research Services, Veterans Administration, Martinez, CA, USA)

ABSTRACT

The neural mechanisms involved in binding features such as shape and color are a matter of some debate. Does accurate binding rely on spatial attention functions of the parietal lobe or can it occur without attentional input? One extraordinary phenomenon that may shed light on this question is that of chromatic-graphemic synesthesia, a rare condition in which letter shapes evoke color perceptions. A popular suggestion is that synesthesia results from cross-activation between different functional regions (e.g., between shape and color areas of the ventral pathway). Under such conditions binding may not require parietal involvement and could occur preattentively. We tested this hypothesis in two synesthetes who perceived grayscale letters and digits in color. We found no evidence for preattentive binding using a visual search paradigm in which the target was a synesthetic inducer. In another experiment involving color judgments, we show that the congruency of target color and the synesthetic color of irrelevant digits modulates performance more when the digits are included within the attended region of space. We propose that the mechanisms giving rise to this type of synesthesia appear to follow at least some principles of normal binding, and even synesthetic binding seems to require attention.

Key words: synesthesia, the binding problem, visual attention

INTRODUCTION

The visual system must solve a number of binding problems in order to achieve accurate perception of the world around us (e.g., Treisman, 1996). In particular, the problem of combining color, shape and other surface features into objects has received considerable attention (for a review see Wolfe and Cave, 1999). According to Feature Integration Theory (FIT) proposed by Treisman and Gelade (1980), spatial attention is crucial for binding such features. Indeed, under conditions of divided attention features may be incorrectly combined and produce illusory conjunctions, e.g., a red X and a green O may be perceived as a green X and a red O (Treisman and Schmidt, 1982). Neuropsychological studies of patients with spatial deficits support FIT by demonstrating the prevalence of illusory conjunctions when spatial attention is disrupted (for a review see Robertson, 1999). Perhaps most striking of those is the case of RM, a Balint's Syndrome patient who nearly completely lost spatial information as a result of bilateral parietal lesions. Subsequently, RM experienced illusory conjunctions even under free viewing conditions (Bernstein and Robertson, 1998; Friedman-Hill et al., 1995; Robertson et al., 1997; see Humphreys et al., 2000 for confirming evidence).

Features such as color and form are initially encoded in different ventral visual areas, and the data from RM suggest that accurately integrating the signals in these areas requires spatial processing of the parietal lobe. In other words, correct binding requires interactions between dorsal and ventral systems.

Another case of abnormal binding can be found in otherwise normal individuals with synesthesia who experience idiosyncratic but consistent binding of sensations (e.g., Cytowic, 1997). Synesthetes may experience the letter Q as crimson with a slight taste of fennel or piano sonatas in B minor as pink dots. However, we are interested in a particular type of synesthesia where seeing letters or digits induces an externally projected color that appears as a surface feature of the letters and digits (e.g., Smilek et al., 2001)[1]. This study focuses on the role of attention in this type of synesthesia. A recurring theme in discussions of synesthesia is that some form of cross-activation between one brain area and another may be present (e.g., Baron-Cohen et al., 1993; Ramachandran and Hubbard, 2001a). If indeed graphemic-chromatic synesthesia is the result of direct communication between ventrally located color and word-form areas synesthesia may not rely on visual attention or

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[1] Note that colored-letter synesthetes may experience the colors projected externally or in their mind's eye; these colors may be experienced as a surface feature of the letter (actual letter or letter image) or independently of the letter (e.g., non localized image or localized percept projected at a certain distance).

require parietal input[2]. However, in the present studies[3] we found that binding of the synesthetic features to their inducing stimuli required visual attention. Synesthesia seems to obey at least some of the rules of normal[4] feature binding.

We tested two graphemic-chromatic synesthetes, AD and CP, who reported that colors were projected in the external world and appeared as "a property" of a letter or digit presented to them (see Figure 3 in Robertson, 2003a). This type of synesthesia seems to most resemble the case of everyday binding of color and shape in which well-localized colors are properties of objects. Our first participant, AD, is a 29-year-old synesthete. She first used a graphic software in order to choose the colors that most closely matched her synesthetic photisms and their corresponding RGB values. She reports that the color mapping has always been this way. Indeed on a consistency test given without prior notice 3 months after her first report, she was asked to write down which color goes with each letter and digit, and selected an appropriate color for all 36 graphemes. Our second participant CP, a 27-year-old synesthete, also displayed a consistent synesthetic mapping, though her reported color-grapheme associations differed from those of AD (particular color correspondences reported by AD and CP can be found in Sagiv and Robertson, 2004).

EXPERIMENT 1

There has been growing interest in synesthesia. Stroop-like paradigms have been used to study synesthesia in the lab (e.g., Odgaard et al., 1999; Bergfeld-Mills et al., 1999; Dixon et al., 2000). Others have used variants of visual search paradigms in synesthetes to address the perceptual reality of color-grapheme synesthesia (Palmeri et al., 2002; Ramachandran and Hubbard, 2001a). These studies have demonstrated that synesthesia is a genuine perceptual phenomenon (rather than mnemonic, associative or metaphoric) by showing that synesthetic colors facilitate search in what are objectively monochromatic displays containing letters or digits. Pre-attentive synesthetic binding could account for these findings (putatively mediated by direct connections between areas that encode features that are developmentally more segregated in most people – in this case – color

and grapheme shape). Indeed, Ramachandran and Hubbard (2001b) tentatively used the term "pop-out" (typically used to refer to a pre-attentive process) to refer to what synesthetes may be experiencing in these experiments. However, the nature of this facilitation remains a mystery.

We first expected to replicate these findings in AD and CP. Most other studies examining visual search used displays where both distractors and targets induced synesthesia (see Palmeri et al.'s last experiment for an exception). In order to ensure that search facilitation is indeed aided by synesthesia, we tested our synesthetes with distractors that do not induce colors and used a within-subject design. We then compared performance with targets that either induced colors or did not. This method has the advantage of each synesthete acting as her own control, avoiding sticky issues in comparing non-synesthetes to synesthetes. Search rates also vary enormously between individuals, making the within subject control an even stronger test of our hypothesis. Nevertheless, in order to verify that under similar conditions, search for a *colored* target becomes trivially easy, we tested non-synesthetes, using a similar procedure in which we colored the target as it would appear to our synesthetes *once detected*.

