ATTENTIONAL LOAD ATTENUATES SYNAESTHETIC PRIMING EFFECTS IN GRAPHEME-COLOUR SYNAESTHESIA

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Abstract

One of the hallmarks of grapheme-colour synaesthesia is that colours induced by letters, digits and words tend to interfere with the identification of coloured targets when the two colours are different, i.e., when they are incongruent. In a previous investigation (Mattingley et al., 2001) we found that this synaesthetic congruency effect occurs when an achromatic-letter prime precedes a coloured target, but that the effect disappears when the letter is pattern masked to prevent conscious recognition of its identity. Here we investigated whether selective attention modulates the synaesthetic congruency effect in a letter-priming task. Fourteen grapheme-colour synaesthetes and 14 matched, non-synaesthetic controls participated. The amount of selective attention available to process the letter-prime was limited by having participants perform a secondary visual task that involved discriminating pairs of gaps in adjacent limbs of a diamond surrounding the prime. In separate blocks of trials the attentional load of the secondary task was systematically varied to yield 'low load' and 'high load' conditions. We found a significant congruency effect for synaesthetes, but not for controls, when they performed a secondary attention-demanding task during presentation of the letter prime. Crucially, however, the magnitude of this priming was significantly reduced under conditions of high-load relative to low-load, indicating that attention plays an important role in modulating synaesthesia. Our findings help to explain the observation that synaesthetic colour experiences are often weak or absent during attention-demanding tasks.

Key words: synaesthesia, selective attention, perceptual load, Stroop effect, priming, awareness

Introduction

Individuals with synaesthesia perceive the world in a way that is foreign to most people. They may see colours for letters, words and numbers, or smell unique odours upon hearing a particular tone or musical instrument. The phenomenon of synaesthesia has attracted renewed interest among cognitive neuroscientists, after languishing for many decades as a curiosity of the late 19th and early 20th centuries (for recent reviews see Rich and Mattingley, 2002; Robertson and Sagiv, 2005). One reason for this renewed interest is that synaesthesia may provide important clues to the cognitive and neural bases of multisensory integration, colour perception, language development, memory and metaphorical thinking, to name just a few. To date, however, most research in the area has focused on whether synaesthesia reflects automatic triggering of multimodal perception, and the extent to which mechanisms of selective attention might contribute to such "anomalous binding" (Mattingley et al., 2001; Robertson, 2003).

A currently unresolved issue in research on grapheme-colour synaesthesia concerns the extent to which synaesthetic colours arise automatically, without the need for conscious effort or strategic control (Rich and Mattingley, 2002; Robertson, 2003; Mattingley et al., 2001). Many synaesthetes report that the colours they experience in association with graphemes are not under voluntary control. These reports have been confirmed by studies demonstrating that synaesthetic colours can interfere with the identification and naming of display colours in Stroop-like paradigms (Mattingley et al., 2001; Mills et al., 1999; Dixon et al., 2000; Odgaard et al., 1999; Wollen and Ruggiero, 1983). On the other hand, synaesthetes often report that they are less aware of their colours, or that the colours disappear altogether, when their attention is engaged elsewhere. For instance, when viewing Navon-type local-global displays, the synaesthetic colour perceived typically depends on whether attention is focused on the local elements or the global form (Ramachandran and Hubbard, 2001; Rich and Mattingley, 2003). Such observations suggest that despite the apparent automaticity of synaesthetic experiences, their occurrence might be modulated by mechanisms of selective attention that prioritise perceptual inputs for further processing. A key question to emerge from such observations is the extent to which perceptual representations of letters and digits must be processed in order for synaesthetic colour experiences to arise.

Evidence that synaesthetic colours may occur without the need for focal attention has come predominantly from visual search data. It is well established in non-synaesthetes that unique features can be extracted rapidly from cluttered visual arrays, with little cost of additional distractor items on the time taken to detect a target. For example, when searching for a red target amongst green distractors, search times remain relatively constant over increases in the number of distractor items (Treisman and Gelade, 1980). Such efficient searches have been taken to indicate that certain visual properties, including unique colours, are processed without the need for serial allocation of focused attention (Treisman, 1998; Treisman and Gelade, 1980).

Several recent studies have adapted the visual search task to address the question of whether synaesthetic colours arise without the need for focal attention. In most cases the basic approach has been to present an achromatic target (letter or digit) in an array of achromatic distractors. For non-synaesthetic observers these search arrays should yield relatively inefficient searches, since there is no unique feature to distinguish the target from the distractor items. For synaesthetes, however, the target and distractor items are associated with distinct colours, and so might provide an additional feature by which to guide search for the target. Two studies that have followed this design have found that synaesthetic colours elicit more efficient visual search (Palmeri et al., 2002; Ramachandran and Hubbard, 2001), with the implication that synaesthetic binding of form and colour arises very early in visual processing, prior to explicit recognition of target identity (see also Smilek et al., 2003). However, a recent study by Laeng et al. (2004) suggests that efficient visual search may arise only for synaesthetically coloured targets close to fixation (within 6º in this instance), presumably because attention is focused on this central region of space at the beginning of each trial. Given that a substantial proportion of targets will occur centrally in a typical visual search task, some cases of efficient search might arise from parallel processing within the spotlight of attention, rather than from processing prior to attentional selection.

