

22. Agrawal, A. A. Induced responses to herbivory and increased plant performance. *Science* **279**, 1201–1202 (1998).
23. Coley, P. D., Bryant, J. P. & Chapin, F. S. Resource availability and plant antiherbivore defense. *Science* **230**, 895–899 (1985).
24. Heath, R. R. & Manukian, A. An automated-system for use in collecting volatile chemicals released from plants. *J. Chem. Ecol.* **20**, 593–608 (1994).

Acknowledgements

We thank G. W. G. De Moraes for discussions; H. T. Alborn, J. G. Hildebrand, P. J. Landolt, W. J. Lewis, K. G. Ross and J. R. Ruberson for comments on the manuscript; and B. Dueben and M. Sammons for technical assistance.

Correspondence and requests for materials should be addressed to J.H.T. (e-mail: jtumlinson@gainesville.usda.ufl.edu).

Unconscious priming eliminates automatic binding of colour and alphanumeric form in synaesthesia

Jason B. Mattingley*, Anina N. Rich*, Greg Yelland† & John L. Bradshaw†

* School of Behavioural Science, University of Melbourne, Victoria 3010, Australia
 † Department of Psychology, Monash University, Victoria 3800, Australia

Synaesthesia is an unusual perceptual phenomenon in which events in one sensory modality induce vivid sensations in another^{1,2}. Individuals may ‘taste’ shapes³, ‘hear’ colours⁴, or ‘feel’ sounds⁵. Synaesthesia was first described over a century ago⁶, but little is known about its underlying causes or its effects on cognition. Most reports have been anecdotal or have focused on isolated unusual cases^{3,7–9}. Here we report an investigation of 15 individuals with colour-graphemic synaesthesia, each of whom experiences idiosyncratic but highly consistent colours for letters and digits. Using a colour–form interference paradigm, we show that induced synaesthetic experiences cannot be consciously suppressed even when detrimental to task performance. In contrast, if letters and digits are presented briefly and masked, so that they are processed but unavailable for overt report, the synaesthesia is eliminated. These results show that synaesthetic experiences can be prevented despite substantial processing of the sensory stimuli that otherwise trigger them. We conclude that automatic binding of colour and alphanumeric form in synaesthesia arises after initial processes of letter and digit recognition are complete.

We studied 15 individuals with colour-graphemic synaesthesia and 15 non-synaesthetic controls. Each synaesthete reported vivid and immediate sensations of colour for specific letters and digits. All reported having had synaesthesia since childhood, and many had biological relatives with the phenomenon, consistent with previous reports¹⁰. Our study focused on colour-graphemic synaesthesia because it is the most common form¹⁰, and because it has received considerable attention¹¹.

A test of consistency verified the presence of synaesthesia in our group⁴. Participants were each given a 150-item list containing letters (A–Z), digits (0–9) and words. They described their synaesthetic colour for each item (or an arbitrary colour in the case of non-synaesthetic controls). Three months later, without warning, the synaesthetes were given the same list and again asked to indicate their synaesthetic colour for each item. For controls, the retest was given just one month later, thus giving them a potential advantage. The synaesthetes were highly consistent in their responses overall, significantly more so than the controls ($F_{1,28} = 162.56, P < 0.0001$; Fig. 1). These findings show that the unusual sensations experienced

by synaesthetes, although idiosyncratic, remain highly stable over time⁴.

Colour-graphemic synaesthesia may be triggered by automatic co-activation of independent brain areas responsible for processing colour and symbolic form^{12,13}. This fits with synaesthetes’ subjective accounts of the involuntary nature of their experiences. We therefore manipulated the physical colours of alphanumeric characters so that they differed from the synaesthetic colours induced. Our approach was based on the Stroop effect¹⁴, in which naming the print colour of an incongruent colour word (for example, RED printed in blue) takes significantly longer than naming the print colour of a congruent colour word (for example, RED printed in red), or a colour patch. This slowing reflects interference arising from an involuntary word-reading response¹⁵.

