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# Conjunction and linear non-separability effects in visual shape encoding

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## Abstract

Four visual search experiments are reported which used simple 2D shapes varying on the global dimensions of aspect ratio/curvature or aspect ratio/tapering. Results indicate serial self-terminating search in all conditions. Most importantly, search rates are markedly modulated by the particular forms of structural relations existing between the targets and their distractors. Thus, single-feature targets with shape properties that are linearly separable from those of their distractors yield markedly faster search rates than linearly separable targets made of a conjunction of distractor features. In addition, linearly separable single-feature targets are searched at a much faster rate than single-feature targets which are not linearly separable. Follow-up experiments demonstrate that these conjunction and linear non-separability effects cannot be attributed to pairwise target–distractor discriminability differences across conditions. The main conclusions are that the shapes used are parsed according to elementary features in visual encoding, and that a linear discrimination mechanism is available which permits fast visual search rates if a single-feature target is linearly separable from its distractors. © 2000 Elsevier Science Ltd. All rights reserved.

*Keywords:* Shape; Visual search; Encoding

## 1. Introduction

A large part of current efforts towards an understanding of visual shape perception is focussed on a specification of the types of features by which our visual system represents shape. This is a fundamental issue since these assumed features are the basis for our capacity of discriminating between shapes as well as of assessing the similarity among them. Many different proposals have been made about the nature and kinds of dimensions along which the features that define visual shapes are specified[1].

Some approaches propose global dimensions that characterise the shape as a whole, such as the amplitudes and relative phases of the frequency components produced by Fourier analysis applied to luminance variations across the extent of the visual pattern (e.g. Cavanagh, 1978; Ersoy & Kim, 1988) or, alternatively, the frequency components obtained using the method of Fourier descriptors (e.g. Cortese & Dyre, 1996). Other, more analytic approaches propose that complex shapes are represented as structural descriptions, that is in terms of a set of parts defined by particular elementary shape features along a restricted number of simple dimensions such as aspect ratio, curvature, etc., and of the spatial relations among those parts (e.g. Biederman, 1987; Hoffman & Richards, 1984; Kurbat, 1994; Marr, 1982; Marr & Nishihara, 1978; Palmer, 1977). Still others have argued that instead of a fixed set of a priori dimensions that invariably serve for shape representation, the visual system may flexibly adjust itself according to context and thus vary the kinds (and possibly the nature) of dimensions by which it characterises the

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[1] A dimension is defined as an aspect or attribute of a set of stimuli that may be varied and of which a particular item may possess only one value. A feature is the particular value of an item along a particular dimension.

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shapes of objects (Feldman & Richards, 1998; Schyns, Goldstone & Thilbaut, 1998; Schyns & Rodet, 1997).

However large the differences between these approaches to shape representation may be, they all hold the common assumption that visual shapes are coded according to a number of features that each characterise the stimulus on particular dimensions (be they global or local). The present research reports visual search evidence that is relevant to the as yet unsettled topic of which dimensions may serve for shape representation. Most importantly however, the present study will address two other fundamental issues regarding shape perception that go beyond the question of which dimensions are used by the human visual system to represent shape.

### *1.1. Integrated versus distributed shape representations*

One of these issues concerns the way in which the multiple features that are necessary to uniquely specify the shape of an object are coded in relation to each other. Indeed, it is difficult to uniquely specify the shapes of most visual objects by a single feature since features tend to be widely shared across items (Smith & Medin, 1981; Rosch, 1975). Considering fruits and vegetables, for instance, it would be difficult to recognise cucumbers on the basis of their elongation alone because carrots and bananas are also elongated. Identifying apples by sphericity alone would be similarly problematic since many fruits and vegetables possess this property. Because of this, we plausibly assume that conjunctions of a number features must be represented in visual object processing. We examine here whether simple 2D visual shapes roughly resembling those of fruits and vegetables are coded as integrated representations, i.e. global, undivided units that code conjunctions of several features, or instead are coded as distributed representations, i.e. as collections of discrete or separate elementary features.

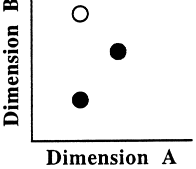

Fig. 1. Locations of three stimuli in a representational space made of dimensions A and B. The notion of integrated representations predicts that the stimuli corresponding to the white and grey dots will be more difficult to discriminate than the pair of items corresponding to the white and black dots. The hypothesis of distributed representations makes the opposite prediction.

This issue is similar[2] to that raised previously by Treisman's feature integration theory (FIT; e.g. Treisman & Gelade, 1980; Treisman & Sato, 1990; Treisman & Gormican, 1988), whose major claim was that visual stimuli are initially parsed into elementary features each characterising the item on a particular dimension, and that these dimensions are processed by separate modules. In other words, FIT argued that perceptual representations are initially made of distributed collections of discrete features and that a subsequent additional integration operation is required to represent feature conjunctions. The work on which this claim is based however, mainly concerned combinations of features from different visual domains such as color and shape. In contrast, the features of interest here all concern the shape domain. The question we ask therefore is whether initial visual shape processing is subdivided into a number of discrete mechanisms each dedicated to characterising an item along a specific shape dimension (i.e. distributed representations) or whether a single mechanism is capable of jointly coding all relevant shape features into a global representation (i.e. integrated representations).

Current theories of visual shape processing are either silent or not entirely explicit regarding the issue of integrated versus distributed representations. Possibly the most elaborate statements in this respect are those of Hoffman and of Biederman and their collaborators, who propose that complex shapes are parsed into parts by the visual system (e.g. Biederman, 1987; Biederman, Subramaniam, Bar, Kalocsai, & Fiser, 1999; Hoffman & Richards, 1984; Hoffman & Singh, 1997; Singh, Seyranian, & Hoffman, 1999). These authors do not specify however, whether these parts are themselves broken down into more elementary properties that define their particular shapes and, most importantly, whether the various shape features that serve to represent visual objects are coded into integrated or distributed representations. This issue is crucial however, since integrated and distributed representations imply different predictions with respect to shape discrimination performance. With integrated representations, the key determinant of shape discrimination performance is the global similarity among shapes; the more similar shapes are, the more difficult the discrimination (Garner, 1974; Shepard, 1991). This global similarity may be conceived as the inverse of the Euclidian distance separating the representations of two different items in a

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[2] Garner's (1974) distinction between integral and separable dimensions is also related to the present issue. This distinction however, was conceived as firstly relevant to the physical properties of visual stimuli rather than to their perceptual processing: " ... the concept of dimensional integrality ... is a stimulus concept, not an organismic concept" (Garner, 1974; p. 187). We are here essentially concerned with the internal mechanisms involved in shape perception. See Section 5 for relevant comments.

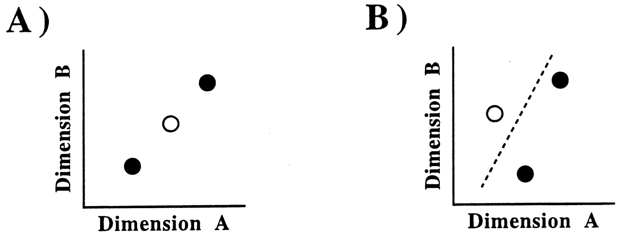

Fig. 2. Linear separability of target–distractor configurations in a representational space made of dimensions A and B. The white dot stands for the target location in this representational space and the black ones correspond to distractor locations. (A) The target is not linearly separable from distractors. (B) The target is linearly separable from distractors.

shape space whose main axes correspond to the dimensions by which the visual system represents shape (Fig. 1). In contrast, with distributed representations, apart from constraints relating to the resolution of the shape processing system, the central determinant of discrimination performance is whether items share features or not; i.e. shapes sharing critical features with one another are more difficult to discriminate than those that do not. There are circumstances, such as those illustrated in Fig. 1 where the two theories of shape perception make diametrically opposed predictions with respect to discrimination performance.

Brown, Weisstein, and May (1992) have provided visual search data consistent with the notion of distributed shape representations. Brown et al. had subjects search for target geons (elementary 3D shapes proposed by Biederman, 1987) among displays containing a variable number of instances of other distractor geons. Parallel (pop-out, i.e. relatively flat slopes of response times as a function of number of items suggesting preattentive target detection) search was found for displays where the target differed from a homogeneous set of distractors by a single feature (shape of cross section or tapering; Exps. 1–4). By contrast, slower serial search was obtained for heterogeneous distractor displays (Exp. 5), where the target effectively shared its defining features with distinct subsets of distractors. The effect of shared features suggested by the Brown et al. data is difficult to interpret however, because the authors did not control for either the heterogeneity of distractors, nor the visual similarity between the targets and distractors across conditions[3]. Either of these factors may easily account for the effect of shared features reported by Brown et al. (see Duncan & Humphreys, 1989). Those methodological artefacts are controlled in the tests reported here.

