Grapheme-Colour Synaesthesia Influences Overt Visual Attention

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Synaesthesia is a fascinating condition in which ordinary stimuli elicit extraordinary sensory experiences. For example, specific tastes may elicit unusual tactile sensations and standard black letters may elicit highly specific colour experiences. These unusual experiences have been shown to have substantial impact on cognition, emotion, perception, and covert attention. Two experiments are presented which show that synaesthesia also influences overt visual attention. In these experiments two grapheme-colour synaesthetes viewed coloured letters while their eye movements were tracked. Letters were presented in colours that were either congruent or incongruent with the synaesthetes' colours. Eye tracking analysis showed that synaesthetes exhibited a colour congruity bias – a propensity to fixate congruently coloured letters more often and for longer durations than incongruently coloured letters – in a naturalistic free viewing task. In a more structured visual search task, this congruity bias caused synaesthetes to rapidly fixate and identify congruently coloured target letters, but led to problems in identifying incongruently coloured target letters. The results are discussed in terms of their implications for perception in synaesthesia.

Acknowledgements

I would like to give special thanks to my advisors Mike Dixon and Daniel Smilek for their guidance, encouragement, enthusiasm for research, and occasional ability to keep me focused and moving forward.

I would also like to thank Mike Reynolds for his support and remarkable ability to debate the benefits of different data analysis techniques apparently well beyond my capacity to understand them.

In addition, I would like to thank all the members of the Smilek lab for ensuring I always feel needed. In particular I would like to thank Donna Kwan for always keeping the lab organized and her assistance with data collection, and Kelly Malcolmson for being the best officemate one could ever hope for.

Last, but certainly not least, I would like to thank DE and KS, without whom I might have nothing interesting to say about synaesthesia.

Dedication

This thesis is dedicated to my wife, without whom I certainly would not have come this far, and my family for always being supportive.

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1.1 Introduction

Synaesthesia is a fascinating condition in which ordinary stimuli elicit extraordinary sensory experiences. For some synaesthetes sounds can have a specific colour (Ward, Huckstep, & Tsakanikos, 2006) or tastes can elicit specific tactile and shape impressions (Cytowic, 1989; 1993). Synaesthesia can also involve multiple extraordinary sensory experiences for a single inducing stimulus; for example, Dixon, Smilek, and Merikle (2004) have described a synaesthete for whom hearing a person's voice elicits both color and taste experiences. In these examples the relations between the inducing stimulus and the concurrent experience are cross-modal, but such extraordinary sensory pairings can also occur within a single modality. For example, grapheme-color synaesthesia, one of the most commonly researched forms of synaesthesia, is characterized by the association of colour (i.e., a photism) to specific letters or numbers (e.g., Dixon, Smilek, Cudahy, & Merikle, 2000; Mattingley, Rich, Yelland, & Bradshaw, 2001; Ramachandran & Hubbard, 2001a; 2001b). One of the most important aspects of synaesthesia is that its extraordinary sensory experiences are believed to occur automatically and without intention for the synaesthete. For instance, in grapheme-colour synaesthesia photisms are elicited automatically, without intention, whenever the synaesthete sees letters, numbers, or even whole words (e.g., Dixon, et al., 2004; Mattingley, et al., 2001; Mills, Boteler, & Oliver, 1999; Svartdal & Iversen, 1989; Nikolić, Lichti, & Singer, 2007). As an example, the grapheme-colour synaesthete C reports that whenever she sees the number 4 it elicits a blue colour, appearing as though overlaid on top of the number itself (Smilek, Dixon, Cudahy, & Merikle, 2001).

An interesting and important characteristic of synaesthesia is that the unusual sensory associations synaesthetes experience are not simply epiphenomenal, but rather appear to profoundly influence the synaesthete's cognition. For instance, studies have shown synaesthesia can have a substantial impact on memory (Azoulai, Hubbard, & Ramachandran, 2005; Smilek, Dixon, Cudahy,

& Merikle, 2002; Luria, 1968), emotional experiences (Callejas, Acosta, & Lupiáñez, 2007; Ramachandran & Hubbard, 2001b; Smilek, Malcolmson, et al., 2007), perception (e.g., Palmeri, Blake, Marois, Flanery, & Whetsell, 2002; Nikolić, et al., 2007, Ramachandran & Hubbard, 2001b; Smilek, et al., 2001) and covert attention (Palmeri, et al., 2002; Smilek, Dixon, & Merikle, 2003; Smilek, Callejas, Dixon, & Merikle, 2007). In the present paper these previous findings were extended by evaluating whether synaesthesia can influence overt exploratory behavior as indexed by eye movements.

To evaluate whether synaesthesia influences eye movements two individuals with grapheme-colour synaesthesia were studied. DE is a 20-year-old male undergraduate student at the University of Waterloo. For DE, seeing black letters and numbers elicits the highly specific colour experiences typical of grapheme-colour synaesthesia. For example, DE would describe the letter D as having an unsightly shade of light pink while the letter E and the number 3 are both a similar bright green. These colour photisms are perceived almost as though emanating from, or overlaid on top of, the letters and numbers themselves, and are present even when he is not looking directly at them. KS is a 23-year-old female undergraduate student also at the University of Waterloo. Like DE, when KS sees black letters and numbers she experiences highly specific colours that appear to be overlaid on top of the letters and numbers themselves. Thus, KS' and DE's synaesthetic experiences fit the definition of a "projector" synaesthete as defined by Dixon, et al. (2004). Illustrating the variability one finds when comparing experiences across synaesthetes (see Calkins, 1893; Rich, Bradshaw, & Mattingley, 2005; Simner, et al., 2005), unlike DE, KS experiences a deep maroon colour for the letter D and a dark green colour for the letter E; as well, she reports having to look directly at a grapheme in order to see its colour. Nonetheless, for any given synaesthete, the grapheme-colour pairings reported are remarkably invariant over time (Baron-Cohen, Harrison, Goldstein, & Wyke, 1993; Dixon et al., 2000; Odgaard, Flowers & Bradman, 1999; Svartdal & Iversen, 1989) and both DE and KS report consistently experiencing the same colour for a given letter every time they see it.

There are two good reasons to believe grapheme-colour synaesthesia may influence overt attention, as measured by eye movements. First, both DE and KS report that they dislike seeing letters presented in the “wrong” (i.e., incongruent) colours (see also Callejas, et al., 2007; Ramachandran & Hubbard, 2001b) and that doing so can make the information presented more difficult to interpret. To elaborate, for KS, seeing a black E elicits the experience of the black E along with a dark green coloured overlay. Because text is most frequently presented as black characters on a white background (books, newspapers, word documents, etc.), this combination is the standard combination of physical colour (black) and photism colour (green) that KS is used to experiencing. So, synaesthetes report that on those rare occasions when instead of a black letter the letter is presented in the "right" (i.e., congruent) colour, this combination of physical colour (green) and synaesthetic colour (green) looks and somehow "feels" right. By contrast, if the letter is presented in the "wrong" (incongruent) colour (e.g., red), synaesthetes experience two conflicting colours: the "wrong" colour (red) in which the letter is physically presented, and the "right" colour (green) – the colour of their synaesthetic photism. Synaesthetes describe these incongruently coloured graphemes as "jarring", "nausea inducing", "difficult to look at" and on some occasions as "difficult to interpret". DE, who also experiences entire words in colour, reports that he has developed computer programs which display words in the “right” (i.e., congruent) colour in order to avoid this problem. A detailed qualitative study of the experiences of 192 synaesthetes conducted by Rich, Bradshaw and Mattingley (2005), found 10% of these synaesthetes reported difficulty interpreting conflict between the meaning of a word and its colour. Akin to DE’s subjective report, one of the synaesthetes in their study, KM, reported often getting confused when sailing because green lights in a harbour are meant to indicate starboard, but for her the word starboard is red. Such subjective reports afford two potential interpretations, both of which may in part explain how synaesthetic experiences could influence overt attention. First, the synaesthetes' reports suggest incongruently coloured information may be more difficult to interpret than congruently coloured information, potentially increasing the amount of time necessary for identification of incongruently coloured letters, numbers, or words. Second, these reports reflect a clear preference for congruently coloured information, suggesting their everyday viewing behaviour could exhibit an attentional colour congruity bias.

The second reason to propose that grapheme-colour synaesthesia may influence overt visual attention, as measured by eye movements, comes from investigations of how synaesthetic photisms influence performance in visual search tasks (e.g., Smilek, et al., 2001). A number of authors have shown synaesthetic photisms can enhance search efficiency when photism colour differentiates achromatic targets from their distractors (Palmeri, et al., 2002) or the background of the display (Smilek, et al., 2003), helping to attract attention toward the target. In addition, studying eye movement data has proven informative about the attentional processes involved in the completion of visual search tasks between the onset of the search display and the ultimate manual response (Findlay, 1997; Gilchrist & Harvey, 2006; Hooge & Erkelens, 1996).

The present study examines eye movements in two types of tasks – a free viewing task and a more traditional, highly constrained visual search task. In order to examine the effects of grapheme-colour congruity on eye movements in naturalistic viewing behaviour I first had participants complete a free viewing task while their eye movements were monitored (see Smilek, Malcolmson, et al., 2007). The free viewing task incorporated displays containing an equal number of congruently and incongruently coloured letters and the goal for the task was to simply view each display, ensuring all items had been "seen". Importantly, the letters in these displays could be seen either by fixating the item or via peripheral viewing of the item. The eye movement data collected throughout the task was subsequently used to assess the effects of congruity on synaesthetes' overt visual attention. Consistent with subjective reports that synaesthetes prefer congruently coloured information compared to incongruently coloured information, I expected to find a colour *congruity bias* in the synaesthetes' eye movements. Specifically, I anticipated the synaesthetes would fixate congruently coloured letters significantly more often and for a longer duration on average than incongruently coloured letters.

In a second experiment the extent of the synaesthetes' congruity bias was further examined using a visual search task. As in the free viewing task, the search displays contained an equal number of congruently and incongruently coloured letters. This meant that on half of the trials when the target was present, the target could be displayed in a colour that was either congruent or incongruent with their synaesthetic photism for that target letter. Consistent with the notion of a synaesthetic congruity bias in overt attention, I expected to find substantial overall search time differences when comparing search performance for congruently and incongruently coloured targets. In addition, I again monitored eye movements to further explore the nature of the congruity bias in visual search behaviour. Specifically, I evaluated (1) whether target congruity rapidly influences eye movements within the first few fixations, and (2) whether target congruity influences the extent to which targets are re-fixated before being fully identified.