We began by comparing synaesthetes and controls on the standard Stroop task to check for any baseline differences in their susceptibility to interference. Colour words were displayed in either congruent or incongruent colours; solid colour patches were used in a baseline condition (see Methods). Participants named the colour of each stimulus aloud. As expected, both groups were significantly slower to name colours in the incongruent than the congruent condition ($F_{1,28} = 119.72, P < 0.001$). Critically, there was no overall difference between the groups ($F_{1,28} = 0.66, P > 0.10$) and no interaction ($F_{1,28} = 1.56, P > 0.10$; Fig. 2a), indicating equivalent interference for synaesthetes and controls. Moreover, their colour naming times in the baseline condition were the same (535 ms versus 536 ms; $t_{28} = 0.03, P > 0.10$).

If synaesthesia is an involuntary phenomenon, then having participants judge the physical colour of an alphanumeric character that elicits an incongruent synaesthetic colour should yield significant interference, and slow response times accordingly. We therefore constructed unique stimulus ensembles for each synaesthete, which

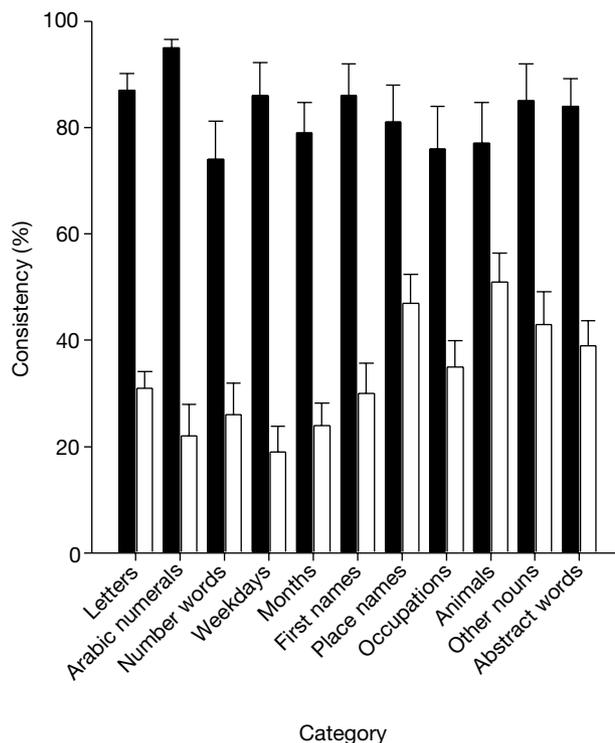


Figure 1 Mean (+1 s.e.) consistency of colour associations for 150 items (letters, arabic numerals and words), plotted separately for each of 11 categories tested. Results for synaesthetes (filled bars) represent performance with a 3-month retest interval; those for non-synaesthetic controls (open bars) represent performance with a 1-month retest interval. For every category tested synaesthetes were more consistent in their colour associations than non-synaesthetic controls.

were based on a detailed colour-matching procedure, to obtain congruent and incongruent stimulus sets (see Methods).

Participants named aloud the physical colour of alphanumeric stimuli presented individually on a computer display. In one experiment, synaesthetically congruent and incongruent stimuli were presented in separate blocks of trials. Synaesthetes took significantly longer to name display colours when these were incongruent with their induced synaesthetic colours, as compared with the congruent condition in which the physical and synaesthetic colours were matched ($F_{1,28} = 12.00, P < 0.01$; Fig. 2b). Notably, there was no difference between congruent and incongruent conditions for the non-synaesthetic controls ($F_{1,28} = 0.31, P > 0.10$; Fig. 2b).

In a second experiment, congruent and incongruent trials were randomly intermingled. Additional 'neutral' stimuli, comprising non-alphanumeric typographical symbols, were also included (see Methods). Synaesthetes again showed a significant effect of congruency ($F_{2,28} = 7.43, P < 0.01$; Fig. 2c), whereas the controls did not ($F_{2,28} = 1.17, P > 0.10$). These results show that colour-graphemic synaesthetes cannot consciously suppress their unusual colour sensations. This is consistent with individual case reports of