We have examined visual search for achromatic target digits in arrays of achromatic distractor digits in a group of grapheme-colour synaesthetes (see Edquist et al., 2006, in this issue, p. 222). We compared synaesthetes' efficiency in searching for targets defined by a unique synaesthetic colour (achromatic displays) with their performance for targets defined by a unique display colour (chromatic displays). Visual search slopes for synaesthete and control groups were indistinguishable for the achromatic displays, and both groups were significantly more efficient in searching for coloured targets than in searching for targets in achromatic displays. Together with the results of the study by Laeng et al. (2004), these new visual search findings challenge the idea that synaesthetic colours "pop out" prior to the allocation of focused attention.

Contrary to the early perceptual view of synaesthesia is evidence from studies suggesting that induced colours arise only with considerable perceptual processing, after explicit recognition of the inducing form. For instance, Mattingley and colleagues (Mattingley et al., 2001) presented synaesthetes with an achromatic letter prime, which induced a synaesthetic colour that was either congruent or incongruent with a subsequent colour target. When the prime was visible, synaesthetes were slower to name the target colour on incongruent relative to congruent trials; when the letter was pattern masked to prevent conscious recognition of its identity, however, this synaesthetic priming effect disappeared.

Rich and Mattingley (2003) demonstrated that synaesthetic congruency effects induced by coloured stimuli in Navon-type local-global displays (e.g., a global **A** made from local **B**'s) were reduced when synaesthetes focused their attention on congruently coloured local letters and actively ignored an incongruently coloured global letter. Similarly, Sagiv and Robertson (2005) observed that when achromatic inducing digits appeared outside the spatial focus of attention, their effect on naming times for coloured targets was significantly smaller than when the digits appeared within the attentional focus.

Given the conflicting findings of previous studies, we designed an experiment to investigate whether selective attention can modulate grapheme-colour synaesthesia. Our approach was to manipulate the availability of processing resources during the brief presentation of letters that acted as primes for subsequent coloured targets. Lavie has suggested that perceptual load determines the locus of the processing bottleneck in tasks requiring selective attention (Lavie, 1995; Lavie and Tsal, 1994). According to this account, perception proceeds unselectively until its capacity is reached. In tasks with a low perceptual load, therefore, irrelevant or distractor items will be processed automatically and may thus interfere with target performance. Tasks with a high load, on the other hand, will be more likely to exceed the limit of available attentional resources, and irrelevant items will no longer be processed. As a general rule, for tasks that require minimal attentional resources, there is likely to be sufficient residual capacity to process any irrelevant items. In contrast, for difficult perceptual tasks that require substantial attentional resources, the amount of residual capacity to process irrelevant stimulus items will be reduced.

In contrast to our previous synaesthetic priming study in which we employed pattern masks to reduce processing of the primes (Mattingley et al., 2001), here we had participants perform a demanding secondary task that engaged their attention during presentation of an unmasked prime. There were three conditions of attentional load during the prime display: a *no-load* condition, in which there was no secondary task; a *low-load* condition, in which the secondary task was relatively undemanding, leaving residual attentional capacity for processing the prime; and a *high-load* condition, in which the secondary task was relatively demanding, substantially reducing the attentional resources available for processing the prime.

Our analyses focused on whether the cost of incongruent relative to congruent trials was attenuated in the high-load condition relative to the low-load condition. If synaesthetic colours are elicited prior to, or independent of, the allocation of focused attention, then any congruency effect observed should be equivalent under different conditions of load. Conversely, if attention is required to bind letters with their synaesthetic colours, then the cost of incongruent relative to congruent trials should be significantly attenuated in the high-load condition. In addition to the critical attentional load experiment, we conducted several subsidiary experiments to rule out potential contributions from factors unrelated to the manipulation of attention. These included a baseline colour-naming task, a standard Stroop task (Stroop, 1935) and a "synaesthetic Stroop" task (Mattingley et al., 2001; Wollen and Ruggiero, 1983; Mills et al., 1999; Odgaard et al., 1999). In each experiment the performances of the synaesthetes were compared with those of a matched group of non-synaesthetic controls.

Method

Participants

Fourteen grapheme-colour synaesthetes (12 female, mean age = 46.0 years, SD = 13.1 years, range: 20-62 years) were selected on the basis of self-reported experiences of colour for orthographic presentation of letters. Most individuals also reported colours for words and Arabic numerals. The consistency of synaesthetic experiences was assessed by having participants report their colours for Arabic numerals, letters and words on two separate occasions three months apart, as described in detail elsewhere (Mattingley et al., 2001). Mean consistency of synaesthetic colours elicited by letters across the group was 93% (SD = 9%). Fourteen age-, sex- and handedness-matched non-synaesthetic controls were tested for purposes of comparison (mean age = 47.1 years, SD = 13.6 years, range: 21-66 years). The mean ages of the groups were not significantly different, $t(26) = -.21$, $p > .05$. All participants gave informed consent and were screened for anomalous colour vision using the Ishihara colour plates.

