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# Linear separability and redundant colour coding in visual search displays

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**Abstract**

Subjects sought a unique target shape in a display of distractor shapes under three colour coding conditions. In the no colour coding condition (**NCC**) all shapes shared the same colour. In the two colour-coded conditions, the target was uniquely and redundantly colour coded with a colour whose CIE 1976 UCS chromaticity coordinates were either linearly separable (**LS**) or not linearly separable (**NLS**) from the set of distractor chromaticity coordinates. Performance was optimal under **LS** coding, was reduced under **NLS** coding and was least efficient in the **NCC** condition. We discuss the implications of these results for refining colour selection algorithms and for colour coding in situations where the gamut of available colours is limited. Crown Copyright © 1997 Elsevier Science B.V.

*Keywords:* Linear separability; Colour coding; Visual search

## 1. Introduction

In this paper, we link a recent finding from colour psychophysics to the issue of how to optimize a set of colours for coding in a complex visual display. We present the results from an experiment that demonstrates the superiority of redundant colour coding of symbology over monochromatic coding which, on its own, is not new. However, we also demonstrate that all redundant colour coding is not equally effective and provide evidence that coding according to *linear separability* (see below) can further enhance performance.

D'Zmura [1] and Bauer et al. [2] have shown that the linear separability of a target chromaticity from distractor chromaticities can affect visual search performance. They demonstrated that when a target chromaticity was linearly separable (**LS**) from distractor chromaticities (see Fig. 1) visual search was easy. When a target chromaticity was not linearly separable (**NLS**) from distractor chromaticities, (see Fig. 2) search was difficult.

One of the goals of applied colour research is to identify colours that are easily discriminable from each other for the purpose of colour coding information in complex visual displays [3–8]. The objective is to select colours that will facilitate rapid, ideally error-free extraction of pertinent information from these displays within the parameters of monitor gamut, operator limitations, and environmental variables such as high ambient illumination or off-axis viewing. Algorithms based on established colour difference metrics are available to help in the selection of appropriate colours [3–8]. However, the research reported by D'Zmura [1] and Bauer et al. [2] clearly demonstrates that colour difference magnitudes alone are not sufficient to predict search performance: linear separability is an additional factor with potent effects on search performance. That is, selection of a set of colours based on pairwise discriminability, or maximization of minimum colour differences, is no guarantee of discriminability of a given colour or subset of colours in the presence of additional colours. Furthermore, in applied settings there may be severe constraints on desired hue, saturation, and luminance (e.g. low luminance displays for night viewing, or low saturation colours to increase luminance and reduce effects of chromatic aberration [9]) or on the realizable colours due to ambient illumination or display gamut limitations (see Ref. [10]). This means that colour selection may be more a task of optimization than of maximization. A general principle that serves to guide the selection of effective colours for coding under such constraints would be a useful tool for the display engineer. Linear separability has been shown to exert powerful effects on search

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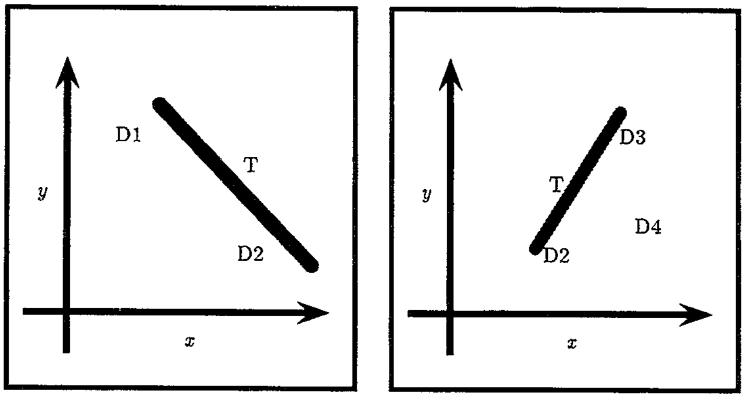

Fig. 1. Linearly separable **LS** two distractor (left) and three distractor (right) configurations plotted in an arbitrary colour space. Under these conditions, search is relatively easy. The thick line is the linear separator. T = target chromaticity, D*n* = distractor chromaticity.

performance and the display designer can exploit this finding in identifying colours for coding of symbology.