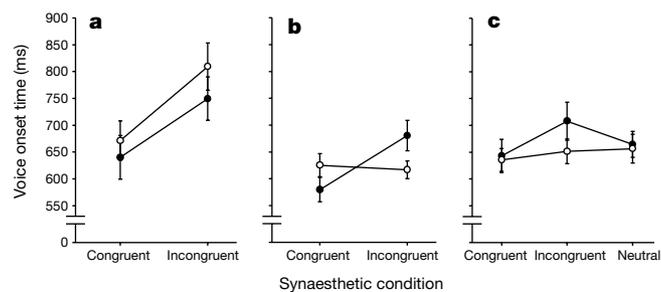


Figure 2 Mean voice-onset times (± 1 s.e.) for colour naming in the standard and synaesthetic Stroop tasks, plotted as a function of congruency condition. Data are shown as separate lines for synaesthetes (solid symbols) and non-synaesthetic controls (open symbols). **a**, Randomized presentation of congruent and incongruent colour words in the standard Stroop task. Means for baseline condition are reported in the text. **b**, Blocked presentation of synaesthetically congruent and incongruent alphanumeric characters. **c**, Randomized presentation of synaesthetically congruent, incongruent and neutral alphanumeric characters. The faster responses of synaesthetes relative to controls in the congruent condition of **b** (but not **c**) implies a strategic benefit from blocked presentation.

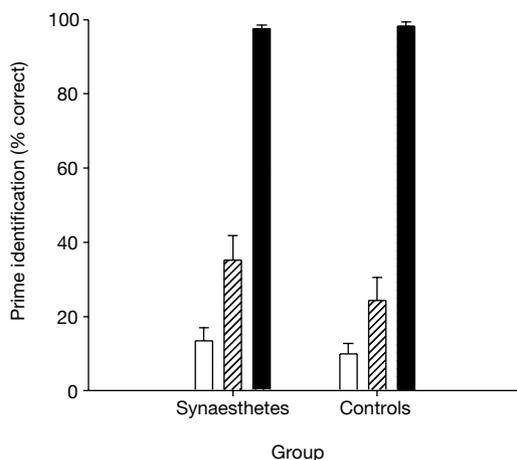


Figure 3 Mean percentage correct prime identification (± 1 s.e.) for the priming experiments. Data are plotted separately for synaesthetes and non-synaesthetic controls. Prime durations were 28 ms (open bars), 56 ms (hatched bars) and 500 ms (filled bars); identification scores were not different for the two groups at any of the durations ($P > 0.10$ for all comparisons).

synaesthetic interference^{7-9,11}, as well as our synaesthetes' subjective experiences of overwhelming mental effort in the synaesthetically incongruent trials.

We next determined whether the involuntary binding of colour and form occurs when the triggering stimuli are not available for conscious report. Visual stimuli that are displayed briefly and masked may receive considerable unconscious processing¹⁶⁻¹⁸. We modified our synaesthetic Stroop task so that an achromatic alphanumeric character was presented briefly and masked. Participants named the colour of a target patch presented immediately after the masked prime. The colour of the target patch was congruent, incongruent or neutral with respect to the synaesthetic colour induced by the alphanumeric prime. In an initial experiment, the prime was presented for 500 ms so that it was clearly visible. We tested prime identification in a separate task in which participants had to name the alphanumeric prime, instead of naming the colour of the target patch (see Fig. 3).

In the colour-naming task, synaesthetes were significantly affected by prime-target congruency ($F_{2,28} = 14.22, P < 0.001$; Fig. 4a). Naming times were slower in the incongruent and neutral conditions than in the congruent condition ($P < 0.01$ for both). In contrast, controls showed no significant effect of congruency ($F_{2,28} = 0.137, P > 0.10$; Fig. 4b). The unexpectedly slow naming times in the neutral condition reveal a further intriguing characteristic of the synaesthetic group (see Fig. 4a), most of whom reported 'weak' or 'faint' colours for these non-alphanumeric symbols. The achromatic primes in the neutral condition thus elicited incongruent colours for most of the synaesthetes, leading to significant interference.