Stimuli and Procedure

A Pentium III (128 MHz) desktop computer controlled all aspects of stimulus presentation and response-time recording. Stimuli were displayed on a 17-inch Samsung SyncMaster 710 fast-decay monitor with a vertical refresh rate of 75 Hz. A Labtec AM-22 microphone interfaced via the serial port was used to record voice-onset times in the colour-naming tasks, and errors in colour-naming were scored manually. Unspeeded responses for the attentional load task were recorded via the up- and down-arrow keys of the computer's keyboard.

Prior to the main experimental session, synaesthetes were asked to match their synaesthetic colours for letters, using a standard RGB colour palette displayed on the computer screen. Following each selection they were asked to rate on a scale of 1 (not at all matched) to 5 (perfectly matched) how closely the display colour matched their synaesthetic colour. Letters that received a subjective rating less than 4 (very well matched) were excluded. The experimenter selected six letters, with the principal criterion being that the synaesthetic colours elicited by the letters were vivid and perceptually distinct from one another. The mean colour-match rating for the group was 4.3 (SD = .3). The six letter-colour combinations selected for each synaesthete were used to create the "congruent" and "incongruent" items for the experimental tasks (see below).

Participants were tested individually in a dimly illuminated, sound-attenuated booth. A chin-rest was used to ensure that the viewing distance to the computer monitor remained constant at 50 cm. The order of the experimental tasks was counterbalanced across participants, with the constraint that the colour-naming task was always conducted first to permit participants to become accustomed with the colours they would be required to identify in the experimental tasks; and that the prime-identification task was always conducted at the completion of the experimental session.

Baseline Tasks

The basic procedure for the three baseline tasks was identical. Each trial began with a grey fixation cross, presented for 500 msec, followed by the coloured target item presented for 4 sec or until a response was made. Participants named aloud the colour of the target as quickly as possible. The interval between trials was 1 sec.

The aim of the *Colour-Naming task* was to check that the synaesthetes and controls did not differ in the speed with which they could name target colours. The colour target was a small, filled rectangle ($5.04° \times 5.61°$) presented at fixation. There were six practice items at the commencement of the task (one for each of the six possible colours), followed by 48 experimental trials consisting of eight repetitions of the six colours, presented in random order.

The *Standard Stroop task* was conducted to check that the two groups did not differ in their susceptibility to interference from incongruent

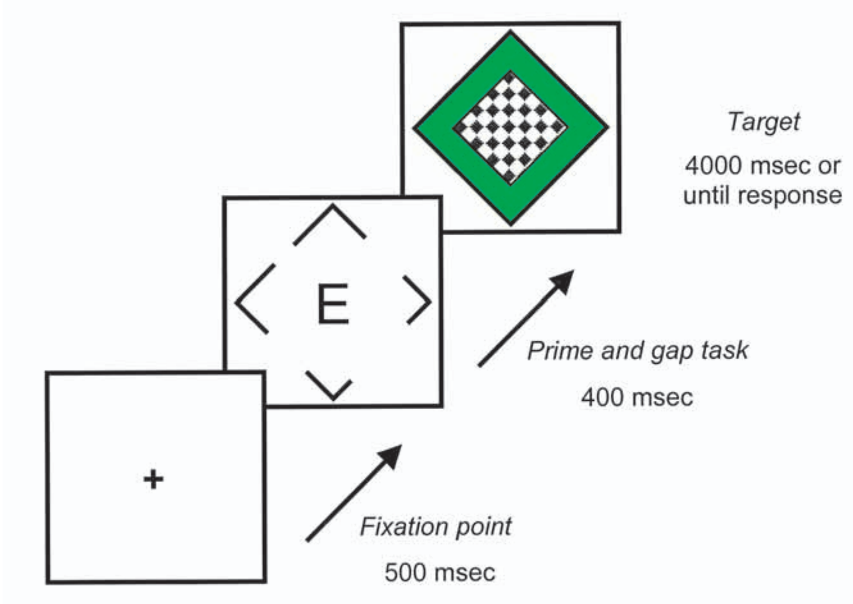

Fig. 1 – *Sequence of displays in a typical trial of the attentional load task. Participants attended to diagonally opposite sides of the diamond throughout a block of trials. In this example focusing attention on the top-left and bottom-right gaps constituted the low-load condition (a relatively easy discrimination); focusing attention on the top-right and bottom-left gaps constituted the high-load condition (a difficult discrimination). Participants first named the colour of the target display as quickly as possible ('green' in this case), and then indicated which gap in the attended pair was larger.*

colour words. Participants named aloud the display colours of uppercase colour-names (BLUE, BROWN, GREEN, PURPLE, RED, YELLOW) presented individually at fixation. The words were presented in Arial font and subtended a visual angle of 1.60° × 4.12° – 9.15°. Each word appeared either in its own colour (*congruent trials*) or in one of the other colours (*incongruent trials*). Each colour name was presented 8 times in its congruent colour and 8 times in a single incongruent colour, giving a total of 96 trials per block. Congruent and incongruent trials were equiprobable and were randomly intermingled within a block. Participants completed two blocks of trials, each of which was preceded by 8 practice trials.