In their psychophysical experiments, both D'Zmura [1] and Bauer et al. [2] used coloured discs of identical size for their search items (targets and distractors). Though such conditions were informative in the investigation of the linear separability phenomenon, this type of display is far removed from applied settings such as those studied by Smith [11,12], Carter [13], and Carter and Carter [3]. In applied settings, colour coding is used to facilitate the detection, localization, or discrimination of symbology such as alphanumerics or geometric shapes that may represent information such as system status in process control, landmarks or hazards in electronic charting, or obstacles and other craft (friendly or hostile) in guidance and defence systems. Under these conditions, rapid and accurate integration of signal information is critical. These considerations emphasize the need for optimal colour coding. Because the issue of linear separability in colour research is relatively recent, no experimental data on its effects in applied settings are available.

The present experiment investigates the effectiveness of linearly separable colour coding under conditions that more closely parallel an applied situation, that is, under conditions where the target is a specific shape that may always be differentiated from all other items in a display by its shape alone, and may or may not be differentiated by its colour. Because the present experiment includes conditions under which the colour coding is redundant with shape coding, only modest effects of linear separability are expected. This is because the task can be performed using shape information alone, and this imposes a practical ceiling on the magnitude of linear separability effects. Previously, redundant colour coding has been shown to improve visual search performance for a variety of tasks and stimulus types [14–19] (see also, Ref. [20]). The present experiment was designed to investigate whether **LS** coding improves performance over **NLS** coding and how both these colour coding methods perform with respect to no colour coding at all.

## 2. Method

### 2.1. Subjects

Subjects were the two authors, other researchers at the Defence and Civil Institute of Environmental Medicine, and civilians. A total of seven subjects (age range 19–49) participated. All but one scored in the normal range on the

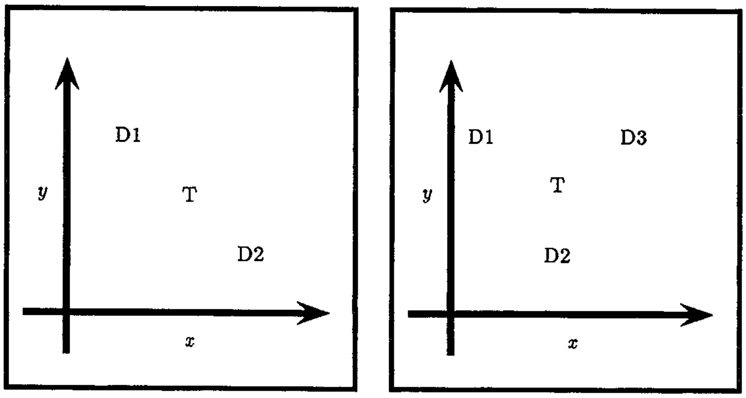

Fig. 2. Not linearly separable **NLS** two distractor (left) and three distractor (right) configurations plotted in an arbitrary colour space. Under these conditions, search is relatively difficult. T = target chromaticity, D*n* = distractor chromaticity.

Farnsworth–Munsell 100 hues test. The low scoring subject produced random errors suggesting no systematic colour deficiency and was therefore not excluded.

### 2.2. Apparatus

The experiment was performed on a Macintosh Quadra 800 computer with a RasterOps Paintboard Li driving a RasterOps 20 in colour monitor (model 2075RO) using software that accessed each colour gun with 8 bits of resolution. Responses were collected via the computer keyboard. Chromaticity and luminance values were measured using a Minolta CS-100 Chromameter.

