Running head: CATEGORICAL EFFECTS IN COLOUR SEARCH

Categorical effects in visual search for colour

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Abstract

The role of categorisation in visual search was studied in 3 colour search experiments where the target was or was not linearly separable from the distractors. The linear separability effect refers to the difficulty of searching for a target that falls between the distractors in CIE colour space (Bauer, Jolicoeur, & Cowan, 1996a). Observers performed nonlinearly separable searches where the target fell between the two types of distractors in CIE colour space. When the target and distractors fell within the same category, search was difficult. When they fell within three distinct categories, response times and search slopes were significantly reduced. The results suggest that categorical information, when available, facilitates search, reducing the linear separability effect.

Categorical effects in visual search for colour

A well documented phenomenon imposing constraints on visual search is the linear separability effect (Bauer, Jolicoeur, & Cowan, 1996a; D'Zmura, 1991). In visual search for a target among a display of heterogeneous distractors, search is 'easy' or 'efficient'—as demonstrated by flat search slopes— if it is possible to draw a single line in stimulus space that separates the target from the distractors (linearly separable). Conversely, search is 'difficult' or inefficient', resulting in steeper search slopes, if the target falls inside the area defined by the distractors in stimulus space (linearly nonseparable). The effect has been demonstrated in CIE colour space (Bauer et al., 1996a, 1996b, 1998; D'Zmura, 1991) but also in other feature spaces such as size (Hodsoll & Humphreys, 2001) or shape (Arguin & Saumier, 2000).

Figure 1 shows the simple case where there are two types of distractor. As can be seen, when the target T falls between the two distractors D1 and D2, it is not linearly separable from the distractors as no single line can be drawn that separates T from both D1 and D2. When however the target is offset from the D1-D2 line, or when it is still co-linear with the distractors but does not fall between them, it is possible to separate the target from the distractor space with a single line. D'Zmura (1991) suggested the operation of a linear discrimination mechanism which is available only if the search items are linearly separable. For nonlinearly separable searches, a single discrimination mechanism is not adequate and serial inspection of the items on the display is necessary.

Insert Figure 1 about here

As mentioned above, Bauer et al. (1996a) demonstrated the linear separability effect in CIE colour space. In a series of visual searches using a wide range of colour stimuli varying in hue, saturation and/or lightness, they showed that search for targets linearly separable from the distractors is easy, producing essentially flat slopes, while search for nonlinearly separable colours is difficult, producing steeper slopes. They also showed that the linear separability effect wanes as the target-distractor distance increases to more than 30 CIELUV (ΔE) units, and is eventually abolished. For large colour differences, therefore, the linear separability effect no longer holds and search becomes effortless.

The findings of Bauer et al. suggest a quite clear dichotomy between ‘serial’ and ‘parallel’ search: a linearly separable target pops out, while a nonseparable target does not. In the former case it can be assumed that search is stimulus-driven and mediated by bottom-up processing. In nonseparable searches, however, the task becomes much more demanding, since low-level discrimination between target and distractors is no longer adequate. One question that arises is whether, in this case, observers could make use of top-down processing to guide search. In other words, if observers had access to specific knowledge about the target, would use of this knowledge facilitate search performance? In the present study we addressed the possibility that categorical knowledge of the search stimuli may improve performance even if the target and distractors are not linearly separable.

To address this, we needed to manipulate not only the spatial arrangement of the target and distractors in colour space (linearly separable versus linearly non-separable) but also their categorical status. Consider, for example, the case when the target falls between the two distractors (Figure 1). If the observer categorises the target as ‘purple’ and the two distractors as ‘blue’ and ‘pink’, then the three stimuli fall in separate colour categories. We suggested that observers could use this categorical distinction could be to guide and facilitate search, even in the case where linear nonseparability makes the search difficult. Conversely, if, for example, all three colours were categorised as 'blue', there would be no categorical information to assist search and nonseparable search would remain difficult.

Bauer et al. (1996a, Experiment 1) used colours that "could be described as desaturated red, orange, and yellow" (p. 1443), as well as colours that were all 'green' or 'blue' (p.1453). Their results showed that nonlinearly separable search was difficult, replicating the findings of D'Zmura (1991). There was no evidence of search being more efficient when the target and distractors fell in separate categories. Thus it could be argued that the categorical status of the stimuli is unlikely to have an effect on search performance. However, Bauer et al. did not have naming data on the colours they used in their study; although they briefly considered the possibility of categorical effects in visual search, they did not address this issue systematically. In the present study, we used colours that clearly fall in separate colour categories, as established by naming consensus, and which are considered good examples of each category. Our aim was to examine whether knowledge of the categorical status of target and distractors can aid search.

A number of studies provide evidence for the operation of top-down mechanisms in visual search. Comparison of blocked and mixed conditions, i.e. when the target is known in advance and when it is not, has shown that pre-knowledge of the target facilitates performance (e.g. Bravo & Nakayama, 1992; Hodsall & Humphreys, 2001). Advance knowledge of the target may be particularly useful under resource-limited conditions (Lavie, 1995; Moore & Egeth, 1998). Laarni (1999, 2001) also showed that visual search benefits most from colour cues when the processing load is high, by prioritising selection of the cued item. Task difficulty, as determined, for example, by display size, low target-distractor discriminability or low target salience, can be controlled by top-down guidance (Laarni, Koski, & Nyman, 1996). As nonseparable searches are demanding tasks, they should also be subject to top-down control.

There is also evidence implicating the use of categorisation in visual search, although it is debatable whether the reported categorical effects can be attributed to physical or conceptual differences between the stimuli (see below). In a series of experiments on visual search for orientation, Wolfe, Friedman-Hill, Stewart, and O'Connell (1992) found that search efficiency increased when the target could be identified as belonging to a different, mutually exclusive category from the distractors. The categorical effect may assist the grouping of the heterogeneous distractors, thus permitting the target to be assigned a unique attribute which facilitated search.

Interestingly, Wolfe et al. (1992, Experiment 2) included an experiment where the target was not linearly separable from the distractors (the target, whose orientation was either 0^{o} or 20^{o}, was flanked between two distractors tilted 20^{o} or 40^{o} away from the target). In line with Bauer et al. (1996a), searches for the nonlinear separable target (for the 20^{o} target) were not efficient, although search became easier when the target-distractor distance increased. However, the linear separability effect appeared to be reduced considerably (leading to almost flat slopes) when the target was 0^{o}. In this case the target could be labelled as 'vertical' among distractors labelled as 'tilted'. Wolfe et al. point out, however, that the categorical effect could be attributed either to top-down selection of the 'vertical' feature or to bottom-up activation of orientation-tuned channels. It remains unclear, therefore, whether categorical effects are related to the early perceptual processes or to activation of higher level conceptual representations.

Indeed, as mentioned above, there is a debate in the literature on categorical effects in visual attention. Early studies on visual search for digits among letters, or the reverse, suggested that it is category membership, rather than perceptual features, that accounts for parallel visual search (Egeth, Jonides, & Wall, 1972). Jonides and Gleitman (1972) also argued for ‘conceptually driven’ visual search: search occurred in parallel even for an ambiguous O, which would be categorised as the letter O or the digit 0 prior to search. However, there have been problems with replicating this result (Duncan, 1983). Krueger (1984) attributed the category effect to physical rather than conceptual differences between target and distractors: when structural differences between the stimuli were eliminated, the category effect was abolished. More recently, Levin, Takarae, Miner, & Keil (2001) re-addressed the role of categorical information in visual search. In a series of searches for animals among artefacts and vice versa, they demonstrated essentially shallow slopes and fast response times for target present trials. They mainly discussed structural factors to account for their results. Basic features such as contour shape and rectilinearity and higher-level factors, like rated visual typicality, affected search efficiency. As a number of factors operating at different levels were involved, it is difficult to draw conclusions about the locus of the categorical effect. However, Levin et al.’s study is interesting as it provides evidence for the involvement of categorisation in a perceptual task.