### 1.2. Linear separability

Another key issue of interest in the present study concerns the possible criteria upon which a particular visual shape is discriminated from other stimuli (e.g. Ashby, 1992). Previous visual search studies have been conducted in the colour and orientation domains with respect to this question. These have shown that a target which is not linearly separable from the distractors presented with it on the dimension(s) relevant for target discrimination is harder to detect in the visual search task than a linearly separable target (Bauer, Jolicoeur, & Cowan, 1996a; Bauer, Jolicoeur & Cowan, 1996b, 1998, 1999; D'Zmura, 1991; Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992).

The typical condition where the target is not linearly separable from distractors is one in which the feature value of the target is intermediate between that of two distractors in the relevant feature space (Fig. 2A; see Bauer et al., 1999 for a different form of linear non-separability). In this case, no straight line can be established in feature space to separate the target from both distractors. By contrast, a linearly separable target is located off the straight line joining the two distractors in feature space, (Fig. 2B). This condition allows the establishment of a linear criterion in feature space to reliably discriminate between the target and the distractors.

In the colour domain for instance, which has been the most studied, the visual search rates for targets that are not linearly separable from distractors are substantially slower than those for linearly separable targets, which sometimes yield pop-out effects (Bauer et al., 1996a,b; 1998; D'Zmura, 1991). These findings (see also Bauer et al., 1999; D'Zmura, Lennie, & Tiana, 1997) have served to argue for an early linear discrimination mechanism that allows rapid target detection if a single straight line serving as decision criterion can effectively separate the location of the target in colour space from those of all distractors. If this linear mechanism cannot apply, such as when the target is not linearly separable from distractors, search becomes slow and laborious, presumably because a more elaborate discrimination criterion is required. Bauer et al. (1996a) have argued that a linear discrimination mechanism akin to that identified through the linear non-separability effect with colour targets may also exist for other stimulus domains. The visual search data of Wolfe et al. (1992) with stimuli varying in orientation is congruent with this notion. We will examine here whether this generalisation also applies to the shape domain.

### 1.3. The present study

The present paper reports a series of visual search experiments designed to examine the issues of inte-

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[3] It should be noted however, that Brown et al.'s main objective was not to examine the conjunction effect and in fact, that their discussion does not even address the issue.

grated versus distributed representations of shape as well as that of linear separability described above. Previous demonstrations that the visual search paradigm may be helpful in resolving key questions regarding shape perception have been provided by Enns and Rensink (1991).

The stimuli used in the present experiments were continuously contoured shapes corresponding to deformations of a basic ellipse along the global dimensions of aspect ratio (i.e. ratio of lengths of minor over major axes), curvature of main axis, and tapering along main axis (see Figs. 3 and 7 for examples)[4]. The selection of these dimensions was motivated, on the one hand, by the facts that they are closely analogous to those found in parametric image transformations used in synthetic solid object modelling and that there is a theoretical basis for the psychological validity of these dimensions (e.g. Barr, 1981; Biederman, 1987; Brooks, 1981; Marr, 1982; Marr & Nishihara, 1978; Pentland, 1985). Most importantly, empirical support for the psychological validity of these dimensions was provided by Arguin, Bub and Dudek (1996), who report a series of experiments conducted on a brain-damaged patient (ELM) with visual agnosia (see also Dixon, Bub, & Arguin, 1997; Dudek, Arguin, Dixon, & Bub, 1997 for congruent evidence). The relevant tests performed on ELM involved synthetic shapes similar to those used in the present experiments, which were manipulated on the dimensions of aspect ratio, curvature, and tapering. ELM's shape recognition performance with sets of items that shared features with one another (conjunction sets) relative to sets where each possible target possessed a unique feature value on a particular shape dimension (single-dimension sets) was compared (Exp. 4; Arguin et al., 1996). Whereas processing a single feature value on the relevant dimension is sufficient for the unique recognition of the target shape in the single-dimension condition, the processing of conjunctions of shape features is required in the conjunction condition. Because of this difference, the hypothesis of distributed shape representations predicts a lower performance in the conjunction than in the single-dimension condition. ELM's error rates were about twice as high with conjunction (56.7% errors) than with single-dimension sets (29.2% errors). This result demonstrates a cost in processing feature conjunctions that is consistent with the notion of distributed shape representations. This result indicates, in turn, that the dimensions along which stimulus shapes were manipulated are either strongly correlated with or actually correspond to some of the psychological dimensions on which the representation of shapes is based. Thus, if the physical dimensions manipulated to produce the stimuli had been poorly correlated with the psychological dimensions by which shapes are internally represented, the observation of a conjunction effect would have been very improbable. Indeed, in such a case, even stimuli from conjunction sets would have been likely to possess a unique value on one of the dimensions of psychological *shape space*, effectively transforming the task in the so-called 'conjunction condition' to one involving discriminations along a single dimension — this issue is elaborated in greater detail in Section 4; see also Arguin et al., 1996. There are thus a priori theoretical and empirical reasons for believing that the dimensions of aspect ratio, curvature, and tapering may contribute to shape perception and representation. The observations reported below are congruent with this position.

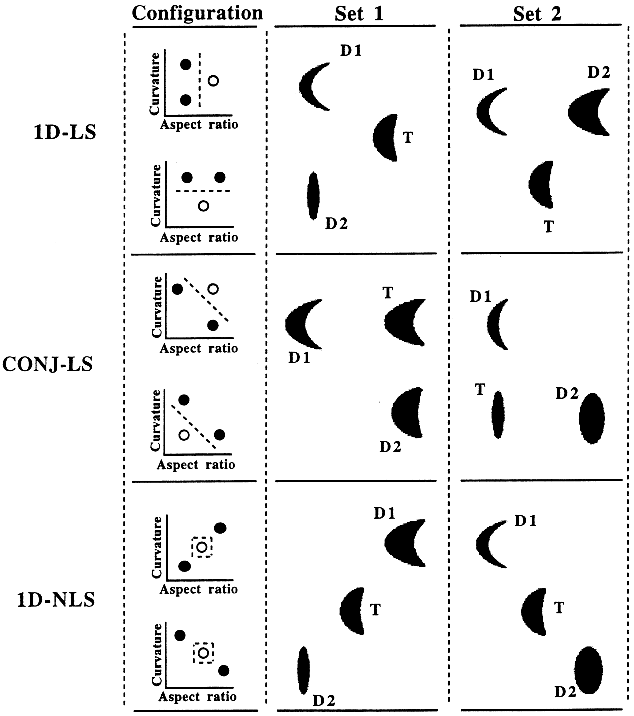

Fig. 3. Target–distractor configurations in shape space (leftmost column) for stimuli used in the 1D-LS, CONJ-LS, and 1D-NLS conditions of Experiments 1a and 1b, along with the actual items used (central and rightmost columns). The white dots in the graphs of the leftmost column correspond to targets and the black dots correspond to distractors. Dashed lines in these graphs indicate the form of the boundary allowing a segregation of the target from distractors, in shape space. T, target; D1 and D2, distractors.

The present experiments examined visual search performance under three basic conditions defined by variations of target–distractor relations in a two-dimensional shape space defined by the dimension pairs aspect ratio/curvature or aspect ratio/tapering. In

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[4] Since, as specified below in Section 2.1, the stimuli used had a major axis of a constant length, the dimension of aspect ratio was highly correlated with the surface area occupied by an item. Aspect ratio cannot be identified completely with surface area however, as shape manipulations along the dimensions of curvature and tapering do not affect aspect ratio whereas they do involve changes in the surface area of the stimulus.

each case, subjects searched for a single pre-determined target among a variable number of replications of two distractor shapes. The pairwise similarity between the target and either of its distractors was held constant across search conditions.

One condition (1D-LS), which served as baseline, involved linearly separable single-feature targets. These targets can be segregated from the distractors by a linear boundary in shape space that runs perpendicular to the axis defining one of the critical dimensions (Figs. 3 and 7). Furthermore, 1D-LS targets possessed a unique feature value that reliably distinguished them from their distractors on either of the relevant dimensions.

In another condition (CONJ-LS), linearly separable targets were defined as conjunctions of their distractors' features, i.e. targets shared a different feature with each distractor (Figs. 3 and 7). Target–distractor discriminations in this second condition required the representation of feature values defining the target along both of the relevant shape dimensions but could rest on a linear decision criterion that is oriented obliquely in relation to the axes defining the critical dimensions. Basically, the target–distractor configurations in the CONJ-LS condition corresponded to 45° rotations of the configurations used in the 1D-LS condition.