Method

In the first two blocks of trials, the target was a 180° rotated L-like shape and the distractors were 90° rotated T-like shapes that were shown to the participants on the screen, but were not described with reference to letters (Figure 1). In the following two blocks of trials the display was a 180° rotated version of same stimuli (i.e., the target L-shape was shown upright). Although here we are describing these shapes as Ls and Ts for narrative purposes, they were not referred to in this way to the synesthetes themselves. Critically, distractors in both conditions were equally unlikely to evoke color, and the target was likely to evoke color only in the upright conditions[5]. We will refer to these conditions as "inverted" and "upright". Each block consisted of a short practice session, followed by 72 experimental trials. A PC computer running "Presentation" (www.neurobehavioralsystems.com) was used for stimulus delivery and data recording in all experiments.

The task was to decide as rapidly as possible whether the target was present or absent by pressing the left or right mouse-button. Target probability was 50%. Set size was 4, 9 or 16 (randomly presented in each block). Displays were centered in a square region on a 17" screen and

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[2] Further, one might say that since the induced synesthetic color is not actually present in the scene, there is no a priori reason to assume attentional mechanisms may underlie normal and synesthetic binding. However, since the color is experienced as a surface feature (with well-defined spatial extent), it would be more parsimonious to take advantage of existing circuits subserving spatial attention. For example, subjects seeing two line fragments as eyes, engage brain mechanisms subserving face perception (Bentin et al., 2002).
[3] Some of these data have been reviewed in Robertson (2003a) and in Sagiv and Robertson (2004).
[4] We use the word normal to denote non-synesthetic. Not having synesthesia is normal in the sense that it is more common although it may be as perplexing to synesthetes as synesthesia is to non-synesthetes.

[5] We verified that the L used as stimulus did induce a vivid synesthetic color: green for AD and orange/mustard for CP. When debriefed after the experiment, both reported that only the L induced a vivid color. The horizontal line in all stimuli was made shorter in order to meet this criterion in CP who was tested after AD.
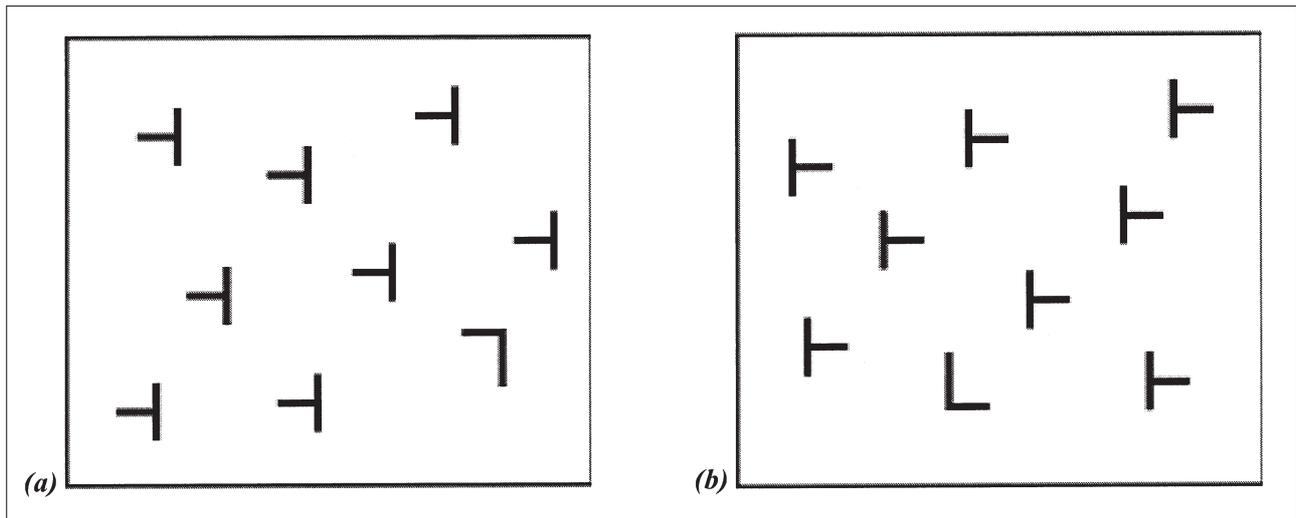
Fig. 1 – *Sample search displays (with target present) used in Experiment 1. (a) Initial "inverted" block – a non-letter target; (b) Second 'upright' block – a letter target.*

had a visual angle of 12°, 18° and 24°, to maintain density (Northdurf, 2000). Each element size was 2°. Reaction times (RTs) for correct trials for each subject were analyzed with a repeated-measures analysis of variance (ANOVA) with target (present, absent), set-size (4, 9 or 16) and orientation (inverted, upright) as factors. Trials for each condition were numbered from 1-12 and used as the random factor. The Greenhouse-Geisser correction was applied where appropriate.

Eight age and education-matched non-synesthetes, were tested using a similar procedure. In contrast to AD and CP who were shown a black and white display throughout the experiment, non-synesthetes searched for an upright L-shaped target that was colored in either green (as AD sees it) or orange-mustard (as CP perceives the letter L). The inverted L used as a target in the first half of the experiment remained black, as it does not induce a synesthetic color for AD and CP. Here, subject averages were used as random factor.

Results and Discussion

If synesthetic colors do pop-out, we would have expected to see shallower search slopes in the upright condition. This would have resulted in an interaction of orientation with both set-size and target, as well as the triple interaction. None of these were significant in AD and CP [F < 1, p ≅ .5]. For both, the main effect of set-size [F (2, 22) = 127.1, p < .001; F (2, 22) = 63.1, p < .001 respectively] and target [F (1, 11) = 96.3, p < .001, F (1, 11) = 37.1, p < .001] were significant. AD also showed a significant main effect of orientation [F (1, 11) = 13.6, p < .005]. For both AD and CP the interaction of target and set-size was significant [F (2, 22) = 44.8, p < .001, F (2, 22) = 8.7, p = .002 respectively]. Slopes were steeper when targets were absent than when they were present,

thus replicating the standard findings of serial search (Figure 2).