The *Synaesthetic Stroop task* was conducted to verify in synaesthetes the presence of an interference effect for colour-naming of incongruent *versus* congruent letters (Mattingley et al., 2001; Wollen and Ruggiero, 1983; Mills et al., 1999; Odgaard et al., 1999). The target displays consisted of coloured letters. Each letter subtended a visual angle of 4.58° × 2.52° – 5.84°. Individual synaesthetes were tested with a unique ensemble of six colours. Each control participant viewed the identical stimuli as his or her matched synaesthete. Each letter appeared either in the synaesthetic colour it elicited (*congruent trials*), or in one of the other colours (*incongruent trials*). All other parameters, including trial numbers, were identical to the standard Stroop task.

Attentional Load Task

Figure 1 shows the sequence of displays in a typical trial of the attentional load task. Each trial began with a grey central fixation cross for 500 msec, followed by the prime display for 400 msec, and then the target display which remained for 4 sec, or until a response was made.

The prime display contained both the letter prime and the attentional load stimulus. The letters were the same as those used in the synaesthetic Stroop task, but now were presented in grey on a white background. The attentional load stimulus was an outline diamond surrounding the letter prime; it subtended a visual angle of 13.12° × 13.12°. On every trial, each side of the diamond contained a gap, ensuring that the displays remained identical across the manipulation of attentional load. Participants were asked to judge which of two gaps was larger; in separate blocks of trials they focused their attention on the lower-left and upper-right sides of the diamond, or on the lower-right and upper-left sides of the diamond. In each block, the gaps in the attended sides of the diamond were either low-load or high-load. In the low-load condition the gaps were 2.06° *versus* 5.14°, and were relatively easy to discriminate; in the high-load condition the gaps were 3.21° *versus* 4.00º, and were more difficult to discriminate. The target displays consisted of one of the six target colours selected for each synaesthete surrounding a grey pattern mask (7.10° × 7.10°). For synaesthetes, this colour was either congruent or incongruent with the synaesthetic colour elicited by the letter prime. The primary task was to name aloud the colour in the target display as quickly and as accurately as possible. The secondary task was to give an unspeeded two-alternative, forced choice response to indicate the larger of the two gaps. In a baseline condition, participants ignored the gaps in the prime display and performed the colour-naming task alone (no-load condition).

Each condition (no-load, low-load, high-load) consisted of two blocks, each containing 96 equiprobable congruent and incongruent trials, randomly intermingled. The order of blocks was counterbalanced across participants. There were 12 practice trials prior to each experimental block.

To examine the effect of the attentional load manipulation on the ability of participants to identify the letter prime, participants performed an additional *Prime Identification task*. Instead of naming the colour in the target display, participants were required to identify the letter prime while performing the secondary gap discrimination task. There were again no-load, low-load and high-load conditions, each with 96 trials collected in separate blocks.

RESULTS

In all tasks, trials on which there were colour-naming errors were removed from the analyses. In all tasks, errors for each group accounted for less than 2% of trials; the error data were therefore not submitted to statistical analysis. Outliers were defined as colour-naming times more than three standard deviations from individual condition means for each participant, and were removed prior to group analysis. Trials in which the microphone was activated by extraneous noises were also removed.

Colour-Naming Task

Microphone errors and outliers accounted for 7.8% of trials for synaesthetes and 5.8% of trials for controls. There was no significant difference between the mean correct colour-naming time for the synaesthetes (mean = 589 msec) and that for the controls (mean = 613 msec), $t(26) = -.64$, $p > .1$.

Standard Stroop Task

Microphone errors and outliers accounted for 4.0% of trials for synaesthetes and 4.5% of trials for controls. Both synaesthetes and controls were slower to name display colours in the incongruent condition (synaesthetes: mean = 813 msec, controls: mean = 825 msec) than in the congruent condition (synaesthetes: mean = 682 msec, controls: mean = 699 msec). A two-way ANOVA on the mean correct colour-naming times with the between-subjects factor of group (synaesthetes, controls) and the within-subjects factor of congruency (congruent, incongruent) revealed a significant main effect of congruency, $F(1, 26) = 105.18$, $p < .001$, but no significant main effect of group, $F(1, 26) < 1$, ns, and no significant group by congruency interaction, $F(1, 26) < 1$, ns This demonstrates that the magnitude of the Stroop effect did not differ between synaesthetes and controls. Thus there is no evidence for a baseline difference in susceptibility to Stroop interference between the groups.

