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An investigation of the cognitive and perceptual dynamics of a colour – digit synaesthete

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Abstract. L, a 47-year-old female of Choctaw descent, was first identified as a potential synaesthete on the basis of self-report data regarding digit – colour associations. Upon completion of the identification procedures typified in the literature, it was concluded that L met the classic memory-performance criteria used to identify synaesthetic ability. A series of Stroop-type tasks were then performed to identify the dynamics of her synaesthetic experiences. The results of these analyses provided three findings of note. First, the clear pattern of response-time differences between L and the control group suggests that tasks designed to produce involuntary divisions of attention can be an effective means by which to demonstrate that synaesthetic experiences are involuntary but elicited. Second, the significantly slower performance by L on a negative-priming Stroop list shaped around her colour – digit associations indicates the presence of a lexical component in her synaesthetic experience. Third, the use of a manual colour-classification task for which a verbal response was not employed served to confirm the presence of a lexical component in L's synaesthetic experiences. The implications of these results for current synaesthetic theories are then discussed. Finally, a clustering solution of a portion of L's colour – digit experiences is presented, along with the ramifications of its results on the nature of L's perceptual experience.

1 Introduction

Synaesthesia refers to the experience of an atypical dual perception: that is, the synaesthete experiences both the actual perception of the sensory input of some particular stimulus and a simultaneous perception of some attribute, dimension, or modality not normally associated with the given stimulus. While it has been noted that this description of perceptual experience is also indicative of certain hallucinogenic experiences as the result of various drugs, synaesthetic perceptions are distinguishable because they are discrete, memorable, durable, and involuntary but elicited (Cytowic 1989).

Synaesthetic percepts have been recorded in almost all possible intermodal combinations, including at least one case of synaesthetic experience in all five of the classic sensory modalities (Luria 1968). By way of example, some of the most well-documented cases of synaesthetic ability have included the perception of colour blobs to music (Marks 1975) and the tactile perception of geometric shapes in response to taste (Cytowic 1993). While these intermodal manifestations are the most readily recognisable (since tasting shapes or creating a musical instrument that projects colours instead of sounds are relatively spectacular), synaesthesia can also manifest itself intramodally (Wollen and Ruggiero 1983; Cytowic 1989; Svartdal and Iversen 1989). The most common intramodal manifestations occur in the visual modality. These manifestations can be either relatively general in nature, such as the perception of colour blobs to letters, or fairly specific, as when colour blobs are perceived in response to vowels or digits (Cytowic 1989).

2 Cognitive dynamics

The current study came about, as is often the case with synaesthesia, as the result of happenstance. That is, a colleague of the authors who was familiar with our interest in cross-modal research referred a fellow graduate student (L) to us on the suspicion that this person's self-report that "two is yellow, of course" might be indicative of some unusual perceptual infrastructure. A series of interviews convinced us that L experienced a form of colour–digit synaesthesia, and so we set about an empirical investigation of her experiences.

As detailed below, this investigation sought to address three primary issues in L's synaesthetic percepts. First, it was necessary to establish L as possessing synaesthetic ability, as outlined in the diagnostic criteria set forth by Cytowic (1989). Aside from the diagnostic criteria set forth in his work, Cytowic (1989) also theorised that synaesthetic experiences occur precortically, in the limbic system. Such a theory seems to be at odds with synaesthetic experiences such as L's that involve cortically processed stimuli such as numbers. Therefore, the second goal of the current work was to demonstrate the presence of a lexical processing component in L's synaesthetic experiences. Last, section 3 of this paper makes an initial investigation into the perceptual organisation of L's synaesthetic experiences. In previous compilations of synaesthetic research it has been noted that synaesthetic colour percepts seem to be unsystematic across individuals (Marks 1978; Cytowic 1989), in terms of which colours are associated with specific stimuli. The current work addresses this issue somewhat differently, by investigating the structure of L's perceptual organisation within Euclidean space.

2.1 *Experiment 1*

Up to this point, the typical methodology for the identification and/or diagnosis of synaesthetic ability has been primarily limited to a variety of memory tasks (generally characterised by the performance of extended recall tasks across intervals of weeks or years) and phenomenological report (Luria 1968; Marks 1978; Cytowic 1989). While this has proven to be a robust means by which to investigate potential cases of synaesthetic ability, the lack of any further investigation of the perceptual experiences of potential synaesthetes is somewhat confusing, given that a strong memory component meets only two of the five diagnostic criteria set out for the phenomenon (Cytowic 1989). Put another way, the problem with providing only memory tests as a means of identification is that it is possible, however improbable, that extreme demonstrations of memorability are in fact the result of some highly overlearned associations (rather than synaesthetic perception). Therefore, in addition to a memory-recall task, a Stroop-type task was introduced.

A Stroop (Stroop 1935) task has been used on at least one other occasion to investigate reported synaesthetic ability (Wollen and Ruggiero 1983). Since Stroop tasks are specifically intended to identify involuntary divisions in attention as a result of meaningfulness in the task distracter, variations of this sort of task designed around L's reported synaesthetic associations were constructed to investigate whether her colour–digit associations were in fact involuntary and unelicited. The following types of Stroop lists were constructed for the first experiment: groups of four coloured Xs; incongruently coloured colour–word associates (ie 'sky' printed in red ink, 'grass' printed in purple ink, etc); incongruently coloured colour words; incongruently coloured digit pairs (based on L's self-report of colour–digit associations); and a negative-priming version of incongruently coloured digit pairs (that is, a series of incongruently coloured digit pairs whose synaesthetic associations serve as distracters immediately preceding the use of that colour as the target stimulus for the next digit pair).