### 2.3. Stimuli

Stimuli were displays containing the geometric symbols: ● ■ ▲ . These symbols were drawn approximately equal in area (about 1.2° square visual angle) because colour discriminability is known to vary with area [21]. The symbols were presented at a luminance of 18.0 cd/m$^2$. At all times during the experiment, the screen background was maintained at 18.0 cd/m$^2$ with CIE 1976 UCS chromaticity of ($u' = 0.218$, $v' = 0.466$). Details regarding the acquisition of the DAC values for the desired colours can be found elsewhere [2].

#### 2.3.1. Displays

The symbols were presented in the cells of an imaginary 6 × 6 grid with small positional offsets ( ± 3 pixels) selected at random for each item displayed. The array of items subtended about 15° × 15° on the screen which in turn subtended about 45° × 45°. A schematic illustration of a display of set-size 27 is presented in Fig. 3.

The target shape never appeared in any of the extreme corner cells of the imaginary grid and occurred equally often in each quadrant of the grid within a block of 24 trials. To create set-sizes of 9, 18, or 27 items, sufficient numbers of distractor items appeared in random cells within the grid at any location that was not occupied by the target if present. Target presence or absence, and quadrant of the target were randomized such that no value on either of these dimensions was constant over more than four contiguous trials. The same set-size did not appear in more than three contiguous trials. On a given trial, distractor shapes were selected at random without replacement from the set of three non-target shapes until the set of three was exhausted. The set of three non-target shapes was then re-introduced, and re-sampled, and so on, until all required distractor positions were filled. This method was used to ensure that no distractor symbol would be systematically under-represented. For target-absent trials, this algorithm resulted in equal numbers of the three distractor shapes. For target-present trials, one of the shapes was under-represented by one. On the colour coded trials (**NLS** and **LS** conditions), the allotment of the non-target colours to the distractors was accomplished using a selection algorithm similar to that described above for selection of non-target shapes. This resulted in approximately equal numbers of each of the distractor colours in the colour coded displays.

#### 2.3.2. Colours

The two colour sets used are illustrated in Fig. 4. CIE 1976 UCS and CIE 1931 ($x$, $y$) coordinates of these colours are tabled in Appendix A.

Colours in both sets were spaced by a minimum of about 30 $\Delta E^*_{uv}$ units. Carter [21] states that 20 $\Delta E^*_{uv}$ units is sufficient for easy discrimination of colours in visual search. Therefore, the nearest colours in either set were at least a few JNDs apart and perhaps at or near the critical

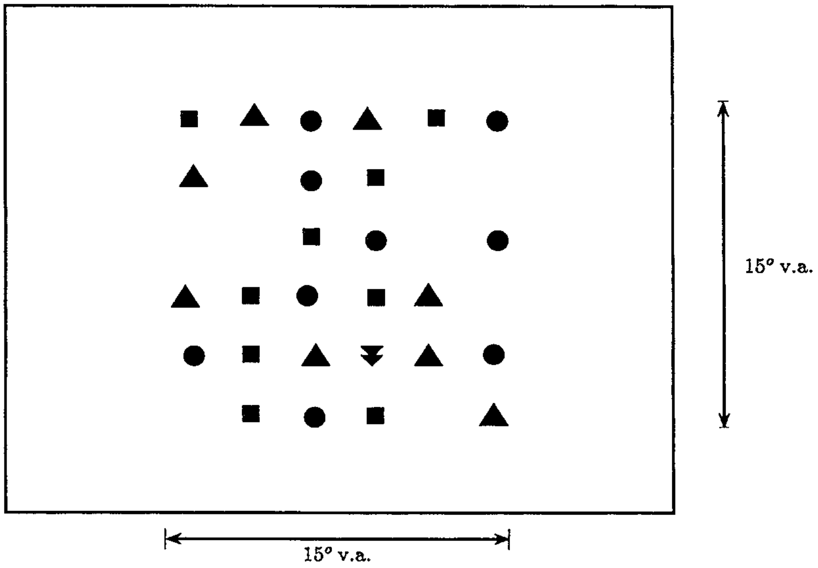

Fig. 3. A schematic illustration of a set-size 27 display. In this display, the target (double triangle) is present, and all items share the same colour. (Dimensions not to scale, v.a. = visual angle.)