Current models of visual search and attention may also be consistent with the role of stimulus categorisation in visual search efficiency. Particularly relevant here are the similarity model of Duncan and Humphreys (1989) and the guided search model (Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). According to the similarity model, the visual field is represented as a hierarchy of ‘structural units’ sharing a property such as colour. During visual search, each structural unit is compared to a template of the information being sought i.e. the target. A poor match between the template and a structural unit leads to rejection of other units that are strongly grouped to the rejected unit. When the target is similar to the distractors, more structural units match the template, so search time increases. Similarly, search times increase when the distractors are dissimilar, as it is difficult to group together and reject large numbers of structural units. Thus, when the target is nonlinearly separable from the distractors, processes based on similarity only will be inadequate and search inefficient.

According to the guided search model (Wolfe, 1994; Wolfe et al., 1989), three stages are involved in visual search: (1) During early stages in vision the image is divided into individual feature maps, with one map for each feature (e.g. colour, orientation etc.). Within each map, a feature is filtered into multiple categories (e.g. colour categories). (2) Bottom-up processes compute differences between stimuli. If there is more than one feature map (e.g. conjunction searches) differences for each feature map are combined. (3) Top-down activation guides attention to items with a specific set of properties (e.g. a red square). (4) An activation map is built from bottom-up and top-down elements, where priority is given to stimuli meeting the search criteria of the activation map.

The findings of Hodsoll and Humphreys (2001) in the size dimension are particularly interesting in this respect. Foreknowledge of the target, allowing top-down guidance, was most beneficial when the stimuli were linearly separable, i.e. when the target was either the 'large' or the 'small' square. Nonlinearly separable searches where the target was the middle square benefited considerably less from advance target knowledge. Hodsoll and Humphreys attribute the linear separability effect to the operation of a top-down linear separator mechanism that allocates attentional priority to the target. This mechanism is most successful for linearly separable stimuli because, in this case, target-distractor similarity is low and distractor-distractor similarity is relatively high.

As mentioned above, here we suggest that if the target is categorically distinguishable from the distractors, top-down guidance can also facilitate performance in nonlinearly separable searches. Duncan and Humphreys (1989) would suggest that a nonlinearly separable search is difficult because the similarity between stimuli makes the linear separator mechanism inadequate (see Hodsoll & Humphreys, 2001). The guided search model, on the other hand, would predict that if the target is known in advance and possesses a unique attribute, then this may provide access to a clearly defined template that is used to guide search. This is the case, for example, in some conjunction searches where top-down activation of the target's identity facilitates search (Wolfe et al., 1989). In a nonlinearly separable search where the target is categorically distinct from both distractors, search performance should be a compromise between: (1) discrimination difficulty imposed by low distractor-distractor similarity and high target-distractor similarity and (2) facilitation through use of categorical information.

The experiments reported below addressed the possibility that observers are able to use categorical information to facilitate visual search for nonlinearly separable stimuli. Experiments 1 to 3 compared nonseparable and linearly separable conditions when the stimuli straddled category boundaries and when they did not, while the perceptual distance between the colours was controlled. As in Bauer et al. (1996a), the colours were chosen to be equidistant in CIELUV space. Since this colour system is intended to be perceptually uniform (for a description see, for example, Hunt, 1987), it should be expected that discriminability between colours would be roughly the same in all conditions.

EXPERIMENT 1

Experiment 1 partly replicated the study by Bower et al. (1996a), using the same visual search procedure: search for one previously learned target among two types of distractors. As in Bauer et al., linear separability was manipulated: nonseparable search (expected steep slopes) and separable search (expected flat slopes). However, categorical information about the stimuli was also introduced as a factor, to explore whether this information can be used to facilitate difficult (nonseparable) search. The categories used were drawn from the eleven basic colour categories of English (Berlin & Kay, 1969) and should thus have been familiar and salient to our subjects. When there was a categorical distinction among target and distractors, the target and two types of distractor were in three different categories. Thus there were four conditions in total: linearly separable/within category (same category target and distractors); linearly separable/cross-category (different category target and distractors); nonseparable/within category; and nonseparable/cross category.

Method

Participants

Eight observers took part, 3 male and 5 female (mean age = 28 years). They were students or staff from the University of Surrey and they all had normal or corrected-to-normal vision and normal colour vision as assessed by the City University Colour Vision Test (Fletcher, 1980).

Stimuli

Six colour stimuli were used: three each for the within and cross-category conditions. The within category stimuli were all green (green1, green2 and green3) and the cross-category stimuli were blue, purple, and pink. The CIELUV co-ordinates are shown in the Appendix (Figure 1). Within each category condition, the CIELUV distance between the target and distractor was approximately 20 ΔE (see Table 1 in the Appendix). This distance is near the critical colour difference in visual search (see Nagy & Sanchez, 1990). All stimuli in each set had the same lightness (L = 76.07 for the cross-category set; L = 62.87 for the within category set[1]). Naming reliability was checked beforehand by asking 15 observers who did not participate in the experiment to name the stimuli presented singly on the monitor. In addition, the participants in the experiment named the stimuli at the end of the search task. Minimum naming reliability was 98%.

As can be seen in the Appendix (Figure 1), the three stimuli were co-linear in LUV space for all conditions. In the two nonseparable conditions, the target was always the middle colour. In the two separable conditions, the same stimuli were used, but the target was either of the two lateral colours. Thus, in the within category condition, the target was green2 (nonseparable); either green1 or green3 was the target in the separable condition. In the cross-category condition, purple was the target for the nonseparable search and either blue or pink was the target for the separable condition (see Table 2 in the Appendix).

Stimuli were positioned on a notional 6 × 6 grid in the search display, against a nearly white background ($x = 0.31$, $y = 0.32$, $Y = 35$). Each location had dimensions of $17mm^2$, subtending a visual angle of approximately 1.9^0 at an average viewing distance of 500 mm. There were three set sizes: 4, 16 and 36. For set size 4 or 16, stimulus locations were randomly selected in the grid. For set size 36, stimuli were present in all locations in the grid. For target-absent trials, there was an equal number of each of the two distractor colours. For target-present trials, a target replaced one of the distractor colours. As in Bauer et al. (1996a), the location of targets in the matrix was random, with the exception that targets never appeared in any of the four corners of the grid. The target occurred equally often in the remaining 32 positions within each condition.

<u>Procedure</u>

Each participant performed all four conditions. The order of category condition (within/across) was counterbalanced. Linearly separable and nonseparable conditions were presented alternately. Each condition consisted of a training phase immediately followed by the search task.

Training phase. The first part of the training consisted of showing the target and the two distractors at the same time. Labels indicated the target and the distractors. When the observers thought they could remember the target, they proceeded to the second training stage, a forced-choice identification task in which stimuli were presented one at a time, after the onset of a fixation cross. For each presented stimulus the observers had to decide whether it was the target or a distractor. Decisions were indicated by pressing the mouse-buttons (left, target; right, distractor). Twenty presentations of each of the three stimuli in the condition were given in a random order. If participants made fewer than 20% misidentifications, they proceeded to the search task. If their performance on the training stage was poorer than 80%, training was repeated.

Visual search task. When it was established that the observers had learned the target, they moved on to the search task. In this stage, 192 trials were given, 64 for each display size: 4, 16 or 36 stimuli. For each display size, the target was present in 50% of the trials and absent in the other 50% of the trials. Trials were presented in random order.

Each trial was preceded by a fixation cross that remained on the screen for 250 ms, followed by a 400 ms blank interval before presentation of the search display. The search display remained present until a response was made. Decisions were indicated by pressing the mouse button (left for target present, right for target absent). A 400 ms interval was given between successive trials. The observers were instructed to respond as fast as possible, but not to compromise accuracy.

Results and Discussion

Insert Figure 2 about here

Median response times (RTs) for correct trials were calculated for each participant for each condition. All reported RTs are cross-participant means of the median correct RTs. Figure 2 shows RT as a function of display size for each condition, for target present and target absent, respectively. Search slopes and overall percentage of errors for each condition are shown in Table 1.