In sum, there was no evidence of pop out when distractors were not synesthetic inducers whether the target itself induced color or not. Since distractors in both phases of the experiment were equally unlikely to induce a color it is not surprising that orientation and set-size did not interact on target-absent trials. However, the complete lack of even a trend toward an interaction on target-present trials [F (2, 22) = .001, p = .999 in AD; F (2, 22) = .9, p = .4 in CP] strongly suggests that, for our synesthetes, synesthetic binding only began when the target was detected and became the focus of attention. It should be noted that both made only 3 errors showing a pattern inconsistent with speed-accuracy tradeoff.

In contrast, when we 'simulated' what search would be like if synesthetic color were available preattentively by presenting the upright L in color to non-synesthetes, a markedly different pattern was seen. As can be seen in Figure 3, while serial search was evident in the inverted case (black and white stimuli), search for the colored target was very efficient. Additionally reaction times in the target absent case were also faster, because the presence or absence of a target could have been determined solely based on color information, thus avoiding the relatively difficult shape discrimination. The main effects of set-size [F (2, 14) = 34.6, p < .001], target [F (1, 7) = 17.4, p < .005], and orientation [F (1, 7) = 51.5, p < .001] were highly significant. The interaction of target and set-size was also significant [F (2, 14) = 18.4, p < .005]. Crucially, the interactions involving orientation were all highly significant: orientation by set-size [F (2, 14) = 39.2, p < .001], orientation by target [F (1, 7) = 16.8, p = .005], and orientation by target by set-size [F (2, 14) = 12.0, p < .005]. These are due to the flattening of search
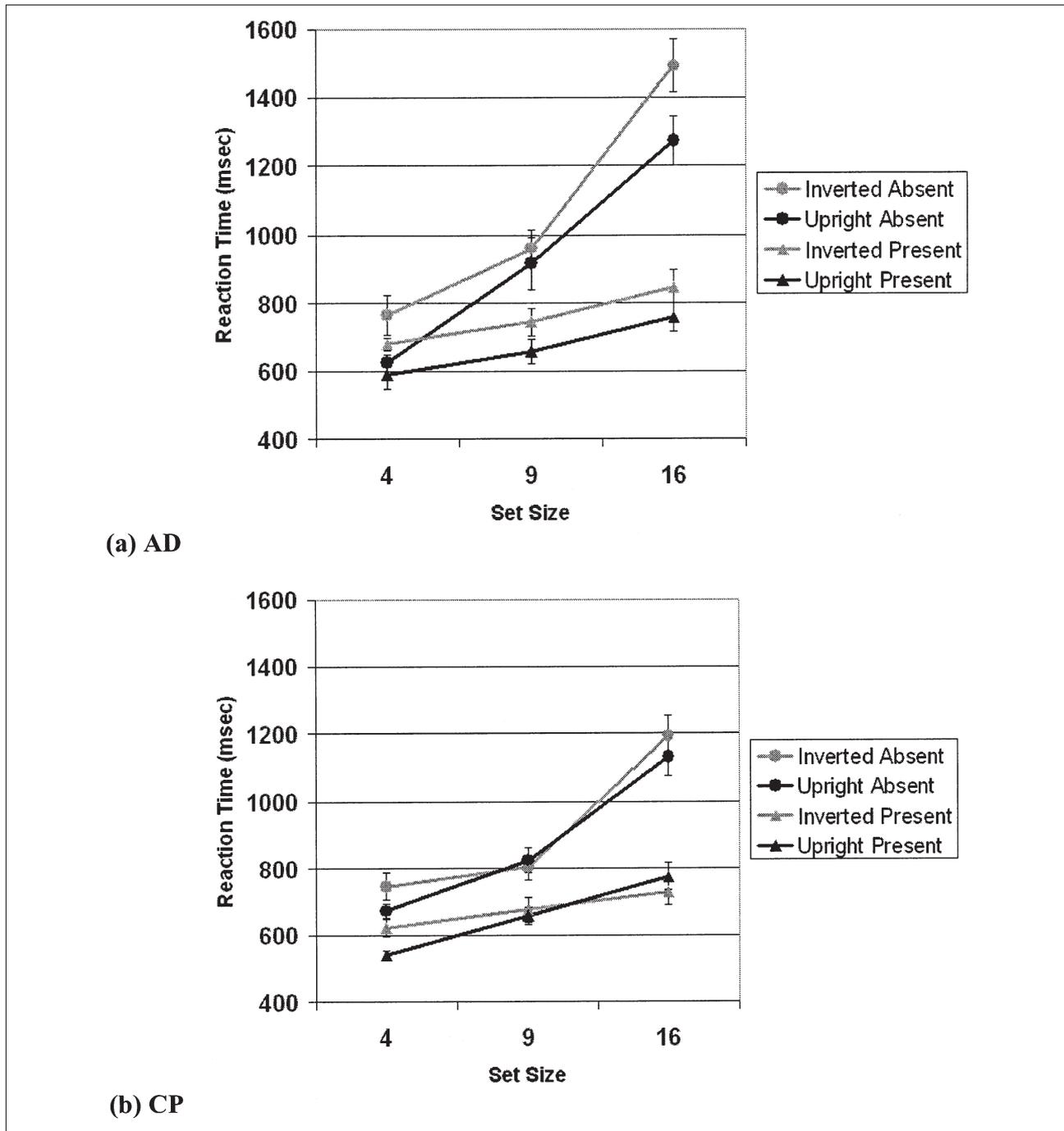
Fig. 2 – *Mean reaction times (in msec) as a function of set size for (a) AD and (b) CP.*

slopes in the upright (colored) condition, an effect which is more dramatic for the target absent case which yields a steeper slope when color is not available and the search is serial for the inverted target. AD and CP's search for the upright L-shapes target looks very different than search for a colored target, inconsistent with the idea that synesthetic color may be available pre-attentively.

