Journal of Experimental Psychology: General
2006, Vol. 135, No. 1, 116–131

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0096-3445/06/$12.00 DOI: 10.1037/0096-3445.135.1.116

Perceptual Encoding Efficiency in Visual Search

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The authors present 10 experiments that challenge some central assumptions of the dominant theories of visual search. Their results reveal that the complexity (or redundancy) of nontarget items is a crucial but overlooked determinant of search efficiency. The authors offer a new theoretical outline that emphasizes the importance of nontarget encoding efficiency, and they test this proposal using dot pattern stimuli adapted from W. R. Garner and D. E. Clement (1963). The results provide converging support for the importance of nontarget encoding efficiency in accounting for visual search performance.

Keywords: visual search, search asymmetry, encoding efficiency, redundancy, complexity

Visual search is among the most fruitful empirical paradigms in contemporary psychological research: It has been used to investigate the nature of elementary visual features, the binding problem, the role of perceptual organization in scene segmentation, the efficiency of object recognition, and the mechanisms of top-down and bottom-up attentional control; it has also been used to assess neuropsychological damage, as a component in IQ tests, and as a common task to test machine vision systems. Because of its generality, theories of visual search performance that have been developed over the last two decades are among the most explicit and detailed theories of visual perception we have. Perhaps a dozen theories of visual search have been proposed (e.g., Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Wolfe, Cave, & Franzel, 1989, to name only some of the most prominent ones).

The abundance of theories of visual search attests to its importance as a basic cognitive task. Often overlooked, however, is the reason why visual search is so interesting to begin with: It is arguably one of the most basic of visual behaviors. Even during apparently idle moments, we constantly survey the visual scene for novel impressions. Because of the universality of visual search behavior, most comprehensive theories of visual search are also theories of active visual perception.

Among the most influential and enduring theories of search is feature integration theory (FIT; Treisman & Gelade, 1980). For FIT, search was not conceived as a uniform phenomenon; instead, the original formulation of FIT distinguished between search for basic features (such as vertical or red), which proceeds in parallel across a display, and search for conjunctions of basic features (such as vertical *and* red), in which each item must be attended successively in a serial search. This distinction was motivated by the idea that the visual system cannot represent all possible combinations of basic features in parallel (i.e., simultaneously across all display locations) because this would result in a combinatorial explosion (Tsotsos, 1990). Instead, each perceptual dimension is registered in a separate feature map—a hypothetical construct that was explicitly inspired by the functional specialization of the visual system that was revealed by physiological studies (see Treisman & Gelade, 1980): Simple visual properties like color and motion, for example, are represented selectively in distinct cortical regions (e.g., Livingstone & Hubel, 1988; Zeki et al., 1991); this fact gives rise to the binding problem (e.g., Roskies, 1999). If the target in a search task is defined by a simple feature (*feature search*), its presence can be detected as activity somewhere (it does not matter where) in the corresponding feature map. If instead the target is defined by a conjunction of features (*conjunction search*), the separately registered features of each display item must be conjoined across maps to be certain that the relevant features were expressed in a single object.

The distinction between parallel feature search and serial conjunction search has since been refined by Treisman and others (e.g., Treisman & Sato, 1990; Wolfe et al., 1989). However, attempts have also been made to reject it completely. Such attempts have been fueled by findings that even searches for high-level "features" (e.g., Enns & Rensink, 1990; Ramachandran, 1988) or for conjunctions (e.g., Duncan & Humphreys, 1989; Nakayama & Silverman, 1986; Wolfe et al., 1989) can be remarkably efficient. The problem for FIT is that if efficient search is possible only for features that can be represented in a dedicated feature map, the apparently endless number and complexity of such features has become implausibly large.

One proposed alternative to FIT is attentional engagement theory (AET; Duncan & Humphreys, 1989). According to AET, search is neither serial nor parallel but rather falls along a continuum of efficiency (see also Wolfe, 1998). The efficiency of search is determined mainly by two factors: the similarity of targets and

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This research was supported by National Science Foundation Grant BCS-0418179 to Robert Rauschenberger and by National Institutes of Health Grant R01-DA13165 to Steven Yantis.

The research reported here was previously presented at the November 1999 Annual Meeting of the Psychonomic Society in Los Angeles, California, as well as the March 2000 Annual Eastern Psychological Association Vision and Attention Meeting in Baltimore, Maryland.

We thank Barbara Dosher, Steve Luck, Ron Rensink, Anne Treisman, and Jeremy Wolfe for helpful comments on a draft of this article.

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nontargets (T-NT similarity) and the similarity of the nontargets to each other (NT-NT similarity). With increasing similarity of the nontargets to each other (which is at least nominally maximal when the nontargets are all identical), they can be suppressed as a group with greater ease and are less likely to be further considered as targets; in contrast, a heterogeneous collection of nontargets will tend to group poorly and therefore might require scrutiny to individual items. With increasing similarity between the target and the nontargets, the suppression of nontargets becomes ever more difficult because the target itself is eventually affected by the suppression of the nontargets.

Even theorists who are sympathetic to Treisman's account have recently abandoned the strict serial–parallel division in favor of a continuum of search slopes, ranging from shallow (0–10 ms/item) for an efficient search to steep (20 ms/item and beyond) for an effortful search (Wolfe, 1998). This new classification of search slopes is quite sensible in view of the fact that the purely serial self-terminating search that constitutes one half of the serial–parallel dichotomy predicted by FIT is encountered empirically only rarely (cf. Ward & McClelland, 1989).

