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Distinct mechanisms account for the linear non-separability and conjunction effects in visual shape encoding

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In a series of visual search experiments involving simple 2D shapes, Arguin and Saumier (2000) showed that targets that were made of conjunctions of distractor features or that were a linear combination of distractor features were searched at significantly slower rates than single-feature linearly separable targets. The present study assessed whether these conjunction and linear nonseparability effects can be attributed to distinct mechanisms. Specifically, we studied the impact of target–distractor similarity on the search rates for single-feature, conjunction, and linearly nonseparable targets. The results replicate the conjunction and linear nonseparability effects obtained by Arguin and Saumier. They also show that the conjunction and linear separability effects are differently modulated by variations in target–distractor similarity. This dissociation demonstrates that both effects are based on distinct mechanisms. The possible nature of these mechanisms is discussed.

INTRODUCTION

The visual system is often confronted with the problem of detecting objects that are surrounded by distracting visual information. Important insights into the perceptual mechanisms that solve this problem have been gained from research employing the visual search task. In this task, subjects report the presence or absence of a prespecified target from among varying numbers of distractors. Efficiency of target search is jointly determined by the type of

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contrast by which the target differs from distractors and by the number of items in the display (see Wolfe, 1998, for a review).

Numerous studies have found that search performance tends to be more affected by display size if the target is made of a conjunction of distractor features than if it differs from distractors by a unique feature (e.g., Treisman & Sato, 1990). This difference (cf. conjunction effect) suggests that early visual representations do not code the integral objects, but instead are made of a distributed collection of discrete elementary features (see also, e.g., Treisman & Gelade, 1980). Consequently, the representation of feature combinations required in the conjunction condition necessitates an additional integration operation that is costly in terms of processing time, thus resulting in larger slopes of response time as a function of set size than with single-feature targets. The notion of early visual representations as being distributed has been largely supported by visual search studies investigating the conjunction effect with feature combinations from distinct stimulus domains, such as colour and shape. In contrast, within-domain conjunctions have so far been little studied.

Arguin and Saumier (2000) have recently reported a conjunction effect with feature combinations from within the shape domain. They used simple 2D ellipsoids varying on the global dimensions of aspect ratio/curvature or aspect ratio/tapering (see Figure 1 for an illustration of the class of shapes used) in the context of the visual search task. Importantly, the features defining these shapes are not local spatially, in contrast to other conjunctions of shape features that had been examined previously (e.g., Treisman & Patterson, 1984). Rather, the shape features studied by Arguin and Saumier are global and reflect properties of the whole stimulus. Their observation of a conjunction effect with such stimuli implies that early

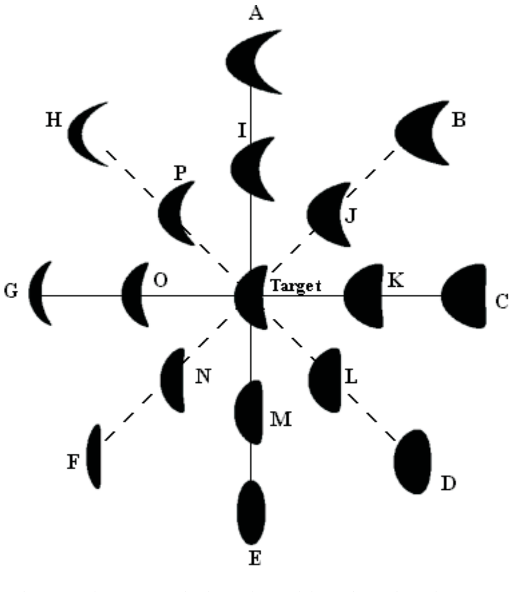

Figure 1. Stimuli used in the experiment. Each shape is positioned at a location corresponding to its location in a shape space made of the dimensions of aspect ratio (horizontal axis) and curvature of main axis (vertical axis).

representations of even global visual shapes are made of collections of distributed features, each coding a particular property of the stimulus, such as its aspect ratio or its curvature.

In their visual search study, Arguin and Saumier (2000) reported observations relevant to another key issue: that regarding the decision mechanisms involved in visual shape discrimination (e.g., Ashby, 1992). Thus, they found that the search rate for a single-feature target is affected by whether its defining features are a linear combination of those of the distractors. If they are, the target is said to be linearly nonseparable from the distractors—that is, no single straight line can separate the location of the target in shape space (with dimensions corresponding to the relevant stimulus properties) from those of the distractors. If the target is not made of a linear combination of distractor features, then it is said to be linearly separable since a straight line can separate the target location in shape space from those of the distractors.[1] Results showed that the rate of visual search was much slower if the target was not linearly separable from the distractors than if it was. This result, referred to as the linear nonseparability effect, has also been observed in the colour and orientation domains (e.g., Bauer, Jolicoeur, & Cowan, 1996a,1996b, 1998, 1999; D'Zmura, 1991; Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992). The linear nonseparability effect suggests the existence of a linear mechanism in the relevant representation domain that allows the fast detection of the target if it is linearly separable from distractors. If such a mechanism cannot apply, as in the linearly nonseparable case, a more complex decision process must be involved, leading to increased slopes of response times as a function of set size.