The findings in AD and CP are also in agreement with subjective reports that the experience of color did not occur before finding the target, and that there was no experience of color in the initial, inverted condition but there was when the L was upright. Further, they did not

report that color preceded target detection when directly asked if this occurred. The synesthetes also reported that they did not experience the distractors as colored most of the time[6]. Thus, we found no evidence for more efficient search when distractors were not inducers as well. When distractors induce color they can form groups or clusters that will then be perceived as the synesthetic color, making them more easily rejected. Search could then turn

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[6] Both subjects reported experiencing a pale "T-color" on a few trials. It should be noted that for both, the color of T is substantially different than the color of L, ruling out that these results are due to similarity of target and distractor colors (Palmeri et al., 2002) even on those few trials.
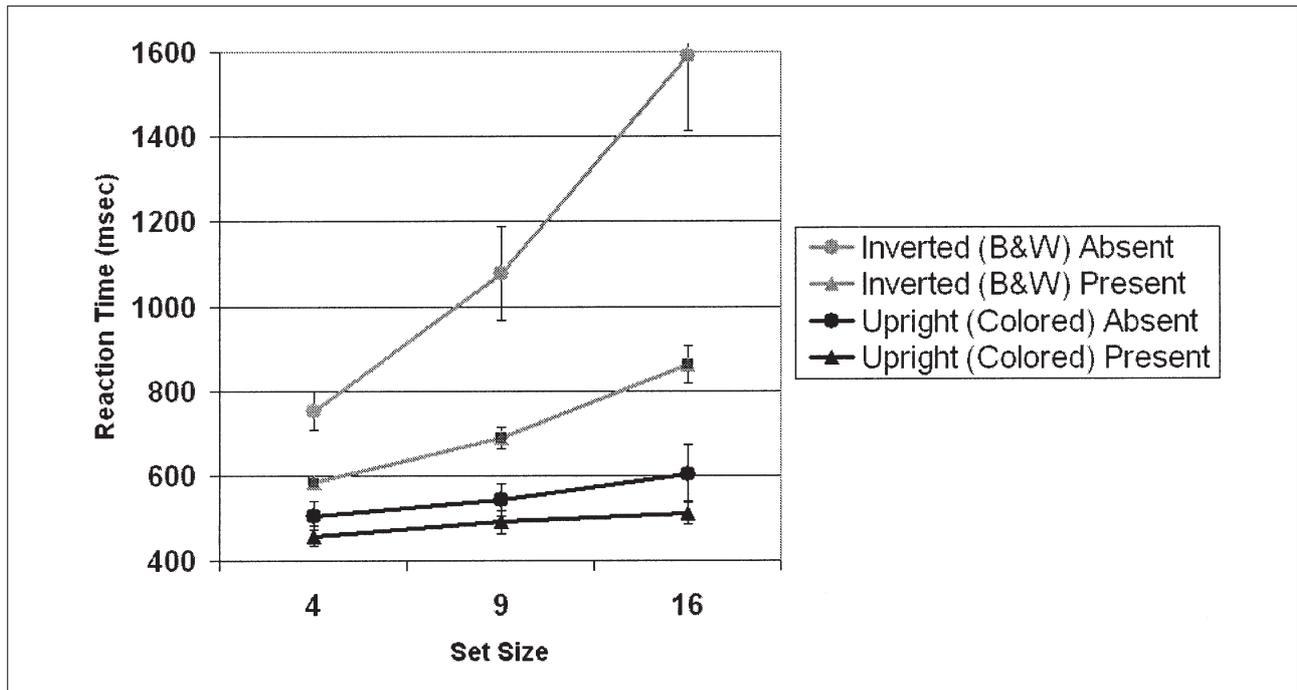
Fig. 3 – *Mean reaction times (in msec) as a function of set size for a group of eight control subjects.*

into a type of guided search. However, when we used distractors that induced little or no color, evidence for facilitation in search was not found. This is an important consideration, since increased density would place more distractors within the area of an attentional window or spotlight, and thus allow more distractors to be rejected "per glance".

Although we used smaller set sizes than Palmeri et al. (2002) and Smilek et al. (2001), we can rule out that our task was too easy and allowed very efficient search in all conditions: serial search was clearly evident both in the increasing slopes over set size and the target present/target absent slope differences. When the target was absent, all the distractors had to be rejected, but when it was present only half on average could be rejected.

Palmeri et al. (2002) found reduced slopes on "target present" trials in a synesthete when the target and distractors induced different colors than when they induced the same color, but the slopes were not flat. Furthermore, in a control experiment in which distractors were not inducers, they failed to replicate efficient search seen in other experiments. These data are in agreement with our claims and help to rule out that synesthesia may only influence performance in more difficult tasks or with larger set sizes than the ones we used. It also rules out the possibility that the constant stimulus density we used somehow wiped out the influence of synesthesia seen in other studies. We do not deny that synesthesia can influence performance, but rather suggest constraints on the nature of this process. In the case of visual search it appears that synesthesia allows subjects to guide

search based on synesthetic color, but as Palmeri et al. point out, it does not "pop-out" as real color does.

Ramachandran and Hubbard (2001a) showed that a form defined by distributed items among distractors was difficult to find for non-synesthetes but not for synesthetes. However, they too included target and distractors that both induced color. Importantly, when Hubbard et al. (2005) tested AD and CP using the same paradigm, both showed this facilitation (demonstrating that AD and CP's performance does benefit from the presence of synesthesia-inducing distractors). Ramachandran and Hubbard (2001b) also demonstrated that grouping items into rows or columns was influenced by the synesthetic colors and that synesthetes were better than non-synesthetes in detecting targets among distractors . The stimuli in the first case were presented in free view, giving ample time to group according to the synesthetic colors, and the distractors in the second case were also synesthetic inducers.