1.2 Experiment 1

The purpose of Experiment 1 was to evaluate whether grapheme-colour congruity can influence the allocation of visual attention for synaesthetes. For Experiment 1a simple free viewing task allowed observation of how grapheme-colour congruity influences overt visual attention in naturalistic viewing behaviour, without the constraint of specific task demands (e.g., searching for a pre-specified target, as in a visual search task). Two synaesthetes first identified the colours they associate with each letter of the English alphabet. The two synaesthetes and two groups of non-synaesthete participants then viewed displays containing an equal number of coloured letters that for the synaesthetes elicited either congruently or incongruently coloured photisms. The participants were required simply to view each display until they felt they had seen all of the letters it contained. Eye movements were monitored throughout the free viewing task in order to evaluate the specific prediction that synaesthetes would show a *congruity bias* in their viewing behaviour. That is, for synaesthetes, congruently coloured letters should be fixated significantly more often and for a longer duration on average than incongruently coloured letters.

1.2.1 Method

Participants. A 20-year-old male with grapheme-colour synaesthesia (DE) participated in the approximately one-hour free viewing task. As well, a 23-year-old female with grapheme-colour synaesthesia (KS) participated in the same one-hour free viewing session. Six non-synaesthetic students from the University of Waterloo served as yoked controls for each synaesthete (i.e., they were presented with exactly the same letter displays in the same order, and were required to perform the same task as the synaesthete to whom they were yoked). Yoked control participants received partial credit toward their Introductory Psychology course as compensation. One of the non-synaesthete participants yoked to DE was removed because of a disproportionately large number of fixations falling on entirely blank portions of the screen. This participant was replaced.

Stimulus Displays. Displays were created using colours previously identified by the synaesthetes as the colours that corresponded to each letter of the alphabet. These colours were applied either to the "right" letter (congruent) or a different letter (incongruent). Each display always contained an equal number of congruently and incongruently coloured letters. The letters used for any given display were selected such that all letters in the display carried a different colour. The letters shown on the free viewing displays were presented against a standard black background, so the maximum number of letters available to be presented was constrained by being able to select only those colours that were discernable against a black screen (24 for DE, 23 for KS). For both synaesthetes there were several letters of the alphabet that elicited photisms with similar colours. To ensure a unique colour of presentation for each letter, however, letters with similar colours were not presented in any of the displays. Given these constraints the displays used in the free viewing task included a maximum of 14 of the 24 letters available for DE and 12 of the 23 letters available for KS. Non-synaesthetes received the exact same displays as the synaesthetes to whom they were experimentally yoked.

Each display was constructed by dividing the screen into an imaginary 6 x 6 grid and randomly assigning each letter to one of the resulting 36 locations. All letters were presented in 36 point Lucida Console font for DE. To ensure the results would generalize beyond this specific font size, for KS font size was randomly adjusted such that on any given display up to four items were presented at a size 45% larger than the 36 point Lucida Console font used for the other letters. As the size adjustment was irrespective of colour, any effects of size would serve only to add noise to the eye movement data. Displays were viewed from a distance of approximately 81 cm. Items measured from 0.6 cm (0.4°) to 1.5 cm (0.9°) horizontally and from 1.2 cm (0.7°) to 2.0 cm (1.2°) vertically depending on the letter and size of presentation (see Figure 1). Each item was presented in the centre of its grid location (cell), which measured approximately 6.9 cm (4.2°) horizontally and 5.2 cm (3.2°) vertically. A letter was considered fixated when the pixel coordinates of the averaged fixation location landed inside its cell.

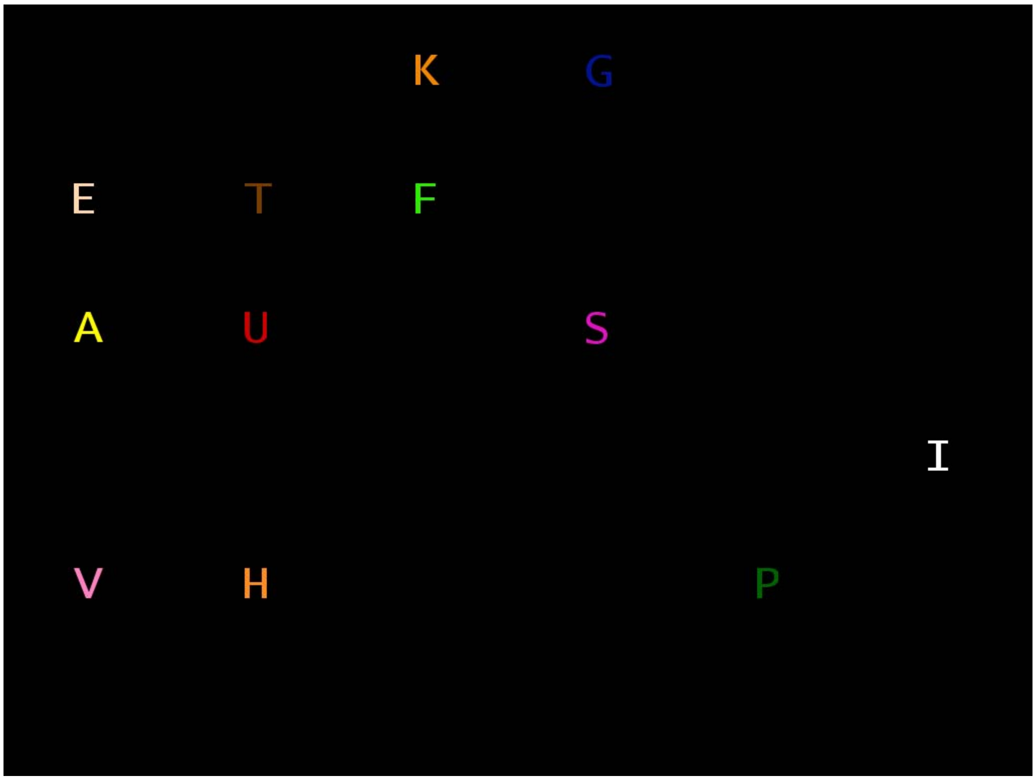


Figure 1. An example of the stimulus displays created for the free viewing task.

Eye Tracking. An SR Research Ltd. EyeLink II head-mounted eye tracking system was used to display the stimuli and collect response time and eye movement data. The EyeLink II head band contains three cameras for simultaneous tracking of both eyes and of head position for head-motion compensation. Pupils and corneal reflections were tracked on the most accurately calibrated eye for each participant. The system was calibrated using a randomly ordered 9-dot pattern, and the mean error in the computation of gaze position was less than 0.55° visual angle on average. The system's default settings for acceleration and velocity thresholds were used for saccade detection.

Two display screens were used. The stimulus displays were presented to the participants on a Dell P1230 22" CRT flat screen colour monitor with a medium short phosphor persistence; the monitor resolution was set at 1024 x 768. The displays were also presented to the experimenter on a second monitor so that real-time feedback could be given about gaze position. This allowed the experimenter to evaluate system accuracy throughout the experiment and to initiate a recalibration if necessary.

Procedure. Prior to the free viewing task the synaesthetes had identified the colours they associate with each letter of the English alphabet. For this process black letters were presented on a white paper. Synaesthetes then matched the photism that was elicited by the letter to a colour on a computer screen using the colour palette included in Microsoft Paint. Once a colour was identified, the RGB values were recorded. This process was repeated until a colour had been selected for each letter. For some letters the synaesthetes indicated the letter had more than one colour, and in these cases they were asked to identify the primary colour associated with that letter; only the primary colour was subsequently used for the free viewing displays.

For the free viewing task participants were instructed to view each display until they believed they had seen everything on the display, and that they could view the displays for as long as they wished. Participants were further instructed to press a button when they were finished viewing a display and ready to proceed to the next display. In order to ensure a similar mean viewing time to that of DE and KS, non-synaesthete participants were also instructed to attempt to view the displays for at least 8 seconds, on average, but to do so without counting the time in their heads.

The free viewing task was split into two blocks: a practice block of 12 trials and an experimental block of 180 trials. Non-synaesthetes viewed the same displays in the same randomized order as the synaesthete to whom they were yoked. A trial began with presentation of the stimulus display, which then remained on screen until the participant pressed a button. After the button press a blank screen was presented for 2000 ms before the onset of the next stimulus display. Following every set of 12 trials participants had a brief rest period. A drift correction, performed after this rest period, also took place once every 12 trials.

1.2.2 Results and Discussion

Recursive outlier removal analyses were first performed for each trial based on the participants' average fixation duration for congruently and incongruently coloured items. Fixations were removed in which fixation durations were greater than three standard deviations from the mean for the trial. This removed 1.26% of the total number of fixations for DE (0.31% incongruent, 0.95% congruent), 1.74% of the total number of fixations for KS (0.67% incongruent, 1.07% congruent), and an average of 1.67% of the total number of fixations for the non-synaesthetes (mean 0.83% incongruent, 0.98% SD; mean 0.85% congruent, 1.20% SD).

Figure 2 illustrates the mean number of fixations which participants made on incongruently and congruently coloured letters on a given display. Panel A of Figure 2 shows that DE fixated congruently coloured letters significantly more than incongruently coloured letters, $t(179) = 8.41$, $p < .001$. By comparison, none of the non-synaesthetes showed a significant difference on this measure, all $t < 1.5$, all $p > .13$. DE's viewing performance was compared to the non-synaesthetes using difference scores. DE's difference score (average congruent fixations minus average incongruent fixations) was 12.5 standard deviations greater than the mean of the same difference scores computed for his yoked non-synaesthetes. The data clearly support the presence of a congruity bias in DE's viewing behaviour. The mean number of fixations on incongruently and congruently coloured letters on a given display for DE and yoked non-synaesthete participants are shown in Appendix A.