SEARCH ASYMMETRIES

Because of its reliance on basic features to explain results from visual search, FIT makes the interesting prediction that if a target possesses a certain feature and the nontargets do not, one should observe an asymmetry in the efficiency of search when the roles of the target and the nontarget stimuli are exchanged. In Figure 1, for example, the target in the bottom right panel (circle with line) can be found efficiently, because participants can simply monitor the "vertical line" feature map: If some activity is registered in this map, a target present response is made; otherwise, a target absent response is issued. By contrast, the target in the panel on the top left (circle without line) is not found efficiently, because there is no unique activity in either the circle or the line feature map; the successive deployment of attention to individual item locations is required to conjoin the circle–line pairs and reveal which location contains a circle without an intersecting line. Treisman and her colleagues have reported a large number of search asymmetries and regard search asymmetries as a powerful diagnostic for determining the canonical set of basic visual features (Treisman & Gormican, 1988; Treisman & Souther, 1985).

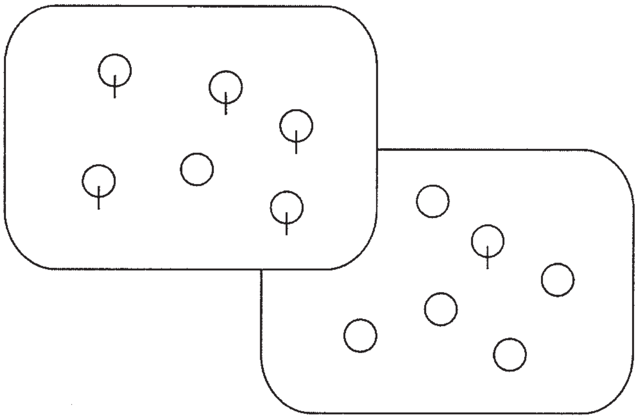

Figure 1. The stimuli and displays used in Experiment 1 (redrawn from Treisman & Souther, 1985).

Search asymmetries present an especially interesting problem for AET, because it is difficult to argue that T-NT or NT-NT similarity (the factors determining search efficiency according to AET) are in any systematic way affected by a simple swap of target and nontargets. This is because (a) perceptual similarity should not depend on whether an item happens to be a target or a nontarget—hence T-NT similarity should not change when targets and nontargets are swapped; and (b) the nontargets in search asymmetry experiments are always all identical, yielding maximal NT-NT similarity. Proponents of AET are therefore compelled to resort to an explanation of search asymmetries that appeals to the difficulty of generating a target template that is defined by the absence of a feature (see Duncan & Humphreys, 1989, p. 451). This solution, however, is not particularly satisfying, for a number of reasons. First, it makes AET more similar to FIT, which undermines AET's status as an alternative to FIT. Second, one can easily produce asymmetrical searches for which only a very generic target template is required, as recently confirmed in a study by Saiki, Koike, Takahashi, and Inoue (in press). Such a case arises, for example, when participants are instructed to find the "odd" item, rather than being explicitly told a particular target for which to search (e.g., Wang, Kristjansson, & Nakayama, 2005). In this case, the target template is identical for both halves of the asymmetry ("the odd item"), and a difference in the facility with which either template can be formulated cannot easily explain the asymmetry. Finally, search asymmetries occur just as clearly when comparable templates can readily be generated for both halves of the search asymmetry. For example, Wolfe, Alvarez, Wong, and Klempen (2000, Experiment 4) have shown that search for (a schematic rendition of) an inverted elephant among right-side-up elephants is more efficient than the converse. This result is difficult to explain in terms of the presence or absence of a simple feature.

PART 1: THE EXPERIMENTS

Section 1: Testing FIT and AET

In this section, we report experiments that are intended to explore the predictions of FIT and AET. These seven experiments are based on Treisman and Souther's (1985) Experiment 1, which used displays like the ones illustrated in Figure 1. Participants either searched for a circle with an intersecting line among circles without lines, or they searched for a circle without a line among circles with lines. FIT predicts that search should be efficient in the former case but inefficient in the latter case, as described above. AET predicts the same outcome, but for different reasons: For AET, the search asymmetry arises because of the difficulty of formulating a target template for a circle without a line, relative to the facility of generating a template for a circle with a line. In keeping with the terminology used by Treisman and Souther, in all of our experiments (both in Section 1 and in Section 2), we refer to the condition predicted (by FIT and AET) to yield efficient search as the *easy* condition and the condition predicted to produce inefficient search as the *difficult* condition.

Experiment 1: Replication of Treisman and Souther (1985)

The first experiment is a straightforward replication of Treisman and Souther's (1985) Experiment 1. The results of this experiment will serve as a baseline against which to contrast the results of the subsequent experiments in this part of our article. The methods remained constant for all of the experiments reported; the only difference between experiments is in the stimuli. Because the stimuli in the present experiments were generated on a computer, rather than being drawn on cardboard by hand, as in Treisman and Souther's experiments, it was necessary to demonstrate that we could replicate the results of the earlier experiments using our equipment.

Method

Participants. All participants were Johns Hopkins University undergraduates or members of the local community. A new set of naive observers was recruited for each experiment. All participants reported normal or corrected-to-normal vision.

Twelve participants (4 men, 8 women) were recruited for Experiment 1. The participants ranged in age from 17 to 28 years ($M = 20.8$ years) and participated in return for extra credit in an introductory course. The research protocol was approved by the Johns Hopkins Homewood Human Subjects Review Board.

Stimuli and equipment. The displays consisted of a varying number of circles with or without an intersecting line. Each circle measured 1.4° in diameter, and the lines, 1.0° in length. The lines were oriented vertically and intersected the circles in the bottom center, extending 0.5° above and below the point of intersection, as shown in Figure 1. The stimuli were black (0.02 cd/m^2) on a white (58.5 cd/m^2) background and were presented on a computer monitor.