In a further experiment, primes were presented for either 56 or 28 ms, in separate blocks of trials. At these durations, conscious identification of the alphanumeric primes was severely curtailed (Fig. 3); indeed, participants were not aware of their presence. As shown in Fig. 4a, the effect of congruency on colour-naming times at these shorter prime durations was completely absent in the

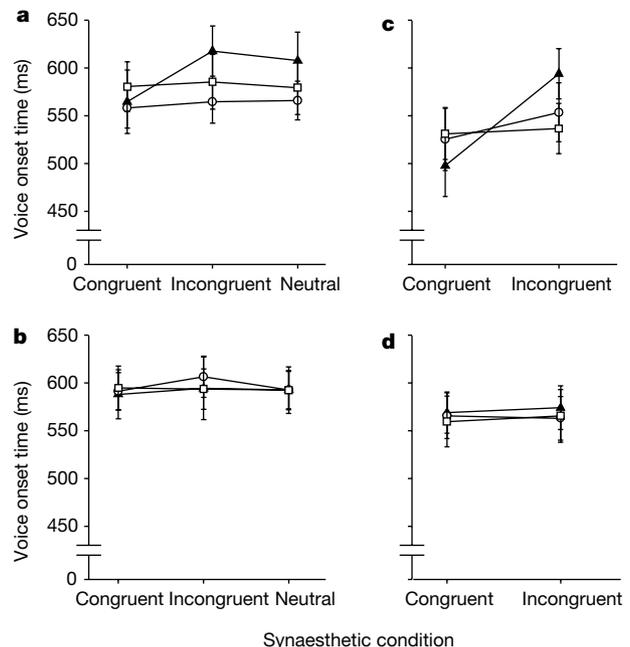


Figure 4 Mean voice-onset times (± 1 s.e.) for colour naming in the visible priming (500 ms) and masked priming (56 and 28 ms) experiments, plotted as a function of synaesthetic congruency condition. **a**, Synaesthetes: standard priming. **b**, Controls: standard priming. **c**, Synaesthetes: temporal-gap priming. **d**, Controls: temporal-gap priming. Data are shown as separate lines for each of the three prime durations of 500 ms (filled triangles), 56 ms (open circles) and 28 ms (open squares).

synaesthetes, whose performance was now similar to that of the controls ($P > 0.10$; Fig. 4b). These results show for the first time, to our knowledge, that synaesthesia is eliminated when inducing stimuli are unavailable for conscious report.

We verified that the primes were processed unconsciously in a separate interference task involving letter naming. In this task letters replaced the colour-patch targets, and were either congruent (such as $a \rightarrow A$) or incongruent (such as $b \rightarrow A$) with the preceding primes. At prime durations of 56 and 28 ms, both groups were significantly slower to name letters in the incongruent condition (costs of 21 ms and 7 ms, respectively; both $P < 0.001$). This interference effect indicates unconscious processing of the letter prime, consistent with previous reports for whole-word priming¹⁷.

To determine whether the absence of interference might be due to the time required for synaesthetic colours to be elicited by the primes, we repeated the initial priming experiments with the prime-target onset interval held constant (see Methods). Alphanumeric primes appeared for 28 or 56 ms, and were followed by a 100-ms backward mask to curtail identification. The screen then remained blank for 372 or 344 ms before the onset of the coloured target. A 500-ms prime duration was also included (no prime-target gap), in which all primes were clearly visible. Thus, the onset asynchrony between prime and target was held constant at 500 ms in all three conditions. At the 500-ms prime duration synaesthetes' colour naming was significantly slower for incongruent versus congruent conditions ($F_{1,12} = 15.12$, $P < 0.01$; Fig. 4c), whereas there was no such effect for controls ($F_{1,12} = 0.45$, $P > 0.10$; Fig. 4d). This replicates the interference effect observed in the initial visible priming experiment (see Fig. 4a). With masked priming, however, the congruency effect disappeared entirely for synaesthetes ($F_{1,12} = 2.06$, $P > 0.10$; Fig. 4c), and was again absent for controls ($F_{1,12} = 3.25$, $P = 0.10$; Fig. 4d) despite the constant interval between prime and target across all conditions.