It was hypothesised that both L and the members of the control group would demonstrate the classic patterns of Stroop interference. That is, it was hypothesised that performance on a list of incongruent colour-associated words would take longer than for a baseline ink-colour-naming task (coloured Xs), and that performance on a list of incongruently coloured colour names should take longer still. Further, it was expected that if in fact L's colour–digit percepts were synaesthetic, her ink-colour-naming speed on the synaesthetically incongruent list of coloured digits would be significantly slower than that of the control group (where no effect was expected in this condition). The inclusion of a synaesthetic-negative-priming list to this type of study has not been previously documented. The condition was included as an exploratory investigation of potential lexical contributions to synaesthetic experience [a conclusion that seemed feasible, despite one current theory (Cytowic 1995) dismissing the possibility, since L's percepts included the lexically acquired concepts of numbers].

2.1.1 *Method*

Participants. L is a female graduate student in the department of Psychology at the University of Nebraska – Lincoln (aged 46 years at the time of initial investigation, she is now 47 years old). She is a member of the Choctaw tribal rolls, and was raised in both Choctaw and Anglo heritage. Her educational career up to this point has focused on areas other than perception and cognition. As a result, she is (and was) relatively naïve of both the cognitive and the perceptual principles involved in the tasks set before her.

The control group for this study comprised seven males and four females, ranging in age from 19 to 39 years (mean = 27.64 years, SD = 7.67 years). The control-group members were all students (either undergraduate or graduate) enrolled at the University of Nebraska – Lincoln.

Stimuli. Prior to the actual experiment, L was interviewed and tested over the course of some eight weeks. These meetings provided the baseline information for these studies, including a complete listing of all 110 one-digit and two-digit Arabic numeral combinations (both from extended verbal reports and by using the colour wheel of Microsoft's Power Point 97 for matching purposes).

Eight different randomly ordered Stroop-style lists (of thirteen items each) were then constructed for each of five conditions: baseline (four Xs per item), incongruent colour – word associates (eg 'grass' printed in red ink), incongruent colour names (eg 'blue' printed in purple ink), synaesthetically incongruent coloured numbers, and negative-priming coloured numbers. Colour – number pairs were selected from the matching information mentioned above in order to produce incongruency between the related ink colour and the reported synaesthetic experience generated by the numbers.

For the traditional memory-performance criterion, a set of twenty one-digit and two-digit numbers were selected. These numbers were printed on a sheet of paper in 18-point Arial font, with a blank line for recording responses next to each number. A second sheet of the same twenty numbers (presented in a different random order) was used for the retest condition.

Procedure. Prior to the presentation of the Stroop lists, participants in the control group were presented with one of the lists of twenty randomly selected numbers, and were instructed to generate and write down colour – digit associations for each item. After completion of the Stroop tasks (an interval of approximately 10 min), each of the participants was then presented with the second list of twenty numbers, and was again instructed to generate and write down digit – colour associations for each item. Responses for the control participants were counted as correct if the two answers to each number coincided to any extent for hue (eg 'navy blue' and 'dark blue' were counted as the same response), although only 14 of the 440 total responses included any such brightness or saturation distinctions.

L also took part in the 10-min test – retest, although this was several weeks prior to the initial Stroop-list task, and with a different intervening task between trials (discussion of the characteristics of ligand-gated ion channels). In addition, L was held to a more stringent criterion for the evaluation of her test – retest performance. That is, since her original verbal reports of colour – digit associations included such colours as 'brick', 'cyan', and the like, her responses were counted as correct only in the event of an exact match.

In addition to the 10-min test – retest, L received a more extensive 6-week test – retest task. Specifically, 6 weeks after the initial interview in which colour names were identified for all 110 one-digit and two-digit numbers, L was presented with a randomised list of the same set of numbers, and was asked to write down the digit – colour associations for each item. Accuracy on this test was assessed by using the same criterion as for L's 10-min test (eg a complete match).

For the Stroop tasks, lists were presented to participants in a random order on individual clipboards, covered by a legal-sized sheet of black construction paper. Participants were instructed to remove the construction paper on the command "ready ... set ... go", and to read aloud as quickly as possible the ink colours in which the characters on the page were printed. Participants were then instructed to signal completion of each list by saying "done". All participants were timed with a hand-held stopwatch.

Control participants were given one randomly selected list from each type on a trial run in order to acquaint them with the task, and were then timed on a second set of one randomly selected list from each category. L received all eight versions of each type of list over the course of two different sessions, with presentation order randomised across two subsets of four of each type of list.

2.1.2 *Results.* Cytowic's (1989) durability and memorability requirement was met through the two test – retest conditions to which L was exposed. While the participants in the control condition had a mean accuracy rate of 28.4% (SD = 11.4%), L's test – retest accuracy rate for the 10-min task was 95% (with the only 'error' an assignment of 'canary' to an initial response of 'yellow'). In addition, the 6-week retest of all 110 one-digit and two-digit combinations of Arabic numerals provided an accuracy rate of 93.6% (103 of 110 correct). Again, the errors in this retest were characterised by such responses as 'maroon' for 'brick', and 'light pink' for 'pinkish-grey'. These results are consistent with the accuracy rates of synaesthetes and nonsynaesthetes as identified in previous research (Marks 1978; Svartdal and Iversen 1989).