Throughout each session, the target positions were distributed evenly across the display within a region subtending 8.8° × 11.4° visual angle from a viewing distance of 54 cm using the procedure described by Treisman and Souther (1985) for their first experiment. Head position was stabilized by a chin rest. Responses were made on a custom-built button box. The positions for all display items were stored and read in for each of the following experiments, so as to equate the conditions for all experiments as much as possible.

Design. All experiments reported here followed a 2 (condition) × 2 (target presence) × 3 (display set size) factorial design. Participants completed six blocks of 72 trials each, yielding a total number of 432 experimental trials. Each block was preceded by 15 practice trials, which were identified as such to the participants and separated from the experimental trials by a pause and a message that invited participants to "Press any key to continue." For half of the trials, the target was a circle with an intersecting line and the nontargets were circles without lines (easy condition), and for the other half, the target was a circle without a line and the nontargets were circles with lines (difficult condition; note that these labels were not used when instructing participants in the task). These two conditions were presented in separate sets of blocks, with the order counterbalanced across participants. On half of the trials, the prespecified target was present; on the other half, it was absent. Three display set sizes were used: 1, 6, and 12 items. Target presence and display set size were varied randomly within blocks.

Results and Discussion

The first experiment very closely replicated the results of Treisman and Souther's (1985) Experiment 1. The response time (RT) data are summarized in Figure 2 (left panel), and the error

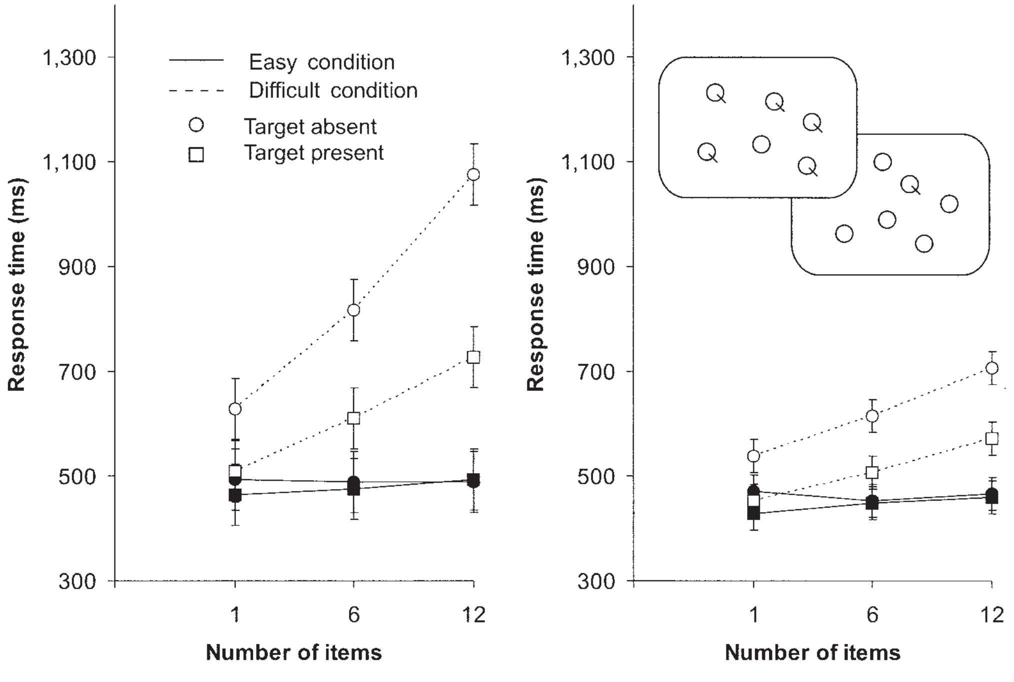

Figure 2. Response time data from Experiment 1 (left) and displays and response time data from Experiment 2 (right). Error bars denote the within-subject confidence intervals for each condition (cf. Loftus & Masson, 1994; Masson & Loftus, 2003).

data for this and all subsequent experiments in Section 1 of Part 1 are presented in Table 1. The easy condition yielded search slopes of 3 and 0 ms for target present and target absent trials, respectively (4 and 3 ms/item, respectively, in Treisman and Souther's original experiment), and the difficult condition yielded search slopes of 20 and 41 ms/item, respectively (20 and 39 ms/item, respectively, in Treisman and Souther's experiment). These are the results predicted by both FIT and AET.

The fact that we closely replicated the results of Treisman and Souther (1985) is significant because it demonstrates that the findings from search asymmetry experiments using these stimuli are extremely stable. The results of a given search therefore appear to be a reliable measuring stick against which the results from other search experiments with different stimuli can be compared.

Experiment 2: Qs and Os

In Experiment 2 we rotated the stimuli from Experiment 1 by 45°, so that they appeared as *Q*s and *O*s. FIT predicts the same results as for Experiment 1 because, once again, line and circle features must be conjoined by a serial application of attention. The predictions from AET are less obvious because the target template could be formulated, without recourse to the presence or absence of a feature, simply as either a *Q* or an *O*. This strategy, however, begs the question of why the target template cannot be reformulated in positive terms for any given feature-absent target. For example, the target in the difficult condition in Experiment 1 could have been interpreted as a circle among "trees" rather than a circle without a line among circles with lines. This approach to the problem is unsatisfactory, because it renders AET inert in making specific predictions and furthermore undermines its account of search asymmetries in general (which depends on the idea of a feature-absent template).

Method

Twelve new participants (5 men, 7 women) were tested in Experiment 2; they ranged in age from 17 to 21 years ($M = 19.6$ years). The same design was used as in the previous experiment. The only change to the stimuli was as follows. In Experiment 2, the intersecting line was tilted 45° to the left and now intersected the circle in the bottom right, so that the resulting stimulus appeared as a *Q* and the circle without a line consequently appeared as an *O* (see Figure 2, right panel). Participants were not explicitly told to look for a *Q* or an *O*, however.