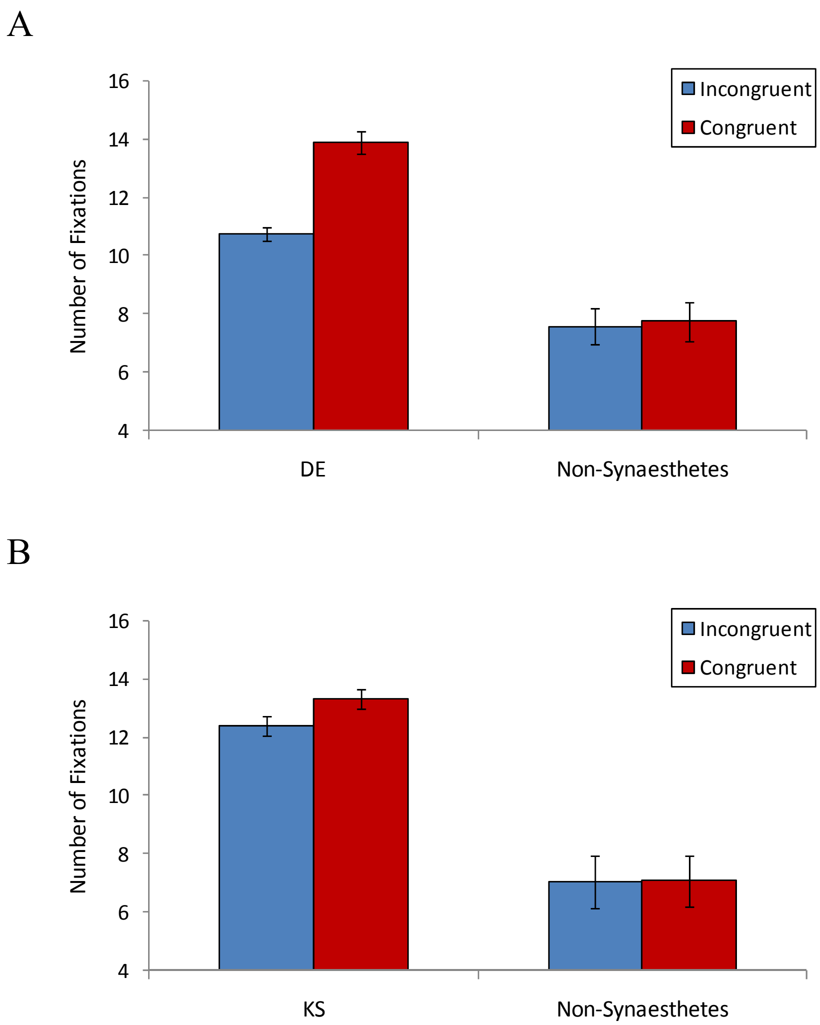
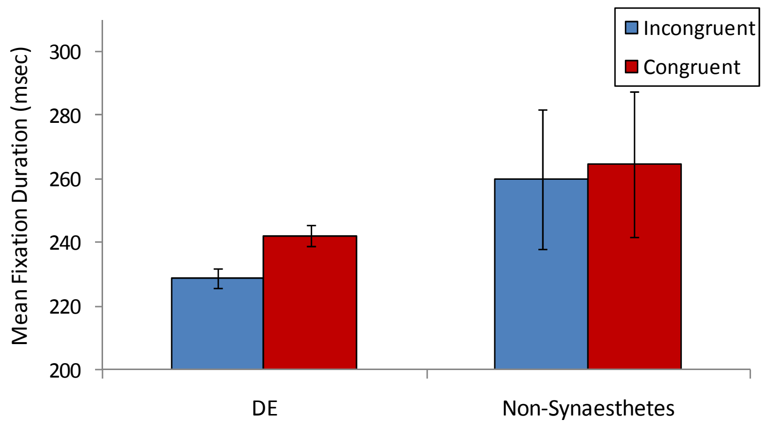


Figure 2. Mean number of fixations on incongruent and congruent items for DE and non-synaesthetes (A), and KS and non-synaesthetes (B). Error bars indicate one standard error of the mean.

Given the congruity bias observed with DE, I predicted KS would show the same pattern of results. Indeed, Panel B of Figure 2 shows KS' performance parallels that of DE. She fixated congruently coloured letters significantly more often than incongruently coloured letters, one-tailed $t(179) = 2.13$, $p < .05$. Again, none of the non-synaesthetes who completed the same free viewing task showed a significant difference, all one-tailed $t < 1.4$, all $p > .08$. KS was also compared to her yoked non-synaesthetes using difference scores. The difference between her average number of fixations on congruent and incongruent letters (congruent minus incongruent) was 3.3 standard deviations greater than the mean of her yoked non-synaesthete participants. Thus, both KS and DE show evidence of a congruity bias in their overt viewing behaviour. The mean number of fixations on incongruently and congruently coloured letters on a given display for KS and yoked non-synaesthete participants are shown in Appendix B.

In addition to the number of fixations made on congruently and incongruently coloured letters, the congruity bias was also expected to be evident in the synaesthetes' average fixation duration. Specifically, the synaesthetes were predicted to show significantly longer fixation durations for congruently coloured letters than incongruently coloured letters. Figure 3 shows DE did indeed fixate congruently coloured letters significantly longer than incongruently coloured letters in the free viewing task (Panel A), $t(179) = 3.00$, $p < .01$. None of DE's yoked non-synaesthetes showed significant differences between congruent and incongruent duration times, however, all $t < 1.6$, all $p > .12$. This suggests that DE's fixation durations were not attributable to a simple stimulus bias (i.e., his congruently coloured letters were not also somehow more "attention holding" to non-synaesthetes). KS also showed a congruity bias in her viewing behaviour, fixating congruently coloured letters significantly longer than incongruently coloured letters (Panel B), one-tailed $t(179) = 1.87$, $p < .05$. None of her yoked non-synaesthetes showed significant differences between these conditions, all one-tailed $t < 1.0$, all $p > .16$. As can be seen by comparing the standard error bars for the non-synaesthetes in Figures 2 and 3, there was much more variance in the fixation duration measure. Likely because of this variability, difference score measures akin to the ones computed for number of fixations failed to show that the synaesthetes were outliers from the control distributions. That said, the fact that both synaesthetes showed significant differences between fixation durations for congruent and incongruent letters, while none of the non-synaesthetes showed such differences, lends converging evidence for a congruity bias in grapheme-colour synaesthesia. The mean fixation durations on incongruently and congruently coloured letters on a given display for DE and his yoked non-synaesthete participants as well as KS and her yoked non-synaesthete participants are shown in Appendixes A and B, respectively.

A



B

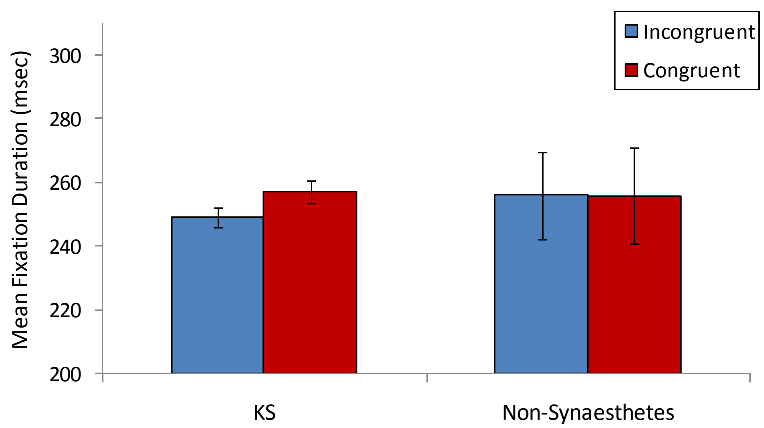


Figure 3. Mean fixation durations on incongruent and congruent items for DE and non-synaesthetes (A), and KS and non-synaesthetes (B). Error bars indicate one standard error of the mean.

Taken together, the mean numbers of fixations and the mean fixation durations clearly show the presence of a colour congruity bias in the synaesthetes' eye movements, and are consistent with the original prediction that the synaesthetes would show a tendency to fixate congruently coloured letters both more frequently and for longer than incongruently coloured letters. As such, the present findings support the conclusion that the combination of specific grapheme-colour pairings can rapidly and systematically influence overt visual attention even at the level of eye fixations. They also validate the subjective reports of a preference for congruently coloured information. Remaining to be seen, however, is whether this congruity bias is capable of influencing behaviour in a more structured viewing task where such a bias could often negatively affect a synaesthete's ability to achieve the intended goal. This possibility was examined in Experiment 2, in the context of a visual search task.

1.3 Experiment 2

Experiment 2 was designed to evaluate whether the congruity between synaesthetic experiences and the video colour of a grapheme would influence overt attention, and therefore eye movements, in the context of a visual search task. That synaesthetes spent significantly longer fixating congruently coloured letters than incongruently coloured letters in a free viewing situation suggests this congruity bias could facilitate search for congruently coloured targets while hampering search for incongruently coloured targets. In this experiment participants were shown a single, achromatic letter that was to be the target of the search for that trial. They then searched displays of randomly selected coloured letters for a single target letter, while their eye movements were monitored. As in Experiment 1, all search displays contained an equal number of congruently and incongruently coloured letters. Participants were instructed to ignore the colour of the letters and respond based on the identity of the letter alone (i.e., if the target is a T, then either a green T or a red T should be identified as targets). For synaesthetes, one strategy for doing this task would be to note the colour of their photism for the item they were to search for and simply look through the display for an appropriate colour match. To discourage the use of this type of colour search strategy, the task was designed so that relying on their synaesthetic colour associations would help lead synaesthetes to the target on only 25% of the trials.

Three possible influences of grapheme-colour synaesthesia on performance in the visual search task were evaluated. First, I expected to find significant overall search performance differences between congruently and incongruently coloured target letters for synaesthetes but not non-synaesthetes. As a corollary of this prediction, relative to their yoked non-synaesthetes, the synaesthetes were predicted to show enhanced search performance for congruently coloured targets but poorer performance for incongruently coloured targets. Second, because of their congruity bias, I predicted that their attention should be drawn to congruently coloured targets, more so than incongruently coloured targets. As such, I anticipated that the eye movement data would reflect this bias in the first two fixations of their search. In this case, I sought to evaluate two possible outcomes of a synaesthetic congruity bias: (1) an increased likelihood of quickly fixating congruently coloured target letters (i.e., within the first two fixations of searching), and (2) a decreased likelihood of quickly fixating incongruently coloured target letters. Third, based on the synaesthetes' subjective reports, I also sought to evaluate whether the synaesthetes had difficulty **identifying** incongruently coloured targets in this visual search task. As a result, I examined whether the synaesthetes would be more likely to miss (i.e., fail to press the "target detected" button) for incongruently coloured targets even when they were directly fixated.

1.3.1 Method

Participants. DE and KS were the synaesthetes, and a different group of six non-synaesthetic students from the University of Waterloo served as yoked controls for each synaesthete. The non-synaesthetes received partial credit toward their Introductory Psychology course as compensation.

Stimulus Displays. The colours and letters used were the same as those in Experiment 1. As in Experiment 1 the search displays were presented against a standard black background, so the number of items present was again constrained by being able to select only those colours that were discernable against a black screen. As a result the maximum number of visually unique colours that could be shown on a search display was 14 for DE and 12 for KS. Thus, in order to maintain a linear increase in the number of items displayed across three set sizes, any given search display contained 6, 10, or 14 letters for DE and 8, 10, or 12 letters for KS. The same 36 location grid was used to display the letters. Figure 1 illustrates an example of a search display for set size 12 with KS.