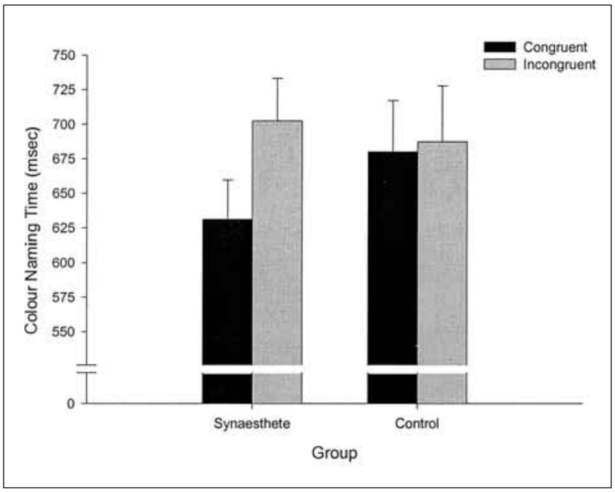

Fig. 2 – *Mean colour-naming times (+ 1 s.e.) for synaesthetes and controls in the synaesthetic Stroop task.*

Synaesthetic Stroop Task

Microphone errors and outliers accounted for 5.7% of trials for synaesthetes and 5.4% of trials for controls. Mean correct colour-naming times are shown in Figure 2. These data were submitted to a two-way ANOVA with the between-subjects factor of group (synaesthetes, controls) and the within-subjects factor of synaesthetic congruency (congruent, incongruent). There was a significant main effect of synaesthetic congruency, $F(1, 26) = 16.83$, $p < .001$, no significant main effect of group, $F(1, 26) < 1$, ns, and a significant group by synaesthetic congruency interaction, $F(1, 26) = 11.22$, $p < .01$. Paired sample t-tests by group confirmed that synaesthetes were slower to name colours in the incongruent condition (mean = 702 msec) than in the congruent condition (mean = 631 msec), $t(13) = -3.97$, $p < .01$, whereas there was no such difference for controls (incongruent: mean = 687 msec *vs*. congruent: mean = 680 msec), $t(13) = -1.10$, $p > .1$. Thus, only synaesthetes showed significant congruency effects in this modified Stroop task.

Attentional Load Task

In the attentional load task, we examined the influence of a secondary gap discrimination task performed during presentation of the letter prime on the magnitude of the synaesthetic priming effect. In this task, microphone errors and outliers accounted for 3.6% of trials for synaesthetes and 5.1% of trials for controls.

First, we verified that our manipulation of relative differences in gap size successfully modulated the load of the task by analysing the

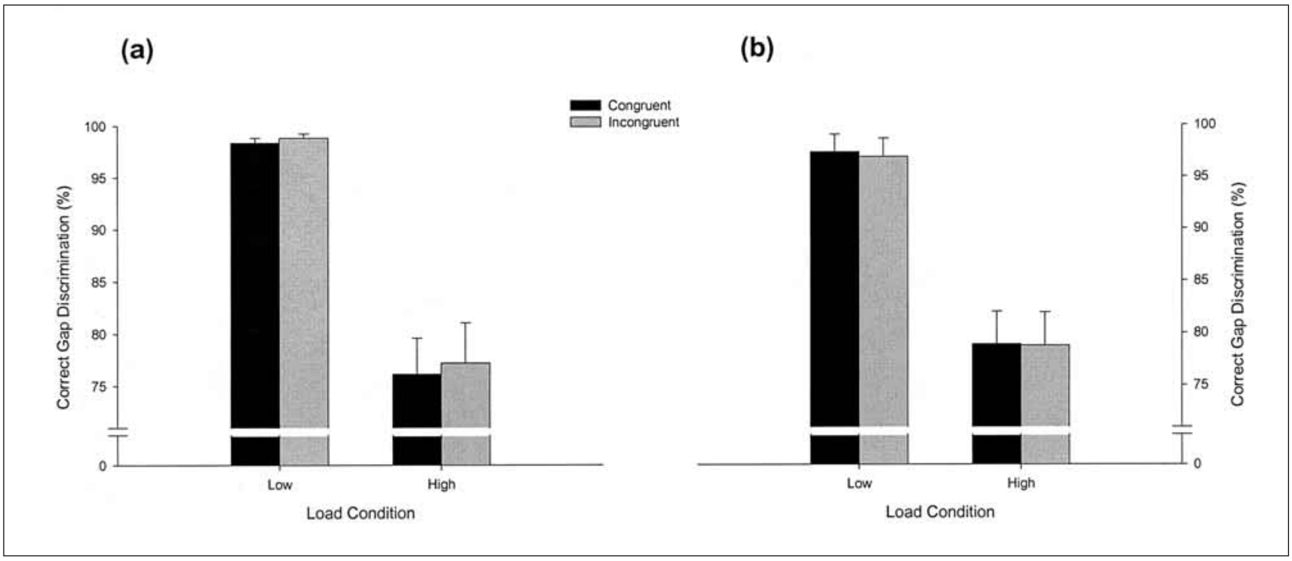

Fig. 3 – *Percentage of correctly discriminated gaps (+ 1 s.e.) in the low- and high-load conditions.* ***(a)*** *Synaesthetes.* ***(b)*** *Controls.*