As synesthetes search through distractors, the distractors too induce colors that can then guide the search process (Wolfe, 1994). Once a distractor turns colored it can be more easily isolated from the remaining distractors and is less likely to be searched again, making search rates more efficient and thus, accounting for reported synesthetes' superior search performance. Non-synesthetes have no additional color that can help guide search, while synesthetes do. Our findings support suggestions that attention is required to bind color and form even in synesthesia and generally do not precede awareness of the inducing stimulus (Mattingley et al., 2001). We explore this further in Experiment 2.
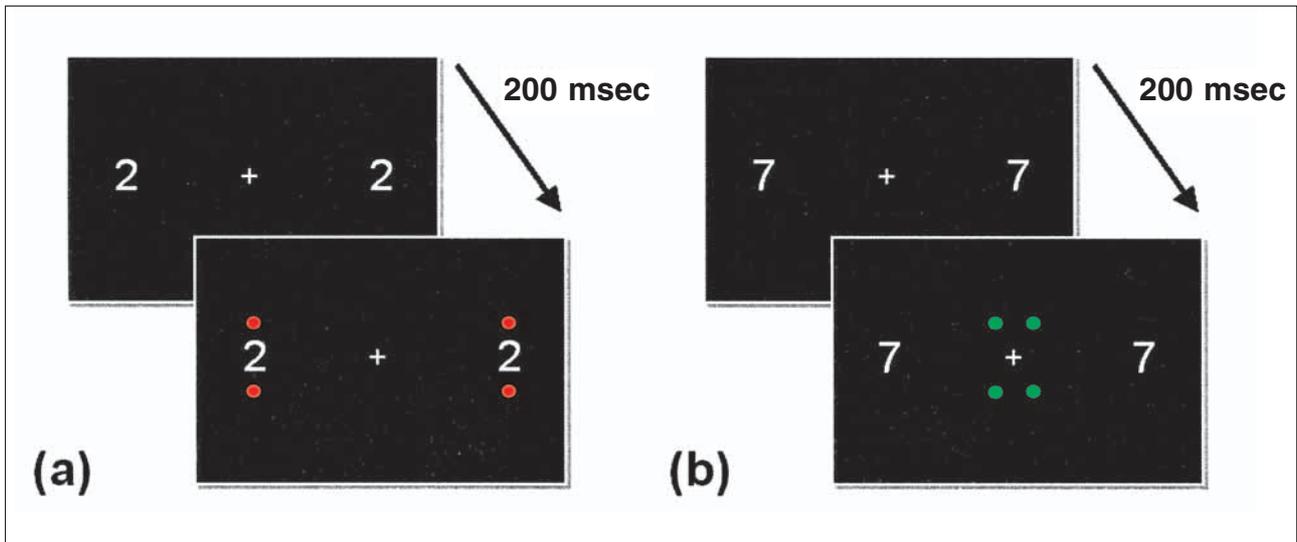
Fig. 4 – *Sample displays used in Experiment 2. Throughout each block, target colored dots appeared in positions that motivated diffuse or focused attention, putting the previously presented digits either inside (a) or outside (b) the attentional window. Colors shown are those used for testing CP (both represent congruent trials: 2 is reddish and 7 is green).*

EXPERIMENT 2

In this experiment we introduced procedures used to vary the size of the spatial extent over which attention is allocated (the size of an attentional window). One of two possible grayscale digits was presented on both sides of fixation. The digits served as synesthetic color inducers and their location was fixed throughout the experiment. To vary attention to the inducers, we varied the size of the area in which targets (4 colored dots) could appear and measured reaction time to judge their color. The dot color was randomly chosen from the two colors corresponding to the two possible digit distractors. Thus, the color was either consistent or inconsistent with (the experience each subject associated with) the two identical digit distractors that onset 200 msec earlier. The location of dots was either close to fixation or in the periphery and was blocked in order to encourage participants to attend throughout each block either to a larger area that would include irrelevant inducers or to a small area that would leave inducers outside the attentional window (i.e., with fewer attentional resources). If attention is required in synesthesia, responding to colored dots inconsistent with the induced color should be slower (relative to the consistent case) when the digit inducers are inside the window of attention than when they are outside, and this is what we found.

It should be noted that we presented the targets only 200 msec after digit presentation in order to allow sufficient time for synesthesia to develop. Mattingley et al.'s (2001) study provides a lower limit of at least 50 msec. Synesthetes' typically report that synesthesia is experienced as soon as the inducer is seen. ERPs to orthographic and non-orthographic material diverge as soon as ~150 msec post stimulus presentation (Bentin et al.,

1999). Indeed preliminary ERP data from both AD and CP suggested that by 150-200 msec the responses to congruently and incongruently colored letters differ (Sagiv et al., 2003). Thus we have chosen a stimulus onset asynchrony (SOA) of 200 msec.

Method

The same two digits (2, 7) were used with both AD and CP, and the respective colors they induced were used to color the target dots. On any given trial, the two digits were identical, either both 2s or both 7s and were located 8° from fixation, one on each side of the screen. In order to allow adequate time for the digits to function as inducers, they appeared 200 msec before a set of 4 dots positioned in a rectangular configuration. Dots appeared either near fixation (.3°) or far from a central fixation (8°), above and below the digits. Dots were presented for 300 msec, at the end of which the digits disappeared too. Subjects were instructed to maintain fixation and their eye movements were monitored. In both conditions each dot was .35° and the vertical distance between dot pairs was 4.7°. Schematic display sequences are given in Figure 4.