In a third and last condition (1D-NLS), targets were a linear combination of the features constituting the distractors (Figs. 3 and 7). Specifically, the shape–space location of the target was midway between those of its distractors. In this case, target–distractor discriminations may be based on a unique feature value that is possessed by the target. However, no linear boundary can be drawn between the shape–space locations of the target and those of the distractors; in other words, the target was not linearly separable from its distractors.

The performance contrast between the 1D-LS and CONJ-LS conditions served to determine whether the initial perceptual representation of simple visual shapes such as those used here is integrated or distributed. Assuming everything else (i.e. linear separability and distractor heterogeneity) is equal, the notion of integrated shape representations predicts that visual search performance will be determined by the global similarity of the target with its distractors. Accordingly, since the 1D-LS and CONJ-LS conditions are matched in terms of target–distractor similarity (see below for details), there should be no performance difference between them. In contrast, the hypothesis of distributed shape representations predicts that search will be more difficult if the target shares its defining features with the distractors, as in the CONJ-LS condition, than if the processing of feature values on a single shape dimension is sufficient to effectively discriminate the target from distractors, as in the 1D-LS condition.

The performance contrast between the 1D-LS and 1D-NLS conditions served to determine whether visual search in the shape domain is susceptible to the linear non-separability effect described previously in the colour and the orientation domains. In both the 1D-LS and 1D-NLS conditions, the processing of a single feature value is sufficient for proper target detection performance. Assuming these conditions are matched in terms of target–distractor similarity, the only difference between them concerns whether the target is linearly discriminable from the distractors. Therefore, a greater difficulty of visual search in the 1D-NLS condition will indicate the existence of a linear discrimination mechanism in the shape domain which allows the rapid target detection if it is linearly separable from the distractors presented with it.

## 2. Experiment 1

Experiment 1 tested for the conjunction and the linear non-separability effects with shapes that varied on the global dimensions of aspect ratio and curvature (Fig. 3). Experiment 1a served as the actual experimental investigation assessing visual search performance variations across the different target–distractor configurations described above (i.e. 1D-LS, CONJ-LS, and 1D-NLS). In this experiment, targets were searched for among heterogeneous distractors (i.e. two distinct shapes) in every condition. Experiment 1b was a control experiment that served to determine that the different target–distractor configurations used in Exp. 1a were effectively matched in terms of the similarity between the target and distractors. In Exp. 1b, search performance was assessed separately for each of the target–distractor pairs used in Exp. 1a; thus, targets were searched among homogeneous distractors.

### 2.1. Method

#### 2.1.1. Subjects

Ten subjects took part in Exp. 1a and five different individuals participated in Exp. 1b. Participants were aged between 19 and 30 and all had normal or corrected vision. All subjects were paid $16.00 for their participation.

#### 2.1.2. Materials and stimuli

Presentation of the stimuli was controlled by a Macintosh computer equipped with a high resolution RGB monitor.

The experimental stimuli were synthetic shapes generated by parametric deformations of a filled 2D ellipse along the global dimensions of aspect ratio (ratio of minor over major axes) and of curvature of the main axis (Fig. 3; see Arguin et al., 1996; for details on

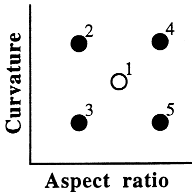

Fig. 4. Illustration of the relative shape space locations of items serving as target and distractors for the 1D-LS and 1D-NLS conditions of Exp. 1 and as targets in the CONJ-LS condition. Specifically, item no. 1 served as target for sets 1 and 2 of the 1D-LS and 1D-NLS conditions. In the 1D-LS condition, items no. 2 and 3 served as distractors for set 1 and nos. 2 and 4 served as distractors for set 2. In the 1D-NLS condition, items no. 3 and 4 served as distractors for set 1 and nos. 2 and 5 served as distractors for set 2. The items labelled 3 and 4 served as targets in the CONJ-LS condition.

stimulus generation). The length of the major axis of all shapes was normalised to 8 cm (5.1° visual angle; viewing distance of 90 cm) while the length of the minor axis was varied to manipulate aspect ratio. The stimuli were solid and presented in black on a white background.

Two distinct target–distractors sets were constructed for each of three search conditions. Fig. 3 represents those target–distractor sets in a two-dimensional shape space whose main axes are defined by the relevant shape dimensions. In the single-feature linearly separable (1D-LS; Fig. 3) condition, the targets were linearly separable from distractors and could be reliably segregated from them along a unique dimension (represented by the straight line separating the target from its distractors). The conjunction (CONJ-LS; Fig. 3) condition was defined by targets that shared a distinct critical feature with each of their distractors. In other words, CONJ-LS targets were made of a combination of distractor features, although they remained linearly separable from distractors as shown by the oblique straight line separating the target from its distractors in Fig. 3. The single-feature non-linearly separable (1D-NLS; Fig. 3) condition involved targets whose shape space location was halfway (as assessed by independent observers) on a straight line joining their distractors, which mutually differed on both critical shape dimensions. No single linear decision boundary in shape space can separate a 1D-NLS target from both of its distractors.

The pairwise visual similarity between the targets and each of their distractors was matched pre-experimentally across conditions. This was achieved by having an independent sample of six subjects, different from those tested in the visual search task, to actually generate several of the stimuli to be used in the experiment. This was done with the aid of a computer program that allowed adjustments of the aspect ratio and curvature of a series of shapes using specific keys on a number keypad. Subjects were shown the shapes that the experimenters had selected as targets and distractors for set 1 of the 1D-LS condition (items no. 1, 2 and 3 on Fig. 4). In producing these items, the experimenters attempted to match the level of similarity between each distractor and the target it was to be used with. This 1D-LS set, which remained visible throughout, served as reference for target–distractor similarity in the generation of the remaining items that were to be used in the experiment. The target for set 1 of the 1D-LS condition (item 1 on Fig. 4) served also as target for set 2 of the ID-LS condition and for sets 1 and 2 of the 1D-NLS condition. Subjects were then presented with this target and one distractor from set 1 of the 1D-LS condition (item no. 3 on Fig. 4). They were instructed to adjust the shape of a third item (no. 4 on Fig. 4) so that it was more curved and had a higher aspect ratio than the target, that the apparent difference between this item and the target was approximately equal on each dimension, and finally that the overall similarity between this new item and the target was comparable to that between the target and the distractor item labelled no. 2 on Fig. 4. Subjects pursued this adjustment until they were satisfied they had met all the imposed constraints. Next, they were presented another display comprising the same target as before accompanied by the other distractor from set 1 of the 1D-LS condition (item no. 2 on Fig. 4). They were then instructed to adjust the shape of a third item (no. 5 on Fig. 4) following constraints similar to those for the generation of item no. 4, except that this time the new shape had to have a lower degree of curvature than the target. The construction of set 2 for the 1D-LS condition and of sets 1 and 2 for the 1D-NLS condition was based on the shapes selected a priori by the experimenters (nos. 1, 2 and 3) along with average curvature and aspect ratio values of those generated by the subjects (nos. 4 and 5). Items labelled nos. 4 and 3 on Fig. 4 were designated by the experimenters as targets for sets 1 and 2 of the CONJ-LS condition, respectively. Subjects generated distractors for each CONJ-LS set separately by performing adjustments on shapes that were allowed to differ from targets exclusively by their curvature or aspect ratio while attempting to equate both the similarity of each of these distractors with the target as well as the target–distractor similarities for these items and for those of set 1 for the 1D-LS condition. Again, subjects pursued these adjustments until they were satisfied they had met all the constraints of the task. The aspect ratio and curvature values of the distractors used in the CONJ-LS condition were averages of those produced by subjects. In the end therefore, the stimuli selected for Exp. 1 obeyed two separate constraints; one was the definitions of the target–distractor configurations in shape space that are described above; the other was that the similarity of the possible target–distractor pairs was matched across conditions.