The performance of the control group across the Stroop tasks also conforms to the research hypotheses ($F_{4,40} = 39.30$, $p < 0.001$, MSE = 0.97). Pairwise follow-ups (df = 10) revealed no significant differences in mean performance time between the baseline list of Xs, the incongruent synaesthetic coloured digits, and the synaesthetic-negative-priming list ($p > 0.05$ in all cases). Each of the expected Stroop effects was present as well: incongruent colour associates required significantly more reading time than the Xs ($p = 0.010$), as did the incongruent colour words ($p < 0.001$).

An analysis of variance also revealed a significant overall difference in mean performance times for L ($F_{4,28} = 21.27$, $p < 0.001$, MSE = 1.00). Pairwise follow-ups (df = 7) revealed that L's performance was also consistent with the original hypotheses. For the classic Stroop tasks, L took significantly longer on average to complete the lists of incongruent colour names than the lists of incongruent colour – word associates ($p = 0.006$), while both lists required significantly more time on average than did the baseline list of Xs ($p < 0.001$ for the incongruent colour names, $p = 0.004$ for the incongruent colour – word associates). The pattern of performance on the coloured-digit lists also supports the hypothesis of synaesthetic ability: incongruent colour – digit pairs ($p = 0.002$) and negative-priming lists ($p = 0.001$) took significantly longer on average to complete than did the baseline list, with the negative-priming lists having a significantly higher mean performance time than the incongruent colour – digit lists ($p = 0.002$).

Figure 1 provides the mean performance times across each type of list for both L and the control-group participants. Between-groups analysis of variance revealed that there were no significant differences in mean performance times between the two groups on either the lists of coloured Xs ($F_{1,17} = 1.30$, $p = 0.270$, MSE = 1.73), the lists of incongruently coloured colour – word associates ($F_{1,17} = 1.54$, $p = 0.232$, MSE = 0.66), or the

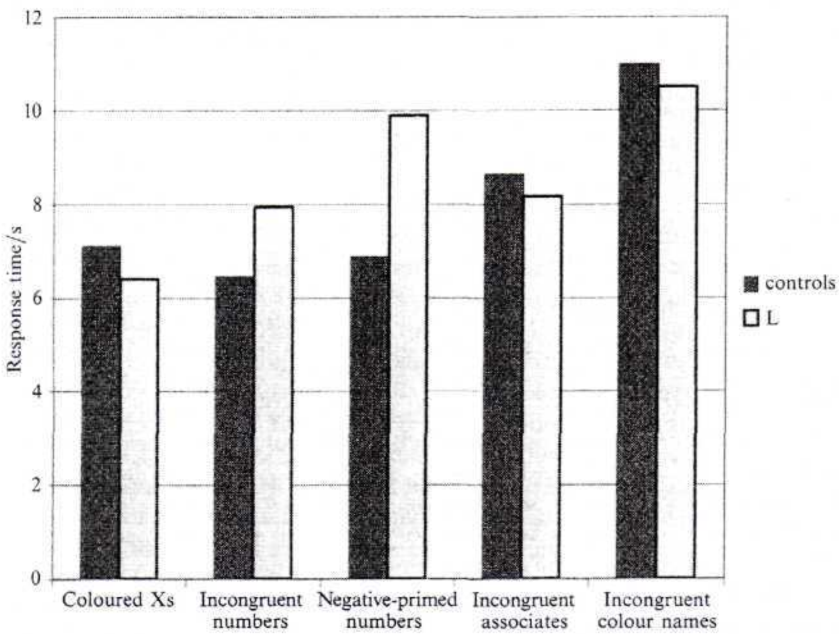

Figure 1. Mean response times across conditions for L and controls in experiment 1.

incongruent colour – word lists ($F_{1,17} = 0.45$, $p = 0.512$, MSE = 2.69). On the coloured-digit lists, however, L took significantly more time on average than did the control group on both the incongruent synaesthetic digit lists ($F_{1,17} = 6.13$, $p = 0.024$, MSE = 1.64) and the synaesthetic-negative-priming lists ($F_{1,17} = 15.32$, $p = 0.001$, MSE = 2.74).

2.1.3 *Discussion.* Analysis of the data from experiment 1 provides several useful pieces of information. First of all, it is worth noting that the data reveal no significant difference between L and the control group on the traditional Stroop tasks. In fact, a review of the mean response times for the lists of coloured Xs, incongruently coloured colour – word associates, and incongruently coloured colour names reveals that L was actually marginally faster than the members of the control group on each of the three lists. These results would seem to suggest that L and the members of the control group comprise a homogenous group.

Beyond this, the data from the initial experiment also serve to meet the memorability, durability, and involuntary-but-elicited criteria for the diagnosis of synaesthetic ability as established by Cytowic (1989). That is, while the control group displayed effectively equivalent performance across the list of coloured Xs and both of the lists of coloured digits (mean response times ranging from 6.47 s to 7.1 s), L exhibited a markedly different pattern of performance. Not only was her performance on the lists of incongruently coloured numbers significantly slower than on the base lists of coloured Xs; her performance on the negative-priming list was significantly slower than even her mean response times on the lists of incongruently coloured digits. In fact, her performance on the two lists targeted at her synaesthetic percepts was functionally equivalent to her performance on the traditional Stroop lists, with performance on the list of incongruent coloured numbers statistically equivalent to performance on the incongruently coloured word associates (means of 7.93 s and 8.17 s, respectively) and performance on the synaesthetic-negative-priming lists statistically equivalent to that of the incongruent-colour-name lists (9.88 s and 10.49 s, respectively).