Dissociating the conjunction vs. linear nonseparability effects

As a matter of principle, the conjunction and linear nonseparability effects described by Arguin and Saumier (2000) appear to be functionally independent—that is, they seem to result from distinct processing mechanisms. Thus, while the conjunction effect is assumed to be a function of the distributed format of early visual shape representations, the linear nonseparability effect appears to be a function of the decision mechanisms involved in visual shape discrimination. More convincingly, the observations of Arguin and Saumier (2000) showed that the relative magnitudes of the conjunction and linear nonseparability effects varied according to the particular dimensions along which the shapes were manipulated. Thus, the conjunction effect was significantly greater than the linear nonseparability effect with shapes varying on aspect ratio and curvature, whereas it was the reverse with shapes varying on aspect ratio and tapering. This reversal suggests that the conjunction and linear nonseparability effects are dissociable and therefore that distinct mechanisms must be assumed to account for them. This evidence for a dissociation remains circumstantial, however.

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[1] It should be noted that conjunction targets are always linearly separable from distractors. Therefore, the contrast condition used by Arguin and Saumier (2000) to assess the occurrence of a conjunction effect was one involving a single-feature target that was linearly separable from distractors.

The literature on the conjunction and linear nonseparability effects suggests an experimental procedure to dissociate them. Indeed, it appears that the occurrence of a linear nonseparability effect (in the colour domain) is strongly dependent on the presence of a sufficient degree of similarity between the target and its distractors (Bauer et al., 1996b; Duncan, 1989). In contrast, the occurrence of the conjunction effect has been shown to be impervious to a manipulation of target–distractor similarity (Treisman & Gelade, 1980; stimuli varying in shape and colour; but see Wolfe, Cave, & Franzel, 1989). The goal of the current study is to examine how the conjunction and linear nonseparability effects in the visual search task are modulated as a function of target–distractor similarity using the same class of shapes as those of Arguin and Saumier (2000). A differential impact of target–distractor similarity on the conjunction and linear nonseparability effects will provide the direct experimental evidence lacking from the Arguin and Saumier study that these effects differ in their causal mechanisms.

The present study

The present study reexamined the effect of the type of contrast existing between the target and a pair of other shapes that served as distractors. One type of target–distractor contrast served as the baseline condition, where subjects searched for single-feature linearly separable targets (1D–LS condition; Figure 2a). Another condition involved linearly separable targets that shared each of their shape features with either of the distractors (linearly separable/conjunction, CONJ, condition; Figure 2b). Two types of single-feature linearly nonseparable targets were used, both of which were made of a linear combination of distractor features. One was similar to the linearly nonseparable condition of Arguin and Saumier (2000), where targets and distractors all differed mutually on both relevant shape dimensions. Thus, the location of the target in shape space was the midpoint of an oblique line (relative to the main axes of shape space) joining the two distractor locations: linearly nonseparable (oblique), LNS(o) condition; Figure 2c. The other linearly nonseparable condition involved targets and distractors whose shapes differed mutually on only one shape dimension, thus constituting a target–distractor configuration that ran in a straight line parallel to one of the main axes of shape space: linearly nonseparable (parallel), LNS(p) condition, Figure 2d. This new condition was used in order to determine the generality of the linear nonseparability effect previously demonstrated by Arguin and Saumier.

A new crucial factor in the present experiment was the similarity of the target with the distractors displayed with it. While some studies suggest that changes in target–distractor similarity may affect the magnitude of the linear nonseparability effect, others indicate that such changes may have a smaller impact on the conjunction effect. However, no systematic examination of the modulation of both the linear nonseparability and conjunction effects as a function of target–distractor similarity has yet been performed within the same study and with the same class of stimulus. The present investigation demonstrates that changes in target–distractor similarity have a differential impact on the conjunction and linear nonseparability effects, and therefore that they require distinct explanatory bases.

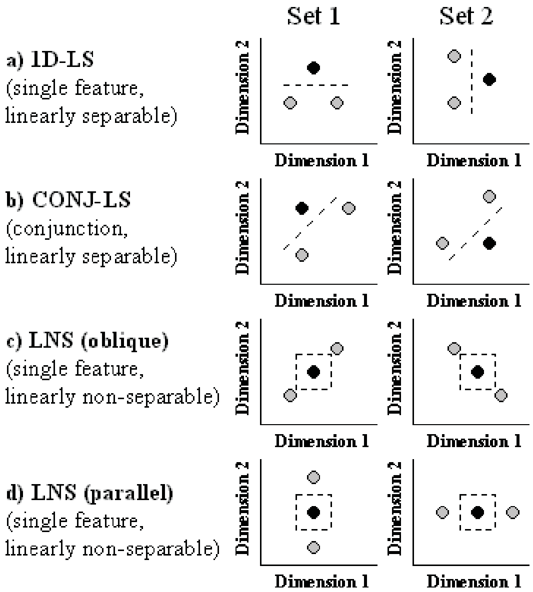


Figure 2. Illustration of the locations in shape space for the different target–distractor conditions used in the present experiment. The target–distractor conditions illustrated in 2a, 2b, and 2c are the same as those used by Arguin and Saumier (2000). White dots represent the target location in shape space, and black dots stand for distractor locations. The dashed lines indicate the decision boundaries that allow a segregation of the target from distractors in shape space. (a) The 1D–LS target is distinguished from distractors by a unique feature value and is linearly separable from the distractors. (b) The CONJ target shares one feature with each distractor and is linearly separable from the distractors. (c) The LNS(o) target is not linearly separable from the distractors and is made of a linear combination of the feature values characterizing the distractors, which mutually differ on two shape dimensions. (d) The LNS(p) target is not linearly separable from the distractors and is made of a linear combination of distractor features. Distractors in this condition differ from each other along a single dimension (see text for explanation of abbreviations).