The dot color was consistent with the synesthetic color of the inducer half the time and inconsistent half the time. The far and near conditions were blocked to encourage maintenance of the same attentional set between trials. The target colors were randomly presented. There were 40 trials in each block and a total of 320 in the experiment. Subjects were instructed to pay attention to the dots. They were told that dots would always appear in the same position throughout a block, and asked to respond as fast as possible by pressing the right or left mouse-button
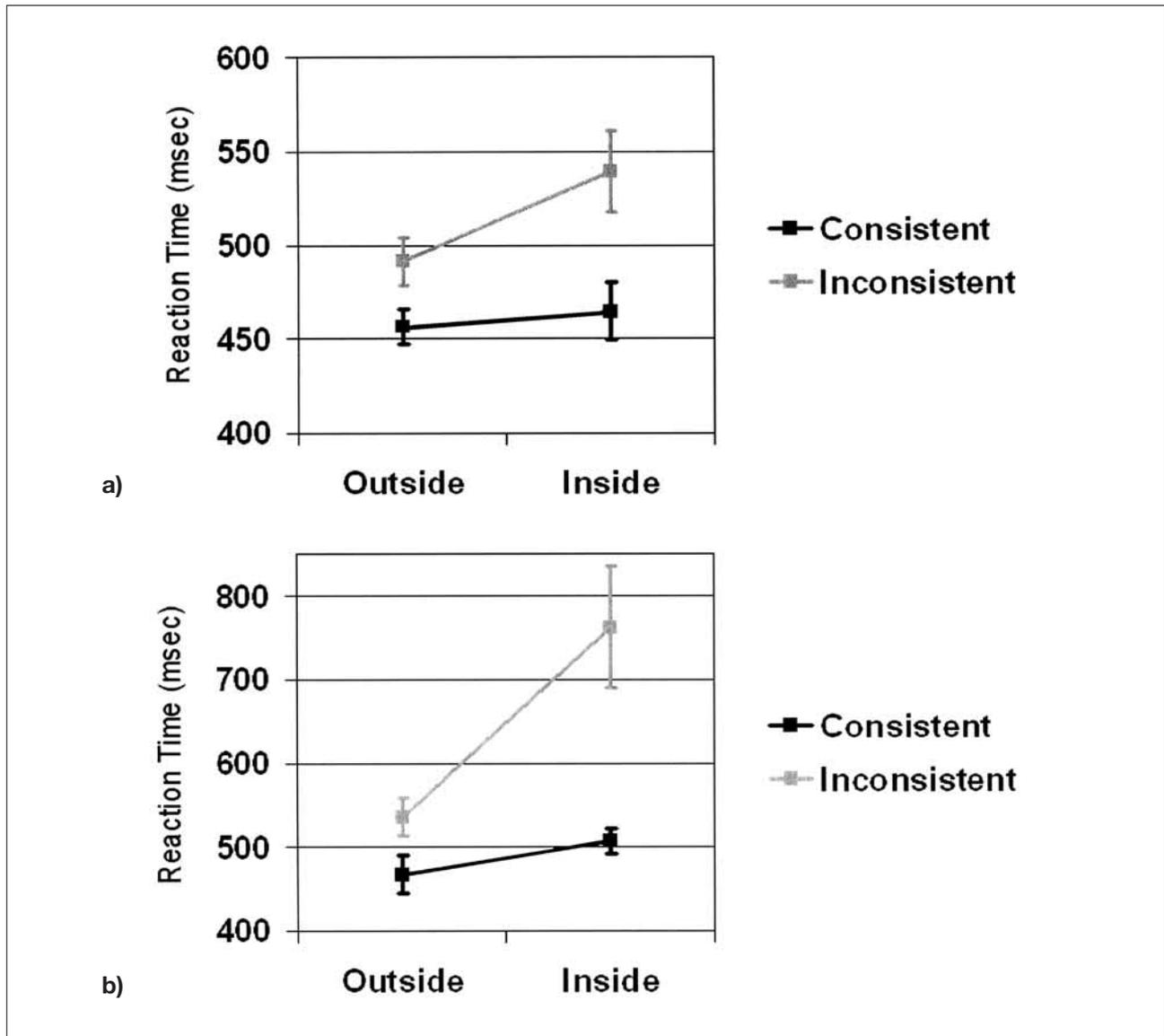
Fig. 5 – *Mean reaction times (in msec) for AD (a) and CP (b) in the inside and outside conditions for achromatic digits inducing either congruent or incongruent synesthetic colors.*

to indicate their colors. Distractor digits appeared in the same location in both the far and near conditions.

RTs of incorrect responses were excluded as well as outliers beyond 3-standard-deviations. Mean reaction times were analyzed for each subject by ANOVA with target color (consistent, inconsistent) and target location (near/far; i.e., leaving digits outside or inside the attentional window) as repeated measures. The 4 blocks in each condition were halved into 8 smaller blocks of trials (resulting in an average of ~9 observations per cell per block). The means of these 8 blocks were used as the random factor.

Results and Discussion

The main effect of target color was significant for both AD [F (1, 7) = 17.7, p < .005] and CP [F (1, 7) = 18.6, p < .005]. The main effect of target location was significant for CP [F (1, 7) = 17.0, p < .005] but not for AD [F (1, 7) = 3.8, p < .1] who was overall more practiced in RT experiments and showed smaller differences. Critically, the interaction between target color and target location was significant for both AD [F (1, 7) = 5.9, p < .05] and CP [F (1, 7) = 6.6, p < .05]. Mean error rate was 2% for AD and 3% for CP. The error pattern was inconsistent with a speed-accuracy tradeoff.

Figure 5 shows RTs in the different conditions. Overall, inconsistent colors produced longer RTs than consistent ones and peripheral targets produced longer RTs than central ones. However, when the digits were outside the attentional window (near condition) the difference between consistent and inconsistent RTs was much smaller (35 msec) than when they were inside the attentional window (far; 74 msec) for AD and similarly for CP (69 msec and 256 msec, respectively). When attention was focused away
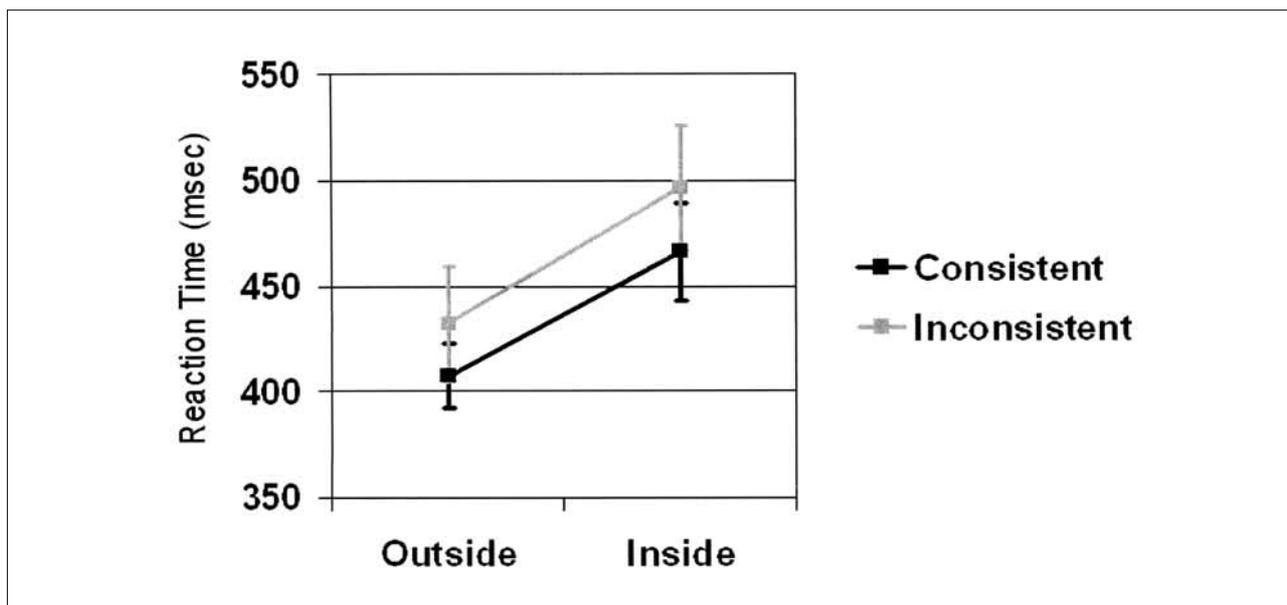
Fig. 6 – *Mean reaction times (in msec) for non-synesthetes in the inside and outside conditions for digits colored either congruently or incongruently with target color.*