In addition, the data from this experiment provide evidence for some intriguing possibilities with regards to L's perceptual experience of digits. First of all, the finding that L's performance on the classic Stroop tasks was not significantly different from that of the control group (in fact, it was somewhat faster than that of the controls) is itself intriguing. This finding runs counter to the conclusions of studies which have previously investigated the effect of age on Stroop performance, which have generally found that older participants perform more slowly on average than do their younger counterparts (Cohen et al 1984; Vakil et al 1996). Three alternative explanations seem plausible. First, as an active experimenter herself, it is possible that L was simply more attentive during the tasks than were the members of the control group. Second, it is possible that L is simply on the fast end of the distribution for members of her age group. Last, it is possible that her synaesthetic percepts have provided her with more processing of colour information in general, thereby improving the processing speed of such information, and so her fast performance on these lists might actually represent a beneficial consequence of synaesthetic experience. Whatever the specific contribution of these three alternative factors may be, however, it is clear that L's synaesthetic percepts are not adversely impacting her performance on traditional Stroop tasks.

The second intriguing finding in this work is that negatively priming L's synaesthetic responses generates a 'second tier' of response delay, so much so that it is as strong an effect as that of incongruent colour names. That is, presenting a series of incongruently coloured digits whose synaesthetic responses serve as distractors immediately preceding the use of that colour as a target stimulus for the next digit pair seems to generate a delay which is statistically equivalent to the robust effect of incongruent colour names. This seems to imply that in the case of the negative-priming task, there is some additional component of interference for L at the lexical level. That is, this pattern of performance seems to suggest the generation of a lexical component for which suppression on each trial N leads to a delay in the activation of the relevant response for each trial $N+1$. This finding is intriguing because it seems to contradict both of the theories of synaesthesia currently in vogue. On the one hand, the theory that synaesthetic percepts actually occur in the limbic system, rather than at the cortical level (Cytowic 1989, 1995), seems to be directly countered by this evidence. At a minimum, the current work suggests that there must be some contribution to synaesthetic experiences at the cortical level. On the other hand, the idea that synaesthesia is actually the result of a failure of neuronal modulation (Baron-Cohen 1996) is still plausible, although the period of modulation breakdown would have to be extended beyond the first few months of life to account for the onset of lexical development.

While these data cannot exclude the possibility of concurrent limbic activity, they do serve to support the conclusion of recent neurological investigations of synaesthesia (Paulesu et al 1995) which suggest that, at least in the case of intramodal experiences, synaesthesia as a phenomenon occurs at the cortical level. Beyond identifying a phenomenological assessment as a replacement for neurological examination, the current findings also raise a new question. That is, the significantly slower performance by L on the negative-priming list provides the first evidence that lexical activation may have a more substantial role in synaesthetic processing than simple sensory processing. A second experiment was conducted to further investigate this phenomenon.

2.2 *Experiment 2*

Previous research with the Stroop effect has demonstrated that verbal code components can be assessed independently of verbal production components (Flowers and Dutch 1976). In this study, the authors constructed normal Stroop lists of coloured Xs and incongruently coloured words. Rather than have the participants verbally identify every printed ink colour, however, the authors instructed the participants to scan the list for previously named target colours, and to cross out any items that were printed in these colours. Target colours for each task consisted of one, two, or three hues, with the multiple-hue conditions broken down into two categories: spectrally adjacent (ie red, orange, and yellow) and nonadjacent colours (ie orange, green, and purple). In comparing the performance of groups across these conditions, the researchers found that single target colours were such an easy task that normal Stroop interference on incongruently coloured word lists could be avoided; lists with three distracters took longer to complete than lists with single distracters; and that searching for adjacent colours was faster than searching for nonadjacent colours. Conditions involving either one or two target hues showed little or no Stroop interference, suggesting the use of a visually coded search image independent of lexical processes. Robust Stroop interference was found, however, in those conditions that required searching for three nonadjacent hues. Such conditions presumably placed a sufficient load on working memory that lexical activation may have been required in order to maintain the list of search targets. These results demonstrated that the Stroop phenomenon included a lexical component, in addition to the issues of divided attention that had been focused on up to that point.

In order to assess further the relative contributions of lexical and visual components to L's synaesthetic percepts, then, a second set of Stroop-style lists based on this research was constructed. While the basic task was the same as in the original Stroop lists (identifying ink colours), the presentation for these lists was somewhat different. Participants were provided with a dry-erase marker before being exposed to each Stroop list, and were instructed to cross out items on the page printed in whichever target colour or colours they were given prior to exposure. Under these conditions, participants are accessing lexical processing areas in the cortex only inasmuch as they are required for stimulus perception and target maintenance (eg working memory).

It was hypothesised that the control group would exhibit a pattern of performance consistent with the results both of the initial application of this type of design (Flowers et al 1976) and from experiment 1. Specifically, it was expected that the average response times on lists with a single target colour would be significantly faster than for nonword lists (in this case, Xs and numbers) with three adjacent colours. Nonword lists with adjacent colours would, in turn, have faster mean response times than nonword lists with three nonadjacent target colours. Last, word lists with three adjacent targets would be significantly faster on average than word lists with three nonadjacent target colours.