accuracy of gap discrimination in the low- and high-load conditions (note that gap discrimination was not performed in the no-load condition, in which participants performed the colour-naming task only). Figure 3 shows the percentage of correct responses in the gap discrimination task in the low- and high-load conditions, plotted as a function of synaesthetic congruency condition. A three-way ANOVA, with the between-subjects factor of group (synaesthetes, controls) and the within-subjects factors of load (low, high) and synaesthetic congruency (congruent, incongruent) revealed a significant main effect of load, $F(1, 26) = 72.99$, $p < .001$, and no other significant main effects or interactions. Thus, gap discrimination was significantly harder in the high- than in the low-load condition, and this effect was equivalent for synaesthetes and controls.

Next, we analysed colour-naming times from the no-load (baseline) condition to verify the presence of a synaesthetic congruency effect with these modified priming displays. Mean correct colour-naming times for synaesthetes and controls are shown in Figure 4. A two-way ANOVA with the between-subjects factor of group (synaesthetes, controls) and the within-subjects factor of synaesthetic congruency (congruent, incongruent) revealed a significant main effect of synaesthetic congruency, $F(1, 26) = 11.72$, $p < .01$, and a significant group by synaesthetic congruency interaction, $F(1, 26) = 13.75$, $p < .01$, but no significant main effect of group, $F(1, 26) < 1$, ns. The synaesthetes were significantly slower to name target colours in the incongruent (mean = 632 msec) than in the congruent condition (mean = 579 msec), $t(13) = -3.81$, $p < .01$, whereas controls showed no such difference (incongruent: mean = 622 msec *vs.* congruent: mean = 624 msec), $t(13) = .40$, $p > .1$.

Having verified the presence of a synaesthetic priming effect with these modified displays, we next analysed the effects of attentional load on colour-naming times for the two groups. Figure 5 shows the mean correct colour-naming times for synaesthetes (Figure 5a) and controls (Figure 5b) as a function of synaesthetic congruency and level of attentional load. A three-way ANOVA with the factors of group (synaesthetes, controls), synaesthetic congruency (congruent, incongruent) and load (low, high) revealed significant main effects of load, $F(1, 26) = 30.21$, $p < .001$ and synaesthetic congruency, $F(1, 26) = 45.71$, $p < .001$, but no significant main effect of group, $F(1, 26) < 1$, ns. All of the interaction terms were also significant, including the crucial three-way interaction of group by synaesthetic congruency by load, $F(1, 26) = 6.34$, $p < .05$.

The data were then analysed separately for each group to examine the source of the three-way interaction. As shown in Figure 5b, controls exhibited very similar naming times for incongruent and congruent trials in both the low-load (mean = 681 msec *vs.* mean = 683 msec, respectively) and high-load conditions (mean = 792

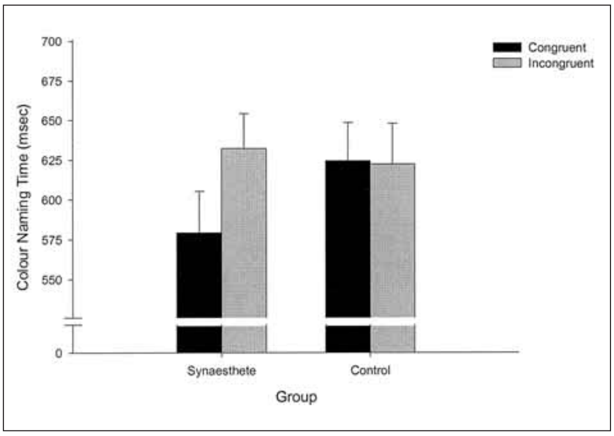

Fig. 4 – *Mean colour-naming times (+ 1 s.e.) for synaesthetes and controls in the no-load condition of the attentional load task.*