For this as well as all subsequent experiments, the alpha level for significance was chosen to be .05. When reporting significant results, we present the mean squared error and partial eta squared (estimated effect size) associated with the *F* value. When reporting *t* tests, we indicate the standard error of the mean. The *p* values of nonsignificant results are presented only when the corresponding *F* (or *t*) value exceeds 1.

Table 1
Error Data for Experiments 1–6 in Percentage Error

		Target present			Target absent		
Experiment	Condition	1	6	12	1	6	12
1	Easy	1.6	0.8	1.2	1.0	0.5	0.6
	Difficult	0.6	1.1	7.2	3.0	1.2	1.4
2	Easy	1.2	1.5	2.6	0.9	0.8	0.6
	Difficult	0.4	1.5	6.3	2.1	0.6	0.8
3	Easy	0.4	1.6	2.2	1.2	0.6	0.6
	Difficult	0.0	2.0	5.4	2.0	0.6	0.7
4	Easy	2.4	2.5	3.6	3.1	1.2	0.3
	Difficult	2.8	1.2	5.0	3.2	1.3	0.2
5	Easy	1.6	4.5	2.6	2.3	1.3	1.1
	Difficult	2.3	2.0	2.2	3.2	1.2	0.9
6	Easy	2.4	2.9	4.2	1.3	1.4	0.0
	Difficult	2.3	2.2	4.9	2.0	0.6	1.1

Results and Discussion

Rotating the stimuli used by Treisman and Souther (1985) by 45° had a strong effect on search efficiency (see Figure 2). The slopes of the difficult condition (11 ms/item for target present trials, 15 ms/item for target absent trials) were now only half as steep as those in the corresponding condition in Experiment 1. Six of the 12 participants exhibited search slopes of 9 ms/item or less in the difficult condition. A more systematic comparison of the results from Experiments 1 and 2 confirms a significant difference between the two experiments: A mixed four-way analysis of variance (ANOVA) with condition (easy, difficult), target (present, absent), and display set size (1, 6, 12) as within-participant factors and experiment as a between-participants factor showed a significant Display Set Size × Experiment interaction, $F(2, 44) = 8.67$, $MSE = 6{,}131.26$, $\eta_p^2 = .28$, as well as a significant effect of experiment, $F(1, 22) = 6.33$, $MSE = 105{,}354.46$, $\eta_p^2 = .22$. The interaction between display set size and experiment reflects the fact that slopes were significantly shallower in Experiment 2, and the main effect of experiment reflects the overall faster RTs for Experiment 2. In addition to the significant two-way interaction, there was a significant three-way interaction between experiment, condition, and display set size, $F(2, 44) = 11.44$, $MSE = 4{,}793.07$, $\eta_p^2 = .34$. This interaction confirms that the search asymmetry was significantly less pronounced in Experiment 2 than in Experiment 1.[1]

How might FIT account for the reduction in the magnitude of the asymmetry in Experiment 2? One possibility is to assume that letters are so highly overlearned that they have effectively become elementary perceptual features, so that participants have a feature map for letters. There are three responses to this point. The first is empirical: In Experiments 4, 5, and 6, we show that the observed reduction in the search asymmetry is not limited to searches that use potentially meaningful stimuli. The second response concerns the utility of continually enlarging the set of "basic" features to accommodate new findings that elude a priori explanation from the previously established set of features. It is always possible to invent new features ad hoc to account for new data. At some point, however, this approach becomes undesirable (Di Lollo, Kawahara, Zuvic, & Visser, 2001; Nakayama & Joseph, 1997). For one, new "features" emerge at an unrealistic rate, some of which are rather implausible as features in the sense originally proposed by FIT. Wolfe, Alvarez, et al. (2000), for example, somewhat facetiously considered the existence of a "dead elephant detector." More important, the ad hoc introduction of new features renders feature-based models of search untestable, because any finding can be accommodated by invoking a new feature tailored to that finding.

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[1] The remaining slight search asymmetry observed here is predicted by the account we present in Part 1, Section 2, and Part 2.

The third response to the suggestion that our findings present no difficulties for FIT because they can be explained by letter feature detectors is that this conclusion is based on hindsight: In the literature, Treisman and Souther's (1985) Experiment 1 is consistently described as *Q*s among *O*s, including by Treisman herself (e.g., Treisman, 1986, 1996). Clearly, the generally expected outcome of Experiment 2 was that it should yield the same results as Experiment 1.

It could be objected that the difference we observed between Experiments 1 and 2 is attributable to the fact that vertical lines behave differently from oblique lines in general. This possibility, however, is quite remote. The difference between vertical and oblique lines typically emerges only when either is placed in the context of the other—that is, when an oblique line, for example, is the target among vertical lines. There is no reason to assume that a circle with an oblique line is found more efficiently among circles without lines than a circle with an intersecting vertical line. To rule out this possibility nonetheless, we ran a control for Experiment 2, in which the oblique line intersected the circle in the top left, so that the resulting stimulus resembled an upside-down mirror-reversed *Q*. The results were statistically indistinguishable from those of Experiment 1 (vertical line), $F < 1$ for the interaction between display set size and experiment; $F < 1$ for the interaction between condition, display set size, and experiment; and $F < 1$ for the main effect of experiment. At the same time, statistical analysis revealed that search was less efficient than in Experiment 2 (oblique line), $F(2, 48) = 9.22$, $MSE = 4{,}133.10$, $\eta_p^2 = .28$, for the interaction between display set size and experiment; $F(2, 48) = 12.93$, $MSE = 3{,}530.39$, $\eta_p^2 = .35$, for the interaction between condition, display set size, and experiment; and $F(1, 24) = 6.94$, $MSE = 184{,}383.80$, $\eta_p^2 = .22$, for the main effect of experiment, reflecting the overall faster RTs in Experiment 2.