As with the members of the control group, it was hypothesised that L would again exhibit the 'classic' Stroop performance patterns on the traditional Stroop lists: performance on lists with single targets would be significantly faster on average than on lists of three adjacent targets, which would in turn be faster than three nonadjacent targets. No explicit hypotheses about L's performance on the incongruent-number lists in this design were formulated, since the procedure was highly exploratory in nature. While it seemed likely that these lists would yield a pattern of performance consistent with other cognitive tasks performed on synaesthetes (eg number lists with adjacent targets would be faster than lists with nonadjacent targets, with both types of lists being slower than their nonword equivalents), the hint of lexical processing from the first experiment suggested the possibility that something more complex was occurring.

2.2.1 *Method*

Participants. The control group for this experiment consisted of six males and four females, ranging in age from 18 to 20 years (mean = 19.0 years, SD = 0.667 years). All of the control-group members were undergraduate students enrolled in the Introductory Psychology course at the University of Nebraska – Lincoln, who participated in the study in partial fulfilment of course requirements.

Stimuli. Stimulus materials were lists of eighty items printed in four columns of twenty items each on white paper 20 cm × 30 cm. Since the task required subjects to mark through items using a dry-erase marker, the sheets were subsequently laminated to allow for reuse. Each item on the lists was printed in 24-point Arial font in one of eight colours: purple, red, pink, orange, yellow, green, blue, or black. Lists were constructed of three different types of items: X lists (sets of either three, four, five, or six Xs), number lists (items in which sets of a single digit appeared in groups of either three, four, five, or six, such as '444444'), and word lists (in which colour names were printed in incongruent ink colours).

Within each type of list, various subtypes were developed for target set size (either one or three target colours) and, within the three-target sets, for target colour adjacency/ nonadjacency. Five different randomly ordered lists for set size 1 were developed with Xs and numbers (with targets in each of either red, yellow, blue, green, or pink). Likewise, five different randomly ordered lists of set size 3 were constructed for both adjacent and nonadjacent targets in lists of Xs, numbers, and words. Adjacent three-colour lists were all designed with the colours red, orange, and yellow as targets. Non-adjacent three-colour lists employed either red, green, and blue ink or orange, green, and purple ink as the designated targets. Regardless of set size, each list contained twenty-four positive instances of the colour(s) belonging to the target set. Number lists were all constructed so that every number appeared in ink colours incongruent with L's synaesthetic colour percepts. Cumulatively, this provided eight different types of lists: Xs with a single-colour target (X1), Xs with three adjacent-colour targets (X3A), Xs with three nonadjacent-colour targets (X3non), numbers with a single-colour target (N1), numbers with three adjacent-colour targets (N3A), numbers with three nonadjacent-colour targets (N3non), words with three adjacent-colour targets (W3A), and words with three nonadjacent-colour targets (W3non).

Procedure. Prior to beginning the experiment, each participant was shown a sample list of sets of coloured Xs, and had identified to them each of the ink colours used in all the lists. Each participant was allowed to scan the sample list as long as they desired. The experiment was begun upon the return of the list to the researcher.

Lists were presented to participants in a random order on individual clipboards, covered by a legal-sized sheet of black construction paper. Participants were instructed to remove the construction paper on the command "ready ... set ... go", and to then scan the list as quickly as possible, crossing out any items on the list printed in whatever target colour(s) they had been given for that trial. Participants were then instructed to signal completion of each list by saying "done". All participants were timed with a hand-held stopwatch.

Control participants were presented with one randomly selected list from each of the eight different types of lists, and had these randomly selected lists presented in random order. L received all five versions of each type of list over the course of a single session, with presentation order block-randomised into five subsets containing one of each of the eight types of lists.

2.2.2 *Results.* Mean performance times for both L and the control group across all conditions are presented in figure 2. For the control group, statistical analysis of the data via repeated-measures ANOVA revealed a significant mean difference in response time across list types ($F_{7,63} = 44.40$, $p < 0.001$, $\mathrm{MSE} = 18.40$). Paired-samples t-tests ($\mathrm{df} = 9$) were then performed to explore the research hypotheses. Mean response times on single-target lists (X1 and N1) were not significantly different from each other, but were significantly faster ($p < 0.01$ in all cases) than for all other lists. Also, while there were no significant differences between either X3A and N3A or X3non and N3non, both nonword lists with three adjacent targets were performed significantly faster on average than either nonword list with three nonadjacent targets ($p < 0.05$ in all cases). Last, word lists were significantly slower on average than their nonword counterparts in terms of adjacency/nonadjacency ($p < 0.05$ in all cases), and word

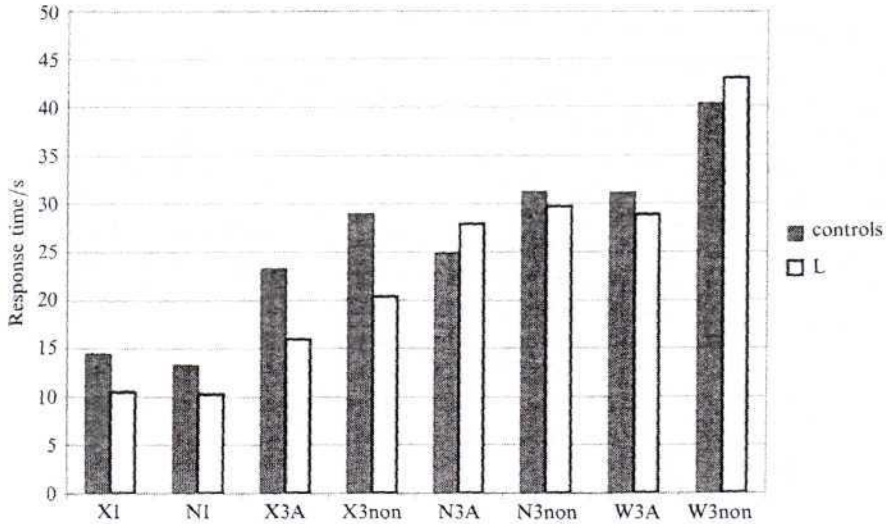

Figure 2. Mean response times across conditions for L and controls in experiment 2. See text for details of conditions.