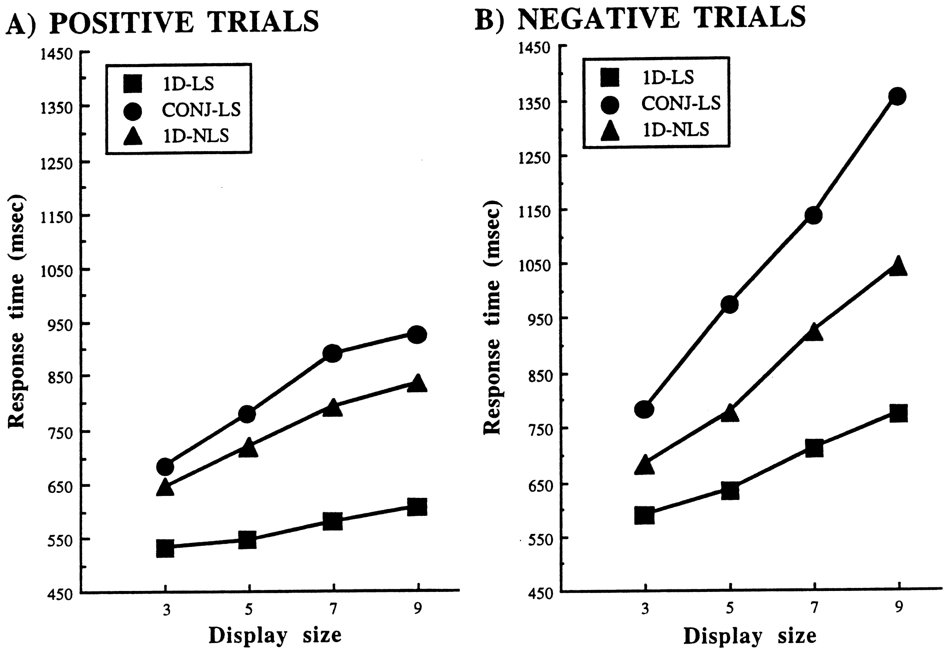

Fig. 5. Average correct RTs as a function of display size in Exp. 1a on (A) positive and (B) negative trials.

Experiment 1a tested performance contrasts across the different target–distractor configurations illustrated in Fig. 3. Exp. 1b served as a follow-up control test for the target–distractors similarity match across conditions. In this test, targets were searched for among homogeneous distractors which were either of the distractor exemplars they were paired with in Exp. 1a.

### 2.1.3. Procedure

In Exp. 1a, each subject completed two blocks of 160 trials for each of the six target–distractor sets. Each block was made of a balanced crossing of two factors: Display size (four levels: 3, 5, 7 or 9) and target presence (two levels: present or absent). Conditions were distributed randomly and in equal numbers of trials in each block. On positive trials, each exemplar of the distractors serving in a particular target–distractors set was replicated an equal number of times. To maintain display size constant across positive and negative trials, an unequal number of replications of each distractor was presented on negative trials. For these trials, the number of replications of each distractor differed by one, with each distractor exemplar occurring an equal number of times within each block.

In Exp. 1b, subjects completed a total of eight blocks of 200 trials in which the targets serving in Exp. 1a were now searched among homogeneous distractors. Since some of the possible target–distractor pairs illustrated in Fig. 3 re-occur across conditions, the data from these instances contributed to more than one condition. Exp. 1b is identical to Exp. 1a in every other respect.

On each trial, a fixation asterisk (Geneva 24 point font) was displayed for 500 ms at the centre of the monitor, followed immediately by the search array, which disappeared when the subject responded. The targets and distractors were randomly presented at one of 12 locations equally spaced on an imaginary circle of 9.5° in diameter that was centered on the fixation point. The inter-trial interval was of 1 s. Block and trial order was random.

Subjects were instructed to respond as quickly and as accurately as possible by pressing with the index fingers of the left or right hand a key on the left or right side of a computer keyboard, depending on whether they judged the target to be present or absent. The side assigned to the ‘target-present’ and ‘target-absent’ buttons was counter-balanced across subjects. The entire duration of each experiment was approximately 2 h. Subjects were allowed a short pause between blocks, and a minimum 20 min pause was required after half of the blocks were completed.

## 2.2. Results and discussion

### 2.2.1. Exp. 1a

Outlier response times (RTs) were removed from the data of an individual subject if they were more than three standard deviations away from the subject's mean for that condition. This resulted in the removal of a total of 319 data points for the entire experiment (1.7% of trials). Error rates were not analysed since an error occurred on less than 3% of trials for any condition and the correlation between RTs and errors was of $-0.12$ (ns), therefore showing no speed–accuracy trade-off.

Table 1
Linear regressions of RTs as a function of display size for positive and negative trials of each condition in Exp. la

| Condition | Positive trials | | | Negative trials | | | |
|---|---|---|---|---|---|---|---|
| | Intercept | Slope | $R^2$ | Intercept | Slope | $R^2$ | Pos/neg ratio |
| 1D-LS | 490.1 | 12.5 | 0.96 | 489.4 | 31.1 | 0.99 | 0.40 |
| CONJ-LS | 569.5 | 41.5 | 0.96 | 499.3 | 93.7 | 0.99 | 0.44 |
| 1D-NLS | 555.9 | 31.7 | 0.99 | 489.9 | 61.1 | 0.99 | 0.52 |

Fig. 5 displays the average correct RTs as a function of display size for each search condition. Table 1 shows the outcome of linear regression analyses of RTs as a function of display size as well as the positive/negative slope ratios for each search condition.

Correct RTs were analysed with a three-way ANOVA including the within-subjects factors of condition (1D-LS, CONJ-LS, and 1D-NLS), Target presence (present or absent), and display size (3, 5, 7 or 9 items). This analysis showed main effects of condition [$F(2,18) = 53.7$, $P < 0.001$], target presence [$F(1,9) = 78.5$, $P < 0.001$], and display size [$F(3,27) = 91.4$, $P < 0.001$]. The two-way interactions of condition × target presence [$F(2,18) = 40.7$, $P < 0.001$], condition × display size [$F(6,54) = 22.4$, $P < 0.001$], target presence × display size [$F(3,27) = 46.1$, $P < 0.001$], were also significant. These effects were all qualified by a three-way interaction of condition × target presence × display size [$F(6,54) = 5.1$, $P < 0.001$]. This interaction was followed up by planned comparisons contrasting display size effects across pairs of search conditions separately for positive and negative trials. These contrasts showed, for both positive and negative trials, that the display size effect is smaller in the 1D-LS condition than either the CONJ-LS or the 1D-NLS conditions [target present: 1D-LS versus CONJ-LS: $F(3,27) = 21.2$, $P < 0.001$; 1D-LS versus 1D-NLS: $F(3,27) = 22.0$, $P < 0.001$; target absent: 1D-LS versus CONJ-LS, $F(3,27) = 19.7$, $P < 0.001$; 1D-LS versus 1D-NLS, $F(3,27) = 27.2$, $P < 0.001$]. In addition, the display size effect in the 1D-NLS condition is smaller than in the CONJ-LS condition on both positive [$F(3,27) = 5.3$, $P < 0.01$] and negative [$F(3,27) = 7.5$, $P < 0.001$] trials.

Results from the linear regressions show strictly linear effects of display size in each condition and positive/negative slope ratios close to 0.5, which is consistent with a serial self-terminating search (Snodgrass & Townsend, 1980) in all conditions. What may appear as one possible exception however, is the 1D-LS condition, where the positive/negative slope ratio departs to some degree from the theoretical ideal of 0.5 (see Table 1). This departure, which also occurs in Exp. 2a, will be addressed in more detail in Section 4. The relative sizes of the slopes of RTs as a function of display size across conditions are consistent with the outcome of the ANOVA described above.

The most crucial result of Exp. 1 is that visual search rates vary greatly across conditions despite our pre-experimental efforts to match them on the similarity of targets and distractors. Search rates are fastest in the 1D-LS condition, followed next by the 1D-NLS condition, and then the CONJ-LS condition, with all pairwise differences being significant.

The slower search rate in the CONJ-LS than the 1D-LS condition is congruent with the hypothesis of distributed shape representations described in Section 1. The crucial distinction between these conditions is that the 1D-LS condition permits search based on a single feature that uniquely specifies the target, whereas the CONJ-LS condition requires the processing of conjunctions of features on the dimensions of aspect ratio and curvature. With respect to linear separability, both conditions are identical in that a linear boundary can be traced in shape space to separate the target from its distractors. The cost in processing feature conjunctions demonstrated in Exp. 1a therefore implies that shapes are initially broken down into separate features, and that the perceptual representation of feature conjunctions requires a time consuming integration operation responsible for the slower search rates in the conjunction condition.

The search rate difference between the 1D-LS and 1D-NLS conditions indicates a cost in single feature search if no linear boundary can be established to separate the target from its distractors in shape space (i.e. non-linear separability effect). This suggests the existence of a linear decision mechanism in processing visual shapes, such that the target is detected most easily when the shape-space location of the target can be separated from that of its distractors by a single straight line. When this mechanism cannot be applied, such as in the 1D-NLS condition, the search rate is slower, presumably because a more complex decision process must be invoked.