Experiment 3: Nontarget Heterogeneity

Whereas the results of Experiment 2 are difficult to reconcile with the current versions of both FIT and AET, Experiment 2 really addresses only those aspects of AET intended to explain search asymmetries—that is, the difficulty of producing a feature-absent template. In general, however, AET is based on the competition between the target and the nontargets for access to this target template. In Experiments 1 and 2, we used solely homogeneous nontargets. According to AET, when NT-NT similarity is high, T-NT similarity has little or no effect on search efficiency, because only a small number of different types of items are competing for access to the target template (cf. Duncan & Humphreys, 1989, pp. 442–444). (By contrast, when NT-NT similarity is low, every different type of nontarget is competing individually for access to the target template.) Hence, irrespective of whether an account could be contrived on which T-NT similarity was greater in Experiment 2 than in Experiment 1, the simple rotation of the circle–line stimuli should not have had as strong an effect on search efficiency as it did.

Experiment 3 examined the possibility that differences in NT-NT similarity (rather than T-NT similarity) could have caused the differences between Experiments 1 and 2. Because it would have been difficult to make the nontargets more similar to one another than they already were, Experiment 3 evaluated the consequences of making them less similar to each other. This manipulation should disrupt perceptual grouping among nontargets. If greater nontarget grouping caused the differences between Experiments 1 and 2, the results of Experiment 3 should differ in a systematic way from those of Experiment 1 as well, but in the opposite direction.

A difficulty with manipulating similarity is that there are no clear a priori criteria for determining item similarity. One can rely on the degree of heterogeneity in a display. In this case, it is indeed impossible to create a display in which the nontargets are more similar to one another than they already are in a homogeneous display. Another possibility is to rely on intuition and principled arguments about which stimulus should be more similar to itself than other stimuli are (in homogeneous displays). However, this approach lacks scientific rigor because it is based on an arbitrary assumption: For example, a letter is more similar to itself than a nonletter stimulus is to itself because the former is a letter (cf. Experiments 1 and 2). Finally, one can base similarity on such measures as the ease of texture segregation. However, texture segregation is always not merely a function of the similarity of the "ground" elements to one another but also a function of the similarity of the "figure" elements to the "ground" elements; furthermore, the similarity of texture items to one another cannot be predicted straightforwardly from the similarity of two items considered in isolation (cf. Beck, 1966). For a theory that bases search efficiency on the grouping between target and nontargets, on the one hand, and nontargets among themselves, on the other, predicting search efficiency from the ease of texture segregation invariably results in circularity.

It should be noted that Duncan and Humphreys (1989) explicitly rejected the suggestion that "raw" perceptual grouping can affect search efficiency—that is, without reference to whether the factors on which the display items group increase their competition for access to visual short-term memory (VSTM). However, this caveat is reserved for instances of nontarget heterogeneity on irrelevant dimensions (cf. Duncan & Humphreys, 1989, pp. 455f). Experiment 3 therefore used a manipulation that has been shown by Duncan and Humphreys to produce quite strong effects on search efficiency: the use of nontargets that are rotations of one another. Within the framework of AET, the results from the difficult condition of Experiment 1 argue that even with homogeneous nontargets, T-NT similarity must have been considerable, given that search was relatively inefficient (20 ms/item on target present trials). Rotating the circle–line stimuli to produce heterogeneous displays should therefore produce an appreciable decrement in search efficiency as compared with Experiment 1.

Method

Twelve new participants (3 men, 9 women) were recruited for Experiment 3. The participants' ages ranged from 18 to 30 years ($M = 21.8$ years). Experiment 3 essentially replicated Experiment 1, with the exception that the circle–line stimuli were given 1 of 12 different randomly assigned orientations within a single display, introducing nontarget heterogeneity.

Results and Discussion

The search slopes were almost entirely unaffected by the introduction of nontarget heterogeneity into the display, as can be seen from Figure 3. The target present slopes for Experiment 3 (21

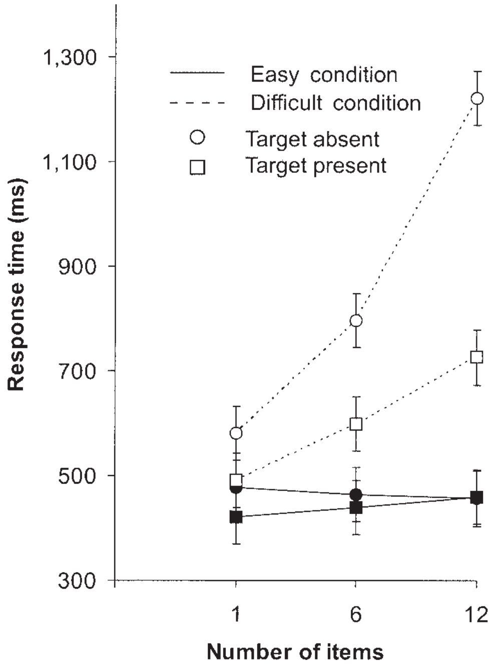

Figure 3. Response time data from Experiment 3. Error bars denote the within-subject confidence intervals for each condition.