lists with three nonadjacent targets were performed significantly more slowly on average than word lists with adjacent targets ($p < 0.05$).

Likewise, statistical analysis of L's data via repeated-measures ANOVA revealed a significant mean difference in performance time across list type ($F_{7,28} = 43.14$, $p < 0.001$, MSE = 14.48). Paired-samples *t*-tests revealed the expected pattern of performance on nonnumber lists: X1 was significantly faster than X3A ($p < 0.01$), which was in turn significantly faster than X3non ($p < 0.05$), while average performance on W3A was significantly slower than on X3A, but significantly faster on average than W3non ($p < 0.05$ in both cases). In reviewing L's performance on the synaesthetically incongruent number lists, we find that performance on N1 was statistically equivalent to that of X1 [a finding which is not surprising, given that Flowers et al (1976) demonstrated that a single target is insufficient to elicit involuntary divided attention].

Beyond that, however, results did not meet the expectations of performance from the traditional Stroop literature. Specifically, while mean performance times on both three-target number lists were significantly slower than on all X lists, there was no statistical difference in mean performance times for the two three-target number lists, regardless of whether the distracters were adjacent or not. This would seem to suggest that the attention required for identifying three targets simultaneously was sufficient to provide interference from all of the incongruently coloured numbers, regardless of distracter type.

While these simple effects, taken as a whole, show a significant main effect for type of list in a mixed factorial analysis of these data ($F_{7,91} = 76.75$, $p < 0.001$), there was no main effect for group ($F_{1,13} = 0.80$, $p > 0.05$). Follow-up analyses of the simple effect of group for each list show that the only significant difference in performance time was that L was significantly faster on average than the control group for X3A ($F_{1,13} = 6.50$, $p = 0.0242$).

While the simple effects for group membership did not produce a significant main effect for group, they did contribute to the analysis in the form of a significant interaction between group membership and type of list ($F_{7,91} = 3.36$, $p = 0.003$, MSE = 17.19). The pattern of this interaction is made clear in the statistical analyses of simple effects in the previous paragraphs, and can be summed up in the following way. Average performance time on lists with single targets is faster than on lists with multiple targets.

When considering multiple targets, lists of spectrally adjacent targets are significantly faster on average than lists of spectrally nonadjacent targets. In addition, lists of incongruently coloured words are more difficult to search than lists of nonword targets. This pattern is different for L, in that lists of digits printed in synaesthetically incongruent colour numbers cause equivalent delays in mean performance time, regardless of whether or not targets are spectrally adjacent.

2.2.3 *Discussion.* Analysis of the data from experiment 2 shows that the control group performed as expected, given the results of both the study on which this design was based (Flowers et al 1976) and those of experiment 1 (suggesting that numbers generate no more interference for nonsynaesthetes than do Xs). Specifically, lists with a single target colour were completed much more quickly than were lists with multiple targets, and multiple-target lists with adjacent target colours were completed significantly more quickly on average than were multiple-target lists with nonadjacent target colours. In addition, lists of incongruently coloured colour words were completed more slowly on average than were their nonword equivalents (in terms of target colour adjacency versus nonadjacency).

The results of the second experiment for L, on the other hand, provide both expected and intriguing findings. With regards to the nonnumber Stroop lists, her performance pattern matched that of the control group (eg single targets faster than three targets, adjacent targets faster than nonadjacent targets, Xs faster than words). Despite the results of experiment 1, however, L's performance on the synaesthetically incongruent number lists was surprising. First of all, the use of three targets on the synaesthetically incongruent number lists all but tripled mean response times (from 10.30 s for single-target number lists to almost 28 and 30 s respectively for adjacent and nonadjacent three-target lists). Also surprising was the amount of interference caused by the synaesthetically incongruent number lists: 12.07 s in the case of three adjacent targets (X3A to N3A), and 9.3 s in the case of three nonadjacent targets (X3non to N3non).

There was also an unexpected finding in the analysis of L's performance in this experiment, in that her performance across the multiple-target number lists (27.99 s on average for adjacent targets, 29.71 s for nonadjacent targets) was statistically equivalent. This suggests that the provision of three simultaneous colour targets is enough to overload her attentional capacity for processing colour information, regardless of whether the targets are spectrally adjacent. In other words, the lexical component of her synaesthetic experience can be said to be sufficient to overload her working memory when given just three colour targets for which to search.

3 Perceptual structure

Aside from the extensive descriptions of the abilities of a pair of extremely potent synaesthetes (Luria 1968; Cytowic 1993), most scientific reports in the literature have focused on the classification of the specific synaesthetic manifestations in each case, rather than investigating the perceptual structure of the synaesthetes per se. Given that an initial investigation of L's perceptual structure had already been completed in order to construct the stimuli for the two experiments previously discussed it seemed only natural to explore the available data.