EXPERIMENT 1

Method

Participants

A total of 14 University of Montréal undergraduate and graduate students (4 males and 10 females) aged between 20 and 39 years participated in the experimental phase for a nominal monetary compensation. All participants had normal or corrected vision.

Stimuli

The target and distractors were synthetic shapes created by parametrically deforming a filled 2D ellipsoid along the dimensions of aspect ratio (i.e., ratio of lengths of minor over major axes) and curvature along the major axis, as illustrated in Figure 1 (see Arguin, Bub, & Dudek, 1996, for additional details). The length of the major axis of all stimuli was normalized to 8 cm (4.8 degrees of visual angle, from a viewing distance of 95 cm), while the length of the minor axis varied according to the particular aspect ratio value of the stimulus. Stimuli were presented in solid black on a white background.

Two target–distractor sets were constructed for each of the linearly separable (single), linearly separable (conjunction), linearly nonseparable (oblique), and linearly nonseparable (parallel) conditions. Figure 1 presents the entire set of stimuli in a two-dimensional shape space defined by the dimensions of aspect ratio (horizontal axis) and curvature (vertical axis). The stimuli included one target (T) that remained the same in all conditions and 16 different shapes that served as distractors. Half of the potential distractors were similar (i.e., close in shape space) to the target, and the other half were dissimilar (i.e., distant in shape space).

The parameters defining the shapes used were determined by an independent group of six observers who adjusted the aspect ratio and/or curvature of stimuli in order to meet the subjective criteria described below by using a computer program. This procedure was preferred to the alternative of generating the desired set of shapes according to some particular mathematical function, whose relation to the psychological dimensions actually used by the visual system, which we intended to target, would remain unknown. The procedure began with the experimenters initially fixing the feature values defining the shapes of the target T and of the dissimilar distractor E (see Figure 1). These stimuli served as the reference for target–distractor similarity for the production of the remaining distractors.

The dissimilar distractors were subsequently produced by having six other independent observers view shapes T and E (which remained visible throughout the process of generating the dissimilar distractors) and create distractor C by increasing the aspect ratio of a copied target such that the overall similarity between the new item C and the original target was comparable to that between the target and distractor E. Subjects pursued their adjustments until they felt they had met the imposed constraints. Distractors A and G were then generated by using the same procedure, but by either increasing the curvature of the target (to produce distractor A) or decreasing the aspect ratio of the target (to produce distractor G). The aspect ratio and curvature values of the distractors A, C, and G used in the visual search task were averages of those produced by all subjects. The subjects then created (by altering in the proper directions the curvature and aspect ratio of target copies) shapes B, D, F, and H using the same criterion as before. In addition, however, they were also asked to ensure that these new shapes were equally similar to each of their neighbouring distractors (e.g., A and C for the generation of distractor B), which were also shown on screen. Again, the final distractors B, D, F, and H used in the experiment were produced on the basis of the average adjustments performed by all subjects.

To generate each of the similar distractors (I, J, K, L, M, N, O, and P), subjects viewed separately the target with each dissimilar distractor and adjusted the curvature and/or aspect ratio of a copied target such that each new item was as similar overall to the original target as it was to the dissimilar distractor. Thus, the shape space location of each similar distractor was adjusted to be at a subjective midpoint between the target and a dissimilar distractor. The similar distractors used in the experiment were made of the average curvature and aspect ratio values produced by the subjects.

Two target–distractor sets were constructed for each of the similar and dissimilar linearly separable (single), linearly separable (conjunction), linearly nonseparable (oblique), and linearly nonseparable (parallel) conditions (shapes listed in Table 1 and illustrated in Figure 2). All stimulus sets consisted of the same target and of two distinct distractors. In the linearly separable (single) condition, the target differed from all distractors by a unique feature, and a linear decision boundary could separate its location in shape space from those of the distractors. For the linearly separable (conjunction) condition, the target shared a distinct feature with each of its distractors and thus was effectively made of a combination of distractor features. In the linearly separable (conjunction) condition, the location of the target in shape space was linearly separable from those of the distractors. In the linearly nonseparable (oblique) condition, the target was made of a linear combination of the feature values of the distractors, which differed mutually on both aspect ratio and curvature. In shape space, the location of a linearly nonseparable (oblique) target was halfway on the straight line joining the two distractor locations, which ran at a 45-degree angle relative to the main axes of shape space. In the linearly nonseparable (parallel) condition, the target was defined by a linear combination of the feature values of the distractors, which differed from

TABLE 1
List of distractor sets involved in the target–distractor conditions

	Distractor sets			
	Similar		*Dissimilar*	
Condition	*Set 1*	*Set 2*	*Set 1*	*Set 2*
1D-LS	N-L	P-N	D-F	F-H
CONJ	K-M	I-O	A-G	C-E
LNS(o)	J-N	L-P	B-F	D-H
LNS(p)	K-O	I-M	A-E	C-G

each other on either aspect ratio or curvature. Thus, in shape space, the target in the linearly nonseparable (parallel) condition was halfway along the straight line joining the two distractor locations, which ran parallel to one of the main axes of this space.