Insert Table 1 about here

As can be seen in Figure 2, search for linearly separable stimuli was faster than search for nonseparable stimuli (linear separability effect). This effect was dramatically reduced in the cross-category condition, indicating efficient search even for nonseparable cross-category searches. The slopes and error rates displayed in Table 1 also support this pattern of results. Note, particularly, that the error rate for the within category nonseparable condition (19.08%) is considerably larger than the rate for the cross-category nonseparable condition (2.80%).

Three-way analyses of variance (ANOVA) were carried out separately for target present and target absent trials, with linear separability (separable/nonseparable), category (cross/within) and set size as factors. For target present trials, RTs were faster in the cross-category conditions than the within category conditions, $F(1, 7) = 112.14$, $p < 0.001$. The linearly separable conditions were also faster than the nonseparable conditions: $F(1, 7) = 60.83$, $p < 0.001$. RT also increased with set size: $F(2, 14) = 15.44$, $p < 0.001$. All two-way interactions were also significant. The effect of linear separability was greater for the within category condition than the cross-category condition, $F(1, 7) = 77.20$, $p < 0.001$. The effect of set size was also greater for within category than cross-category searches, F (2, 14) = 12.40, $p < 0.002$, and greater in nonseparable searches than linearly separable searches, F (2, 14) = 12.36, $p < 0.002$. The three-way interaction was also significant, F (2, 14) = 10.24, $p < 0.003$. This resulted from the linear separability effect on search slopes being larger for the within category condition but significantly smaller in the cross-category condition. The above effects were also significant in the analysis of target-absent trials and ANOVA on error rates also showed a similar pattern of results.

As predicted, search was more efficient when for linearly separable stimuli than for nonseparable stimuli. The linear separability effect reported in Bauer et al. (1996a) was therefore replicated. Moreover, an important finding in Experiment 1 was the effect of categorical separation on search performance. This was evident as faster search in both the nonseparable and separable conditions. Search slopes also indicated very efficient search when the target and distractors fell in distinct categories, even if they were nonlinearly separable. Indeed, the search slopes in this condition, being smaller than 10 msec/item, suggest perceptual pop-out of the nonlinearly separable target. It could therefore be argued that, when the target is categorically distinguishable from the distractors, it can be used more efficiently as a template in guided search: searching for the purple item among non-purple distractors is evidently easier than searching for the ‘middle green’ item among green distractors. Moreover, it seems that possessing clearly defined categories for the target and distractors is important for the category advantage in search. As discussed earlier, Bauer et al. (1996a) examined search performance using an orange target among yellow and red distractors, reporting difficult search when the stimuli were nonseparable. If the results of the present experiment can be attributed to categorical effects, it seems that agreement on stimulus naming is necessary, and that the search stimuli must be good examples of a colour category. It is therefore possible that Bauer et al. did not observe a category effect because their stimuli were unlikely to be good examples of red, orange and yellow: as the stimuli were desaturated and equiluminant, it was unlikely that they would be good members of colour categories that are mainly distinguished by changes in saturation and lightness (see, for example, the Munsell system; Indow, 1988).

The level at which the categorical advantage operates is not clear. It seems unlikely that the categorically distinct target is easier to detect because it contains some salient basic feature information, as, in perceptual space, it is the ‘middle’ stimulus. Some categorical representation of the categorically distinct target must therefore be available. Conceptual representations of colour categories, available for ‘purple’ but not for ‘middle green’, could drive the search process by directing attention to the relevant stimulus. It is also unclear how search facilitation operates: does using the categorical template facilitate search by enhancing perception of the target, or simply by prioritizing its selection? These issues will be discussed in more detail in the General Discussion.

However, there is also the possibility that the findings are peculiar to the particular stimuli used, rather than being due to their category membership. The within- and cross-category stimuli differed in luminance, and were drawn from different areas of colour space. It is therefore possible that cross-category search was easier because of easier discrimination of the cross-category colours, and not because of their categorical status itself. In Experiment 2 we examined the same effects using equiluminant stimuli from the green-blue region of colour space.

EXPERIMENT 2

Experiment 2 was a replication of Experiment 1 in a different region of colour space. To check that differences in search performance between category-conditions were not due to incidental differences between the stimulus sets, the differences were reduced by using stimuli of the same luminance. The within category set were all blue, and the between-category set were green, blue and purple. The target in both nonseparable conditions was blue.

Method.

Participants.

Twelve observers, (6 men and 6 women; mean age 26 years) drawn from the same population as in Experiment 1, took part in the experiment.

Stimuli and procedure.

Six colour stimuli were used, three each for the within (blue) and cross-category (green-blue-purple) conditions respectively. Chromaticity coordinates (CIELUV) are shown in the Appendix (Figure 1). Both sets of stimuli (cross-category and within category) had the same lightness (L = 68.75). Target-distractor distance was approximately 20 ΔE (see Table 1 in Appendix). Assessment of naming consensus and the general procedure were the same as in Experiment 1.

Results and Discussion

Insert Figure 3 about here

Data treatment was as in Experiment 1. Figure 3 shows mean RT as a function of display size for each condition, for target present and target absent, respectively. Search slopes and overall percentage error for each condition are shown in Table 2.

Insert Table 2 about here

As can be seen from Figure 3, the main findings from Experiment 1 were replicated. The linear separability effect was considerably smaller in the cross-category condition than the within category condition. The error rate for the within category condition (5.73%) was considerably less than in Experiment 1 (19.08%), but still more than four times the cross-category rate (1.30%). Although the search slopes in the nonseparable cross-category condition (23.74 ms/item) are not consistent with pop-out, it was nevertheless less than half of the equivalent within category condition (54.85 ms/item).

This pattern of findings was supported by three-way ANOVAS (category × linear separability × display size) carried out separately for target present and target absent trials. For target present trials the linear separability effect was evident as slower RTs, $F(1, 11) = 60.02$, $p < 0.001$) and steeper slopes, $F(2, 22) = 30.64$, $p < 0.001$) for the nonseparable conditions compared to the linearly separable conditions. The categorical effect was also manifest as faster RT, $F(1, 11) = 53.11$, $p < 0.001$) and reduced slopes, $F(2, 22) = 12.61$, $p < 0.001$) for the cross-category conditions. The interaction between category condition and linear separability was also significant, $F(1, 11) = 27.05$, $p < 0.001$), as was the three-way interaction between linear separability, category and display size, $F(2, 11) = 5.38$, $p < 0.02$, indicating that the magnitude of the linear separability effect differed between category conditions: in cross-category searches, linear separability affected RTs and slopes considerably less than in within category searches. The same patterns were found for target absent trials.

Experiment 2 replicated the findings of the first experiment in a different area of colour space. The differences in results between conditions cannot be attributed to differences in luminance between the stimulus sets, as this was constant across all stimuli. However, there were differences in saturation that could possibly affect the results. In both experiments, the cross-category sets had lower average saturation than the within category sets. More importantly, perhaps, for the cross-category sets, the middle stimulus was the least saturated of the three, whereas this was not so for the within category stimuli. Considering the saturation dimension alone, the middle stimulus was not linearly separable from the outside stimuli for the within category set, whereas it was approximately so for the between-category set. It could therefore be argued that the categorical advantage was due to differences in separability in the saturation dimension, rather than the categorical difference itself. The target would stand out as the most 'washed-out'stimulus. Although it is difficult to attend to saturation when hue varies (the dimensions are integral; see Burns & Shepp, 1988), Experiment 3 controlled for saturation differences. Stimuli were chosen so that within-set variation among target and distractors was approximately the same for the two sets.

EXPERIMENT 3

Stimuli were chosen to limit the difference between the within- and cross-category sets to the categorical difference, as far as possible. Within category stimuli were purple (purple1, purple2 and purple3) and between-category stimuli were blue, purple, and pink. In both category conditions (cross- and within- category) the stimuli were: at the same luminance; the target-distractor distances were approximately the same; the target was nonseparable in saturation from the distractors; and the target was the same (distractors differed).