The results of Exp. 1a also show that search rates with CONJ-LS targets are slower than with 1D-NLS targets. We had no specific prediction regarding a possible difference between these conditions at the outset and the results from Exp. 2a help in the interpretation of this difference. We will therefore return to this result in Section 4.

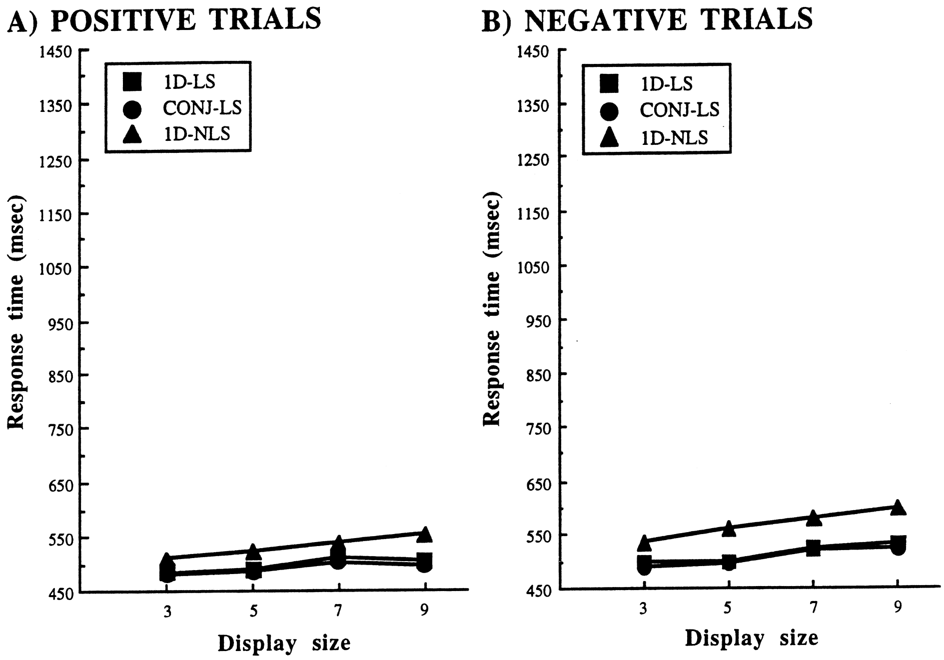

Fig. 6. Average correct RTs as a function of display size in Exp. 1b on (A) positive and (B) negative trials.

Table 2
Linear regressions of RTs as a function of display size for positive and negative trials of each condition in Exp. 1b

| Condition | Positive trials | | | Negative trials | | | |
|---|---|---|---|---|---|---|---|
| | Intercept | Slope | $R^2$ | Intercept | Slope | $R^2$ | Pos/neg ratio |
| 1D-LS | 471.3 | 4.4 | 0.74 | 476.9 | 7.03 | 0.99 | 0.63 |
| CONJ-LS | 472.4 | 6.06 | 0.89 | 467.9 | 10.0 | 0.99 | 0.61 |
| 1D-NLS | 489.1 | 3.2 | 0.73 | 506.5 | 6.01 | 0.84 | 0.53 |

One assumption that is crucial to the validity of our interpretation of the results of Exp. 1a is that the conditions are accurately matched on target–distractor similarity. Although the pre-experimental measures taken to perform this match appeared valid, it remains that the similarity judgements effected may be subject to cognitive factors that have no bearing on speeded visual discrimination performance. Because of this possibility, a follow-up visual search task was conducted in Exp. 1b in order to corroborate the pre-experimental target–distractor similarity ratings.

### 2.3. Exp. 1b

Experiment 1b was designed to determine that the effects obtained in Exp. 1a are not due to artefactual differences across conditions in the discriminability of the targets from individual distractors. For this purpose, subjects searched for each target used in Exp. 1a among each of the distractors it was paired with in that experiment, separately. If the differing search rates found across conditions in Exp. 1a are truly a function of target–distractor configurations rather than of target–distractor similarity, then the search rates for the homogeneous distractor displays of Exp. 1b should be unrelated to those observed in Exp. 1a.

The method to remove outlier RTs was the same as that applied in Exp. 1a. It resulted in the removal of a total of 131 data points for the entire experiment (1.6% of trials). Error rates were not analysed since an error occurred on less than 3% of trials for any condition and the correlation between RTs and errors was of $-0.06$ (ns), therefore showing no speed-accuracy trade-off.

Fig. 6 displays the average correct RTs as a function of display size for each condition. Table 2 presents the results of linear regression analyses of RTs as a function of display size as well as the positive/negative slope ratios for each condition.

A three-way ANOVA of condition (1D-LS, 1D-NLS, and CONJ-LS), target presence (present or absent), and display size (3, 5, 7 or 9 items) served to analyse correct RTs. It showed main effects of condition [$F(2,8) = 17.6$, $P < 0.011$ and display size [$F(3,12) = 10.3$, $P < 0.011$. No other main effect or interaction was significant.

Although the main effect of display size on RTs was significant, search rates in Exp. 1b are quite fast, none exceeding 10 ms/item (Table 2). These search rates are much faster than those observed in Exp. 1a, even when comparing the 1D-LS conditions, i.e. fastest search condition in Exp. 1a. These observations suggest that visual search in Exp. 1b was preattentive, possibly due to the markedly simpler target–distractor configurations in this experiment, where distractors were homogeneous, than in the previous test.

Most importantly, the results of Exp. 1b show no interaction of condition × display size, in contrast to Exp. 1a. Taking the search rates observed in Exp. 1b as an index of the similarity between the target and individual distractors, we may therefore conclude that the differing search rates across conditions that were observed in Exp. 1a cannot be attributed to a target–distractors similarity artefact. Rather, these differing search rates can be attributed exclusively to the particular shape–space relations between the targets and their respective distractors which defined the conditions of Exp. 1a.

The test provided in Exp. 1 focussed on stimuli whose shapes varied along the dimensions of aspect ratio and curvature. In the present report, we wish to make general claims regarding visual shape encoding which are not tied to specific combinations of shape dimensions. For this reason, the tests reported in Exp. 1 were replicated in Exp. 2, but this time with stimuli whose shapes varied along the dimensions of aspect ratio and of tapering along the main axis.

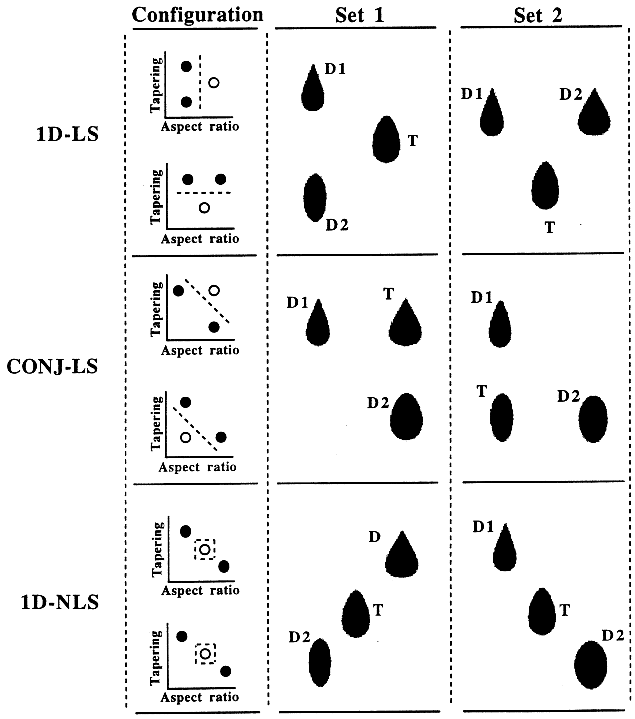

Fig. 7. Shape space configurations for stimuli used in the 1D-LS, 1D-NLS, and CONJ conditions of Experiments 2a and 2b, along with the actual items used. Conventions are the same as in Fig. 3.

## 3. Experiment 2

The goal of Exp. 2 was to examine whether the advantage observed in Exp. 1a for the 1D-LS condition over both the CONJ-LS and 1D-NLS conditions with shapes varying in curvature and aspect ratio generalises to stimuli varying in tapering and aspect ratio.

### 3.1. Method

#### 3.1.1. Subjects

Ten subjects participated in Exp. 2a and five different ones served in Exp. 2b. Participants were aged between 19 and 30 and all had normal or corrected vision. All subjects were paid $16.00 for their participation.