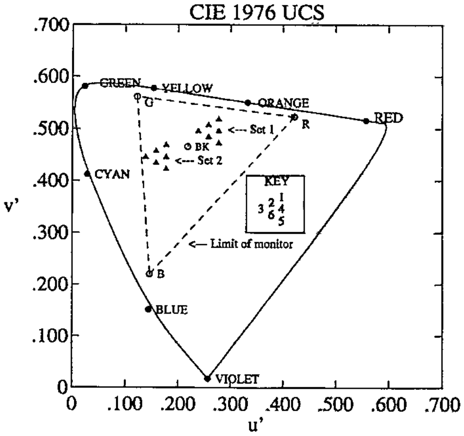

Fig. 4. CIE 1976 UCS representation of the colour sets. Colours at the vertices of each set (odd numbers, see KEY) are **LS** from all other colours. Remaining colours (even numbers) are **NLS** from the other colours. BK = background.

colour difference [22] beyond which no increase in colour difference would significantly improve performance. A set of colours similar to set 1 has previously been shown to have acceptable characteristics for this type of research [23]. The background colour was 47 $\Delta E^{*}_{uv}$ units away from the nearest colour in either set.

### 2.4. Task

Subjects were asked to signal the presence or absence of a single prespecified target symbol in a display containing 9, 18, or 27 symbols. The target symbol was held constant within a block of trials and was presented with a 50% probability on a given trial. On some blocks of trials, the target shape was uniquely colour coded (with a **LS** or a **NLS** target colour) and this colour was made known to the subject before each block of trials. On other blocks of trials, all items in a display shared the same colour, i.e there was no colour coding (**NCC**). Subjects were told to respond as quickly as possible while keeping errors to a minimum. Feedback was provided on the screen after each trial with a ' + ' or a ' − ' signifying a correct or incorrect response respectively.

### 2.5. Procedure

Subjects first signed an informed consent form and then were tested on the Farnsworth–Munsell 100 Hues test. Prior to the visual search trials, subjects adapted to the dim illumination in the room that was provided by two overhead incandescent bulbs. Each subject completed eight runs (a total of 5760 trials) with two runs per testing session. Data collection for each subject was spaced over several days.

#### 2.5.1. No colour coding trials (**NCC**)

Four of the eight runs were not colour coded. Each run consisted of 720 trials. A run consists of 24 blocks of 30 trials (6 practice, 24 test) and over a run there was a complete crossing of the six colours within a set and the four possible target shapes. Within each block, the target shape was held constant and a single colour was used for all shapes. Each subject completed two runs with each of the two colour sets.

#### 2.5.2. Colour coded trials (**NLS/LS**)

Four of the eight runs were composed of trials in which the target symbol was uniquely and completely redundantly colour coded. Each run consisted of 720 trials (again 24 blocks of 30 trials) over which each colour within a set was crossed with each shape as the target shape/colour pairing. The shape/colour pairing was constant within a block and, within a run, only one of the colour sets was sampled. In each run, twelve of the blocks had a **LS** target colour and twelve had a **NLS** target colour (see Fig. 4). Each subject completed two runs with each of the two colour sets.

The ordering of the 24 blocks within a run was randomized. The 24 test trials within each block consisted of four replications of the complete crossing of target status (present/absent) with set-size (9, 18, 27). For a given session of two runs, subjects received one run of **NCC** trials using one of the colour sets, and one run of **NLS/LS** using the other colour set. Subjects were permitted self-paced rest breaks between blocks and runs.