Method

Participants.

Eight observers (3 men and 5 women; mean age 25 years) from the same population as the earlier experiments, took part. They all had normal or corrected-to-normal vision and normal colour vision.

Stimuli and procedure.

Figure 1 in the Appendix shows the CIELUV coordinates of the six stimuli. Target-distractor distance was around 20 ΔE (see Table 1 in the Appendix). The procedures for naming-consensus and the main experiment were the same as in the previous experiments.

Results and Discussion

Insert Figure 4 about here

Data treatment was as in Experiment 1. Figure 4 shows mean RT as a function of display size for each condition, for target present and target absent, respectively, and Table 3 shows mean slopes and error rates for each condition.

Insert Table 3 about here

As can be seen, the findings of the previous experiments were replicated. These patterns of findings were again supported by ANOVA (category × linear separability × display size), which is reported here for target present trials. There was a significant overall effect of linear separability on search times, F (1, 7) = 35.86, $p < 0.002$) and a significant effect of category condition, F (1, 7) = 38.46, $p < 0.001$. Again, therefore, the nonseparable searches were slower than the linearly separable searches and cross- category search was faster than within- category search. Search times increased with display size, F (2, 14) = 70.05, $p < 0.001$. All two-way interactions were, again, significant. The linear separability effect was attenuated in the cross-category condition compared to the within- category condition. This was supported by a significant interaction between category and linear separability, F (1, 7) = 15.18, $p < 0.007$, showing that search times were reduced in the cross- category nonseparable searches. Search slopes also depended on category condition, F (2, 14) = 8.58, $p < 0.005$, for interaction between display size and category condition) and linear separability condition, F (2, 14) = 32.56, $p <$

0.001 for interaction between linear separability and display size. Finally, the 3-way interaction between display size, category condition and linear separability was significant, F (2, 14) = 4.42, $p < 0.04$, but for target-present trials only. Besides this difference between target-present and target-absent trials, Experiment 3 showed the same pattern observed in the previous experiments. Moreover, the effects cannot be attributed to differences in luminance between the stimuli in the two category conditions; neither could within-set variation account for the results.

General Discussion

Experiments 1 to 3 suggest that there is an advantage in visual search when the search stimuli straddle category boundaries. Even when search was difficult (nonlinearly separable target and distractors) the cross- category condition seemed to facilitate search: times and search slopes sometimes approached values consistent with pop-out (Experiment 1). The findings are robust. They were essentially the same in the three experiments, despite variations in the region of colour space and potential confounds in discriminability due to within-set stimulus variation. In Experiment 1, the search stimuli varied in full three dimensional colour space (hue, saturation and lightness); in Experiments 2 and 3 they varied in just two dimensions (hue and saturation); and in Experiment 3, they were nonseparable in hue and saturation independently, and the target was the same in the two stimulus sets.

The linear separability effect reported in Bauer et al. (1996a) and D'Zmura (1991) was therefore replicated. Further, including conditions that manipulated the categorical membership of the search stimuli while controlling for CIE target- distractor distance, allowed us to address the role of categorical information in visual search. The findings suggested that when the target and distractors cross category boundaries, the linear separability effect is considerably reduced.

The cross-category condition offered an advantage in visual search, dramatically facilitating an otherwise difficult task (nonseparable condition).

One further potential confound, however, brought to our attention by one of the reviewers, refers to the observation that CIELUV space is not perfectly uniform, after all. While equating the CIELUV distances between colours should, in theory, control for differences in discriminability, there still are violations of perceptual uniformity. For example, MacAdam ellipses (MacAdam, 1942) suggest discriminability differences between different regions of colour space which not appear to be corrected after transformation into LUV. It is possible, therefore, that the 'category effect' observed in our experiments is the result of lower just-noticeable differences (jnds) in the cross-category sets and higher jnds in the within category sets.

We addressed this problem by looking at jnd data in the regions of colour space where we observed our effects (Wright, 1941; in Hunt, 1987). We chose these data because they provided a larger number of jnds than MacAdam ellipses do, and thus allowed us to find jnds closer to our stimuli. Figure 2 in the Appendix shows the jnds reported in Wright (1941), transformed into LUV, in each region examined in our experiments. As can be seen, there is no systematic relationship between discriminability differences and category status of the stimuli. For example, the jnds observed closest to the within category stimuli in Experiment 2 are lower than the jnds observed around the cross-category stimuli; and yet, we found that cross-category search was more efficient than within category search. Thus, even if LUV space did not ensure perfect control of jnd differences between the stimulus sets, it seems that our pattern of results cannot be attributed to, or confounded by, these differences.

In short, the experiments reported above suggest that it is not only the perceptual relations between search stimuli that affect search performance; category membership also plays a role. What is less clear is the level at which this categorical advantage occurs, and the mechanisms underlying categorical effects. Inspection of the search times and slopes in the cross-category conditions, especially in Experiment 1, suggest pop-out, not only in the linearly non-separable condition, but also in separable conditions. If pop-out takes place, then it can be claimed that the advantage in cross-category search is due to the perceptual distance between the colour categories being larger than the distances within the same category, even if the distances in CIE space were equal in both stimuli sets. Having tested and controlled for the possibility that this stretching of distances is owing to lower jnds in the region occupied by the cross-category stimuli, it can be suggested that the effects reported here are related to colour categorisation. Indeed, this warping of perceptual space around the category boundaries would be consistent with categorical perception (see Harnad, 1987). Such an explanation would mean, in turn, that target detection in the cross-category conditions is driven by the physical characteristics of the stimulus itself (bottom-up process).

On the other hand, it could also be argued that the categorical advantage evident here is driven by top-down processes which guide attention to the target, thus facilitating target-distractor discrimination (Duncan & Humphreys, 1989). In line with this, it seems possible that the categorical advantage is due to a category code which facilitates search in parallel with the physical code (see Bornstein & Korda, 1984). A categorical code would assist search by acting as a template that prioritises search for the target. With within category, non-separable stimuli, search is difficult because there is no mechanism that can set a linear boundary between target and distractors. When the within category stimuli are linearly separable, however, such a mechanism becomes available, facilitating search (D'Zmura, 1991), but only if the target is known in advance. If the target is unknown, no template can be used to guide search (Hodsall & Humphreys, 2001). Here it is suggested that, in cross-category search, top-down guidance is even more facilitated as search is driven by a physical, as well as a categorical, code. The findings suggest that the additional coding is adequate to overcome the perceptual load imposed by linear non-separability of target and distractors. The additional coding also seems to facilitate already effortless search, namely the cross-category separable condition, resulting in faster search times. This is also supported by recent findings suggesting categorical facilitation in visual search with one type of target and distractor, and where other differences between the category conditions were controlled (Davies, Daoutis, Pilling, & Wiggett, 2003).

As already mentioned, the nature of the categorical code is not clear. The fact that visual search is affected by categorical membership of the stimuli suggests that category codes are present early in visual processing. The fast search times also suggest that it is unlikely that the categorical codes are verbal. Direct labelling accounts of the categorical advantage seem plausible in tasks where naming of the stimuli is required or necessary, such as recognition memory tasks (e.g. see Roberson & Davidoff, 2000). In visual search, however, where categorical coding is available early, stimulus naming must have an indirect role, if any, in activating the colour representations relevant to the task.

Indeed, colour representations can operate at a higher level. They may be semantic, referring to the meaning of colour terms and its associations with other meanings; or conceptual, referring to multimodal, non-linguistic representations based on experiential knowledge of the colours (see Pavlenko, 2000, for a distinction between levels of representation of a concept). Multiple codes can be available simultaneously, and dependent upon the nature of the task

(Posner, 1978). It is therefore not necessary to assume that performance in the cross-category condition is mediated by colour naming: there is not always a direct correspondence between stimulus labelling and performance (Malt, Sloman, Gennari, Shi, & Wang, 1999).