Our findings have important implications for understanding the automatic binding of colour and form in synaesthesia. They suggest that synaesthetic colours cannot be consciously suppressed, and that robust cognitive interference occurs when there is a conflict between real and synaesthetic colours. Our results go beyond previous single-case reports^{7-9,11} by showing that such interference is a ubiquitous feature of colour-graphemic synaesthesia, thus providing an objective, cognitive marker for the phenomenon. They also reveal that the obligatory binding of colour and form in synaesthesia can be broken when inducing stimuli are masked, rendering them unavailable for conscious report. We conclude that synaesthetic interactions arise after initial processing of visual form, and that overt recognition of inducing stimuli is crucial. Our view is consistent with the idea that synaesthesia is elicited by selectively attended stimuli that are available for conscious report¹⁹. □

Methods

Subjects

Fifteen colour-graphemic synaesthetes (13 female, 13 right-handed; mean age = 41.26 years; range = 18–60 yr) and 15 non-synaesthetic controls (matched for age, sex and handedness) were tested. All participants were screened for neurological and colour vision impairments. Synaesthetes completed a questionnaire that documented their unusual experiences and personal history.

Synaesthetic Stroop tasks

Individual synaesthetes selected from a standard palette the colour that best matched their synaesthetic experience for each item in a set of alphanumeric characters (letters A–Z, digits 0–9). They rated their choices on a 5-point scale. The six characters yielding the best colour matches for each synaesthete were used in the experimental tasks. The mean colour-match rating for the group was 4.0 ('very well matched'). These synaesthetically matched characters were the 'congruent' stimuli; 'incongruent' stimuli were obtained by making the same characters different in colour to those elicited synaesthetically.

Participants were tested individually in a sound attenuated booth. Their voice-onset times were recorded by a Sennheiser HMD224 head-mounted microphone interfaced with a PC (IBM compatible 486) that controlled all aspects of stimulus presentation and response recording (DMTG software; K. Forster and J. Forster, Monash Univ. and Univ.

Arizona). Stimuli appeared individually in the centre of a 38-cm monitor (Phillips Brilliance 15A) against a black background. Trials were self-paced by means of a foot pedal.

In the standard Stroop task, stimuli were uppercase colour words (BLUE, GREEN, PURPLE, RED, WHITE, YELLOW) presented in Times Roman font ($1.4^\circ \times 2.6\text{--}5.4^\circ$ at a viewing distance of 50 cm). Each colour word appeared eight times, four in its congruent colour and four in a single incongruent colour, for a total of 48 trials per block. Stimuli in the baseline condition consisted of solid rectangles ($3.4^\circ \times 4.6^\circ$) in one of the six colours, each of which appeared eight times for a total of 48 trials in a block. In the modified Stroop task, synaesthetically congruent and incongruent alphanumeric characters (Times Roman, $1.4^\circ \times 0.8^\circ$) were presented either in separate blocks of 36 trials, or randomly intermingled together with non-alphanumeric symbols such as an asterisk ('neutral' condition) within a single block of 48 trials. In the randomized presentation, congruent, neutral and incongruent stimuli appeared in a ratio of 1:1:2, with each colour being equiprobable. Each block was preceded by five practice trials. In all tasks, participants named aloud the colour of the visual target (word, character or colour patch). Stimuli remained visible for 4,000 ms or until a response was made.

Priming experiments

Participants named the colour of target patches consisting of six overlapped typographical symbols (Times Roman, $1.4^\circ \times 1.0^\circ$). These targets formed a pattern mask for the preceding primes, which were the same alphanumeric characters as those used in the synaesthetic Stroop tasks, presented in light grey. Each trial commenced with a light grey forward mask ($1.7^\circ \times 3.3^\circ$), followed by a prime of variable duration (28, 56 or 500 ms in separate blocks), and then a coloured target which remained visible for 4,000 ms or until a response was made. Targets appeared in one of the six colours used in the synaesthetic Stroop tasks. Congruent, neutral and incongruent trials were randomly intermingled within a single block of 48 trials, in a ratio of 1:1:2. In the 'temporal gap' variant of the priming experiments, conducted with 13 of the 15 synaesthetes, only congruent and incongruent trials were included (1:1, 48 trials per condition). Masked primes were followed immediately by an achromatic pattern mask for 100 ms, a blank interval of either 372 or 344 ms, and then a coloured target which remained visible for 4,000 ms or until a response was made.