Subjects viewed the displays binocularly from a seated position at a distance of about 60 cm. No head restraint device was used and the monitor was placed such that the centre of the screen was at eye-height.

### 2.6. Analysis

The primary focus of this experiment was to determine whether performance with **LS** target colours was superior to performance with **NLS** target colours and how performance in these two conditions compared with that in the **NCC** condition. The dependent measures of performance were, reaction time (RT) and error rate, and secondly, search rate expressed as milliseconds per item. Prior to statistical analyses, raw reaction times were collapsed over colour set, target shape, target colour within **LS** and **NLS** conditions, and replication, then screened for outliers using the modified recursive outlier procedure with moving criterion as described in Van Selst and Jolicoeur [24]. This procedure eliminated less than 2.5% of the data.

## 3. Results

Prior to the main analysis of variance (ANOVA), the RT data from the **NCC** condition were analysed under a model that included target status (present/absent), set-size (9, 18, 27), and linear separability as within subjects factors. Obviously, the linear separability factor does not directly apply to the **NCC** condition because all items within a display were the same colour. However this initial analysis was performed to verify that there was no differential performance advantage in the **NCC** condition for the colours that were used as **LS** or **NLS** in the colour coded trials. This analysis did not indicate a main effect or any interactions involving the linear separability factor. The only effect that approached significance was a 13 ms advantage of **NLS** over **LS** coded trials ($F(1, 6) = 1.72, p < .238$), which is small and in the wrong direction to impact on the interpretation of the results from colour coded trials.

There were three factors for the primary RT ANOVA: Coding (**LS** colour coding, **NLS** colour coding, no colour coding **NCC**), target status (present/absent) and set-size (9, 18, 27). The main effect of coding was significant, $F(2, 12) = 37.20$, $p < .001$, with overall performance ranked as follows: **LS** 783 ms, **NLS** 854 ms, **NCC** 941 ms. Target-present responses (663 ms) were faster than target-absent responses (1055 ms), $F(1, 6)$ 63.00, $p < .001$. There was also a main effect of set-size, $F(2, 12) = 88.28$, $p < .001$, with reaction time increasing monotonically as a function of set-size, with significant linear, $F(1, 6) = 89.385$ $p < .001$, and quadratic trends, $F(1, 6) = 40.39, p < .001$. The interaction of coding with target status was significant, $F(2, 12) = 13.69$, $p < .001$, as was the interaction between coding and set-size, $F(4, 24) = 8.41, p < .001$. The form of both of these interactions can be described as a reduction in the effects of presence/absence in the former and increasing numbers of distractors in the latter in going from **NCC** to **NLS** to **LS**. There was also an interaction of target status with set-size $F(2, 12) = 47.48, p < .001$. Finally, the three-way interaction of coding, target status, and set-size was also significant, $F(4, 24) = 3.57, p < .021$. This interaction is illustrated in Fig. 5. From this plot, it is apparent that for both target-absent and target-present trials, the greatest benefit is conveyed by **LS** coding, followed by **NLS** coding with **NCC** resulting in the slowest search times.

Error rates were generally low (3%–5% on average). Nothing in the error rates suggest modification of the interpretation of the RT results. Of note is that the overall error rate was lowest in the **LS** condition (3.1%) and higher in the **NLS** and **NCC** conditions (4.3% and 3.9%, respectively, $F(2, 12) = 4.87$, $p < .030$). Error rates are plotted in the lower panel of Fig. 5.