The similarity judgements effected to construct the stimuli ensured that target–distractor similarity was equated across conditions. However, such judgements may be subject to cognitive factors that are unrelated to speeded recognition performance. For this reason, the stimuli were submitted to a visual search control study (described below) in order to validate the preexperimental similarity ratings.

Procedure

One block of 160 trials was constructed for each target–distractor set listed in Table 1, thus resulting in a total of 16 blocks. Each block was made of an equal number of trials for each combination of display size (four levels: 3, 5, 7, or 9) and target presence (two levels: present or absent), and these trials were presented in a random order. On positive trials, only one instance of the target was presented at a randomly selected location, and each distractor of the particular target–distractor set tested was replicated an equal number of times at other randomly selected locations. In order to maintain set size constant across positive and negative trials, an unequal number of exemplars of each distractor was presented on negative trials. In these instances, the numbers of exemplars of each distractor always differed by one, with each distractor occurring an equal number of times within each block.

Each experimental subject, who had not participated in the stimulus generation procedure (described above) nor in the pilot study (described below), completed eight blocks of trials, one for each combination of target–distractor condition—linearly separable (single), linearly separable (conjunction), linearly nonseparable (oblique), and linearly nonseparable (parallel)—and distractor similarity (similar vs. dissimilar). The set of stimuli used on a particular block of trials was determined randomly, with the constraint that each block was completed an equal number of times across subjects. The order in which blocks were administered to a subject was also random.

Each trial began with the presentation of a 500-ms fixation asterisk (Geneva, 24 point) at the centre of the screen. It was followed immediately by the search array, which remained on the screen until the subject responded. The stimuli were randomly located at 1 of 12 equally spaced locations of an imaginary circle of 9.5-degree diameter centred on the fixation point. The next trial began 1 s after the subject responded.

Subjects were instructed to respond as quickly and as accurately as possible with the index finger of the left or right hand by pressing a key on the left or right side of a computer keyboard (right side = “command” key; left side = “keypad-0” key), respectively, depending on whether the target was present or not. The side of the “target-present” and “target-absent” buttons was counterbalanced across subjects. Subjects were permitted to take pauses between the eight blocks of trials, and a minimum 20-min pause was imposed after the subject completed half of the blocks. The average duration of the experiment was approximately 90 min.

Similarity-control pilot study

The complete distractor sets used were identical across the linearly separable (single) and linearly nonseparable (oblique) conditions and across the linearly separable (conjunction) and linearly nonseparable (parallel) conditions. The pilot study described in this section ensured that target–distractor similarity was also matched across conditions involving different ensembles of distractors. An independent group of 8 subjects searched for the target among homogeneous sets of distractors (see Arguin & Saumier, 2000, for a similar procedure). Half of the subjects searched for the target from among multiple instances of a single distractor serving in the linearly separable (single) and linearly nonseparable (oblique) conditions, while the other half searched for the target from among multiple instances of a single distractor serving in the linearly separable (conjunction) and linearly nonseparable (parallel) conditions. In either case, the particular shape used as the distractor was varied randomly across trials. Otherwise, the procedure was the same as that described for the main experiment.

Outlier correct response times (RTs) from the pilot study were removed from the individual data if they were further than 2.5 standard deviations away from the subject's mean within each condition. Errors were not analysed because they accounted for less than 1% of the data points for any given subject. Table 2 shows the average search rates, intercepts, and *R*-squares obtained from the linear regression analyses of the RTs as a function of display size for the combined linearly separable (single) + linearly nonseparable (oblique) and linearly separable (conjunction) + linearly nonseparable (parallel) conditions.

A four-way analysis of variance (ANOVA) of correct RTs was conducted using the factors of target presence (present vs. absent), distractor similarity (similar vs. dissimilar), target–distractor condition—linearly separable (single)/linearly nonseparable (oblique) vs. linearly separable (conjunction)/linearly nonseparable (parallel) sets—and display size (3, 5, 7, or 9 items). The effect of target–distractor condition was analysed between subjects, while all other factors were analysed within subjects. This analysis showed main effects of target presence, $F(1, 6) = 17.1$, $p < .001$, similarity, $F(1, 6) = 47.8$, $p < .001$, and display size, $F(3, 18) = 17.1$, $p < .001$. Subjects were faster to respond when the target was present than when it was absent and when target and distractors were visually dissimilar than when they were visually similar. RTs also increased linearly as display size increased. Most importantly, however, there was no main effect of target–distractor condition, $F(1, 6) < 1$, nor any significant interaction involving this factor, all *F*s < 1. This indicates that the different target–distractor conditions studied here are matched in terms of the difficulty of discriminating between the target and the individual

TABLE 2
Linear regressions of correct RTs as a function of display size for each condition of the similarity-control pilot study

		Similar			*Dissimilar*		
	Condition	*Intercept*	*Slope*	R^2	*Intercept*	*Slope*	R^2
Target present	1D-LS and LNS(o)	526.9	18.7	.99	501.9	7.8	.89
	CONJ and LNS(p)	537.4	19.3	.99	502.5	6.0	.93
Target absent	1D-LS and LNS(o)	558.0	32.4	.99	518.6	15.1	.97
	CONJ and LNS(p)	582.6	28.4	.99	547.9	6.8	.83

distractors used in these conditions. Thus, it will not be possible to attribute differences in search rates across the different target–distractor conditions in the main experiment to a target–distractor similarity artefact.