All search displays contained an equal number of congruently and incongruently coloured letters, arranged randomly within the 36 cells of an imaginary 6 x 6 grid. The displays were designed to create four search conditions: target present and congruently coloured, target present but incongruently coloured, target absent with a key distractor item carrying a colour equivalent to that of the target letter, and target absent with no target colour equivalent available. For target absent trials where the target colour was carried by a distractor I manipulated the congruency of this key distractor. To do this, (unlike Experiment 1) I took advantage of the synaesthetes having the same photism colour for more than one grapheme. On some trials the key distractor was congruent (a letter with a photism colour equivalent to that of the target), while on other trials this key distractor was incongruent (a randomly selected letter was chosen to carry a photism colour equivalent to that of the target). For a given display the incongruently coloured letters (including incongruently coloured targets) were created by applying a randomly chosen color selected from among the photism colours of the other incongruently coloured letters for that display. Thus, the appropriate photism colour for each letter shown on a display always appeared somewhere on that display.

To ensure font typeface was not responsible for any observed differences in they eye movement data typeface was varied across synaesthetes. For DE letters were presented in 32 point Times New Roman font and for KS they were presented in the same, equivalently sized, 36 point Lucida Console font as used in Experiment 1. Displays were viewed from a distance of approximately 81 cm. Individual letters measured 0.5 cm (0.3°) to 1.7 cm (1.0°) horizontally and 1.2 cm (0.7°) to 1.6 cm (1.0°) vertically depending on the letter and typeface. Each letter was located centrally within its corresponding cell, which measured approximately 6.9 cm (4.2°) horizontally and 5.2 cm (3.2°) vertically. A letter was considered fixated when the pixel coordinates of the averaged fixation location landed inside its cell.

Eye Tracking. The same SR Research Ltd. EyeLink II head-mounted eye tracking system was used to track eye movements during the visual search. The system was calibrated using a randomly ordered 9-dot pattern, and the mean error in the computation of gaze position was less than 0.5° visual angle on average. The system's default settings for acceleration and velocity thresholds were used for saccade detection.

Procedure. For the visual search task participants were asked to search for a target letter among a display of randomly selected coloured letters. As the target item was initially shown achromatically, participants were instructed to identify the target as present as long as it appeared somewhere on the display, regardless of its colour. The visual search task consisted of 360 trials, divided into blocks of 12 trials with equal representation of each of three set sizes (6, 10, 14 *or* 8, 10, 12) and the four search conditions: target present and congruently coloured, target present but incongruently coloured, target absent with a distractor carrying the target's colour, and target absent with no target colour equivalent available. As in Experiment 1, yoked non-synaesthete participants were presented with the same search displays, presented in the same randomized order, as for the synaesthetes to whom they were yoked.

As indicated in Figure 4, a trial began with the presentation of an achromatic target letter located in the center of the screen. The target letter remained on screen for 2000 ms before being replaced by a blank screen for 1000 ms and then the search display, which remained on screen until a "target detected" button press was made, or a "target absent" button press was made. Following every block of 12 trials participants had a brief rest period. A drift correction, performed after this rest period, also took place once every 12 trials.

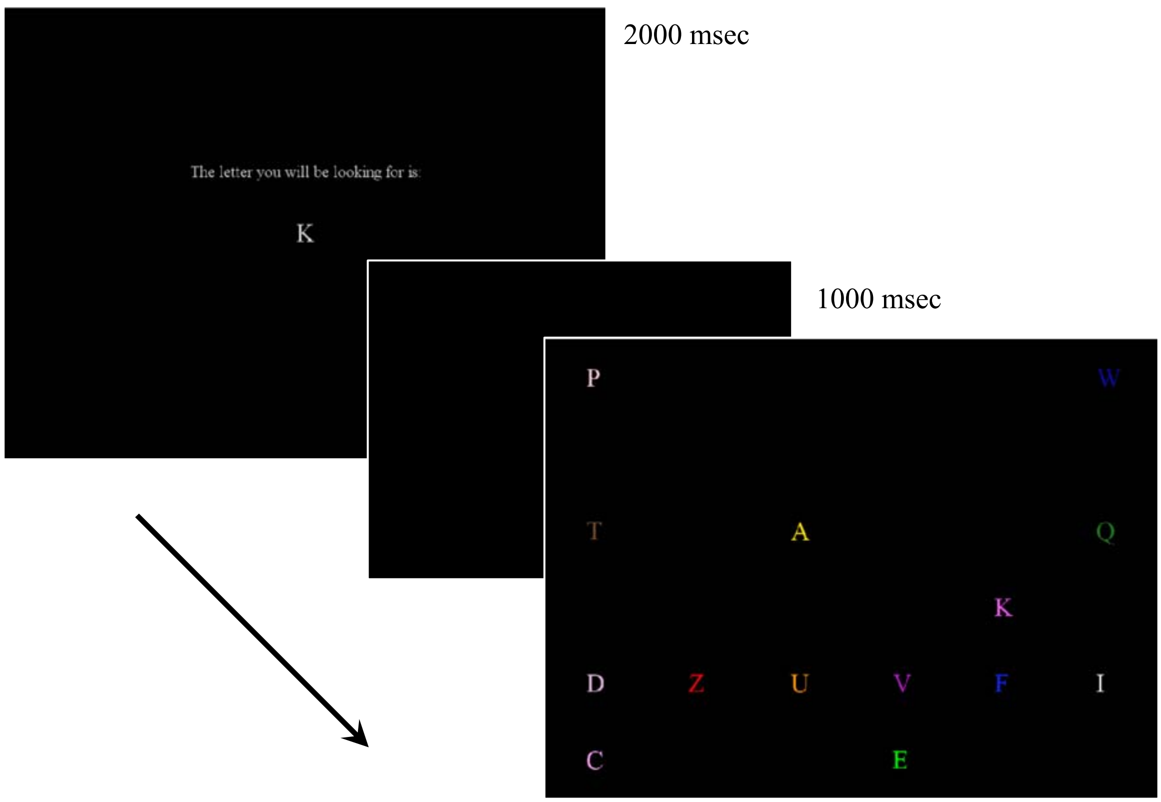


Figure 4. Flow of the visual search task.

1.3.2 Results and Discussion

The first 12 trials were considered practice trials and not analyzed. Each search condition was equally represented among the remaining 348 trials. On 174 trials the target was present (87 with a congruent target, and 87 with an incongruent target). And on 174 trials the target was absent (87 with the target's photism colour carried by a distractor, 87 without the photism colour of the target available). Furthermore, the three set sizes were equally represented among the four search conditions (29 trials per set size in each condition).

Trials on which a participant responded incorrectly with respect to the actual presence of the target on the search display (search errors) were removed from the data set prior to all analyses. Recursive outlier removal analyses were then performed for each search condition based on the participants' reaction time and the number of fixations recorded. Trials were removed in which participants' reaction times and total number of fixations were outside 3 standard deviations from that individual's mean for that condition and set size. Collapsing across set size and search condition, search error and outlier trial removals eliminated 5.7% of trials for DE (8.0% target present; 3.4% target absent), 3.4% of trials for KS (4.6% target present; 2.3% target absent), and an average of 5.8% of trials for non-synaesthete participants (8.3% mean, 3.1% SD target present; 3.4% mean, 2.8% SD target absent).

Reaction Time. Figure 5 illustrates search efficiency for: DE (Panel A) and his yoked non-synaesthetes (Panel B), and KS (Panel C) and her yoked non-synaesthetes (Panel D). Focusing first on the target present trials (Incongruent and Congruent), the figure shows that when the target was present DE was substantially faster to find congruently coloured targets than incongruently coloured targets. The data were submitted to a 2 (congruent vs. incongruent) x 3 (6, 10, 14 letters) independent samples analyses of variance (ANOVA), which confirmed that target congruity had a significant main effect for DE, $F(1,154) = 147.02$, $MSE = 120616.7$, $p < .001$. The ANOVA also confirmed there was a significant main effect of set size for DE, $F(2,154) = 6.53$, $MSE = 120616.7$, $p < .01$, and a small but marginally significant interaction, $F(2,154) = 3.03$, $MSE = 120616.7$, $p < .052$. None of DE's yoked non-synaesthetes showed a significant main effect of congruity, all $F < 2.3$, all $p > .13$, although one of the non-synaesthetes did show a significant interaction, $F(1,163) = 3.68$, $MSE = 96406.9$, $p < .05$, making interpretation of the interaction difficult for DE. Therefore, the remainder of the reaction time analyses are focused primarily on the main effect of congruity. DE's average reaction times were compared to non-synaesthete reaction times for key conditions relating to our congruity bias predictions. First, compared to his yoked non-synaesthetes, DE took significantly longer to find incongruently coloured target letters (his mean search time for finding incongruent targets was 2.25 standard deviations slower than the mean of the non-synaesthetes). Second, he took substantially less time to find congruently coloured targets than his yoked non-synaesthetes (his mean search time for finding congruent targets was 2.95 standard deviations faster than the mean of the non-synaesthetes). Thus, these findings suggest that DE's congruity bias may have improved search performance for congruent targets while hindering search for incongruent targets. The mean reaction times for all search conditions for DE and his yoked non-synaesthete participants are shown in Appendix C.