There are several critical comparisons that address the focus of this experiment. It is noteworthy that the redundant colour coding (irrespective of linear separability) had a dramatic impact on performance. Inspection of Fig. 5 reveals that for target-present trials, there was about 90 ms advantage for **LS** coding and about 40 ms advantage for **NLS** coding over **NCC**. The slopes of these three functions are quite similar suggesting no search rate advantage (in terms of increasing time cost per item). However, recall that these target shapes were redundantly colour coded and therefore relatively easy to detect. In fact, for target-present trials, there is little increase in RT as a function of set-size even in the **NCC** condition supporting the claim that detection of a shape target was quite easy. The picture is quite different for target-absent trials. For the smallest set-size, **LS** search times were 140 ms faster and **NLS** search times were 96 ms faster when compared to **NCC** search times. Furthermore, the estimated search rate (from linear fits) is 18 ms per item for **LS** coding, 23 ms per item for **NLS** coding, and 27 ms per item for **NCC** and this difference in slopes is significant, $F(1, 6) = 26.47$, $p < .002$. In terms of search performance for the largest set-size, this results in a savings of about 0.22 s per search by going from **NCC** to **LS** coding.

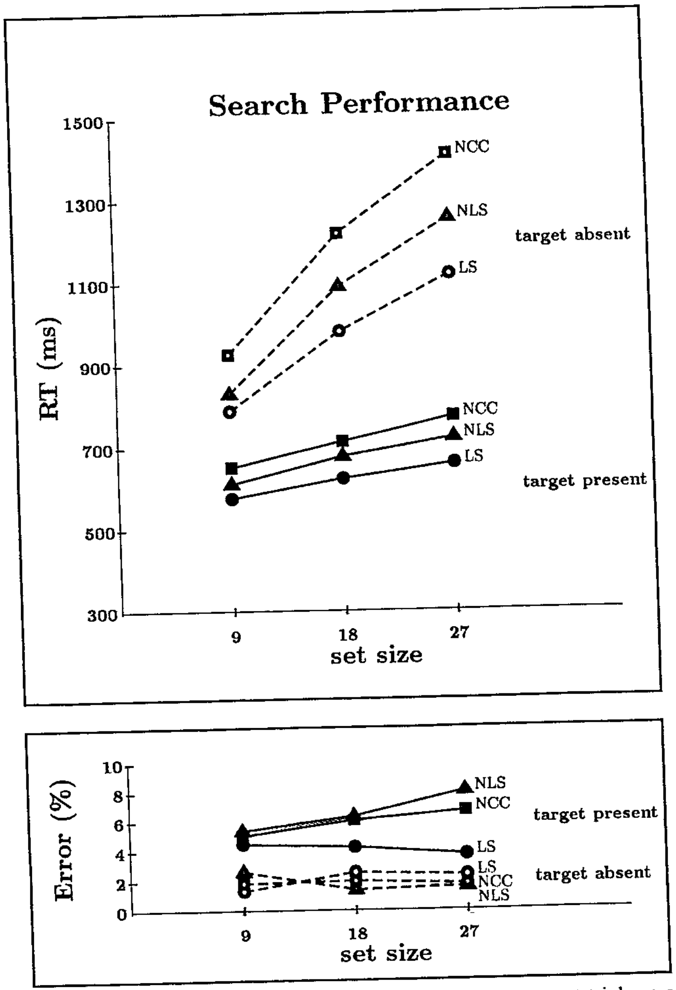

Fig. 5. Group performance for target-absent and target-present trials as a function of set-size and linear separability. Reaction time (RT) is plotted in the upper panel, error rate in lower the panel.

## 4. Discussion

For a given display, linearly separable colour coding can result in faster detection of a target, or a faster decision of its absence. While it is difficult to extrapolate from the present conditions, it seems likely that the effects of linear separability would become more pronounced under more challenging conditions (e.g. larger set-sizes, less discriminable symbology, or divided attention tasks such as those in air traffic control) perhaps even for target-present trials which under the experimental conditions here yielded only modest performance gains. Walrath and Backs [18] found that search performance with colour coded symbology was relatively unaffected by time-stress which was manipulated using a deadline procedure whereas monochrome displays showed a large effect of time-stress. This was true for both locating and counting tasks and demonstrates that under difficult situations, the relative benefit of effective colour coding is amplified. In a similar fashion, we note that in the present data there were significant search time differences as a function of which shape was the target. Overall, the square and triangle were the least readily detected as a target, and the benefit of **LS** coding was the greatest for these two shapes.