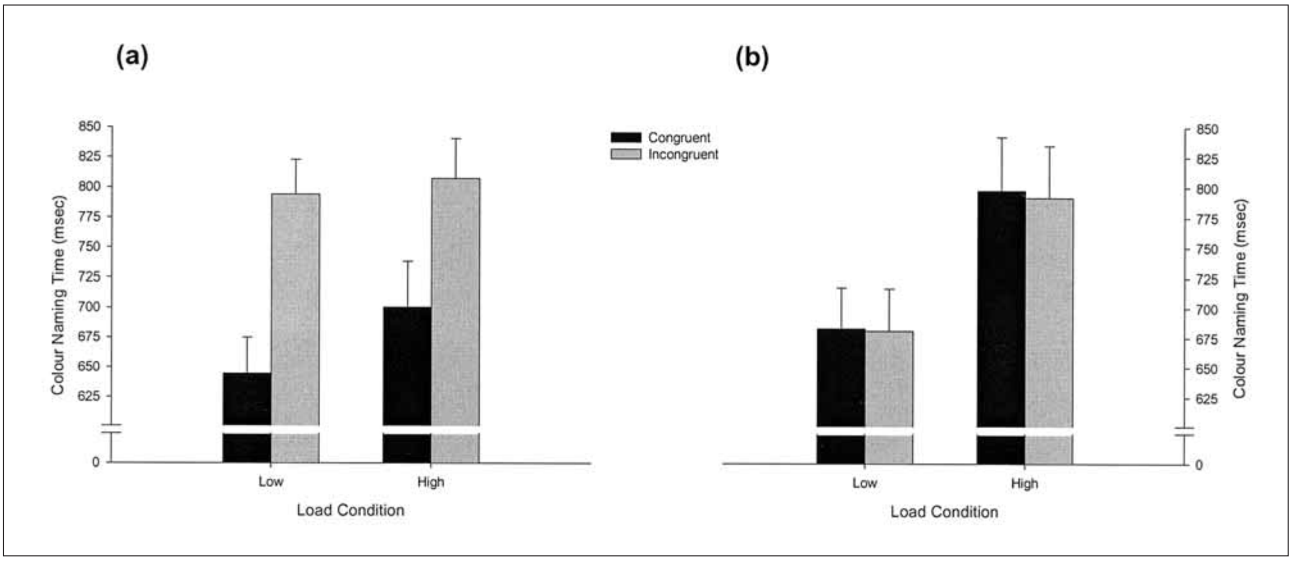

Fig. 5 – *Mean colour-naming times (+ 1 s.e.) in the low-load and high-load conditions of the attentional load task.* ***(a)*** *Synaesthetes.* ***(b)*** *Controls.*

msec *vs*. mean = 798 msec, respectively). A two-way ANOVA on the control data revealed a significant effect of load, F (1, 26) = 32.78, p < .001, but no significant effect of synaesthetic congruency, F (1, 26) = 1.02, p > .1, and no interaction between these factors, F (1, 26) < 1, ns. In contrast, Figure 5a shows that synaesthetes were slower in the incongruent trials than in the congruent trials, and that this effect was attenuated in the high-load condition (mean = 807 msec *vs*. mean = 700 msec, a difference of 107 msec) relative to the low-load condition (mean = 794 msec *vs*. mean = 645 msec, a difference of 149 msec). A two-way ANOVA on the synaesthete data confirmed these patterns: there was no significant main effect of load, F (1, 26) = 3.60, p > .05, but a significant main effect of synaesthetic congruency, F (1, 26) = 50.82, p < .001, and a significant interaction between these factors, F (1, 26) = 10.62, p < .05.

Finally, we examined participants' ability to identify the primes in each of the load conditions. As shown in Table I, both groups performed near ceiling across all three levels of load. Thus, although the attentional load manipulation clearly affected colour-naming times, there was no detrimental effect on overt identification of the primes.

Discussion

The primary aim of this study was to investigate the role of attention in modulating perceptual experiences in individuals with grapheme-colour synaesthesia. We used a synaesthetic priming task in which a letter prime induced a synaesthetic colour that was either congruent or incongruent with a subsequent target colour (Mattingley et al., 2001). In the basic priming task (the *no-load* condition), synaesthetes exhibited a robust effect of prime-target congruency; their colour-naming responses to incongruently primed targets were significantly slower than their responses to congruently primed targets. In contrast, non-synaesthetic controls showed no differences between the synaesthetic congruency conditions. Thus, we successfully replicated synaesthetic priming effects using these modified displays (c.f., Mattingley et al., 2001), again demonstrating the involuntary nature of synaesthetic colours. The synaesthetic priming effect was still evident for synaesthetes when they performed an attention-demanding secondary task during presentation of the letter prime. Crucially, however, the magnitude of this priming was significantly reduced under conditions of high-load relative to low-load, indicating that attention plays an important role in modulating synaesthetic colour experiences.

We also conducted a number of baseline tasks to rule out alternative explanations for differences between synaesthetes and controls in the effects of attentional load on priming. Response times in a baseline colour-naming task did not differ between the groups. Nor was there a group effect in the standard Stroop task, consistent with the findings of Mattingley et al. (2001), thus ruling out a general difference in susceptibility to interference from grapheme-colour stimuli. In the standard Stroop

TABLE I
Percentage of primes correctly identified by synaesthetes and controls for the three levels of attentional load

Group	No-load	Low-load	High-load
Synaesthetes	100.0	99.8	99.7
Controls	99.9	99.7	99.2

task, synaesthetes might be expected to show a larger congruency effect than controls if they experience competition from *both* the colour name and from any synaesthetic colours elicited by letters comprising the name. However, we have found that roughly 70% of grapheme-colour synaesthetes actually see matching synaesthetic colours for colour names (e.g., ‘RED’ tends to be seen as red, ‘GREEN’ as green, etc.; Rich et al., 2005). It therefore should not be surprising that congruent and incongruent colour-word stimuli exert similar effects for synaesthetes and controls in the standard Stroop task. Finally, the prime-identification task, in which participants performed the gap discrimination and also identified the letter primes, demonstrated that participants were at ceiling in identifying the primes, even when performing the difficult high-load task. Thus, the finding of a reduced congruency effect under conditions of high attentional load cannot be attributed to a reduction in conscious perception of inducing letters.