Finally, the argument for the top-down use of categorical structures in visual search could be strengthened if conditions where the target is known in advance were compared to conditions where the target is not known (see, for example, Hodsoll & Humphreys, 2001, in the size dimension). If the categorical effect were not present in conditions where the target is not known in advance, this would lend support to a guided search account. If, on the other hand, a categorically distinct target captured attention even when not known in advance, this would suggest that the category identity of the target somehow altered its physical appearance, resulting in its easier detection.

The experiments presented above suggest the role of category information in perceptual tasks. To further clarify the origin of the effect, however, we need to address more questions about the way visual search works, and the way categories are used in a variety of tasks. Manipulating advance knowledge of the stimuli, interference tasks and cueing experiments, should allow us to assess the contribution of top-down and perceptual factors in search performance. Finally, further exploring the relationship between colour naming and performance in tasks where colour category information is not explicitly used, should help to elucidate the role of categorisation in perception tasks.

Footnotes

1. Although the CIELUV distances between adjacent colours were the same in the within and cross-category sets, the two sets did not have the same luminance in Experiment 1, possibly confounding the results. Subsequent experiments controlled for this.

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Table 1

Mean slopes (msec/item) and overall % errors for each of the search conditions in Experiment 1 (cross-category: linearly separable and nonlinearly separable; within category: linearly separable and nonlinearly separable). Standard deviations in brackets.

Condition		Slope (msec/item) Target present	Target absent	Errors %
Cross-category	Non-separable	5.02	7.42	2.80
		(3.26)	(10.98)	(2.16)
	Separable	0.46	0.50	1.04
		(0.82)	(0.99)	(0.92)
Within category	Non-separable	33.55	64.86	19.08
		(25.37)	(41.80)	(9.78)
	Separable	3.37	10.18	3.71
		(1.92)	(9.82)	(1.90)

Table 2

Mean slopes (msec/item) and overall % errors for each of the search conditions in Experiment 2 (cross-category: linearly separable and nonlinearly separable; within category: linearly separable and nonlinearly separable). Standard deviations in brackets.

Condition		Slope (msec/item) Target present	Slope (msec/item) Target absent	Errors %
Cross-category	Non-separable	9.76	23.74	1.30
		(4.30)	(22.91)	(1.56)
	Separable	0.92	2.02	0.94
		(0.82)	(0.93)	(0.94)
Within category	Non-separable	24.04	54.85	5.73
		(16.16)	(30.28)	(3.52)
	Separable	4.54	15.50	2.24
		(3.89)	(19.64)	(1.45)

Table 3

Mean slopes (msec/item) and overall % errors for each of the search conditions in Experiment 3 (cross-category: linearly separable and nonlinearly separable; within category: linearly separable and nonlinearly separable). Standard deviations in brackets.

Condition		Slope (msec/item) Target present	Slope (msec/item) Target absent	Errors %
Cross-category	Non-separable	6.92	26.87	2.93
		(8.01)	(24.10)	(1.99)
	Separable	1.85	4.01	1.24
		(0.88)	(1.93)	(0.92)
Within category	Non-separable	16.96	29.46	4.88
		(3.82)	(24.31)	(3.19)
	Separable	2.93	4.51	2.28
		(1.17)	(3.07)	(1.34)

Appendix

Table 1 (Appendix)

Perceptual distances (ΔE) between stimuli in each category condition in Experiments 1, 2 and 3. The ΔE distance is the Euclidean LUV distance between adjacent pairs of colours. Colour notations: Pu = purple, B = Blue, Pi = Pink, Gr = Green.

	Experiment 1	Experiment 2	Experiment 3
Cross-category	B-Pu = 21.78	Gr-B = 22.16	B-Pu = 21.49
	Pu-Pi = 19.80	B-Pu = 21.69	Pu-Pi = 22.99
Within category	Gr1-Gr2 = 20.43	B1-B2 = 22.86	Pu1-Pu2 = 21.25
	Gr2-Gr3 = 20.43	B2-B3 = 22.72	Pu2-P3 = 20.46

Table 2 (Appendix)

Design used in Experiments 1, 2, and 3. There were four conditions: cross-category, non-separable and separable stimuli; and within category, non-separable and separable stimuli. One cross-category and one within category set were used. In non-separable conditions, the target was the middle of the three co-linear colours; in the separable conditions, the target was either of the two lateral colours. Colour notations: Pu = Purple, B = Blue, Pi = Pink, Gr = Green.

		Experiment 1	Experiment 2	Experiment 3
Cross-category	Non-separable	T = 1Pu	T = 2B	T = 3Pu
		D1 = 1B	D1 = 2Gr	D1 = 3B
		D2 = 1Pi	D2 = 2Pu	D2 = 3Pi
	Separable	T = 1B or 1Pi	T = 2Gr or 2Pu	T= 3B or 3Pi
		D1 = 1Pu	D1 = 2B	D1 = 3Pu
		D2 = 1Pi or 1B	D2 = 2Pu or 2Gr	D2 = 3Pi or 3B
Within category	Non-separable	T = 1Gr2	T = 2B2	T = 3Pu2
		D1 = 1Gr1	D1 = 2B1	D1 = 3Pu1
		D2 = 1Gr3	D2 = 2B3	D2 = 3Pu3
	Separable	T = 1Gr1 or 1Gr3	T = 2B1 or 2B3	T = 3Pu1 or 3Pu3
		D1 = 1Gr2	D1 = 2B2	D1 = 3Pu2
		D2 = 1Gr3 or 1Gr1	D2 = 2B3 or 2B1	D2 = 3Pu3 or 3Pu1

Figure Captions

Figure 1.

Examples of linearly separable and non-separable stimuli in colour space. The target and two distractors fall on the same line. The target pops out in search if it can be separated from both distractors by a single line (top; linearly separable). When the target falls between the two distractors (bottom, non-separable), search is difficult.

Figure 2.

Experiment 1. Search time (in msec) by display size (4, 16, or 36 colours) in the following conditions: (a) cross-category, non-separable; (b) cross-category, separable; (c) within category, non-separable and (d) within category, separable. Target present trials (top) and target absent trials (bottom).

Figure 3.

Experiment 2. Search time (in msec) by display size (4, 16, or 36 colours) in the following conditions: (a) cross-category, non-separable; (b) cross-category, separable; (c) within category, non-separable and (d) within category, separable. Target present trials (top) and target absent trials (bottom).

Figure 4.

Experiment 3. Search time (in msec) by display size (4, 16, or 36 colours) in the following conditions: (a) cross-category, non-separable; (b) cross-category, separable; (c) within category, non-separable and (d) within category, separable. Target present trials (top) and target absent trials (bottom).

Figure 1 (Appendix)

Colour coordinates (u'v') used in Experiments 1, 2, and 3. Experiment 1, cross-category: 1B, 1Pu, 1Pi (L = 76.07); Experiment 1, within category: 1Gr1, 1Gr2, 1Gr3 (L = 62.87); Experiment 2, cross-category: 2Gr, 2B, 2Pu (L = 68.75); Experiment 2, within category: 2B1, 2B2, 2B3 (L = 68.75); Experiment 3, cross-category: 3B, 3Pu, 3Pi (L = 67.38); Experiment 3, within category: 3Pu1, 3Pu2, 3Pu3 (L = 67.38).

Figure 2 (Appendix)

Nearest observed jnds (Wright, 1941; from Hunt, 1987) to the stimuli used in Experiments 1, 2, and 3, plotted in LUV colour space. Note that the jnds nearer the colours used in Experiment 1 should be compared with caution, as the two sets of stimuli in Experiment 1 were not equiluminous.