from inducers, the inducers had only a small effect, but when attention was spread to include the inducers, inconsistent (synesthetic) colors slowed RT substantially.

These findings provide further support that attention modulates synesthesia. The synesthetic color interfered more when attention was focused widely and included the inducers than when it was focused narrowly and did not. When the inducers were outside the window of attention, they were less likely to induce their colors than when they were inside the window of attention, consistent with subjects' verbal report that the digits appeared more vividly colored in the latter case.

Note that the reaction time difference due to congruency between target color and digit color did not disappear completely in when digits were outside the attentional window. This may reflect a residual synesthetic binding even without attention. However, it is unlikely that the simple attentional manipulation used here resulted in complete inattention to the irrelevant stimuli, nor should this be a concern. The interaction between attention and congruency suggests a major role for attention, whether or not some processing without attention still takes place.

The central role of attention in synesthesia is also consistent with Mattingley et al. (2006, in this issue, p. 213) demonstration of synesthesia modulation by attentional load as well as synesthetes' experiences when viewing hierarchical 'Navon' stimuli, such as a large 2 made of small 5 s (Ramachandran and Hubbard, 2001b; Palmeri et al., 2002; Rich and Mattingley, 2003): the experienced color depended on the attended stimulus level.

In order to rule out that the interaction observed in Experiment 2 was confounded by task difficulty

or by different target-distractor distance in the near and far condition, we ran a control experiment using a similar paradigm. Eight non-synesthetic college students participated in this experiment. Because non-synesthetes do not experience or associate highly specific color with digits, we presented the digits in color – to match what our synesthetes see in each trial with digit stimuli (i.e., in the display shown in Figure 4, the digit 2 would always appear in red and 7 would always appear in green, as CP experiences it). Apart from this difference, the control experiment was identical to the one in which AD and CP took part. Mean subject RT was used as a random factor. Figure 6 shows the RT in the different conditions.

The main effect of target color was significant [$F_{(1, 7)} = 33.8$, $p < .002$]. The main effect of target location failed to reach significance [$F_{(1, 7)} = 4.0$, $p < .1$]. Critically, non-synesthetes showed no trace of an interaction between target color and location [$F_{(1, 7)} = .19$, $p > .5$].

Overall, inconsistent colors produced longer RTs (481 msec on average) than consistent ones (420 msec) and peripheral targets produced longer RTs (464 msec) than central ones (437 msec). However, when the digits were outside the attentional window (near condition) the difference between consistent and inconsistent RTs (59 msec) was similar to the one in the case where the digits were inside the attentional window (64 msec in the far condition).

Like AD and CP, non-synesthetes are faster to respond to targets that are colored consistently with the preceding digits. However, this does not depend on attention. These results are not surprising. Color does pop-out and should therefore interfere with subsequent color judgments whether the distractors were in the focus of attention or

not[7]. Importantly, these results show that the interaction observed in the synesthetes is unlikely to be confounded by physical difference in the target stimulus between the near and far conditions.

EXPERIMENT 3

Experiments 1 and 2 suggested that binding of synesthetic color to forms requires attention to the inducer. Both experiments converge to support a primary role of attention in binding color and shape even when synesthetic color is concerned (Exp. 1). They also demonstrate that synesthesia influences performance more when the inducer is inside the focus of attention (Exp. 2). These results are consistent with those of Mattingley et al. (2001). They demonstrated that Stroop color effects (color naming priming by a synesthetic color) were only present from the inducing stimulus once synesthetes became aware of the inducer. However it should be noted that they tested a more heterogeneous group of 15 synesthetes, while in our study only synesthetes who experienced colors projected externally and bound to the shape were included.

Smilek and Dixon (2002) would classify CP and AD as "projector" synesthetes and have suggested that synesthetic binding could precede awareness of the evoking stimulus and may take place in this type of synesthesia but not others. This classification was based on their studies with a projector color-digit synesthete referred to as C who produced findings that seem inconsistent with ours and those of Mattingley et al. (2001). In one study Smilek et al. (2001) presented a digit briefly on a colored background that was either consistent or inconsistent with the synesthetic color. C detected the digit more often when it was on a background inconsistent with the induced color than when it was on a consistent background. The background color appeared to camouflage the inducer when it was consistent with the synesthetic color, making the digit more difficult to detect.

These results represent the best support for preattentive binding in synesthesia. In order not to see a dark gray target on a colored background yet have it influence performance, the color must be bound to the digit preattentively. Smilek et al. (2001) used several different digits and colored backgrounds. We reasoned that error analysis may be susceptible to strategic biases (e.g., always guessing it is the digit corresponding to the background color or conversely, trying not to be fooled by the background color and always

guessing from the incongruent digit pool). Thus we used a simplified paradigm where only two inducers and two colors were shown throughout a block of trials and measured RT to identify the letter. With only two colors, the chance that a target grapheme evokes a different color than the background color is reduced to 50% and such strategies become ineffective.

Method

One of two possible letters (F or R, extending 3°) was presented centrally for 65 msec on a colored background and followed by a 100 msec mask. The letters were presented in black and the background was either the synesthetic color of the presented letter (consistent) or the synesthetic color of the other letter (inconsistent). The task was to indicate which of the two letters was presented by pressing one of two buttons. Intertrial interval was 2 sec. Background color change was synchronized with letter presentation onset and was presented randomly. The experiment consisted of 3 blocks of 64 trials each (192 trials total; 96 congruent and 96 incongruent). RTs and errors were recorded. RTs for incorrect responses were replaced with the mean. Only AD was available for this experiment (for her – F induces a green color and R is red).