3.1 *The colour wheel*

As mentioned earlier, part of the original series of interviews was the establishment of colour-digit associations for L during her synaesthetic experiences. There were two types of investigation employed to this end: an extended recall task, in which L was asked to report the colour of each number as it was verbally presented to her (which provided the baseline list for the 6-week test-retest assessment); and a matching task, in which L was verbally presented with all one-digit and two-digit combinations of

Arabic numerals in a random order, and asked to select the colour point on the Power Point colour wheel which most closely matched her synaesthetic experience. A partial diagram of the colour space presented in this wheel is included in this work as figure 3.

As shown in table 1, L's synaesthetic percepts generally appear to be driven by the colour percepts of individual digits (0 is white, 1 is black, 2 is yellow, 3 is pink, 4 is blue, 5 is red, 6 is orange, 7 is green, 8 is purple, 9 is pink). Digit pairs seem to follow a general guideline of subtractive combinations of these individual colour – digit associations. For example, the numbers 47 and 74 sit next to each other on the colour wheel where the blue (4) and green (7) regions of the colour template blend.

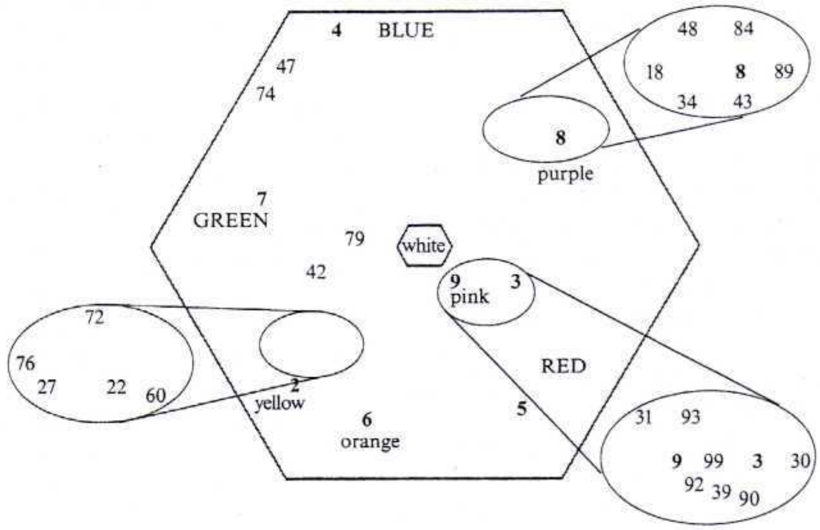

Figure 3. Spatial representation of two-dimensional colour assignment for L's colour – digit synaesthesia.

Table 1. Colour – digit representations by colour category.

Red	Pink	Orange	Yellow	Green	Blue	Purple
5	3	6	2	7	4	8
13	9	12	11	17	14	34
23	15	26	16	27	18	38
25	30	32	20	42	40	43
35	31	56	22	70	41	48
36	33	60	46	71	44	58
50	39	62	67	72	47	80
52	63	66		74	49	81
54	90			76	78	84
55	91			77		87
56	92			79		88
59	93					89
65	94					
69	99					
83						
95						
96						

Digits with nonchromatic colour associations: 19, 21, 24, 28, 29, 37, 45, 51, 53, 57, 61, 64, 68, 73, 75, 82, 85, 86, 97, 98.
The digit 1 is black, the digit pair 10 is grey.

While these sorts of colour mixtures dominate the grid, however, there is a substantial subset of numbers for which no match was available on the grid. That is, L insisted that there were no colour patches even close enough to approximate her experiences, because, for instance, "There is no purple–orange colour patch for 98". The authors originally mistook such comments to mean that there was no patch suitable for that type of colour mixture. It was only after several such instances that L made it clear that she was not looking for a mixed patch. Rather, she was looking for a patch that *was* orange–purple (or red–green, or the like). Such phenomenological self-reports suggested that there was a component to L's perceptual structure of colour beyond what nonsynaesthetes experience. To investigate this, a last experiment was performed.

3.2 *Experiment 3*

The purpose of this final investigation was to identify some of the underlying dynamics of the colour percepts associated with L's experience of numbers. As such, a sorting task was devised that would force L to group numbers she might otherwise identify as dissimilar. This sorting task was performed only by the synaesthetic participant.

3.2.1 *Method*

Stimuli. Twenty one-digit and two-digit numbers were selected for the purposes of this design. Each number was printed in 42-point Arial Bold font on an individual piece of white paper 5 cm × 8 cm. Fourteen numbers were selected because they represented single-patch colour associations from the colour wheel that should provide enough stability to generate a meaningfully interpretable dissimilarity matrix. These numbers were 4, 44, and 47 (bluish); 5, 13, 15, and 52 (reddish); 22 and 26 (yellow–orange); 30, 39, and 91 (pinkish); and 72 and 76 (greenish). Six additional numbers were then selected specifically because they were numbers identified by L as being unique enough on the colour wheel as to be unmatchable: 57, 85, and 86 (red–greenish); 61 and 64 (which were described as 'active' combinations of multiple colours); and 98 (orange–purple).