In a separate task, participants' ability to identify the primes was assessed. Stimuli and display sequences were identical to those used in the colour-naming task. Participants were instructed to identify the primes rather than name target colours. Their untimed responses were recorded verbatim. There were 48 trials, with equal numbers of stimuli from each of the three prime durations. To verify that primes were processed at durations of 28 and 56 ms, a letter-to-letter priming task was conducted in which participants named uppercase target letters aloud. These were preceded by lowercase primes. Primes could appear for 28, 56 or 500 ms, in separate blocks of 48 trials. There were equal numbers of congruent (for example, $a \rightarrow A$) and incongruent (for example, $b \rightarrow A$) trials. All other aspects of the display sequence were the same as those used in the synaesthetic priming experiments.

Received 8 November; accepted 12 December 2000.

- Baron-Cohen, S. & Harrison, J. E. (eds) *Synaesthesia: Classic and Contemporary Readings* (Blackwell, Cambridge, 1997).
- Cytowic, R. E. *Synaesthesia: A Union of the Senses* (Springer, New York, 1989).
- Cytowic, R. E. *The Man Who Tasted Shapes* (Abacus, London, 1993).
- Baron-Cohen, S., Wyke, M. A. & Binnie, C. Hearing words and seeing colours: an experimental investigation of a case of synaesthesia. *Perception* **16**, 761–767 (1987).
- Luria, A. R. *The Mind of a Mnemonist* (Basic Books, London, 1969).
- Galton, F. Visualized numerals. *Nature* **21**, 252–256 (1880).
- Mills, C. B., Boteler, E. H. & Oliver, G. K. Digit synaesthesia: A case study using a Stroop-type test. *Cog. Neuropsychol.* **16**, 181–191 (1999).
- Odgaard, E. C., Flowers, J. H. & Bradman, H. L. An investigation of the cognitive and perceptual dynamics of a colour-digit synaesthete. *Perception* **28**, 651–664 (1999).
- Wollen, K. A. & Ruggiero, F. T. Colored-letter synaesthesia. *J. Mental Imagery* **83–86** (1983).
- Baron-Cohen, S., Burt, L., Smith-Laittan, F., Harrison, J. & Bolton, P. Synaesthesia: prevalence and familiarity. *Perception* **25**, 1073–1079 (1996).
- Dixon, M. J., Smilek, D., Cudahy, C. & Merikle, P. M. Five plus two equals yellow. *Nature* **406**, 365 (2000).
- Paulesu, E. et al. The physiology of coloured hearing: A PET activation study of colour-word synaesthesia. *Brain* **118**, 661–676 (1995).
- Baron-Cohen, S., Harrison, J., Goldstein, L. H. & Wyke, M. Coloured speech perception: is synaesthesia what happens when modularity breaks down? *Perception* **22**, 419–426 (1993).
- Stroop, J. R. Studies of interference in serial verbal reactions. *J. Exp. Psychol.* **18**, 643–662 (1935).
- MacLeod, C. M. Half a century of research on the Stroop effect: an integrative review. *Psychol. Bull.* **109**, 163–203 (1991).
- Dehaene, S. et al. Imaging unconscious semantic priming. *Nature* **395**, 597–600 (1998).
- Forster, K. I. & Davis, C. Repetition priming and frequency attenuation in lexical access. *J. Exp. Psychol. Learn. Mem. Cog.* **10**, 680–698 (1984).
- Marcel, A. J. Conscious and unconscious perception: experiments on visual masking and word recognition. *Cog. Psychol.* **15**, 197–237 (1983).
- Grossenbacher, P. G. in *Synaesthesia: Classic and Contemporary Readings* (eds Baron-Cohen, S. & Harrison, J. E.) (Blackwell, Cambridge, 1997).

Acknowledgements

We wish to thank A. Kritikos, M. O'Boyle, P. Wilken and M. Williams for their comments on the manuscript. This work was supported by a grant from the Australian Research Council to J.B.M.

Correspondence and requests for materials should be addressed to J.B.M. (e-mail: j.mattingley@psych.unimelb.edu.au).