Results and Discussion

AD made few errors discriminating between the two letters (2.6%). RTs when she correctly identified the presented letter were significantly shorter for the congruent condition (641 msec) than for the incongruent condition (711 msec), $F (1, 95) = 6.0$, $p < .02$ .The result that congruent RTs were actually faster than incongruent RTs is not consistent with the view that binding precedes the identification of the letter but does demonstrate that color affected the decision process even though it was irrelevant to the task (c.f., Cohen-Kadosh and Henik, 2006, in this issue, 259).

Smilek et al. (2001) replicated their finding in a second experiment, this time, measuring RTs to target localization in a complex display. C was slower to detect target digits when the color they induced matched the background color. The nature of the differences between AD and C is not yet clear; however individual differences may underlie the discrepancy. It should be noted that like many other synesthetes, both AD and CP report that synesthetic color does not replace the actual color, but rather they coexist. In contrast, C reports that the projected synesthetic color completely covers the presented grapheme (Smilek at al., 2001).

Phenomenological differences may indeed hold the key to understanding some of the differences found between synesthetes (e.g., Dixon et al., 2004). Still, variability in performance among synesthetes

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[7] Note that in the consistent case, the synesthetes do not respond much more slowly to peripheral targets (the 'inside' condition) as do the non-synesthetes. This is likely due to the fact that when inducers are inside the attentional window, synesthetes show not only increased interference (for incongruently colored targets), but also enhanced facilitation of RTs to congruently colored targets.

with apparently similar phenomenologies could be accounted for by neurophysiological heterogeneity (Hubbard et al., 2005). More detailed phenomenological reports in other synesthetes, combined with neurophysiological data could provide further clues to understanding such behavioral differences.

General Discussion

Our findings suggest that binding of color and shape in synesthesia does not precede awareness of the inducing item, at least for AD and CP who reported seeing the color bound with inducers. In Experiment 1, search slopes were unaffected by the synesthetic properties of the target item (i.e., whether or not the target induced a color) under conditions where distractors did not induce color. This is consistent with Palmeri et al. (2002). They noted that the efficient search found in synesthete WO is not analogous to pop-out induced with real colors. In their last experiment they too found that search for an inducer target was not efficient when the distractors were no longer synesthetic inducers. In Experiment 2, a role for spatial attention was supported by showing that synesthesia was induced more strongly when the inducers were inside a window of attention than they were outside. In Experiment 3, background colors congruent with an inducer did not hinder the detection of the inducers.

The findings suggest that pre-attentive binding of synesthetic colors to graphemes is not necessarily warranted. We suggest that attention plays a central role in integrating color and shape in synesthesia. These may be bound at least in part through similar neural mechanisms as in normal perception (Robertson, 2003a). If this is the case we might expect parietal involvement in synesthesia consistent with earlier arguments that parietal-temporal lobe interactions are necessary for proper binding (Robertson et al., 1997). Indeed, Esterman et al. (2004) were able to reduce the synesthetic Stoop interference in a color naming task after applying transcranial magnetic stimulation (TMS) to the parieto-occipital junction.

Previous neuroimaging studies have reported parietal activation during synesthetic experience. For instance, using PET Paulesu et al. (1995) examined brain activity in 6 color-word synesthetes compared to non-synesthetes while listening to words that induced color in the synesthetic group. They found more activation in left posterior temporal areas in the synesthetes and concluded that this activity reflected the linkage of color and words. No differential right ventral activity was found. In contrast, there was strong activation bilaterally in the occipital/parietal junction which the authors considered puzzling. These areas overlap with the damage in patient RM with

Balint's syndrome who had difficulty integrating color and form and are consistent with a parietal role in binding (Robertson, 2003a, 2003b).

Nunn et al. (2002) reported an fMRI study of 13 synesthetes and found temporal activation in color areas (V4/V8) both when synesthetes were shown colors without form and when presented sounds that induced the same colors. They too found increased occipital/parietal activation that overlapped areas of damage in RM in the synesthetic condition. In fact, the activation in parietal lobes was as strong as the activation in V4/V8, again supporting a parietal role in binding even in synesthesia.

Consistent with our conclusions, Mattingley et al. (2001) also argued that synesthesia requires attention. The 15 synesthetes who participated in their study showed no color priming from synesthetic colors of undetected letters, although letter priming from undetected letters was observed. A more recent study of by Laeng at al. (2004) also supports this idea. They noticed that facilitation of visual search by synesthetic color is limited to trials in which targets were closer to fixation (i.e., within the focus of attention). Furthermore, they noted that the search was much more efficient when they used colored stimuli and concluded that synesthetic color is not triggered preattentively. The data from our control experiment, in which we simulate what the search would be like if synesthetic color were to pop-out, are in accordance with these findings.

Together these results suggest that binding of information represented by different processing mechanisms engages attentional mechanisms whether the color information is presented through the sensorium or through an internally generated color induced by an achromatic stimulus.

Whether processing of the evoking stimulus within the focus of attention must be completed before synesthesia begins to influence perception remains a controversial issue. Blake at al. (2004), for example, suggest an intermediate position and do not require complete identification and conscious awareness of the inducer before the synesthetic color processing begins, consistent with Smilek et al. (2001). Although our findings strongly suggest that attention plays a role in synesthetic binding and that synesthetic colors do not pop-out, it is possible that there might still be some preattentive component (c.f., Vanrullen et al., 2004).

Finally, individual differences between participants are always a major concern, and perhaps especially so in the scientific study of synesthesia. Indeed, synesthesia takes many forms and the nature of the subjective experience varies (including additional senses involved, internal or external projection of photisms, the ability to localize them in space, color-letter mapping, etc). For this reason, we used within-subject designs and analyzed each synesthete's data individually. Our results suggest that modulation of performance by

synesthetic colors does indeed require attention to the evoking stimulus. These findings contribute to a growing body of evidence suggesting that synesthesia does share much in common with ordinary perception and may offer a window into mechanisms common to us all.

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Noam Sagiv, Department of Psychology, University College London, 26 Bedford Way, London WC1H 0AP, UK.