#### 3.1.2. Stimuli and procedure

The stimuli were shapes with a straight main axis that varied along the dimensions of tapering (along the main axis) and aspect ratio (Fig. 7; see Arguin et al., 1996; for details on stimulus generation). As in the previous experiment, 1D-LS, CONJ-LS, and 1D-NLS target–distractor configurations were tested, each using two distinct target–distractors sets. The visual similarity between targets and distractors was pre-experimentally matched across conditions using the same procedure as in Exp. 1 except that this time the shape dimensions that were adjusted were those of aspect ratio and tapering. Exp. 2a examined the modulation of visual search performance as a function of the different target–distractor configurations in shape space that are illustrated in Fig. 7. Exp. 2b served as a follow-up control test for the target–distractors similarity match across conditions. In this test, targets were searched for among homogeneous distractors which were either of the distractor exemplars they were paired with in Exp. 2a. The procedure was identical to that of Exp. 1 in all other respects.

### 3.2. Results and discussion

#### 3.2.1. Exp. 2a

The procedure for the rejection of outlier RTs was the same as that used in Exp. 1. It resulted in the removal of a total of 372 data points for the entire experiment (1.9% of trials). Error rates were not analysed since an error occurred on less than 5% of trials for any condition and the correlation between RTs and errors was of $-0.10$ (ns), thus showing no speed-accuracy trade-off.

Average correct RTs for each condition on positive and negative trials are shown as a function of the

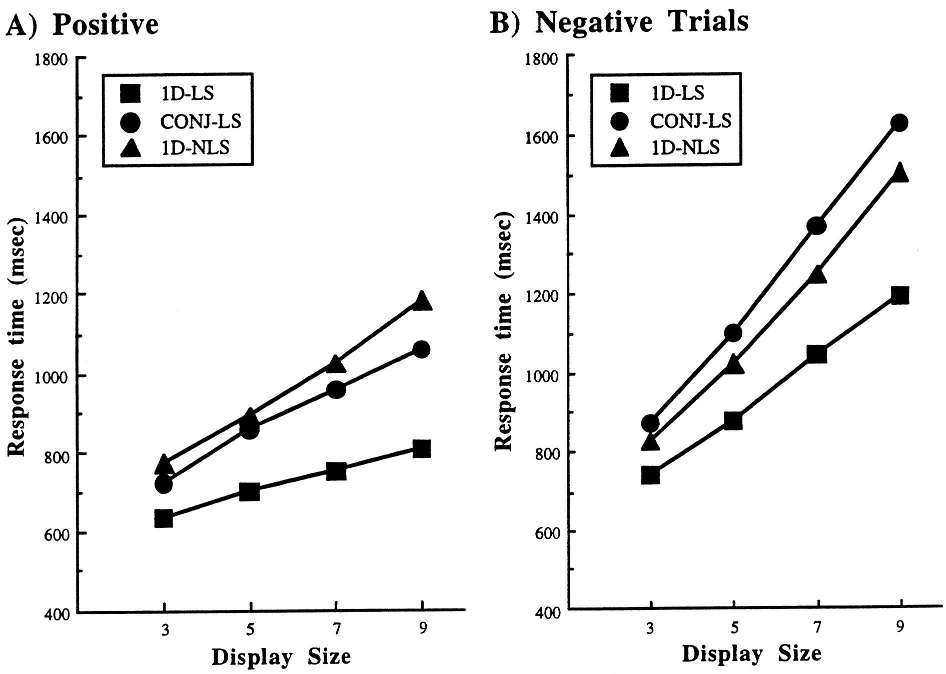

Fig. 8. Average correct RTs as a function of display size in Exp. 2a on (A) positive and (B) negative trials.

Table 3
Linear regressions of RTs as a function of display size for positive and negative trials of each condition in Exp. 2a

| Condition | Positive trials | | | Negative trials | | | |
|---|---|---|---|---|---|---|---|
| | Intercept | Slope | $R^2$ | Intercept | Slope | $R^2$ | Pos/neg ratio |
| 1D-LS | 554.8 | 28.21 | 0.99 | 508.4 | 75.69 | 0.99 | 0.37 |
| CONJ-LS | 564.5 | 55.0 | 0.99 | 473.2 | 112.71 | 0.99 | 0.49 |
| 1D-NLS | 561.3 | 67.74 | 0.99 | 482.6 | 126.14 | 0.99 | 0.54 |

number of items displayed in Fig. 8. The linear regression parameters for each of these search functions are presented in Table 3, along with positive/negative slope ratios.

The ANOVA performed on correct RTs with factors of condition (1D-LS, CONJ-LS, and 1D-NLS), target presence (present or absent) and display size (3, 5, 7 or 9 items) indicated main effects of condition [$F(2,18) = 36.0$, $P < 0.001$], target presence [$F(1,9) = 65.0$, $P < 0.001$] and display size [$F(3,27) = 96.2$, $P < 0.001$]. These main effects were qualified by two-way interactions of condition × display size [$F(6,54) = 43.4$, $P < 0.001$] and of target presence × display size [$F(3,27) = 40.0$, $P < 0.001$]. No other interaction reached significance. The target presence × display size interaction indicates a greater effect of number of items on negative than positive trials (Fig. 8). Planned comparisons concerning the condition × display size interaction showed that the display size effect is smaller in the 1D-LS than in both the CONJ-LS [$F(3,27) = 43.1$, $P < 0.001$] and the 1D-NLS conditions [$F(3,27) = 84.3$, $P < 0.001$]. In addition, the effect of display size was smaller in the CONJ-LS condition than in the 1D-NLS condition [$F(3,27) = 7.2$, $P < 0.01$].

The outcome of the linear regression analyses of RTs as a function of display size (Table 3) show strictly linear functions with the weakest slopes in the 1D-LS condition, followed next by the CONJ-LS condition, and finally by the 1D-NLS condition which produced the largest slopes of all. Positive/negative slope ratios are close to 0.5 in all conditions, thereby suggesting a serial self-terminating search. One positive/negative slope ratio that may appear as an exception however, is that from the 1D-LS condition, which is rather weak compared to the others. A similar result occurred in Exp. 1a and its possible meaning will be addressed in Section 4.

The most important finding of Exp. 2a is that search rates are slower in both the CONJ-LS and 1D-NLS conditions than in the 1D-LS condition. This replicates

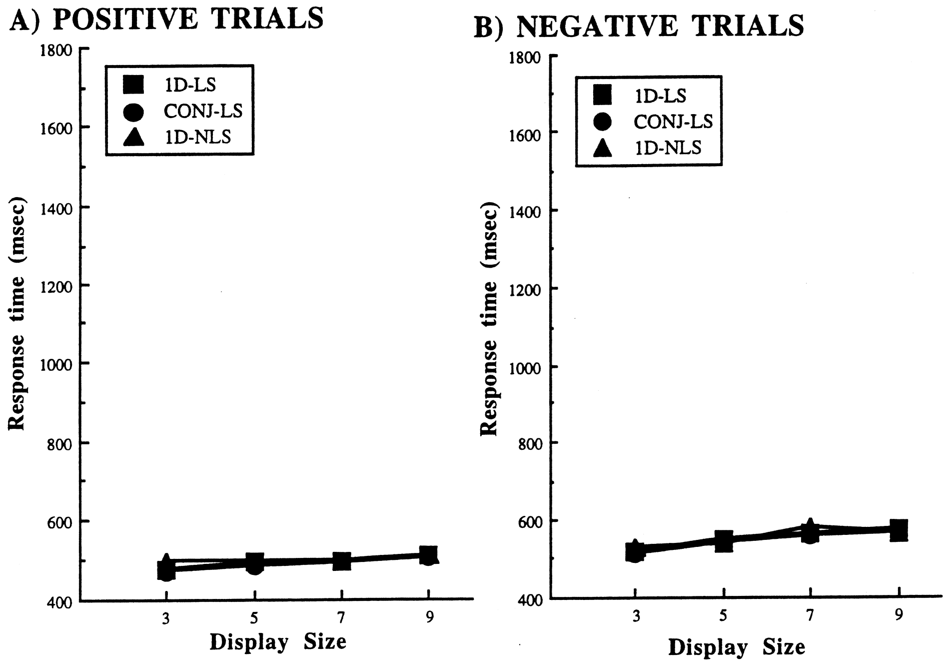

Fig. 9. Average correct RTs as a function of display size in Exp. 2b on (A) positive and (B) negative trials.