Results

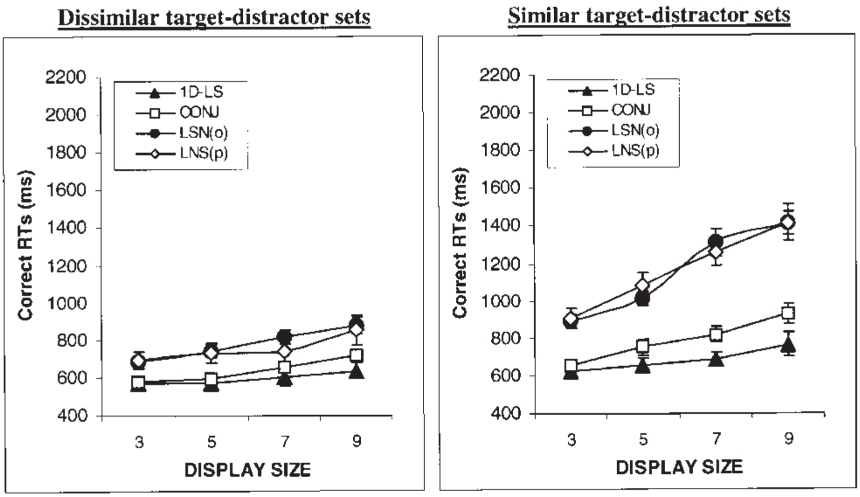
Error trials in the experimental observations were removed from the data of each subject, but were not analysed since they accounted for less than 3.2% of the trials for any condition. Outlier RTs were also removed if they were more than 2.5 standard deviations away from the subject's average RT for that condition (5.2% of remaining data points). The correlation between RTs and errors was +.01 (*ns*), indicating that there was no speed–accuracy trade-off. Figure 3 shows the mean correct RT's as a function of display size for each condition. The results of the linear regression analyses relating the mean RTs to display size are reported in Table 3.

A four-way within-subject ANOVA was performed on correct RTs with the factors of target presence (present vs. absent), distractor similarity (similar vs. dissimilar), target–distractor condition—linearly separable (single), linearly nonseparable (oblique), linearly nonseparable (parallel), linearly separable (conjunction)—and display size (3, 5, 7, or 9 items). All main effects were significant. These indicated a significant variation of RTs as a function of target–distractor condition, $F(3, 39) = 31.2$, $p < .001$, increasing RTs as a function of display size, $F(3, 39) = 92.2$, $p < .001$, and shorter RTs on target-present than target-absent trials, $F(1, 13) = 56.3$, $p < .001$ as well as with dissimilar than with similar distractors, $F(1, 13) = 105.9$, $p < .001$. All of the interactions between each of the four factors were significant (all $p < .01$), except for the four-way interaction, which was not significant, $F(1, 117) = 1.02$, *ns*. Of notable interest is the significant two-way interaction of Target–Distractor Condition × Display size, $F(9, 117) = 15.4$, $p < .001$, which reflects differences in search rates as a function of target–distractor condition. Of greatest importance, however, is the significant three-way interaction of Similarity × Target–Distractor Condition × Display Size, $F(9, 117) = 4.9$, $p < .001$, which indicates that search rates across the target–distractor condition conditions are differently affected by variations of target–distractor similarity. Each of these two interactions was followed up by planned comparisons, as follows.

TABLE 3
Linear regressions of correct RTs as a function of display size for each condition

		Similar			*Dissimilar*		
	Condition	*Intercept*	*Slope*	R^2	*Intercept*	*Slope*	R^2
Target present	1D-LS	547.7	22.2	.93	511.1	11.6	.93
	CONJ	517.8	45.0	.99	466.5	23.7	.94
	LNS(o)	653.7	85.2	.99	583.1	24.1	.85
	LNS(p)	506.1	92.9	.96	546.5	32.9	.99
Target absent	1D-LS	499.8	89.9	.95	480.1	27.1	.97
	CONJ	480.4	122.8	.99	471.8	58.0	.99
	LNS(o)	597.4	166.8	1.0	413.3	77.0	.97
	LNS(p)	483.8	154.9	1.0	528.1	52.1	.99

A) Target Present



B) Target Absent

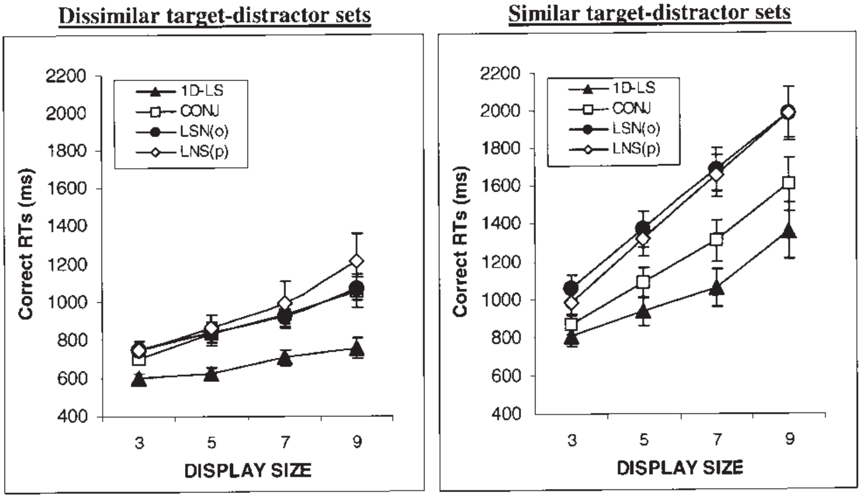


Figure 3. Average correct RTs and standard errors as a function of display size for each target–distractor condition on target present (A) and target absent (B) trials for dissimilar and similar target–distractor sets (see text for explanation of abbreviations).