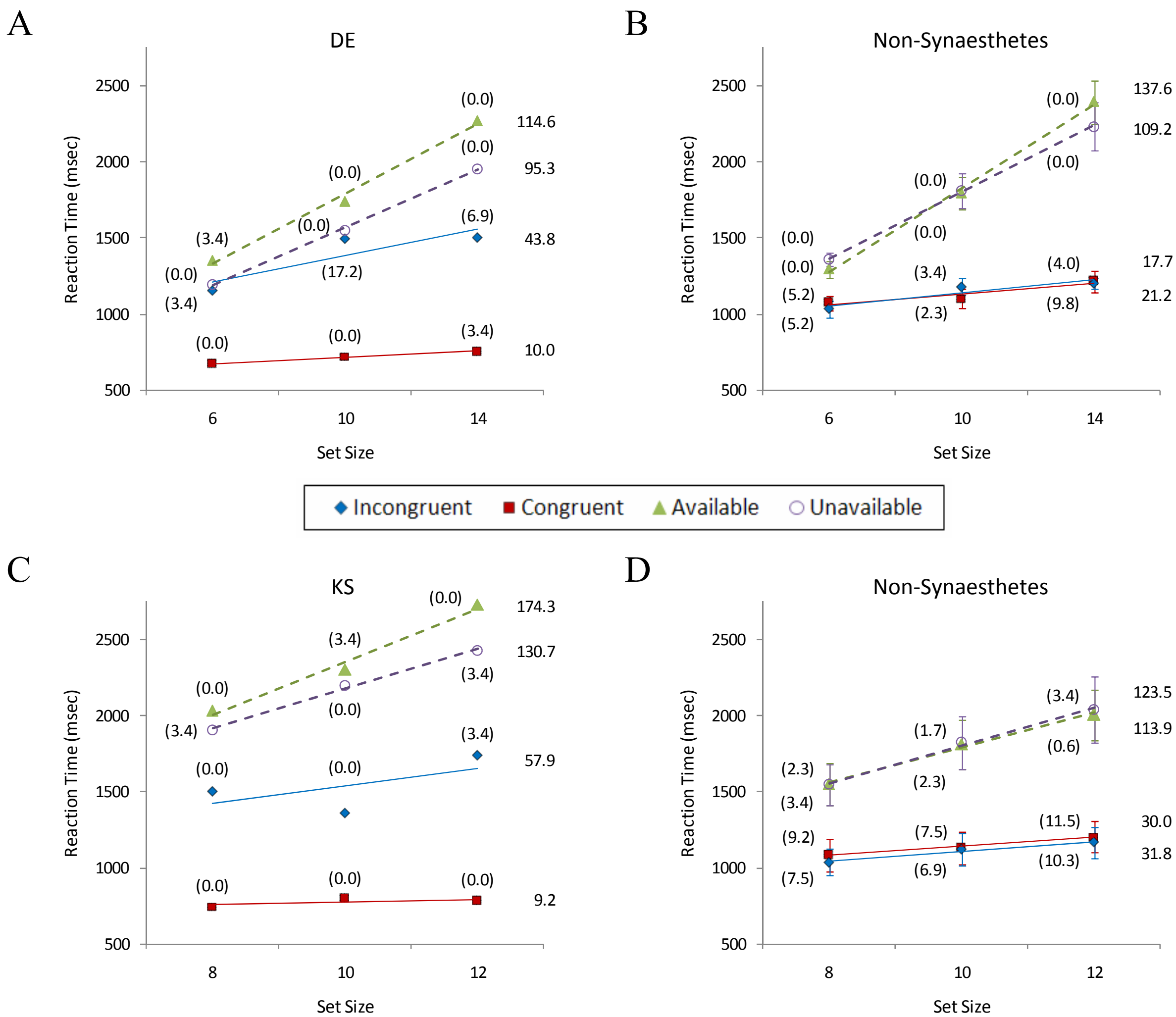


Figure 5. Reaction times for the visual search task for DE (A) and non-synaesthetes (B), and KS (C) and non-synaesthetes (D) on target present trials (Incongruent and Congruent) and target absent trials (Available and Unavailable). Percentage of trials removed due to search errors indicated in parentheses. Search slopes shown at right. Error bars indicate one standard error of the mean of the non-synaesthetes.

KS showed the same general trend in her performance as DE. As can be seen in Panel C of Figure 5, KS found congruently coloured targets substantially faster than incongruently coloured targets. Again the data were submitted to a 2 (congruent vs. incongruent) x 3 (8, 10, 12 letters) independent samples analyses of variance (ANOVA), which confirmed target congruity had a significant main effect for KS, $F(1,160) = 145.99$, $MSE = 163978.6$, $p < .001$. The ANOVA also confirmed there was a small but marginally significant main effect of set size for KS, $F(2,160) = 2.92$, $MSE = 163978.6$, $p < .058$, and a small but significant interaction, $F(2,160) = 3.09$, $MSE = 163978.6$, $p < .05$. In this case the fairly small effect of set size is understandable given that only two letters were added at each increase. As with DE, none of KS's yoked non-synaesthetes showed faster reaction times for congruent versus incongruent target detection times (all main effects $F < 1.4$, all $p > .24$). Neither did any of the non-synaesthetes show a significant interaction of target congruity with set size, all $F < 2.4$, all $p > .09$. It is worth noting, however, that one non-synaesthete did show a small but significant main effect of congruity, but it was in the **opposite** direction as was found with KS and DE (i.e., this non-synaesthete was faster for incongruently coloured targets), $F(1,155) = 5.44$, $MSE = 120602.6$, $p < .05$. The mean reaction times for all search conditions for KS and her yoked non-synaesthete participants are shown in Appendix D.

The task of comparing KS' mean search times directly to her yoked non-synaesthetes, was made difficult by the fact that one of these non-synaesthetes was much slower overall than the others, substantially inflating the variability around the non-synaesthetes' mean search times. As such, when comparing KS' search times to those of her control group, KS's overall performance did not fall significantly outside the non-synaesthetes' distribution. Individual comparisons, however, revealed that even with this one participant in the distribution KS was significantly slower to find incongruently coloured targets at set sizes 8 and 12, performing more than 2.15 standard deviations from the mean of the non-synaesthetes in each case. For congruent targets, KS was within the standard deviation envelope of her yoked non-synaesthetes. However, if the variability of the non-synaesthetes is reduced by removing the **slowest performing** non-synaesthete for congruent target present trials (i.e., the non-synaesthete who performed least like KS in this condition), KS' mean search time does fall outside the distribution of the non-synaesthetes, more than 2.6 standard deviations faster than the mean of the non-synaesthetes.

Eye Movements. I first examined whether DE showed an increased likelihood of finding congruently coloured targets within the first two fixations of his search. If DE exhibited a congruity bias in his searching behaviour, then relative to the non-synaesthete participants, it should be possible to evaluate whether this bias affected his ability to locate congruently and incongruently coloured targets. Indeed, Figure 6 shows DE fixated the target letter within the first two fixations of his search on 27.8% of trials where the target was presented in an incongruent colour (Panel A), whereas he fixated the target within two fixations on 60.5% of trials when the target was presented in a congruent colour – a difference of 32.6% (congruent - incongruent). This difference was more than 4 standard deviations greater than the mean difference of the yoked non-synaesthetes (6.1% mean, SD = 6.6%). More fine-grained comparisons with DE's yoked non-synaesthetes indicate that it is DE's performance on congruent trials that differentiates him from the non-synaesthetes. Relative to the non-synaesthetes, DE showed an increased likelihood of finding congruently coloured targets within two fixations (he was 2.85 standard deviations away from the mean of the non-synaesthetes in this condition). By contrast he was well within the range of the non-synaesthetes on trials where the target was incongruently coloured. Once again, KS’ performance (Figure 6, Panel B) was remarkably similar to that of DE. KS fixated the target within two fixations on 36.9% of trials where the target was presented in an incongruent colour, compared to 63.4% of trials where targets were congruently coloured. This difference of 26.5% was 3.2 standard deviations greater than the mean difference of KS's yoked non-synaesthetes (2.8% mean, SD = 7.3%). Like DE, the magnitude of KS’ congruity effect was carried by her performance on congruent trials. Her mean for congruent targets was 2.25 standard deviations greater than the mean of the non-synaesthetes, whereas her mean for incongruent targets was indistinguishable from the non-synaesthetes. For all participants, the proportion of target present trials on which the target letter was fixated within the first two fixations are shown in Appendix E.

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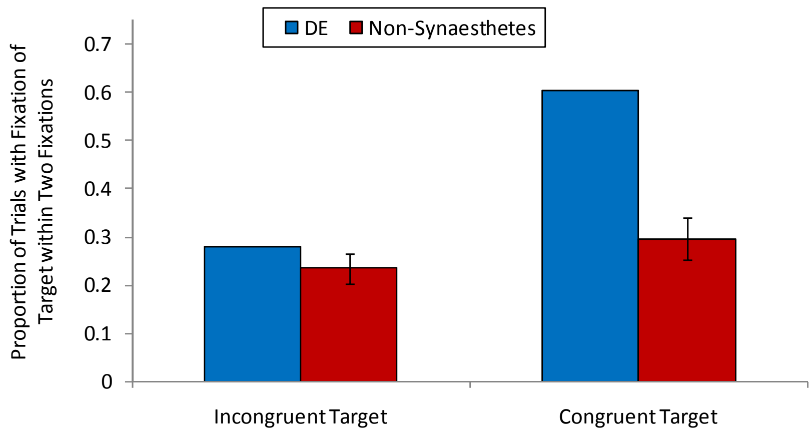

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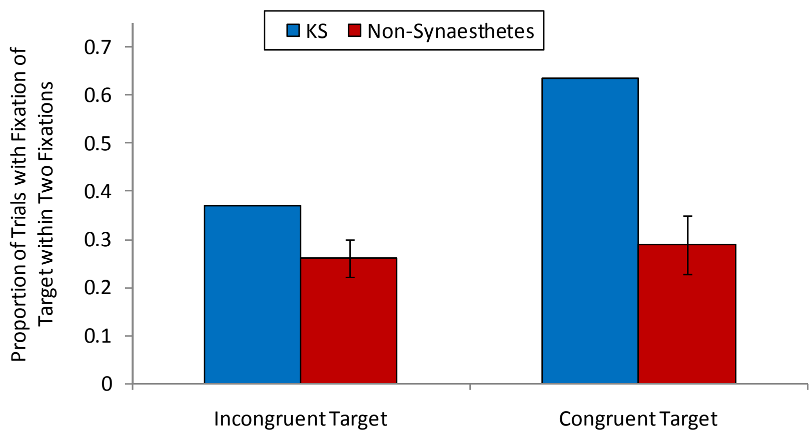

Figure 6. Proportion of trials on which participants fixated the target item within the first two fixations of their search for DE and non-synaesthetes (A), and KS and non-synaesthetes (B). Error bars indicate one standard error of the mean of the non-synaesthetes.

Taken together with the reaction time data, these eye movement data suggest that presenting the target in a congruent colour facilitated the synaesthetes' search, enabling the target to be rapidly located soon after onset of the search display. Presenting the target in an incongruent colour, however, appears to have had no inhibitory effect on the synaesthetes' ability to **rapidly fixate** the target. However, even though incongruent targets were fixated, synaesthetes may have failed to press the "target detected" button, and continued on to examine other letters in the display (i.e., continue their search), leading to their longer overall search durations for incongruently coloured targets. This suggests the possibility that even though the synaesthetes may fixate incongruent targets they fail to realize that they are looking at the object for which they are searching. Such a finding would correspond to the subjective reports of synaesthetes who claim that often they have trouble interpreting what they are seeing when faced with letters in the "wrong" colour.

To address the hypothesis that the synaesthetes had greater difficulty identifying incongruently coloured targets I examined whether target colour influenced the number of **re-fixations** (i.e., the number of non-sequential fixations) made on the target letter during search. Re-fixations of the target letter reflect continued search after target fixation, and can therefore be taken as evidence that the target was not correctly identified as the goal of the search the first time it was fixated.