Table 4
Linear regressions of RTs as a function of display size for positive and negative trials of each condition in Exp. 2b

| Condition | Positive trials | | | Negative trials | | | |
|---|---|---|---|---|---|---|---|
| | Intercept | Slope | $R^2$ | Intercept | Slope | $R^2$ | Pos/neg ratio |
| 1D-LS | 461.8 | 5.1 | 0.94 | 494.6 | 9.4 | 0.92 | 0.54 |
| CONJ-LS | 455.4 | 5.4 | 0.99 | 488.2 | 9.4 | 0.93 | 0.57 |
| 1D-NLS | 490.9 | 1.6 | 0.65 | 502.9 | 8.3 | 0.76 | 0.19 |

the conjunction and the linear non-separability effects of Exp. 1a. The implications of these findings are the same for both experiments.

One result that differs between Exps. 1a and 2a, however, concerns the relative ordering of search rates in the CONJ-LS and 1D-NLS conditions. In Exp. 2a, the display size effect is greater in the 1D-NLS than in the CONJ-LS condition, whereas the ordering was the reverse in Exp. 1a (see Tables 1 and 3). This finding will be addressed in Section 4.

At this point however, the most immediate preoccupation concerns the matching of the target–distractors similarities across conditions. As for Exp. 1, matching was achieved pre-experimentally on the basis of similarity judgements performed by independent observers. Since these judgements may possibly be contaminated by cognitive factors which do not accurately reflect speeded visual discrimination processes, Exp. 2b was conducted to perform an empirical verification of the matching achieved. This was done by having subjects search for the same targets as in Exp. 2a, but this time with either of their distractors alone.

### 3.2.2. Exp. 2b

Data analysis was performed following the same approach as in the previous experiments. Across all trials run in Exp. 2b, 137 data points (1.7% of trials) were outliers and were rejected accordingly. The errors were not analysed for they constituted less than 4% of trials in any condition, and the correlation between RTs and errors was of + 0.08 (ns), thus showing no speed–accuracy trade-off. The results are summarised in Fig. 9 and Table 4.

The ANOVA of condition (1D-LS, CONJ-LS, and 1D-NLS) × target presence (present or absent) × display size (3, 5, 7 or 9 items) indicated main effects of target presence [$F(1,4) = 43.2$, $P < 0.01$] and of display size [$F(3,12)$ 18.56, $P < 0.001$], as well as a two-way interaction of target presence × display size [$F(3,12) = 6.1$, $P < 0.01$]. This interaction indicates a larger display size effect on negative than positive trials. No other main effect or interaction was significant. In particular, the condition factor had no impact on performance either as main effect or interaction. This implies that variations in search rates across conditions in Exp. 2a cannot have been due to mismatches between these conditions on the similarity of the targets with their distractors.

Even though significant, search rates in Exp. 2b were very fast — all below 10 ms/item as was the case in Exp. 1b, suggesting a preattentive visual search. Most importantly, no difference was observed on either RTs or search rates across conditions. From these results, we can confidently infer that the 1D-LS, CONJ-LS, and 1D-NLS conditions in Exp. 2a were accurately matched on target–distractor similarities, thus validating the conjunction and linear non-separability effects found in that experiment.

## 4. General discussion

Experiments 1a and 2a show that the visual search rates for target shapes are modulated as a function of the form of the structural relations that characterise a particular target–distractor set. None of these modulations is attributable to artefactual mismatches across conditions on distractor heterogeneity or on the similarities of targets and their distractors. Indeed, in the critical experiments (i.e. Exps. 1a and 2a), all conditions were equated in terms of distractor heterogeneity and a particularly high degree of control was achieved with respect to target–distractor similarity, cf. pre-experimental matching procedure and Exps. 1b and 2b.

Both Exps. 1a and 2a demonstrate that serial, self-terminating search rates are slower if detection of a linearly separable target requires the processing of a conjunction of shape features (CONJ-LS) than if the target can be accurately detected on the basis of a single feature (1D-LS), cf. conjunction effect. These experiments also show that serial search rates are slower if a single-feature target is not linearly separable from its distractors (1D-NLS) than if it is (1D-LS), cf. linear non-separability effect. The conjunction and linear non-separability effects are replicated across shape sets that vary either along the dimensions of aspect ratio and curvature (Exp. 1a) or aspect ratio and tapering (Exp. 2a). One notable difference across Exps. 1a and 2a however, concerns the relative magnitude of the conjunction and linear non-separability effects. Whereas the conjunction effect was significantly greater than the linear non-separability effect in Exp. 1a, the reverse pattern was obtained in Exp. 2a. This reversal suggests that both effects are dissociable and thus that their account requires the assumption of distinct mechanisms.

### 4.1. Conjunction effect

The conjunction effect we find in our shape visual search experiments is congruent with the relatively inadvertent observation of Brown et al. (1992) cited in Section 1. These authors reported very fast, presumably preattentive, visual search for 3D target shapes that differed from homogeneous distractor displays according to either shape of cross-section or tapering along main axis. In contrast, search rates were considerably reduced when the target shared its defining features with distinct heterogeneous subsets of distractors, such that subjects had to encode a conjunction of features to correctly detect the target. Our observation of the conjunction effect in Exps. 1a and 2a however, was obtained under markedly better controlled conditions than those of Brown et al. (see Section 1) which, we argue, significantly increases the validity of the phenomenon.

Empirically, the conjunction effect is defined by a greater increase of RTs as a function of display size in the CONJ-LS than the 1D-LS condition. Given that these conditions were matched on both target–distractor similarity and distractor heterogeneity, the present conjunction effect can only be attributed to the fact that the detection of the target requires the processing of a conjunction of features in the CONJ-LS condition, but only of a single feature in the 1D-LS condition. In support of the hypothesis of distributed shape representations, this implies that visual encoding parses shapes according to a number of separate dimensions. In other words, the present results are congruent with the notion that initial shape representations are based on sets of discrete features, each characterising the stimulus on a particular dimension. Accordingly, the perceptual representation of conjunctions of shape features should require a special feature integration operation, which we believe is responsible for the slower search rates obtained in the CONJ-LS condition.

One possible limitation to the present conclusions regarding the distributed nature of initial shape representations which is important to emphasise is that they must, at present, be limited to the particular combinations of shape dimensions studied here, namely aspect ratio/curvature and aspect ratio/tapering. It remains conceivable that the present findings do not reflect a general principle of visual shape encoding, but rather that they are entirely specific to the combinations of dimensions used. Further research studying other combinations of shape features will be required before a general conclusion about the parsing of visual shapes into elementary dimensions can be reached.

Regarding potential future research, the crucial importance of the specific nature of the shape dimensions used must be emphasised. In particular, if the dimensions along which the shapes of stimuli are manipulated are poorly correlated with the actual dimensions used by the visual system to parse stimuli into a distributed representation, the evidence produced may wrongly point to a conclusion of integrated shape representations. Fig. 10 illustrates this kind of situation. In the stimulus domain, the target–distractor configuration illustrated in Fig. 10a meets the definition of the CONJ-LS conditions used here. However, the physical dimensions chosen to characterise the stimuli need not correspond exactly to the psychological dimensions used by the visual system to represent shapes, which remain largely unknown (see Section 1). In case of a mismatch, the relative locations of stimuli in psychological shape space will be distorted and, therefore, this internal representation will not meet the requirements of the intended CONJ-LS condition. One instance of such a distortion is illustrated in Fig. 10b, where the internal representation of the intended CONJ-LS target would in fact possess a unique value on psychological shape dimension A. This situation would most likely allow a fast rate of visual search similar to that obtained in a baseline 1D-LS condition. The absence of a conjunction effect in this case could not support a conclusion of integrated shape representations however, since the psychological representation of the stimuli does not obey the definition of the CONJ-LS condition.

This fundamental distinction between physical and psychological shape dimensions and its consequence regarding the visual search results that may be obtained across different target–distractor configurations has implications regarding the psychological validity of the dimensions studied here. Specifically, the fact that a conjunction effect was obtained in the current study with CONJ-LS targets defined by particular combinations of either aspect ratio and curvature or of aspect ratio and tapering provides support for the psychological validity of these dimensions. In other words, the occurrence of the conjunction effect in the present experiments suggests that the physical parameters along which shapes were manipulated either match or strongly correlate with those that contribute to an internal representation of shape in the visual system. Other previous data from Arguin et al. (1996) that was cited in Section 1 is also congruent with this conclusion.

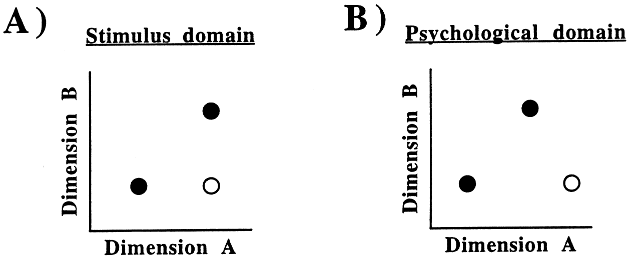

Fig. 10. Shape space locations of stimuli from an intended CONJ-LS target–distractor configuration. The white dot represents the target and black dots represent distractors. (A) Target–distractor configuration according to the physical dimensions by which shapes are characterised by the experimenter. (B) Possible form of the target–distractor configuration within psychological shape space if the physical dimensions are poorly matched to the dimensions actually used by the visual system to represent shapes.