ms/item) differed by only 1 ms/item from the target present slopes in Experiment 1. Although the target absent slopes appeared to be somewhat steeper in Experiment 3 (58 ms/item), this apparent difference is not statistically reliable (as discussed below). The correct RT data from Experiments 1 and 3 were subjected to a four-way mixed ANOVA with condition (easy, difficult), target (present, absent), and display set size (1, 6, 12) as within-participant factors and experiment as a between-participants factor. This ANOVA revealed no significant interaction between display set size and experiment, $F(2, 44) = 2.02$, $MSE = 17{,}171.32$, $p = .15$. The main effect of experiment was likewise not significant ($F < 1$). Although the three-way interaction between target, display set size, and experiment also failed to reach significance, $F(2, 44) = 2.02$, $MSE = 10{,}972.50$, $p = .15$, we conducted a three-way ANOVA with condition (easy, difficult) and display set size (1, 6, 12) as within-participant factors and experiment as a between-participants factor for the target absent RT data alone, because we wanted to be sure that a potential effect did not get washed out by a complete absence of an effect in the target present data. The Display Set Size × Experiment interaction remained nonsignificant, $F(2, 44) = 2.14$, $MSE = 27{,}720.77$, $p = .13$, as did the main effect of experiment ($F < 1$).

Heterogeneity in the line orientation dimension did not produce an appreciable decrement in search efficiency. This result argues against an explanation by AET of the differences between Experiments 1 and 2 in terms of NT-NT similarity. It could be contended that the nontargets never truly competed for access to VSTM because they distinguished themselves from the target by the presence or absence of a line. A target template for a circle without a line could categorically exclude all circles with lines, so that it would not matter if the lines of the nontargets were oriented randomly. However, in this case, if the nontargets never represented true competition for the target to begin with, one might wonder why search slopes were not flat in the difficult condition of Experiment 1. Furthermore, a search asymmetry would never have arisen in the first place if none of the nontargets had competed for access to VSTM.

Experiments 4–6: "Meaningless" Stimuli

In the next three experiments, we examined further variations of the same circle–line conjunctions used in the previous three experiments. These stimuli were designed to explore the role of "meaningfulness" in increasing search efficiency in Experiment 2 (*Q* vs. *O*). Of the experiments reported thus far, only the results of Experiment 2 deviate from the general range of search slopes obtained by Treisman and Souther (1985). The difference between Experiment 2 and the other experiments is that only the stimuli in the former are meaningful to English speakers. It is conceivable, therefore, that "meaningfulness" plays a pivotal role in making search efficient. In this case, meaningfulness refers to a conventionally agreed on symbolic mapping between signifier and signified: No doubt, any stimulus can acquire meaning to its observer over time. In next three experiments, the stimuli are "meaningless" in the sense that they lack conventionally recognized semiotic mapping.

Method

Twelve new participants (7 men, 5 women), aged 18 to 22 years ($M = 20.0$ years), were tested in Experiment 4, and another 12 (3 men, 9 women), aged 17 to 21 years ($M = 19.3$ years), in Experiment 5. Twelve more participants (3 men, 9 women), aged 18 to 22 years ($M = 19.9$ years), were recruited for Experiment 6. The stimuli differed from those of the previous experiments in that the line feature no longer intersected the circle but was rather placed completely inside the circle. In Experiments 4 and 5, the line was drawn as a chord passing through the center of the circle. The length of the line was therefore increased from 1.0° to 1.4° (i.e., the diameter of the circle). In Experiment 4, all of the lines were oriented vertically; in Experiment 5, each line was randomly given 1 of 12 different orientations. The stimuli in Experiment 6 were similar to those in Experiments 4 and 5, with the exception that the length of the line was decreased to 0.5°. As in Experiment 5, each of the resulting stimuli was given 1 of 12 different orientations. Examples of the stimuli for Experiments 4–6 are shown in Figure 4.

Results and Discussion

As can be seen from Figures 4a–4c, the slopes in all three experiments are quite shallow in the difficult condition (13, 9, and 11 ms/item, respectively, for target present slopes and 15, 18, and 33 ms/item, respectively, for target absent slopes)—especially when compared with those of Experiment 1, $F(2, 44) = 11.62$, $MSE = 102{,}960.22$, $\eta_p^2 = .35$ (Experiment 1 vs. Experiment 4); $F(2, 44) = 10.95$, $MSE = 62{,}951.57$, $\eta_p^2 = .33$ (Experiment 1 vs. Experiment 5); and $F(2, 44) = 4.13$, $MSE = 20{,}968.17$, $\eta_p^2 = .16$ (Experiment 1 vs. Experiment 6), for the interaction between condition, display set size, and experiment, reflecting a significantly attenuated search asymmetry in Experiments 4, 5, and 6, respectively, compared with Experiment 1. A comparison of the results for Experiments 4 and 5 furthermore once again fails to demonstrate an effect of nontarget heterogeneity, $F < 1$ for the