As can be seen in Figure 7, DE re-fixated targets on more than 20% of the trials in which the target was incongruently coloured (Panel A); more than 12 standard deviations greater than the mean proportion of re-fixations made by the non-synaesthetes on these same trials. Interestingly, on 37.5% of the trials in which DE re-fixated an incongruent target he had already fixated the distractor carrying the synaesthetic colour of the target (presented on one of the incongruently coloured distractors) prior to his first fixation of the target item. This suggests that even when it was already apparent the target item would be incongruently coloured DE still had trouble identifying it. By comparison, DE did not re-fixate **any** of the congruently coloured targets and, as expected, the non-synaesthetes showed no effect of target congruence on the number of target re-fixations they committed. The proportion of target present trials on which all participants re-fixated incongruently and congruently coloured target letters are shown in Appendix F and the proportion of trials on which participants re-fixated incongruently coloured targets after having fixated the synaesthetic colour of the target letter are shown in Appendix G.

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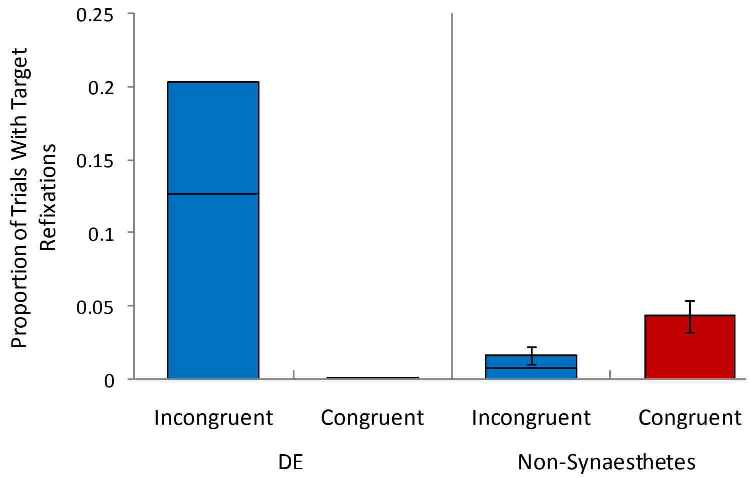

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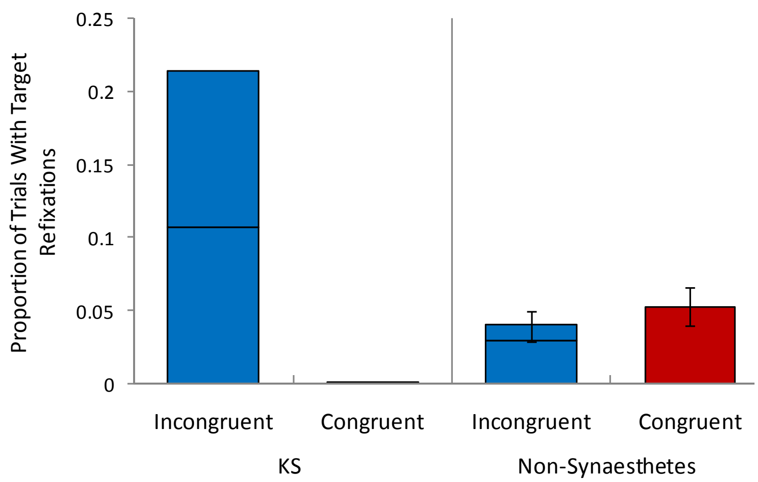

Figure 7. Proportion of trials on which participants re-fixated incongruently and congruently coloured target items for DE and non-synaesthetes (A), and KS and non-synaesthetes (B). The area below the horizontal line dividing the re-fixations on incongruent targets shows the proportion of trials on which participants fixated the actual target prior to the colour of the target. Error bars indicate one standard error of the mean of the non-synaesthetes.

KS showed a remarkably similar pattern of results (Figure 7, Panel B). As with DE, KS re-fixated targets on more than 20% of the trials in which they were incongruently coloured; more than 9.7 standard deviations greater than the mean proportion of re-fixations made by the non-synaesthetes. Once more, KS also failed to identify incongruent targets on first fixation even after having already fixated the item bearing the colour of the target, which took place on 50% of the trials in which a target re-fixation was made. Finally, just like DE, KS did not re-fixate a single congruently coloured target. Taken together these findings suggest that although the synaesthetes had no difficulty identifying congruently coloured targets they did have trouble identifying incongruent targets – even when they were looking directly at them. Importantly this re-fixation data explains the relatively long RTs for incongruent trials. That is, incongruently coloured targets were initially looked at but not recognized, and thus had to be re-fixated before the synaesthete could identify these items as the goal of their search.

Combining the results of the eye movement data with the main effect of congruity observed in the reaction time data reveals two main conclusions. First, the synaesthetes rapidly fixated congruently coloured targets at the beginning of their search and did not have difficulty fully identifying the target letter once fixated, leading to an overall performance improvement relative to the non-synaesthetes. Second, the synaesthetes rapidly fixated incongruently coloured targets at the beginning of their search just as often as the non-synaesthetes, but showed increased difficulty fully identifying incongruently coloured target letters once fixated, leading to an overall performance decrement relative to the non-synaesthetes.

There is an alternative explanation for the finding that both synaesthetes performed significantly faster when searching for congruently coloured targets than incongruently coloured targets, without relying on a synaesthetic colour congruity bias. Namely, the synaesthetes could have employed a simple colour search strategy. Recall that prior to search trials participants were shown an achromatic target letter that indicated the goal of the upcoming search. Synaesthetes could have noted the colour of their photism for the target and simply looked through the display for an appropriate colour match. This alternative explanation is not supported by the eye movement data, however, as is clear when considering the data collected when the target was absent. For half of the trials on which the target was absent (25% of trials overall), there was a distractor letter that also elicited the photism colour of the target. This key distractor was either randomly assigned an incongruent letter-colour combination, or presented as a congruently coloured letter that happened to have the same colour as the synaesthete's photism for the target.

If the synaesthetes employed a simple colour search strategy, one would predict they should be equally likely to fixate the item coloured like the target regardless of whether it was itself congruently coloured. That is, using a colour matching strategy, the congruity relations of the colour matching distractor should not matter. This was clearly not the case. Figure 8 illustrates the proportion of trials on which participants fixated the item bearing a colour very similar to that of the intended target within the first two fixations of their search. For DE the data clearly rule out the possibility of a simple colour matching search strategy influencing his search behaviour. He quickly fixated congruently coloured distractor items substantially more frequently than incongruently coloured distractor items; performing more than 3.9 standard deviations from the mean of the non-synaesthetes for congruent distractor configurations (Figure 8, Panel A). By contrast DE was no less likely than his yoked non-synaesthetes to fixate the key distractor item when it was incongruently coloured – a pattern of data that contradicts the "colour search" hypothesis. KS once more performed very similarly to DE on these trials. KS showed a similar congruity bias, quickly fixating congruently coloured items more frequently than the incongruently coloured items and performing more than 4.65 standard deviations from the mean of her yoked non-synaesthetes when the key distractor was congruently coloured but indistinguishable from the non-synaesthetes when it was incongruently coloured. For all participants, the proportion of target absent trials on which the key distractor letter was fixated within the first two fixations are shown in Appendix E.

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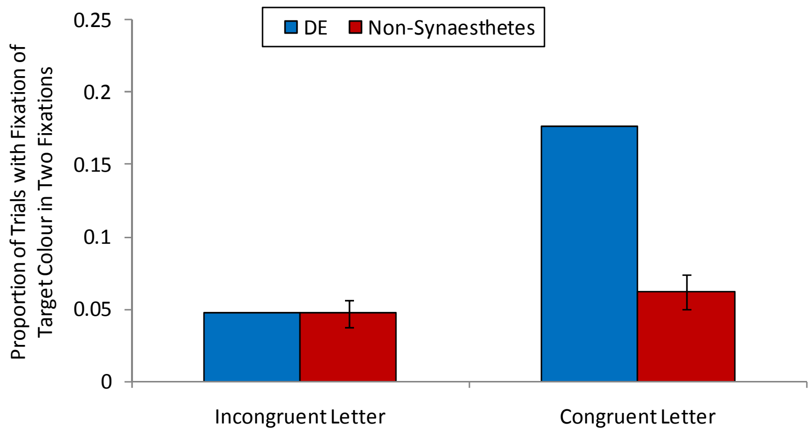

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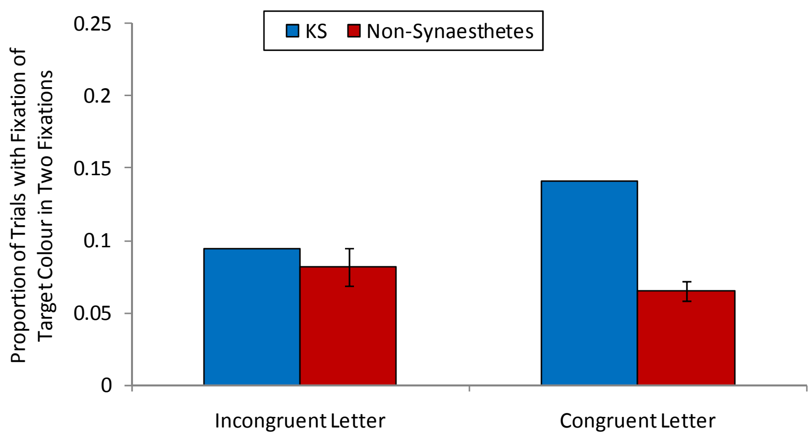

Figure 8. Proportion of target absent trials on which participants fixated the item bearing the colour of the intended target within the first two fixations of their search for DE and non-synaesthetes (A), and KS and non-synaesthetes (B). Error bars indicate one standard error of the mean of the non-synaesthetes.

In addition to the evidence against the colour search hypothesis found in the eye movement data for trials on which the target was absent, similar inconsistencies with the colour search hypothesis can be found in the data already presented. For example, if DE and KS had employed a colour matching search strategy, then their ability to **quickly** fixate congruently coloured targets (i.e., within the first two fixations) should have been enhanced at the expense of incongruently coloured targets, when compared to their yoked non-synaesthetes. Instead, the data presented in Figure 6 and Appendix E suggest search performance for congruently coloured targets was enhanced without affecting search performance for incongruently coloured targets for the synaesthetes, as both DE and KS quickly located incongruently coloured targets just as frequently as the non-synaesthetes. In addition, the simple colour search explanation also would not predict that on 62.5% of the trials in which DE re-fixated an incongruently coloured target and on 50% of the trials in which KS re-fixated an incongruently coloured target (Figure 7 and Appendix G) they did not go to the item bearing the colour of the target prior to fixating the actual target. Together, both findings show the synaesthetes' attention was being drawn to the target item irrespective of its colour, though full identification of incongruently coloured target letters ultimately proved to be more difficult once they were fixated.