Procedure. L was presented with identical copies of this set of twenty cards on a total of fourteen different occasions. The decks were presented in a different random order on each occasion, with the time between each sorting separated either by a period of at least 24 h or by a variety of distracter tasks (ie discussion about departmental issues, coursework, teaching duties, etc). On each occasion, L was instructed to sort the cards into piles based on the similarity of the synaesthetic percept associated with the number printed on each card. L was instructed that each group must contain at least two cards, and that she must divide the set into somewhere between three and six piles. The latter instruction was included in order to generate some variations between each sorting (since she would presumably otherwise wish to sort the chosen numbers into no less than eight different groups under these parameters). The resulting card sorts were recorded, and later condensed into a single dissimilarity matrix.

3.2.2 *Results.* A within-groups hierarchical cluster analysis was performed on the dissimilarity matrix. Given that the coefficient dropped from 52.23 for one cluster to 24.06 for two clusters, to 8.47 for three clusters, and then to zero for four clusters, the four-cluster solution was retained.

The four-cluster solution leads to a three-concept division for those of us who are not synaesthetic. The major division in this set appears to be serviceably defined as 'reddish coloured' (5, 13, 15, 30, 39, 52, 57, 91) versus 'not red, but typically chromatic' (4, 22, 26, 44, 47, 61, 64, 72, 76). It is worth noting that three of the numbers previously identified as being problematic to the colour wheel loaded into these groups: 57, 61, and 64. Although nonempirical, it should be mentioned that sorting sessions were often punctuated by objecting commentary on L's part, especially when the six difficult numbers were all that were left. On the basis of this clustering solution, we can conclude that L found it less objectionable to assign 57 as being more similar to reds (presumably as a result of the '5' component), while 61 and 64 were most closely associated with the off-greens of 72 and 76 (on the basis of order of clustering), than to assign them all to a 'doesn't fit' group.

The final two clusters seem to be best fit by the label 'other', at least to those of us who do not experience this form of synaesthesia. 85 and 86 were the second-to-last components to load in the overall clustering solution, although they were grouped with each other very early on in the analysis. L has reported these two digit pairs as being associated with the colour 'green – red'. The last number to load in the clustering analysis was the sole member of the final cluster: L identified 98 as the colour 'orange – purple'.

3.2.3 *Discussion.* Cluster analysis of L's sorts of twenty one-digit and two-digit numbers provides us with a general characterisation of her synaesthetic colour space that can be summarised as 'reddish hues' versus 'not-reddish typical hues' versus 'atypical opponent-process hues'. One possible explanation is that the two 'typical' groupings here may represent a metaphorical/emotional dichotomy between 'warm' and 'cool' colours. This suggestion has not been investigated as yet, although it seems a worthwhile place to begin deciphering this information. It should be noted, however, that even if this hypothesis is correct, it does not account for the unusual colour – digit associations that seem to violate opponent-process theory.

One conclusion that was made clear by this sorting task is that Euclidean space is apparently an inadequate means by which to describe the structure of L's synaesthetic percepts. This conclusion is supported by L's description of some of her stronger atypical colour – digit associations. 98, for example, was vividly described on one occasion as a "hollow sphere of orange and greyish purple that is as real a colour as red or green", but that she had "never seen anywhere in the world".

4 General discussion and conclusions

The current study has demonstrated several useful pieces of information regarding the study of synaesthesia. First of all, the use of Stroop-type tasks has been demonstrated here as one avenue by which researchers may meet diagnostic criteria of synaesthesia other than memorability and durability. As scientists committed to the idea of scepticism, it seems only natural that we should seek out ways in which to confirm the authenticity of phenomena when we cannot directly observe their origins. This design has demonstrated one such alternative.

Second, the identification of a lexical component in this case of synaesthetic ability serves to cast further doubt on the theory that synaesthesia occurs solely below the cortical level, in the limbic system (Cytowic 1989). As a result, theories that suggest synaesthesia is a failure of the cortex to properly modulate its sensory input (Baron-Cohen 1996) seem more parsimonious at this time.

There is an implication in these results that would seem to require a modification of the original theory. Given that most complex lexical components do not develop until well into the toddler period, theories which indicate that synaesthetic percepts develop in the first few months of life seem somewhat unsatisfactory.

There are two exciting alternatives that seem to provide plausible explanations for this apparent discrepancy. The first possibility is that synaesthetic percepts develop as the result of atypical developmental sequences. In other words, these perceptual dualities are not developing outside of normal critical periods of development. Rather, they are developing specifically because normally separate critical periods are actually occurring simultaneously within each synaesthete.

Alternatively, it may actually be the case that synaesthetic percepts are the result of experience, rather than of genetics. Consider the following: theories of cortical modulation of sensory input (Baron-Cohen 1996) suggest that it takes place (for the most part) in the first few months of life. In contrast, synaesthetic associations involving lexical components would seem to require the acquisition of the lexical components prior to taking on a dual perception, which does not take place until months or years after the potential neuronal mismodulation. Therefore, it seems plausible to suggest that, while the neural structure of dual perception develops in early infancy, the specific pattern of synaesthetic associations may be the result of experience, rather than of genetics. In other words, while the physical structure is in place early on for synaesthetic perceptions, the specific nature of those associations may be the result of whatever sensory code happens to be written at some later date on the 'synaesthetically prepared' neuronal regions.

Finally, the current project has sought to demonstrate the utility of expanding investigations of synaesthetic ability beyond the cognitive and neurological dynamics of the phenomenon. Failing to investigate the perceptual structures of synaesthetes may be causing us to miss information that could significantly contribute to both our understanding and our appreciation of the perceptual experiences of persons with synaesthetic ability.

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