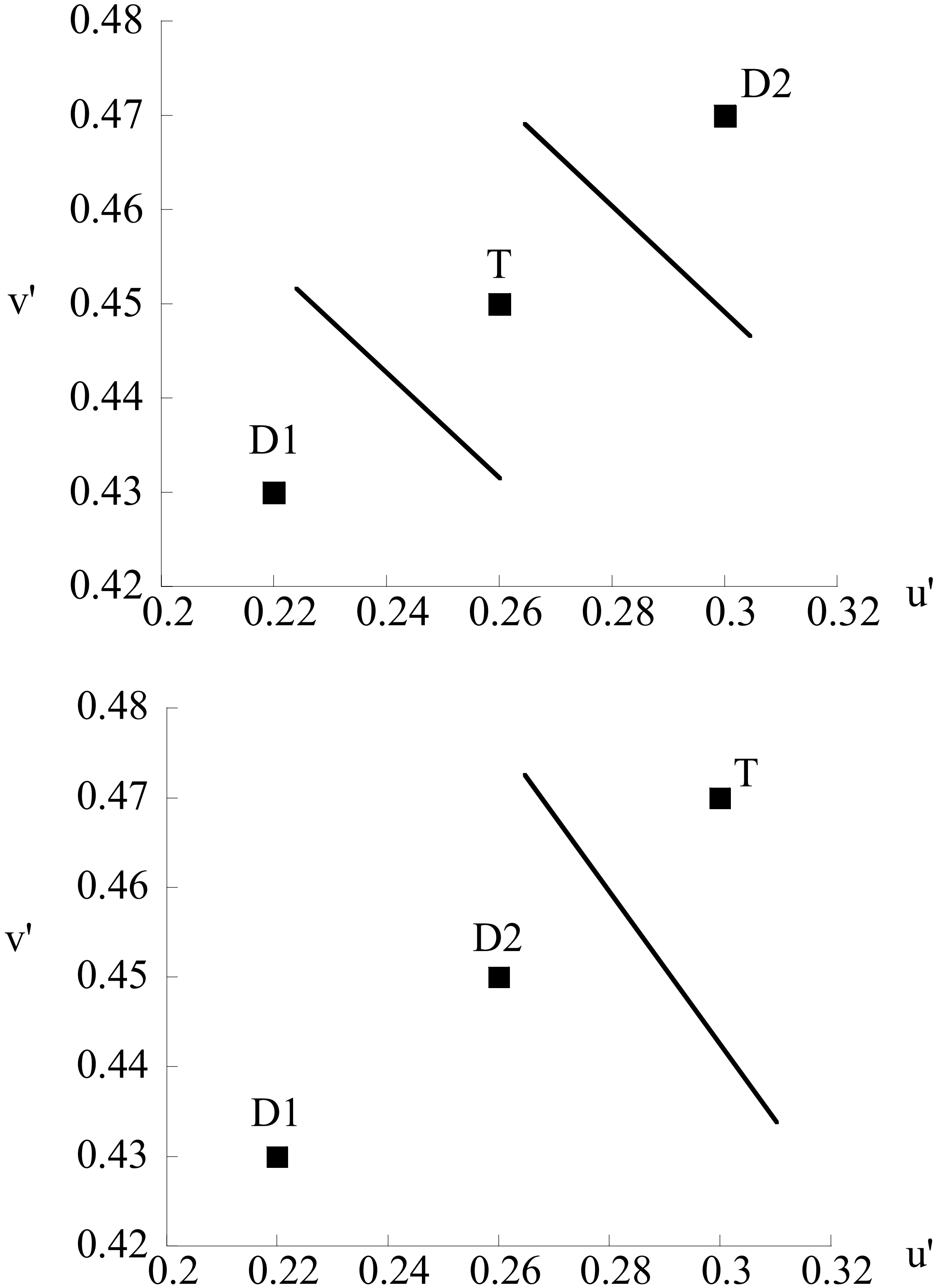

0.48
0.47
0.46
0.45
0.44
0.43
0.42
v'
D2
T
D1
0.2
0.22
0.24
0.26
0.28
0.3
0.32
u'
0.48
0.47
0.46
0.45
0.44
0.43
0.42
v'
T
D2
D1
0.2
0.22
0.24
0.26
0.28
0.3
0.32
u'

Figure 1

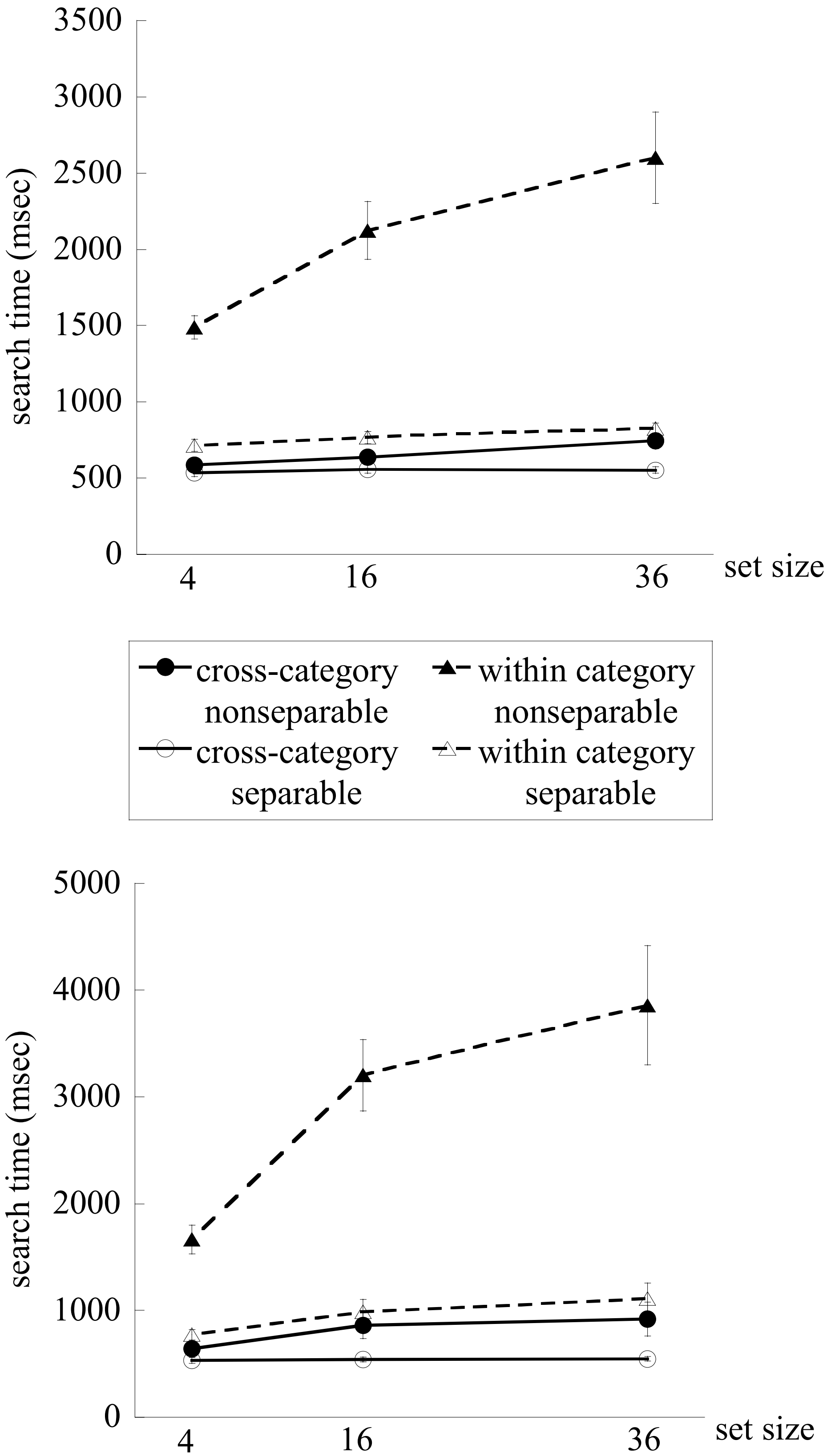
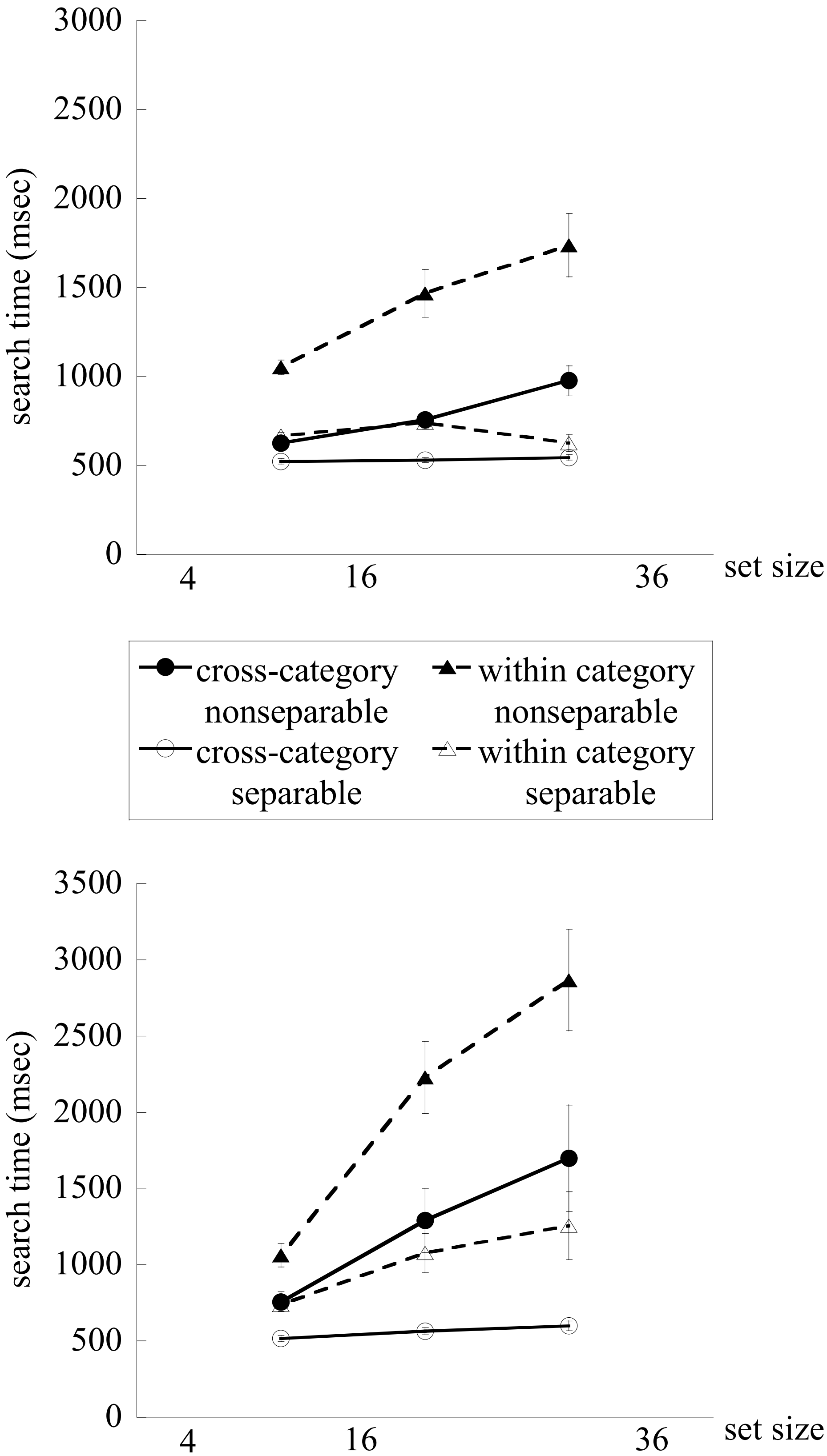