### 4.2. *Linear non-separability effect*

A second major observation from the present research is the linear non-separability effect in the shape domain. The linear non-separability effect in visual search was first documented in the colour domain by D'Zmura (1991). His findings were later replicated and qualified in detail by Bauer et al. (1996a,b, 1998, 1999) and related observations have been reported in the orientation domain by Wolfe et al. (1992). The contrasting visual search performances with linearly separable and not linearly separable has been interpreted as resulting from a discrimination mechanism that allows the rapid and automatic detection of a target if a single straight line is sufficient to separate the representations of the target and its distractors in the relevant feature space. The present results demonstrate that the linear non-separability effect also exists in the shape domain, and this has been verified with shapes varying either along the dimensions of aspect ratio and curvature, or along aspect ratio and tapering. We therefore argue that the linear discrimination mechanism initially proposed by D'Zmura, in the colour domain may also apply in the shape domain. Further research involving other shape dimensions than those used here will be required to establish that this linear discrimination mechanism does constitute a general principle in visual shape processing.

One objection that may be raised against the notion of a linear discrimination mechanism in the shape domain is that CONJ-LS targets also produce low visual search rates despite their being linearly separable. Indeed, this result contradicts the rule that search rates should be fast in all cases where a linear boundary can separate the target from its distractors in shape space. However, the contradiction only exists when the issue of linear separability is conceived within an integrated shape space such as those illustrated on Figs. 3 and 7. Within an integrated shape space, the CONJ-LS condition is just one particular case of linear separability where the boundary separating the target from the distractors must be oriented obliquely relative to the main axes of shape space, i.e. the dimensions that define the space.

As argued in the preceding section however, the conjunction effect reported here suggests that the psychological shape space within which stimuli are initially represented is not an integrated space. Rather, it points to a system whereby *distinct mechanisms* are involved in coding the feature values of stimuli on different dimensions, which is the standard interpretation for conjunction effects (e.g. Treisman & Gelade, 1980; Treisman & Sato, 1990; Treisman & Gormican, 1988). In this context, a CONJ-LS target is no longer an instance of linear separability.

In fact, there is no single aspect of a distributed representation that allows reliable target–distractor discriminations in the CONJ-LS condition, be it through a linear mechanism or not. Thus, the CONJ-LS target is identical to one set of distractors on a particular critical dimension (e.g. aspect ratio) and identical to the other set of distractors on the other critical dimension (e.g. curvature). Only subsequent to a feature integration operation is it assumed that the conjunctions of shape features required for the detection of CONJ-LS targets become available. Therefore, the results from the CONJ-LS condition do not oppose the hypothesis of a linear discrimination mechanism since the level of processing at which this mechanism is assumed to operate does not support target–distractor discriminations in the CONJ-LS condition[5].

Important differences may be noted however, between the results reported here and those of previous studies demonstrating linear non-separability effects in visual search (Bauer et al., 1996a,b, 1998, 1999; D'Zmura, 1991; Wolfe et al., 1992). One of these differences pertains to the effect of the orientation of the linear boundary separating the target from distractors. The CONJ-LS condition of the present experiments forces this boundary to be oriented obliquely when considered within an integrated shape space and this situation is associated with slow search rates. In contrast, linear boundaries that are oriented obliquely in relation to the main axes of colour space seem to pose no particular problem in the visual search for a colour target (multiple examples of this may be found in Bauer et al., 1996a,b, 1998, 1999; D'Zmura, 1991). In nearly all the cases documented thus far however, the linear boundary separating the target from distractors could actually be oriented orthogonally to one of the main axes of colour space since the targets possessed a unique feature value on at least one of the critical colour dimensions. Nevertheless, a number of tests were conducted by D'Zmura (1991) where the linearly separable colour targets could be construed as conjunctions of distractor features (see Figs. 2c, 3c and 8c,d in D'Zmura, 1991). These conditions invariably led to very fast visual search rates. Assuming the colour dimensions manipulated by D'Zmura. are valid, these observations suggest that colour representations are integrated, in contrast to the distributed nature of initial shape representations documented here (see discussion above).

In the previous visual search studies on the linear non-separability effect, linearly separable single-feature targets displayed among heterogeneous distractors almost invariably resulted in relatively faster search rates (slopes on negative trials almost never exceeding 20 ms/item) than those observed here in the 1D-LS condition (weakest slope on negative trials: 31 ms/item; Exp. 1a). Exceptions to this rule have been reported by Bauer et al. (1996a): Fig. 18; 1999: Exps. 1 and 2) however, who obtained colour visual search slopes on negative trials as high as 65 ms/item in some linearly separable conditions. One factor that has been implicated in these slow search rates is the reduced capacity of subjects to resolve the differences between the target and distractors when they are close together in colour space. The relatively slow search rates observed here with 1D-LS targets in Exps. 1a and 2a also seem to involve this factor, as discussed in Section 4.3.

### 4.3. The contribution of preattentive processing

Another finding of interest in the present set of experiments is the very fast, apparently preattentive search rates that we observed in Exps. 1b and 2b. In these experiments, all distractors were made of the same shape (i.e. homogeneous distractors) whereas two distinct shapes served as distractors in Exps. 1a and 2a (i.e. heterogeneous distractors). The fact that the search rates obtained with the heterogeneous distractors of the 1D-LS condition (which yielded the fastest search rates) of Exps. 1a and 2a are substantially slower than with the homogeneous distractors of Experiments 1b and 2b may appear surprising. Indeed, in all cases, the target was linearly separable from distractors and could be distinguished from them by a unique feature. This finding may be readily explained however if we assume that the shape representations on which visual search is based are not exact, but rather involve some degree of noise, e.g. a spread of activation along a range of feature values (e.g. see Rosenholtz, 1998 and Wolfe et al., 1992 for relevant proposals in the motion and orientation domains, respectively). Under this assumption, the level of activation produced by the distractors for feature values lying on the target side of the decision boundary in shape space is likely to be greater if the distractors are heterogeneous (Exps. 1a and 2a) than if they are homogeneous (Exps. 1b and 2b). This difference would account for the faster and apparently preattentive search rates observed in the latter experiments.

Congruent with the proposal that preattentive mechanisms may contribute to shape visual search are the observations from the 1D-LS conditions of Exps. 1a and 2a. Findings from these conditions suggest a serial self-terminating search, but the positive/negative slope ratios are relatively low compared to the theoretically

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[5] An alternative counter-argument to the objection discussed here might simply be to assume that the linear discrimination mechanism can only be oriented perpendicularly to one of the axes (i.e. dimensions) defining the shape space under study, and therefore that it is ineffective when the linear boundary separating the target from distractors must be oriented obliquely, as in the CONJ-LS condition. Such an argument does not solve the issue however, since it begs the question of what determines this constraint, which otherwise appears arbitrary.

ideal value of 0.5 (Tables 1 and 3). This may be explained by the assumption that preattentive shape discrimination mechanisms may contribute in guiding attention towards the target location in the serial search for a 1D-LS target (Wolfe, 1994). Obviously, such preattentive guidance may occur only on trials where the target is present. This would therefore cause faster search rates on positive trials than those predicted by the results on negative trials, as we observe here. Preattentive guidance seems unavailable in the CONJ-LS and 1D-NLS conditions however, as the positive/negative slope ratios in these conditions are very close to 0.5 in both Exps. 1a and 2a.

## 5. Conclusion

This paper has reported a series of visual search experiments using shapes varying along the pairs of dimensions aspect ratio/curvature or aspect ratio/tapering. The results show modulations of visual search performance according to the nature of the structural relations existing between the target and its distractors. Most importantly, the observations indicate that: (1) in visual encoding, the shapes used here are parsed into a distributed representation according to elementary features, each characterising the item on a particular shape dimension; (2) processing conjunctions of features on the pairs of dimensions aspect ratio/curvature or aspect ratio/tapering requires a time consuming feature integration process; (3) a linear discrimination mechanism is available in shape processing, which permits relatively fast visual search rates if a single-feature target is linearly separable from its distractors in shape space compared to when it is not; and (4) preattentive search for visual shapes is possible when the target differs from homogeneous distractors by a single feature.

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