In order to assess the presence of the conjunction and linear nonseparability effects, the Target–Distractor Condition × Display Size interaction was broken down by conducting planned pairwise comparisons between the baseline linearly separable (single) condition and each of the linearly nonseparable (oblique), linearly nonseparable (parallel), and linearly separable (conjunction) conditions on the effect of display size. The results showed a significantly faster search rate in the linearly separable (single) condition than in the linearly nonseparable (oblique), $F(3, 39) = 21.9$, $p < .001$, the linearly nonseparable (parallel), $F(3, 39) = 35.7$, $p < .001$, and the linearly separable (conjunction), $F(3, 39) = 11.1$, $p < .001$, conditions. These findings indicate that the linearly separable (single) condition produces faster search rates than any of the other conditions.

The most critical issue in the present experiment is whether changes in distractor similarity have different effects on search rates across the different target–distractor conditions studied. Examination of this issue involved planned pairwise comparisons of the linearly separable (single) condition against the linearly nonseparable (oblique), linearly nonseparable (parallel), and linearly separable (conjunction) conditions on the joint effects of similarity and display size. A significant Similarity × Display Size × Target–Distractor Condition interaction in these comparisons indicates that the search rates for the pair of target–distractor contrasts compared are affected to different degrees by changes in the similarity between the target and distractors. Significant Similarity × Display Size × Target–Distractor Condition interactions were found when the linearly separable (single) condition was compared to the linearly nonseparable (oblique), $F(3, 39) = 13.0$, $p < .001$, and linearly nonseparable (parallel) conditions, $F(3, 39) = 13.9$, $p < .001$. However, the Similarity × Display Size × Target–Distractor Condition interaction was not significant when the linearly separable (single) condition was compared to the linearly separable (conjunction) condition, $F(3, 39) < 1$. Moreover, significant Similarity × Display Size × Target–Distractor Condition interactions were also found when the linearly separable (conjunction) condition was compared to the linearly nonseparable (oblique), $F(3, 39) = 5.6$, $p < .001$, and linearly nonseparable (parallel), $F(3, 39) = 13.9$, $p < .001$, conditions. However, the triple interaction of similarity, display size, and target–distractor condition was not significant when the linearly nonseparable (oblique) and linearly nonseparable (parallel) conditions were compared, $F(3, 39) < 1$, to each other.

Linear regression analyses of RTs as a function of display size for each condition (Table 3) indicate that all conditions produced linear display size effects and positive/negative slope ratios that approximate 0.5, which is consistent with a serial self-terminating search. Congruently with the results from the above ANOVA, the differences in search rates as a function of target–distractor similarity are much greater for the linearly nonseparable (oblique) and linearly nonseparable (parallel) conditions than for the linearly separable (single) or linearly separable (conjunction) conditions.[2]

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[2] Arguin and Saumier (2000) found that the linearly nonseparable condition produced faster search rates than the linearly separable (conjunction) condition. In contrast, the present findings show that search rates in the linearly separable (conjunction) condition were relatively slower than those in the linearly nonseparable conditions. However, the targets and distractors used in Arguin and Saumier (2000) were more visually disssimilar than those used in the current study. We also note that there is a greater variation in search rates across studies as a function of target–distractor similarity for linearly nonseparable targets than for linearly separable (conjunction) targets. Thus, the difference in results between the two studies appears to be due to a greater impact of target–distractor similarity in the linearly nonseparable condition than in the linearly separable (conjunction) condition, which is congruent with the evidence shown here.

Discussion

One important observation from the present study is that visual search performance is largely dependent on the factors of linear separability and feature sharing that distinguish the different types of target–distractor conditions tested. In particular, if a target is not linearly separable from the distractors, or if it is made of a conjunction of the features that define the distractors, then the search rates are significantly slower than those when the target differs from distractors by a single feature and is also linearly separable from them. These results concur with those of Arguin and Saumier (2000).

The present study goes further by demonstrating that changes in target–distractor similarity affect search performance differently across the different target-distractor conditions that were studied. Specifically, the manipulation of target–distractor similarity had a much greater impact on visual search performance in the linearly nonseparable (oblique) and linearly nonseparable (parallel) conditions than in either the linearly separable (single) or linearly separable (conjunction) conditions.

This impact may be quantified. From the evidence indicating that search in all conditions was serial and self-terminating, the time required to process an individual item with particular target–distractor configurations and similarities may be estimated as $((2^*p) + n)/2$; where p and n are the slopes on positive and negative trials, respectively. Based on these estimates, the processing time for an individual item increased by 111.4 ms and by 106.0 ms with increased target–distractor similarity in the linearly nonseparable (oblique) and linearly nonseparable (parallel) conditions, respectively. With an identical increase in target–distractor similarity, processing times for individual items in the linearly separable (single) and linearly separable (conjunction) conditions increased only by 42.0 and 53.7 ms, respectively. This observation implies that the effect of linear nonseparability—that is, linearly nonseparable (oblique) or linearly nonseparable (parallel) vs. linearly separable (single)—is much more sensitive to manipulations of target–distractor similarity than is the conjunction effect—that is, linearly separable (conjunction) vs. linearly separable (single).