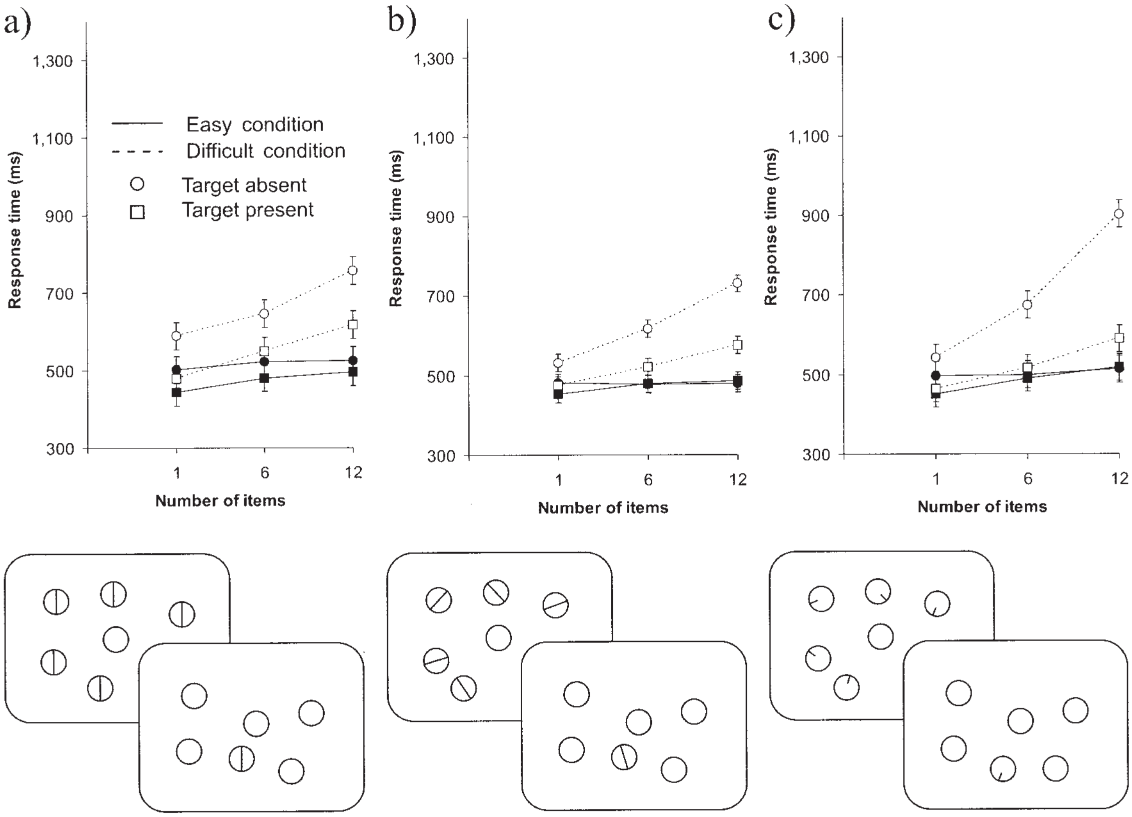

Figure 4. Displays and response time data from Experiments 4 (a), 5 (b), and 6 (c). Error bars denote the within-subject confidence intervals for each condition.

main effect of experiment and $0.11 < F < 2.01$, $.17 < p < .75$, for all interactions involving experiment. If anything, the slopes for the homogeneous nontargets in Experiment 4 are slightly steeper on target present trials than those for the heterogeneous nontargets in Experiment 5. The target present slopes for Experiment 5 (in the difficult condition) are below 10 ms/item for 8 participants (as low as 1 ms/item for 1 participant) even though the features of the stimuli are at least nominally the same as in Treisman and Souther's (1985) Experiment 1 (but see discussion below). Making the line significantly shorter in Experiment 6 does not alter this result. This finding undermines the possibility that the results of Experiments 4 and 5 were due to the potentially greater discriminability of the lines in those experiments.

Like the results from the previous three experiments, the findings of the present three experiments are unexpected from the perspective of both FIT and AET. Although it remained plausible that the nontargets in Experiment 2 were more similar to each other than those in Experiment 1 because of their "letterness," there is no corresponding reason why the nontargets in Experiment 4, 5, or 6 should be any more similar to each other than those in Experiment 1. Furthermore, the results of Experiment 5 reinforce the conclusion that NT-NT similarity cannot account for search efficiency in our experiments. Similarly, there is no reason why T-NT similarity should have been any weaker in Experiments 4, 5, and 6 than in Experiment 1. If anything, the fact that the line was contained inside the circle in the former three experiments should have rendered them more similar to a simple circle at some coarse level than a circle with a line segment sticking out at the bottom. Finally, in terms of featural overlap (cf. Duncan & Humphreys, 1992), there were no differences between the stimuli in Experiments 4, 5, and 6 and those in Experiment 1; all three contained a single line and a single circle feature.

This final point is also of significance for FIT. Given the very same features, the experiments reported here yield strikingly different results. A proponent of FIT might therefore conclude that some overlooked set of features is responsible for the observed differences. For example, perhaps participants coded the stimuli in Experiment 4 as a diameter and two T-junctions instead of an intersection, as in Experiment 1.[2] This approach, however, begs the question of why a diameter and two T-junctions should produce more efficient search than an intersection. The answer could be that search becomes more efficient as more features distinguish the target from the nontargets (cf. Duncan & Humphreys, 1989; Treisman, 1992; see also Wolfe, 2001, for such an account of search asymmetries). However, why would Experiment 6 produce such efficient search, then? The circle–line stimuli in Experiment 6 are characterized by a single T-junction, and yet they permit more efficient search than the stimuli in Experiment 1. It could be objected that, this time, we are overlooking the line termination

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[2] We are grateful to Anne Treisman for this suggestion.

present in the circle–line stimulus in Experiment 6. However, such line terminations are also present in the circle–line stimulus in Experiment 1, raising the number of features in Experiment 1 to three. The greater search efficiency in Experiment 4 could therefore no longer be explained in terms of the greater number of features. Furthermore, the stimulus in Experiment 6 would be left with one fewer feature than the corresponding stimulus in Experiment 1, leaving the feature-based account in a no-win situation. Also, determining the number of features coded by participants in each experiment, or determining their fluency as features, runs the danger of becoming a circular enterprise: How do we know that participants must have used a different set of features in, say, Experiment 4 than in Experiment 1? Because search was more efficient.