Combining all the results of the visual search task, I find clear support for the presence of a colour congruity bias in the synaesthetes' search performance. As well, I find behavioural support for the synaesthetes' subjective reports of difficulty dealing with the visual conflict of incongruently coloured information. Together, these findings suggest the synaesthetes' search was substantially facilitated by presenting target letters in a colour congruent with their synaesthetic photisms and somewhat hampered by presenting targets in a colour incongruent with their photisms.

1.4 General Discussion

Our investigation of the influence of grapheme-colour synaesthesia on overt visual attention provided support for the presence of a colour congruity bias in two key respects. First, the results of the free viewing task used in Experiment 1 showed both DE and KS exhibited a colour congruity bias in their overt viewing behaviour, fixating congruently coloured letters significantly more often and for longer durations than incongruently coloured letters. Given that eye movements are believed to represent the allocation of one's visual attention at any given moment (Findlay & Gilchrist, 2003), finding a congruity bias in the synaesthetes' viewing behaviour suggests congruently coloured information receives greater attention than incongruently coloured information.

Second, the results of the visual search task used in Experiment 2 showed that when searching for a target among displays of congruently and incongruently coloured letters the synaesthetes located and identified congruently coloured target letters substantially faster than incongruently coloured target letters. This enhanced search performance for congruently coloured targets was present not only as an overall difference in search time but also as a significantly greater likelihood of fixating the target letter within the first two fixations for the synaesthetes, in comparison to both incongruently coloured targets and in comparison to non-synaesthetes performing the exact same task. Importantly, the beneficial effect of congruity on the rapid direction of the synaesthetes' attention to the target letter did not prevent the rapid direction of attention toward incongruently coloured target letters, relative to the non-synaesthetes. This finding suggests the congruity bias observed in Experiment 1 was indicative of an attentional preference for congruently coloured information rather than a particular inhibition of attention for incongruently coloured information.

The synaesthetes did not show only an attentional bias toward congruently coloured letters, however. While the synaesthetes were just as likely as non-synaesthetes to rapidly fixate incongruently coloured target letters in the visual search task, they appear to have had significantly greater difficulty **identifying** those letters as the goal of the search for that trial. Reflecting this identification difficulty, both synaesthetes re-fixated incongruently coloured targets on more than 20% of the trials in which they were presented. By contrast they never re-fixated congruent targets – that is, once fixated, congruent targets were immediately recognized as the goal of the search. Thus, the finding that both synaesthetes took somewhat longer than the non-synaesthetes to find incongruently coloured target letters appears to be due to a difficulty identifying incongruently coloured information even after it is fixated rather than an attentional redirection away from that information.

Taken together, the present findings indicate synaesthesia can indeed influence overt visual attention. As well, it is clear that the congruity bias observed in the synaesthetes' viewing behaviour for the free viewing task also affected search performance for the visual search task. As such the results both confirm the subjective reports of the synaesthetes and, just as in other aspects of synaesthetic experiences, suggest that a high degree of automaticity is involved in their reported preference for congruently coloured information. Separately from the facilitative effects of congruity in the visual search task, the results also provide objective evidence that synaesthetes that have problems identifying incongruently coloured graphemes. Furthermore, it was this difficulty that was responsible for the synaesthetes' slowed search performance when presented with incongruently coloured target letters, rather than an attentional avoidance of incongruity.

1.4.1 Implications for Perception in Synaesthesia

In an examination of the perceptual processes underpinning synaesthetic experiences Mattingley, et al. (2001) have shown that it is possible to prevent perception of synaesthetic photisms through rapid masking of stimuli, even though such masking does not prevent initial perceptual processing of the form of the inducing stimulus. As such, they suggest synaesthetes must have some awareness of the identity of a stimulus before a synaesthetic photism can be perceived (i.e., that all synaesthetic experiences operate in a top-down fashion). In comparison to this assertion, however, the present findings suggest a greater degree of interaction between perception and identification in synaesthesia. Supporting the notion of bottom-up perceptual effects in synaesthesia (e.g., Kadosh, et al., 2005; Nikolić, et al., 2007), the synaesthetic congruity bias as it was observed in the visual search task appears to occur prior to awareness, and serves to direct attention toward objects that the synaesthete ought to examine further. As well, the difficulty DE and KS had interpreting the identity of incongruently coloured target letters in the visual search task highlights the potential for interactive effects of meaning and synaesthetic colour prior to full conscious awareness of the identity of an object. That is, while DE and KS may have first become at least partially aware of the identity of an incongruently coloured target letter prior to activation of the corresponding synaesthetic photism, the incongruity between the photism and the video colour of the letter nonetheless made conscious identification of that letter more difficult. Such difficulty implies a pattern of repeating activation in the brain areas responsible for interpreting the form, colour, and meaning of a stimulus.

Addressing this issue, Smilek and Dixon (2002) have argued for the presence of unusually enhanced feedforward and feedbackward neural connections in the brains of synaesthetes. In this model perception does not occur all at once, but is built up over successive iterations of activity flowing from low level (e.g., form, colour) areas to higher level (i.e., meaning) areas and then from higher level areas back to low level areas, with the pathways activating repeatedly as a conscious percept emerges. Providing some support for this model of increased neural connectivity, a recent brain imaging study by Rouw and Scholte (2007) has shown the brains of grapheme-colour synaesthetes do indeed exhibit hyperconnectivity in the white matter areas of the right inferior temporal cortex near the fusiform gyrus, which Smilek and Dixon hypothesized would play an important role in the experience of grapheme-colour synaesthesia.

The present findings are fully consistent with the reentrant activation model proposed by Smilek and Dixon (2002) and the imaging findings of Rouw and Scholte (2007), adding further credence to the importance of both forward and reentrant processing in synaesthesia. In particular, it is worth highlighting again that KS reports only (consciously) experiencing a synaesthetic photism for letters after she is aware of their identity, while DE reports seeing colours even for letters he hasn't fully identified. In combination with the present findings, these differing subjective reports can be interpreted as providing further support for the iterative model proposed by Smilek and Dixon. That is, given the strikingly similar performances of KS and DE on the free viewing and visual search tasks, it seems low level synaesthetic processes can bias overt attention prior to awareness of identity and that full identification may come after a varying number of successive iterations between low level and higher level areas of processing, especially in the face of incongruity between the actual stimulus and synaesthetic colour activations.

1.4.2 Future Directions

At present the origins of the grapheme-colour synaesthetes' congruity bias are an open question. Given the difficulty both DE and KS showed when trying to identify incongruently coloured target letters it is possible this difficulty plays a causal role in the development of an attentional congruity bias for synaesthetes. This is not the only feasible interpretation of the data, however, as it is also possible for a congruity bias to develop independently of any incongruity identification deficit – in which case the results of the visual search task reflect two separate influences of synaesthesia on overt behaviour. Finally, a preexisting congruity bias might even play a causal role in the development of an incongruity identification deficit if this bias typically serves to direct attention away from incongruently coloured information and thus reduces the opportunities the synaesthete has to develop expertise at resolving incongruity. Additional research is therefore necessary to determine the origins of both the incongruity deficit and the congruity bias.

Further research is also necessary to uncover the exact mechanisms by which perception and meaning interact to influence overt attention in synaesthesia. While the present findings offer support for the notion of successive iterations of feedforward and reentrant activation in synaesthesia as proposed by Smilek and Dixon (2002), they do not indicate which areas of the brain in particular are responsible for the observed congruity bias and incongruity identification deficit. Nonetheless, the fact that DE and KS show such strikingly similar overt attentional influences in both the free viewing and visual search tasks, despite differences in how they consciously experience their synaesthetic photisms, highlights the potential universality of the congruity bias and incongruity identification deficits presented here. Thus, uncovering the neural bases of these effects should improve our ability to understand the cognitive and perceptual processes underlying synaesthesia and go a long way toward establishing the importance of enhanced feedforward and feedbackward neural connections in the brains of synaesthetes.

1.4.3 Implications for Normal Cognition

Finding a congruity bias in the viewing behaviour of grapheme-colour synaesthetes has clear implications for studies of the attentional effects of colour interference in normal cognition. The Stroop (1935) task has long been used to show interference effects for incongruity between colour words and the colour of their presentation (e.g., the word "red" presented in a blue colour), but the present findings suggest incongruity may not be the only factor worth considering in such tasks. Indeed, given the parallels between Stroop interference effects and the incongruity identification deficit observed in the present visual search task, it seems likely that word-colour congruity may influence the deployment of attention in non-synaesthetes as well. Future research would therefore benefit from an exploration of whether a colour congruity bias is in fact present in the viewing behaviour of non-synaesthetes.

1.4.4 Conclusion

I believe the present findings have direct bearing on recent debates concerning the influence of meaning on the allocation of visual attention in synaesthesia. Some studies have previously shown the importance of feedbackward (or top-down) influences in synaesthesia, while other studies suggest feedforward (or bottom-up) influences are more important. The present findings make an important contribution to this debate by showing that both a congruity bias and an incongruity identification deficit can influence the eye movements of grapheme-colour synaesthetes. As such, these findings strengthen the general conclusion that theories of the perceptual and cognitive influences of synaesthesia on behaviour ought to incorporate a substantial degree of interaction between low level perception and higher level interpretation of meaning. As well, I believe further study of the congruity bias observed in the viewing behaviour of grapheme-colour synaesthetes may provide valuable insights into the cognitive and brain mechanisms underlying synaesthesia**.**

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Appendix A

Mean Number of Fixations and Fixation Durations for Incongruently and Congruently Coloured Letters on a Given Display for DE and Yoked Non-Synaesthetes (NS 1-6) in Experiment 1

Participant	Congruity	Mean Number of Fixations	N	Mean Fixation Durations (msec)	N
DE	Incongruent	10.77 (3.27)	180	229.10 (40.74)	180
	Congruent	13.92 (5.11)	180	242.30 (43.76)	180
NS 1	Incongruent	9.46 (4.43)	180	197.15 (48.71)	178
	Congruent	9.86 (4.58)	180	197.33 (51.06)	178
NS 2	Incongruent	7.49 (3.07)	180	223.88 (62.04)	174
	Congruent	7.47 (3.10)	180	220.54 (59.82)	174
NS 3	Incongruent	4.85 (2.75)	180	240.44 (94.75)	150
	Congruent	4.92 (3.32)	180	264.97 (164.47)	150
NS 4	Incongruent	8.08 (3.24)	180	280.33 (67.76)	175
	Congruent	8.61 (3.54)	180	274.26 (62.56)	175
NS 5	Incongruent	7.92 (3.78)	180	350.68 (119.61)	171
	Congruent	7.86 (3.47)	180	359.54 (113.75)	171
NS 6	Incongruent	7.67 (3.21)	180	268.86 (60.10)	178
	Congruent	7.86 (3.22)	180	273.35 (64.76)	178

Standard deviations of means are shown in parentheses. Displays on which participants did not fixate both incongruently and congruently coloured letters are excluded from the mean fixation durations.