3500
3000
2500
2000
1500
1000
500
0
search time (msec)
4
16
36
set size
cross-category nonseparable
within category nonseparable
cross-category separable
within category separable
5000
4000
3000
2000
1000
0
search time (msec)
4
16
36
set size

Figure 2



3000
2500
2000
1500
1000
500
0
search time (msec)
4
16
36
set size
cross-category nonseparable
within category nonseparable
cross-category separable
within category separable
3500
3000
2500
2000
1500
1000
500
0
search time (msec)
4
16
36
set size

Figure 3

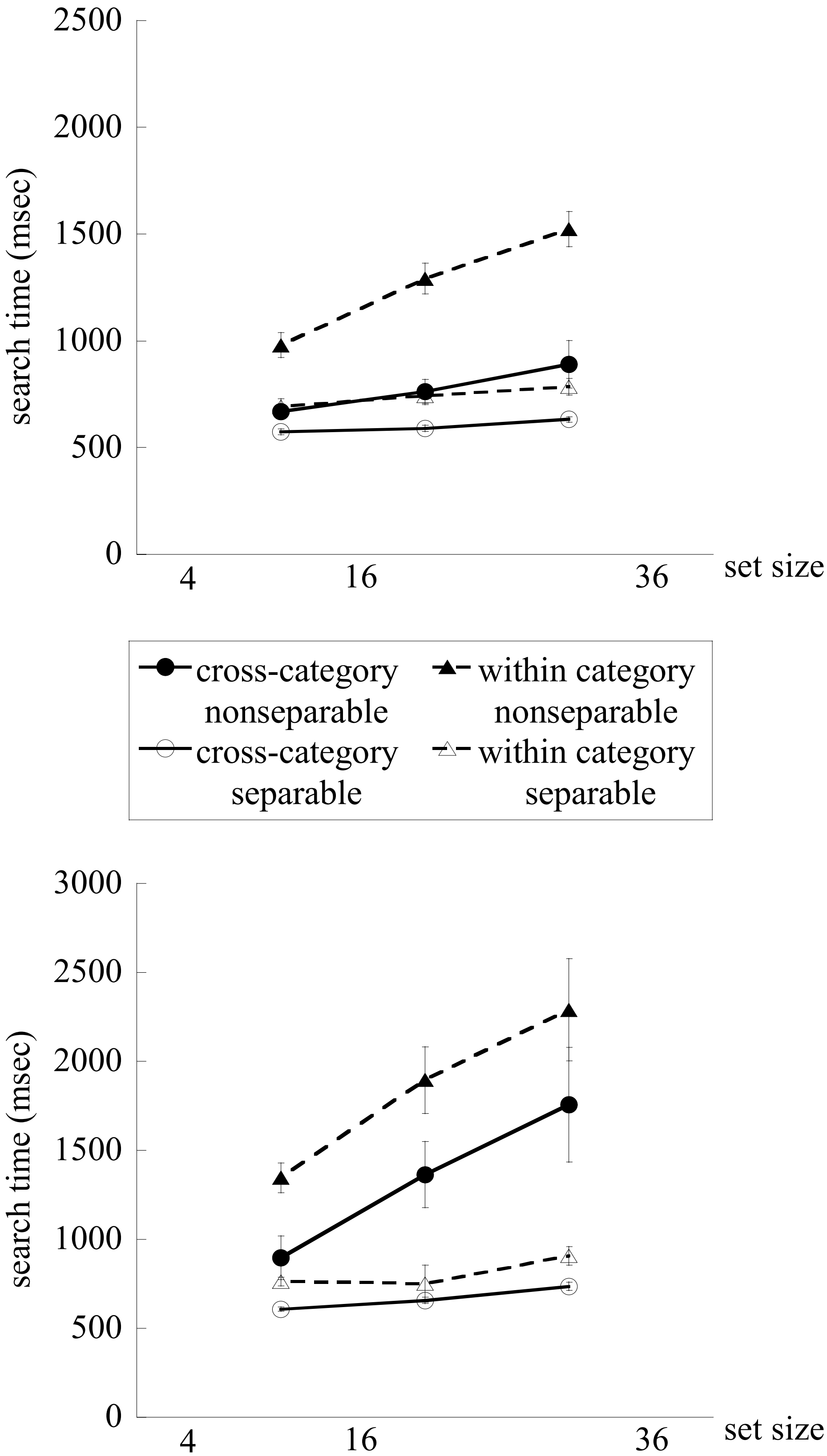

search time (msec)
2500
2000
1500
1000
500
0
4
16
36
set size
cross-category nonseparable
within category nonseparable
cross-category separable
within category separable
search time (msec)
3000
2500
2000
1500
1000
500
0
4
16
36
set size