This result cannot be attributed to artefactual differences in target–distractor similarity across the different types of target–distractor condition that were examined. Indeed, as demonstrated above by the similarity-control experiment, these conditions were appropriately matched in terms of the shape similarity between the target and distractors. As explained in the Introduction, the differential impact of target–distractor similarity on the conjunction and linear nonseparability effects means that they are dissociable from each other and, consequently, that each of these effects is based on distinct mechanisms. In other words, it is argued that an account of the lower search rates in the linearly nonseparable and linearly separable (conjunction) conditions relative to the linearly separable (single) baseline requires different explanatory bases, which differ in their sensitivity to target–distractor similarity.

Figure 4 helps illustrate the mechanisms we propose to be involved in the conjunction and linear nonseparability effects. As indicated previously, the conjunction effect implies that visual shapes are initially parsed according to a number of distinct dimensions, each having its own processing module that signals the feature value of the stimulus on that dimension. Similarly to signal-detection theory (Green & Swets, 1966), it is assumed that stimulus features on any dimension are represented probabilistically along a range of values that is normally distributed around a mean corresponding to the actual feature value of the

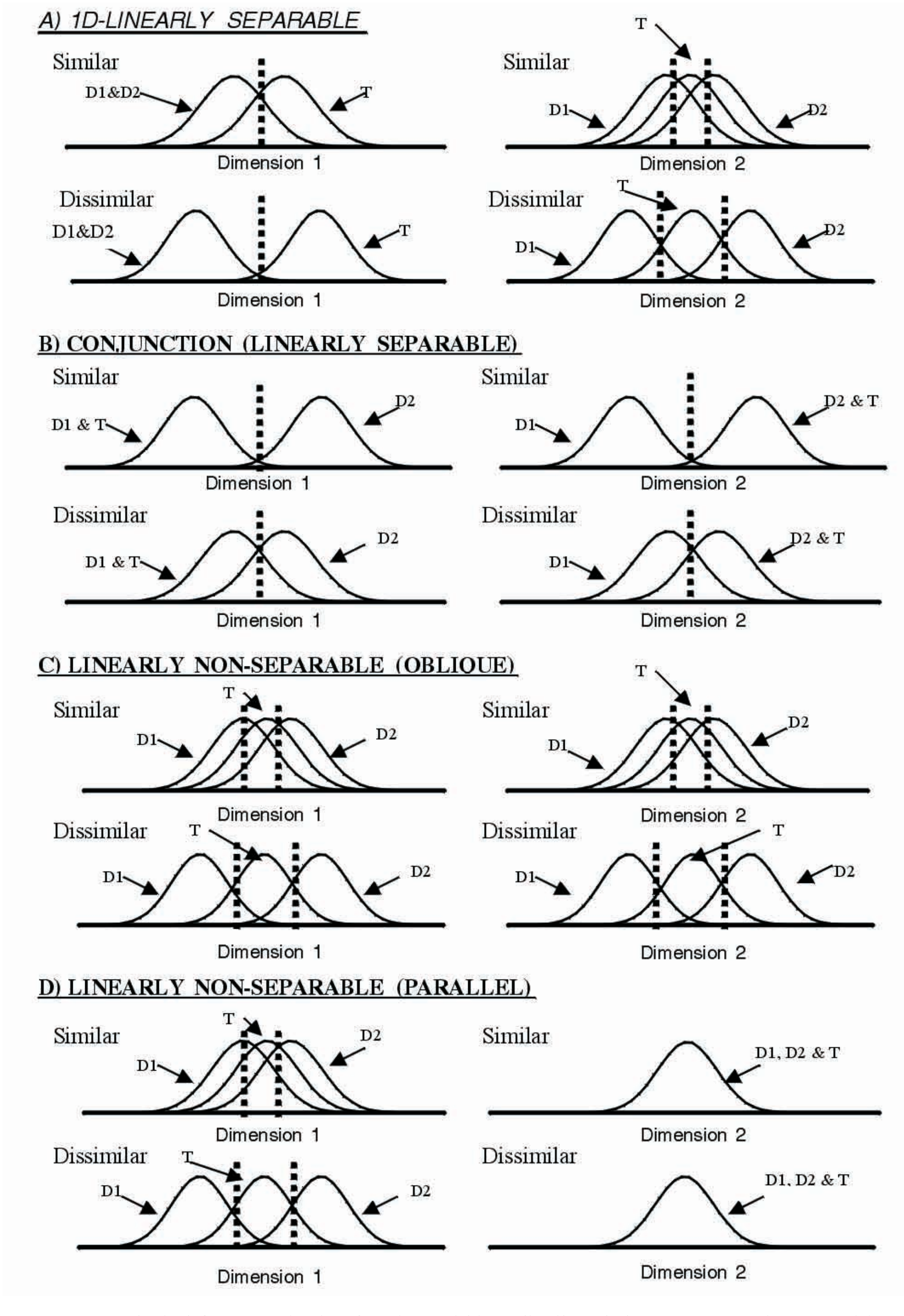

Figure 4. Hypothetical feature activation functions within a distributed shape representation comprising two dimensions for each of the stimuli involved in the different target–distractor conditions studied here. Dashed horizontal lines represent decision boundaries for discriminating between target and distractors. Shared features among items are represented by completely overlapping feature activation functions. See text for other details regarding this figure and for explanation of the abbreviations.