Appendix B

Mean Number of Fixations and Fixation Durations for Incongruently and Congruently Coloured Letters on a Given Display for KS and Yoked Non-Synaesthetes (NS 7-12) in Experiment 1

Participant	Congruity	Mean Number of Fixations	N	Mean Fixation Durations (msec)	N
KS	Incongruent	12.41 (4.78)	180	249.21 (43.37)	180
	Congruent	13.33 (4.74)	180	257.09 (46.77)	180
NS 7	Incongruent	7.75 (3.30)	180	268.74 (53.95)	178
	Congruent	8.16 (3.36)	180	265.81 (51.27)	178
NS 8	Incongruent	6.29 (3.29)	180	274.92 (140.60)	167
	Congruent	6.48 (3.13)	180	268.62 (131.30)	167
NS 9	Incongruent	3.67 (2.73)	180	249.92 (101.89)	116
	Congruent	3.66 (2.81)	180	247.06 (83.77)	116
NS 10	Incongruent	10.53 (4.92)	180	230.31 (57.82)	178
	Congruent	10.14 (5.11)	180	227.31 (50.76)	178
NS 11	Incongruent	6.76 (3.61)	180	210.05 (58.88)	161
	Congruent	6.71 (3.69)	180	210.35 (57.11)	161
NS 12	Incongruent	7.33 (3.86)	180	303.52 (91.76)	158
	Congruent	7.41 (4.02)	180	316.40 (136.78)	158

Standard deviations of means are shown in parentheses. Displays on which participants did not fixate both incongruently and congruently coloured letters are excluded from the mean fixation durations.

Appendix C

Mean Reaction Times (msec) for DE and Yoked Non-Synaesthetes (NS 1-6) for All Search Conditions in Experiment 2

		Target Absent				Target Present			
		Colour Not Available		Colour Available		Incongruent		Congruent	
Participant	Set Size	Mean RTs	N	Mean RTs	N	Mean RTs	N	Mean RTs	N
DE	6	1193.21 (292.42)	28	1351.43 (416.88)	28	1150.64 (397.29)	28	671.69 (138.98)	29
	10	1552.89 (364.49)	28	1741.34 (393.31)	29	1495.29 (446.21)	24	722.38 (142.67)	26
	14	1955.52 (427.29)	27	2268.21 (496.77)	28	1500.96 (548.60)	27	751.69 (185.40)	26
NS 1	6	1390.83 (298.17)	29	1288.00 (241.41)	27	1211.45 (228.17)	29	1269.97 (310.06)	29
	10	1690.76 (329.77)	29	1657.03 (294.71)	29	1349.04 (301.93)	27	1362.63 (416.33)	27
	14	1956.86 (310.54)	29	2120.21 (283.15)	29	1347.62 (362.80)	26	1483.11 (425.07)	28
NS 2	6	1424.31 (342.79)	29	1298.68 (480.56)	28	1006.24 (299.43)	29	1000.69 (256.79)	26
	10	1790.67 (355.38)	27	1633.68 (337.74)	28	1083.36 (265.51)	25	1127.04 (342.04)	26
	14	1994.00 (407.24)	29	2127.38 (468.35)	29	1116.77 (318.16)	22	1088.86 (364.93)	28
NS 3	6	1201.1 (332.30)	29	1139.61 (249.76)	28	1034.24 (365.15)	25	1027.04 (271.63)	26
	10	1486.75 (272.92)	28	1651.90 (327.34)	29	1183.74 (398.67)	27	1004.14 (373.63)	28
	14	2054.64 (380.89)	28	2175.41 (489.86)	29	1274.30 (418.53)	20	1236.21 (399.44)	24
NS 4	6	1381.38 (356.22)	29	1253.72 (281.61)	29	970.41 (293.14)	27	1119.55 (391.20)	29
	10	2151.86 (497.28)	29	2044.25 (402.10)	28	1060.85 (347.04)	26	1114.54 (431.96)	28
	14	2704.03 (494.70)	29	2919.79 (462.43)	29	1166.82 (452.71)	28	1256.65 (598.37)	23
NS 5	6	1255.86 (324.73)	29	1228.55 (244.98)	29	841.07 (217.59)	28	950.21 (322.11)	29
	10	1581.11 (223.19)	28	1594.21 (321.19)	29	1075.72 (348.53)	29	899.97 (264.56)	29
	14	1944.59 (333.80)	27	2285.93 (467.46)	28	1141.00 (372.56)	28	989.54 (311.27)	26
NS 6	6	1499.20 (297.94)	25	1552.39 (591.02)	28	1126.44 (465.70)	27	1066.40 (293.10)	25
	10	2157.81 (557.16)	27	2186.00 (580.76)	27	1334.54 (693.15)	28	1099.76 (340.83)	29
	14	2742.43 (528.04)	28	2735.25 (617.49)	24	1162.96 (621.85)	25	1231.11 (490.92)	27

Standard deviations of means are shown in parentheses.

Appendix D

Mean Reaction Times (msec) for KS and Yoked Non-Synaesthetes (NS 7-12) for All Search Conditions in Experiment 2

		Target Absent				Target Present			
		Colour Not Available		Colour Available		Incongruent		Congruent	
Participant	Set Size	Mean RTs	N	Mean RTs	N	Mean RTs	N	Mean RTs	N
KS	8	1907.18 (463.83)	28	2031.07 (561.73)	28	1505.17 (463.13)	29	746.00 (177.77)	28
	10	2197.86 (479.18)	29	2300.32 (694.78)	28	1362.59 (554.67)	29	794.77 (213.02)	26
	12	2430.04 (592.71)	28	2728.38 (805.13)	29	1736.58 (592.51)	26	782.71 (177.63)	28
NS 7	8	2171.19 (598.11)	26	2163.08 (527.51)	25	1415.00 (506.86)	29	1583.37 (586.87)	27
	10	2658.68 (600.52)	25	2555.57 (701.53)	28	1617.56 (547.12)	25	1608.48 (495.75)	25
	12	3016.44 (751.82)	27	2778.04 (656.26)	27	1605.65 (537.96)	26	1605.04 (540.59)	25
NS 8	8	1598.52 (397.33)	29	1614.14 (334.64)	28	1086.62 (381.90)	26	1083.36 (408.54)	28
	10	1765.28 (348.06)	29	1853.07 (407.03)	28	1150.21 (423.83)	28	1181.36 (476.25)	28
	12	1838.64 (271.71)	28	1944.59 (330.02)	27	1247.88 (499.20)	26	1235.58 (460.29)	24
NS 9	8	1531.85 (325.23)	26	1598.62 (266.25)	29	1038.31 (280.65)	26	977.42 (340.12)	24
	10	1815.82 (411.91)	28	1808.00 (371.28)	29	1110.45 (343.95)	29	1047.54 (338.79)	28
	12	2274.27 (411.32)	26	2108.32 (424.29)	28	1186.15 (384.80)	26	1142.64 (439.51)	25
NS 10	8	1320.24 (254.07)	29	1208.28 (238.14)	29	755.46 (144.52)	28	826.37 (250.45)	27
	10	1459.18 (215.03)	28	1507.68 (293.46)	28	857.46 (275.39)	26	808.61 (258.91)	28
	12	1635.86 (196.53)	28	1667.00 (269.18)	28	881.37 (251.91)	27	827.04 (270.31)	28
NS 11	8	1323.76 (191.97)	29	1334.31 (191.33)	29	944.67 (245.63)	27	1108.22 (396.55)	27
	10	1550.96 (233.73)	28	1577.97 (319.65)	29	1017.71 (298.90)	28	1128.26 (346.84)	27
	12	1650.73 (274.01)	26	1783.29 (265.62)	28	1108.36 (367.40)	25	1217.52 (404.62)	27
NS 12	8	1327.36 (287.79)	28	1379.21 (310.28)	29	994.04 (304.25)	25	921.20 (347.33)	25
	10	1695.25 (436.89)	28	1555.03 (252.78)	29	967.00 (269.01)	26	1012.52 (389.90)	25
	12	1821.93 (289.28)	29	1749.81 (278.57)	27	968.96 (287.79)	26	1192.76 (433.36)	25

Standard deviations of means are shown in parentheses.

Appendix E

Proportion of Trials with Fixation of the Distractor Letter Coloured Like the Target (Target Absent) or Fixation of the Target Letter (Target Present) Within the First Two Fixations for Synaesthetes (DE, KS) and Yoked Non-Synaesthetes (NS 1-12) in Experiment 2

	Target Absent		Target Present	
Participant	Incongruent Letter	Congruent Letter	Incongruent Letter	Congruent Letter
DE	0.047	0.176	0.278	0.605
NS 1	0.059	0.059	0.207	0.310
NS 2	0.024	0.059	0.211	0.288
NS 3	0.081	0.058	0.306	0.321
NS 4	0.023	0.023	0.111	0.150
NS 5	0.058	0.058	0.318	0.476
NS 6	0.038	0.114	0.263	0.235
KS	0.094	0.141	0.369	0.634
NS 7	0.125	0.075	0.288	0.286
NS 8	0.096	0.060	0.150	0.100
NS 9	0.047	0.093	0.259	0.403
NS 10	0.106	0.059	0.432	0.518
NS 11	0.070	0.058	0.238	0.210
NS 12	0.047	0.047	0.195	0.213

Appendix F

Proportion of Trials with Re-Fixation of Target Letter for Synaesthetes (DE, KS) and Yoked Non-Synaesthetes (NS 1-12) in Experiment 2

Participant	Incongruent Letter	Congruent Letter
DE	0.203	0.000
NS 1	0.024	0.012
NS 2	0.000	0.050
NS 3	0.028	0.090
NS 4	0.000	0.038
NS 5	0.012	0.036
NS 6	0.038	0.037
KS	0.214	0.000
NS 7	0.063	0.065
NS 8	0.038	0.025
NS 9	0.025	0.026
NS 10	0.012	0.024
NS 11	0.025	0.099
NS 12	0.078	0.080

Appendix G

Distribution of Fixation Order for the Proportion of Trials with Re-Fixation of Incongruently Coloured Target Letters for Synaesthetes (DE, KS) and Yoked Non-Synaesthetes (NS 1-12) in Experiment 2

Participant	Colour First	Letter First
DE	0.076	0.127
Control 1	0.012	0.012
Control 2	0.000	0.000
Control 3	0.014	0.014
Control 4	0.000	0.000
Control 5	0.000	0.012
Control 6	0.013	0.025
KS	0.107	0.107
Control 7	0.025	0.038
Control 8	0.013	0.025
Control 9	0.000	0.025
Control 10	0.000	0.012
Control 11	0.025	0.000
Control 12	0.000	0.078