Figure 4

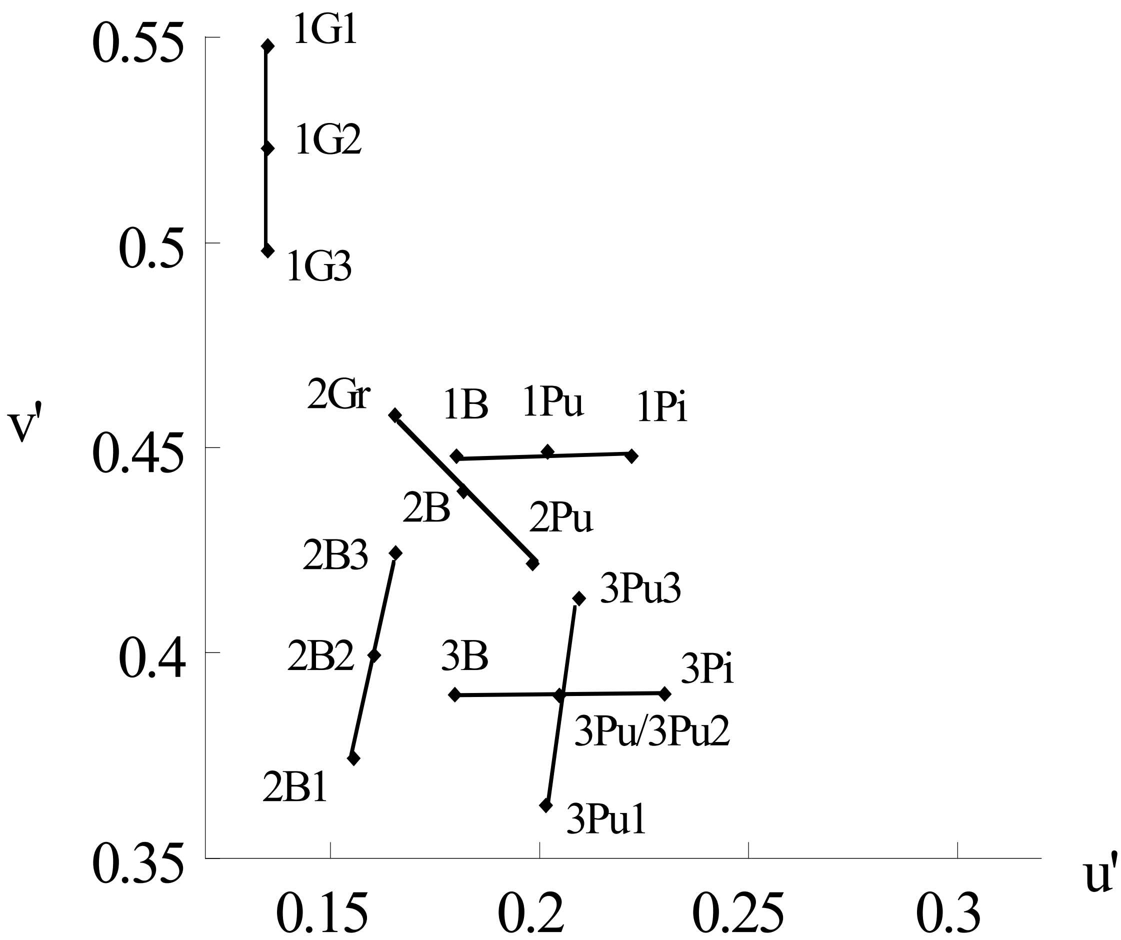


Figure 1 (Appendix)

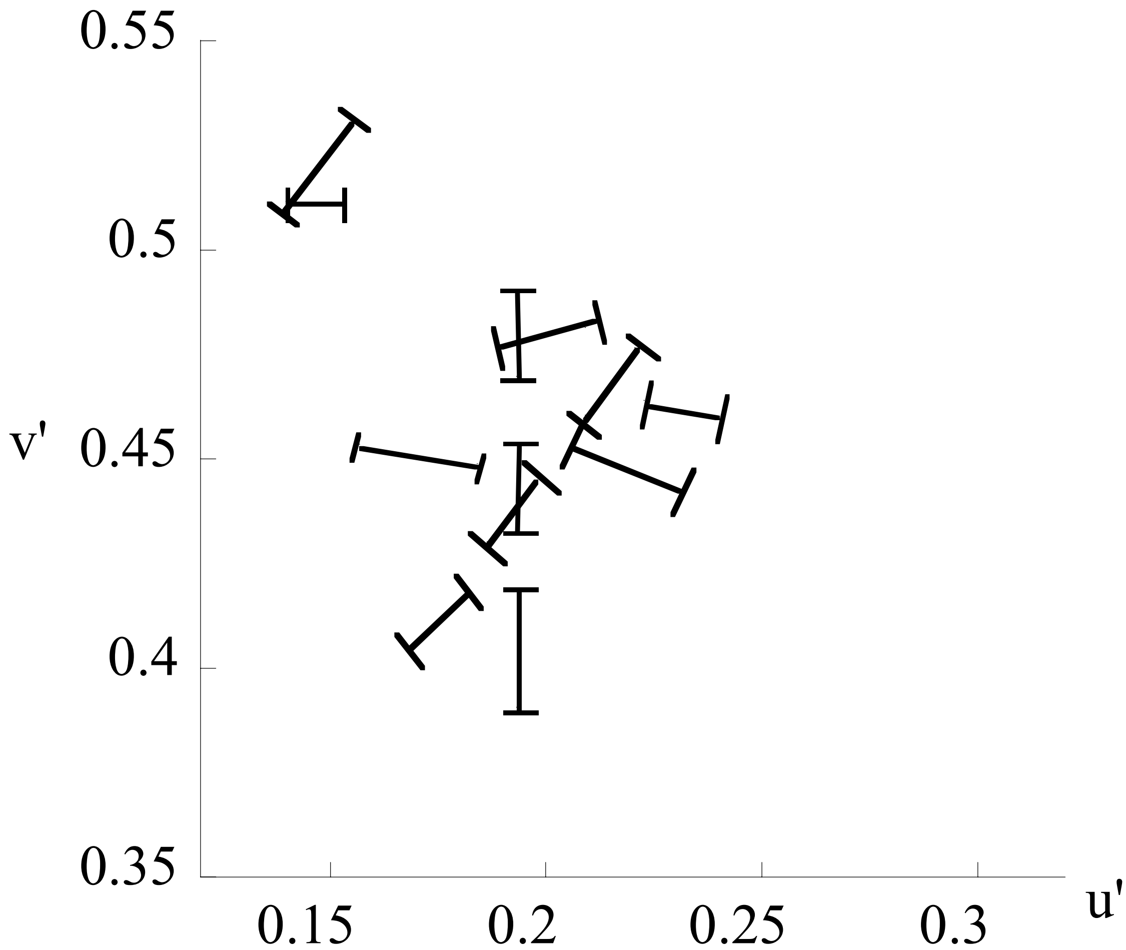


Figure 2 (Appendix)

Authors' Note.

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The data for Experiment 1 were collected as part of the second author's thesis. Experiment 1 was presented at the 25th European Conference on Visual Perception, Glasgow, August 2002. We are grateful to the observers who took part in the experiments, and to Pierre Jolicoeur and John Hodsoll for their very helpful comments.

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