stimulus. It is also assumed that feature discriminations within a particular dimension depend on decision boundaries that are placed at particular points on the feature continuum in order to separate the activation function corresponding to the target from those associated with the distractors.[3]

In the linearly separable (single) condition, the observers may detect the target on the basis of its unique feature value, which may be greater or lesser than those defining the distractors along one dimension (see Figure 2a). A single decision boundary can therefore be placed on Dimension 1, for instance, to discriminate the target from both distractor shapes. In this case, if feature activity is detected for a particular item in the search array that is above the feature value specified by the decision boundary on Dimension 1, the subject should indicate that the target is present. Figure 4a also illustrates the basis for the target–distractor similarity effect observed in the linearly separable (single) condition. Thus, it can be seen that an increase in target–distractor similarity (i.e., reduction of shape-space distance between the items) results in a magnified encroachment of the feature activation functions for the distractors onto that for the target. It is argued that this makes the target more difficult to discriminate from distractors, therefore causing the observed cost of high distractor similarity.

Figure 4b illustrates the initial, distributed representation of stimuli in the linearly separable (conjunction) condition. This condition is identical to the linearly separable (single) condition with respect to the relative positions of the feature activation functions that are involved. Importantly however, one of the feature values of the target is identical to that of a distractor on one of the relevant dimensions, the other target feature being identical to that of the other distractor on the other dimension. In other words, no reliable discrimination between the target and distractors can be performed in the linearly separable (conjunction) condition on the basis of the distributed representation illustrated in Figure 4b. This discrimination thus requires the integration of information from shape Dimensions 1 and 2, which is assumed to be costly in terms of processing time, thereby the conjunction effect documented here and in Arguin and Saumier (2000). In terms of the constraints involved for feature discrimination within each individual shape dimension, however, the linearly separable (conjunction) condition is identical to the linearly separable (single) condition. Specifically, the degrees of feature activation overlap for targets and distractors (similar or dissimilar) and the requirement of a single decision boundary (in opposition to a double decision boundary as in the linearly nonseparable conditions; see below) are identical in the two conditions. Given these common constraints, there is no basis for the linearly separable (conjunction) and linearly separable (single) conditions to differ with respect to the effect of target–distractor similarity, congruently with the observations that we have reported here.

In both linearly nonseparable conditions (Figures 4c and 4d), the target has a feature value that is intermediate between those of the distractors on any of the dimensions where those stimuli differ. This implies that no single decision boundary along either of the shape dimensions characterizing the stimuli can separate the target from the distractors in feature space. The decision that the target is present thus requires the satisfaction of two criteria—that is, the feature value recorded on the relevant dimension must be above a certain value and, at the

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[3] In the examples illustrated here, the decision criteria are assumed to be unbiased, and therefore the boundaries are optimally positioned between the feature activation functions that need to be separated.

same time, below another value. In other words, as illustrated in Figures 4c and 4d, two decision boundaries are required to discriminate the target from distractors on any of the relevant dimensions. Previous evidence by Treisman and Gormican (1988) with respect to colour discriminations in visual search suggests that the application of such complex decision criteria is costly in terms of processing time. Similarly, more recent investigations by Thomas, Magnussen, and Greenlee (2000; see also Magnussen & Greenlee, 1997) indicate a performance reduction in circumstances where observers must make dual instead of single evaluations of stimulus properties on a particular dimension. It is argued that this obligatory complex decision criterion is responsible for the slower search rates in the linearly nonseparable conditions relative to the linearly separable (single) condition, where a single decision boundary is sufficient to separate the target from distractors.

Figure 4 also helps the understanding as to why the effect of target–distractor similarity was greater in the linearly nonseparable conditions than in either the linearly separable (single) or linearly separable (conjunction) conditions. In all conditions, it can be seen that high target–distractor similarity leads to a larger encroachment of the activation functions for the distractors onto that for the target. However, this effect of increased target–distractor similarity is much greater in the linearly nonseparable conditions (Figures 4c and 4d) than in the other conditions (Figures 4a and 4b). This accounts for the greater cost of high target–distractor similarity in the linearly nonseparable conditions since, as proposed above, the degree of overlap of the feature activations associated with the target and distractors modulate search difficulty.

Conclusion

The present findings replicate those of Arguin and Saumier (2000) with respect to the sensitivity of the visual shape encoding system to the conjunction and linear nonseparability effects. The major new finding in the present study is the observation that these effects are differentially affected by target–distractor similarity, thereby demonstrating that they rest on distinct mechanisms. On the one hand, the conjunction effect is attributed to the distributed nature of initial shape representations, which prevent a discrimination of the target from distractors at this level of processing. A time-consuming additional process of feature integration is therefore required for target detection in the linearly separable (conjunction) condition. This extra step results in slower search rates in this condition than in the baseline linearly separable (single) condition, which does not require feature integration. On the other hand, the linear nonseparability effect is attributed to the fact that the unique target features in the linearly nonseparable conditions have a value that is intermediate between those of the distractors. This forces the application of a more complex decision criterion to discriminate the target from distractors than in the baseline linearly separable (single) condition. This is also responsible for the greater impact of target–distractor similarity in the linearly nonseparable conditions than in either the linearly separable (single) or linearly separable (conjunction) conditions.

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