The finding that synaesthetic congruency effects are reduced under conditions of high attentional load is consistent with a growing body of evidence that suggests that attention plays an important role in the binding of synaesthetic colours to their inducing letters (Rich and Mattingley, 2003, 2005; Robertson, 2003; Mattingley and Rich, 2004). It is well established that attention modulates the perceptual representation of stimuli and that high attentional load can attenuate perceptual and neural responses to visual stimuli (Rees et al., 1997; for a review see Kanwisher and Wojciulik, 2000). It is unclear from our results whether the attentional load manipulation affected the perceptual representation of the letter primes or the processes that link the letters with their synaesthetic colours. We know that participants were near ceiling in identifying the letter primes (Table I), even in the high-load condition. This might be taken as evidence that the perceptual representation of the primes themselves was not affected at all by the secondary task. However, the prime-identification task was not speeded, and we did not record response times. It is therefore possible that the primes were processed more slowly under high-attentional load, and that this influenced the magnitude of the congruency effect. Whatever the explanation for the effect of load on letter primes, however, we can say with some certainty that selective attention reliably modulates performance in the synaesthetic Stroop task.

One outcome of our study that does not initially seem to fit with the hypothesis that attention is important for synaesthetic experience is that synaesthetes exhibited a much smaller congruency effect in the no-load condition (53 msec; see Figure 4) than in the low- and high-load conditions (149 and 107 msec, respectively; Figure 5a). If synaesthetes could devote their full attention to the primes in the no-load condition, why didn’t they show the largest congruency effect in this condition? Our answer is based on the fact that attentional selection entails not only facilitation of task-relevant information, but also suppression of irrelevant or distracting information. Recall that on 50% of the trials the prime letter was incongruent with the colour of the target, and thus could interfere with colour naming. It is therefore reasonable to expect that synaesthetes would be motivated to try and suppress the prime displays in an effort to overcome any such interference. The extent to which they were able to achieve this should have been maximal in the no-load condition, since in these trials participants could ignore the prime display (letter and surrounding gap stimulus) altogether. By contrast, because in the low- and high-load conditions the letter appeared simultaneously with the gaps to be discriminated, the prime display could *not* be actively ignored and the congruency effect was magnified. We suggest that any spare attentional capacity from the gap-discrimination task automatically spilled over to the letter prime, and that this yielded a large congruency effect in the low-load task and a significantly smaller effect under high-load.

Our results are reminiscent of findings from attentional manipulations of the conventional Stroop task (Stroop, 1935), in which cues that effectively divert attention away from an incongruent word reduce, but do not eliminate, interference in colour naming (Brown et al., 2002). It has been suggested that diverting attention from a colour name reduces the efficiency of semantic access and therefore reduces the conflict between the word itself and the colour to be named (Besner and Stolz, 1999; Besner, 2001). Similarly, Myles et al. (2003) have shown that the conceptual context in which a letter or digit appears can significantly alter synaesthetic congruency effects. In the present study, having an attentionally demanding task during the prime display may have reduced the extent to which inducing letters were able to activate the appropriate semantic representations, including any synaesthetic colours, and thus reduced the magnitude of the synaesthetic congruency effect.

Although our results clearly demonstrate an attenuation of synaesthetic congruency when attentional resources are required for another task, a residual priming effect was nevertheless observed. Thus, it might be argued that attention is not crucial for linking letters with synaesthetic colours; if synaesthetic colours do arise prior to focused attention, their salience could still be modulated by attention later in the processing hierarchy via top-down influences. Although we cannot rule out this possibility, the residual congruency effect under conditions of high-load is more likely to be a function of surplus processing resources. Performance on the high-load gap discrimination was ~ 80% correct (compared with 98% correct for low-load; and 50% for chance), suggesting that spare attentional capacity may have been available to process the letter primes.

It is also noteworthy that synaesthetes' naming times for incongruent trials remained comparable for low- and high-load tasks, whereas those for congruent trials increased substantially in the high-load condition (Figure 5a). Because we did not include primes that were synaesthetically 'neutral' (e.g., non-alphanumeric symbols; Mattingley et al., 2001), we cannot determine unambiguously whether the congruency effect shown by the synaesthetes reflects a cost of incongruent primes, a benefit of congruent primes or both. To the extent that incongruent primes do interfere with target responses, our results suggest that increasing attentional load does not alter this effect; on the contrary, it seems that any potential benefit for congruent trials is reduced.

In future investigations it will be important to include synaesthetically neutral stimuli as a baseline with which to compare responses to congruently and incongruently coloured targets. It will also be important to examine the extent to which inducing stimuli trigger synaesthetic colours under conditions of complete inattention, such as during the period of the attentional blink (Raymond et al., 1992; Rich and Mattingley, 2005). For the present, however, the results of this study clearly demonstrate that selective attention strongly modulates grapheme-colour synaesthesia.

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