The use of **LS** coding gave rise to the best performance as evident in Fig. 5. However, **LS** coding did not eliminate the effect of increasing set-size, especially for target-absent trials; there is a pronounced slope even in the **LS** target-absent condition. This is not necessarily surprising considering the findings of Bauer et al. [2]. They found that when the two distractor colours were relatively close together (the distractors nearest to the target in the present colour sets were about 30 $\Delta E^*_{uv}$ units apart) and the target colour was less than 30 $\Delta E^*_{uv}$ units from the line joining the distractors (the target in the present colour sets was about 24 $\Delta E^*_{uv}$ units from the line joining the nearest distractors), some residual search slope (approximately 10 ms per item on target-present trials, and 25 ms per item on target absent trials) remained even for highly practised observers (see Bauer et al. [2], Fig. 12). This re-emphasizes the point that pairwise discriminability of colours is not sufficient to predict performance in multi-coloured displays.

One issue that has not been addressed here, is the relationship between linear separability and heterogeneity of displays. Consider a configuration of colours in which the **NLS** target falls between two distractor colours (see Fig. 2 left). Both D'Zmura [1] and Bauer et al. [2] demonstrated that this type of configuration can result in very difficult search compared with a configuration where the target is **LS** from the distractors (see Fig. 1 left). Note also, that in going from the **NLS** to the **LS** configuration, both target–distractor and distractor–distractor differences have changed. The model of visual search proposed by Duncan and Humphreys [25] states that search performance is a function of these two differences: performance improves with increasing target–distractor differences and decreasing distractor–distractor differences. It is easy to imagine why the former is true but the reason for the latter may not be immediately obvious. When distractors are highly similar or uniform, Duncan and Humphreys [25] assume that search performance improves because the distractors can be grouped and rejected as a group rather than individually. D'Zmura [1] argued against this counter-explanation of his results, and Bauer et al. [1] demonstrated that a relatively small change in distractor–distractor difference, paired with a change from a **LS** to a **NLS** configuration, had a dramatic effect on search performance. However, distractor–distractor difference explanation was still consistent with this performance change. Bauer et al. [26] provided a demonstration of the effects of linear separability with distractor heterogeneity held constant and thus we have more confidence that the results in the present experiment are primarily driven by linear separability despite the confounding of target–distractor and distractor–distractor differences with linear separability in our colour configurations.

Whether one wishes to subscribe to the linear separability claim, or to the claims of Duncan and Humphreys [25] does not matter with respect to the performance benefits obtained from **LS** coding versus **NLS** coding or **NCC**. In either case, the present findings point to a shortcoming in many current algorithmic colour selection routines. Just because a set of colours has been chosen according to a criterion of maximized minimum colour difference, does not mean that all colours selected will perform equivalently as targets and distractors. This much is clear from the present results.

A few comments regarding linear separability, colour choice, and coding are in order. First, if there is an adequate number of highly discriminable colours available for coding, then issues of linear separability are not crucial because the effect of **NLS** diminishes as colours become more distant (see, Ref. [2] for an investigation of the boundary conditions of linear separability). For example, a saturated yellow target will be easy to detect in a display of saturated green and red distractors, despite the fact that such a target may be **NLS** from the distractors. However, if all three colours are highly desaturated due to high ambient illumination flooding the display, the same target may become difficult to detect whereas a **LS** target would be far easier to detect. The restriction of monitor gamut and contrast as a function of ambient illumination is well documented [10] (see also Ref. [8]). Note that high ambient illumination may have an effect in addition to desaturation. Under zero ambient illumination, typical CRTs can produce maximum luminances of about 100 cd/m$^2$ with the widest hue gamut at lower luminance levels. Display item luminance differences of about 10–20 cd/m$^2$ or about 20% under zero ambient would be reduced to 1–2% under daylight ambient conditions of tens of thousands of lux or thousands of cd m$^{-2}$ reflected back from the face of the CRT (see Ref. [10]). This is nearly equiluminance and would render such luminance coding ineffective. Note that in the present experiment, the search items and background were equiluminant. The conclusion to be drawn from the present data is to avoid colours that are **NLS** in the equiluminant plane as measured under viewing conditions. Furthermore, the extension of linear separability to the third dimension of colour space, viz., luminance, is an issue that will require additional research. Would a target colour with chromaticity coordinates inside a solid defined by distractor chromaticities **NLS** produce more effortful search than a target colour outside that solid?

Second, in the present experiment two colour sets were used. The effects of **LS** have been demonstrated in many colour space loci [1,2] so we expect that the pattern of results found here will generalize to most or all of colour space. Despite the ubiquitousness of the effects of **LS** it is important to remember that there are significant cognitive/semantic associations to some colours such as the association between red and 'stop/danger' or blue and 'cold'. The person charged with colour selection must not ignore these issues. There is yet another issue. For the primary analyses in the present experiment, data were collapsed over colour-set. Colour set 1 contained colours that might be described as 'pale orangish', 'peach', etc., and set 2 contained colours from the cyan or bluish-green region of colour space. An analysis including this factor, revealed that on average, responses to set 1 were approximately 80 ms faster that responses to set 2. This finding could have two potential causes. First, it is known that CIE UCS is neither isotropic nor uniform in a perceptual sense (see, Ref. [27]) so performance differences across these two colour sets could be a function of this variability. Second, it is also known that response latencies to stimuli predominantly subserved by the short-wavelength sensitive systems (blue in appearance) are longer than for those subserved by the medium- and long-wavelength sensitive systems [28]. The colours in set 2 of the present experiment were desaturated, so the contribution of this 'temporal tritanopia' is uncertain.

Finally, the present and previous results were obtained in displays containing either zero or one instance of the target colour. Whether the issue of linear separability is applicable for multiple instances of a target colour for purposes of display filtering (only search a specific coloured subset of display items for a target) or grouping (monitoring all of a given coloured items), has not been explored and merits investigation. In some applications, the task is based on a subject's ability to count members of a certain class of display item [29] while temporarily rejecting non-members. The benefits of **LS** coding under this type task are not known at this time. However, for tasks requiring quick responses to the presence or especially absence of a target colour/shape item, **LS** colour coding has demonstrated benefits.

## Acknowledgements

The authors thank Dr. Joe Baranski and David Beevis for comments on an earlier draft of this manuscript.

## Appendix A CIE 1976 UCS and CIE 1931 $(x, y)$ chromaticities of the colours used

| Set-colour | $u'$ | $v'$ | $x$ | $y$ |
|---|---|---|---|---|
| Set 1 | | | | |
| 1-1 | 0.277 | 0.519 | 0.465 | 0.388 |
| 1-2 | 0.258 | 0.508 | 0.428 | 0.375 |
| 1-3 | 0.238 | 0.496 | 0.390 | 0.361 |
| 1-4 | 0.277 | 0.496 | 0.435 | 0.347 |
| 1-5 | 0.277 | 0.473 | 0.409 | 0.311 |
| 1-6 | 0.258 | 0.485 | 0.401 | 0.335 |
| Set 2 | | | | |
| 2-1 | 0.177 | 0.469 | 0.287 | 0.338 |
| 2-2 | 0.158 | 0.458 | 0.253 | 0.326 |
| 2-3 | 0.138 | 0.446 | 0.218 | 0.313 |
| 2-4 | 0.177 | 0.446 | 0.269 | 0.301 |
| 2-5 | 0.177 | 0.423 | 0.253 | 0.269 |
| 2-6 | 0.158 | 0.435 | 0.238 | 0.291 |
| Background | 0.218 | 0.466 | 0.335 | 0.318 |

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