Section 2: Accounting for the Results

Before turning to the experiments in Section 3, we first sketch out briefly how the entire set of rather disparate results from Section 1 can be captured by a single, decisive factor. In doing so, we draw attention to the following fact. In the difficult condition of all six experiments presented above, the target was always the same (a circle), whereas the nontargets varied from experiment to experiment. Search efficiency varied substantially with the type of nontarget. In the easy condition, the nontargets remained constant throughout all six experiments (circles), whereas the target changed between experiments. In this case, the efficiency of search remained relatively constant from experiment to experiment. (See Wolfe, Alvarez, et al., 2000, for a similar observation that search efficiency varied as a function of the nontargets in search, rather than as a function of the target. See also Duncan & Humphreys, 1989, Experiment 1.) It is therefore sensible to consider the essential contribution of the nontargets to search efficiency.

We propose that the more efficiently the nontargets—as majority items—can be encoded, the more effectively a representation of the search display can be derived that supports a behavioral response. In focusing on the nontargets, our approach departs radically from previous accounts of visual search. The currently standard view of visual search allots the greatest importance to the target; nontargets are nothing more than "distractors" that need to be rejected as targets but not encoded in any serious way (see, e.g., Treisman, Vieira, & Hayes, 1992). Against this view, we argue that (all other things being equal[3]) the *redundancy,* or perceptual "goodness" (*Prägnanz,* as discussed in the Gestalt literature), associated with the nontargets determines the efficiency of visual search.

Stimulus Redundancy

The concept of redundancy has a long history in information theory as applied to perception (see, e.g., Garner, 1962, 1974; Lockhead & Pomerantz, 1991). Garner (1962, 1974) made the concept of redundancy applicable to individual stimuli by proposing that every stimulus is treated by observers as originating from an *implicit set* of alternative stimuli. In the case of the stimuli in Figure 5, for instance, the stimulus on the right is presumably drawn from a set of stimuli that includes circles with thick outlines, thin outlines, long dashes, short dashes, and so forth, that are positioned in the top left, bottom right, center, and so forth, of the square. In order to specify the stimulus shown, precisely the information that distinguishes it from the other members of its set is necessary. In the case of the stimulus on the left, a very brief description suffices, because it is presumably the only member in its set (i.e., the description "a circle inside a square" would not conjure up many alternatives to the one illustrated).

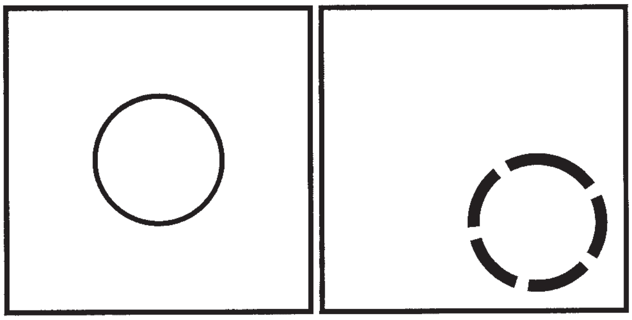

Figure 5. Stimuli redrawn from Pomerantz, J. R., & Lockhead, G. R. (1991). The perception of structure: An overview. In G. R. Lockhead & J. R. Pomerantz (Eds.), *The perception of structure: Essays in honor of Wendell R. Garner* (p. 4). Washington, DC: American Psychological Association. Copyright 1991 by the American Psychological Association. Adapted with permission. See also Garner, 1974, pp. 183–186. The stimulus on the left is more redundant than the stimulus on the right. The implicit set of alternatives for the circle on the right is much larger than for the circle on the left; it therefore requires a longer list of attributes to distinguish itself from the other members of its set.

In a study by Egeth, Atkinson, Gilmore, and Marcus (1973), more efficient search was observed for a target (an *A* or a *4*) among digit nontargets than among letter nontargets. Egeth et al. suggested that their results might be explained by the fact that the set from which the nontargets were drawn in each case differs for letters and digits, with the number of letters being substantially larger than the number of digits. This suggestion captures the essence of Garner's idea of the implicit set and constitutes an early example of an attempt to explain search efficiency by the size of the set from which the nontargets are drawn (i.e., the redundancy of the nontargets).

Note that the preceding explication has focused on individual stimuli. When applied to visual search, this emphasis on the individual stimulus permits a new level of sophistication in discussing the degree of redundancy possessed by the nontarget stimuli. Historically, discussions of display redundancy have been limited to considerations of the degree of redundancy across an entire display (e.g., Krueger, 1970; Meudell & Whiston, 1970; Nattkemper & Prinz, 1984). In this latter sense, any display in which certain features of the nontargets are highly correlated with the nontarget status of these items is redundant, because the other features defining the nontargets overdetermine the nontargets. The most extreme case of a redundant display in this sense is a homogeneous display, which entails complete redundancy of the features of the nontargets. Even in such displays, in which whole-

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[3] As Duncan and Humphreys pointed out, any search can be made arbitrarily efficient if the target is sufficiently dissimilar to the nontargets (see Duncan & Humphreys, 1989, p. 450). Finding a red target among black nontargets, for example, would never be inefficient.

display redundancy is maximal, there might still be differences in the redundancy associated with the individual nontarget stimuli that populate different displays. As the experiments in Section 1 demonstrate, not all homogeneous displays afford equally efficient search. Accounts of whole-display redundancy cannot speak to such differences in search efficiency between homogeneous displays, nor can they explain why heterogeneity does not inevitably lead to a decrease in search efficiency.

In this regard, our account also differs strongly from one proposed by Scharroo, Stalmeier, and Boselie (2001), who discussed the importance of the redundancy (or in their case, complexity) of individual display items—but with respect to the *overall* complexity of the display. In Scharroo et al.'s account, "the complexity of the display as a whole [is] a function of . . . the complexity of the internal structure of the two types of micropatterns [i.e., the target and the nontargets]" (p. 7). However, Scharroo et al. went on to conclude that "the complexity of the display as a whole determines detectability" (p. 14). Although a consideration of the redundancy of the individual display items represents an advance over the earlier approaches discussed above, the recourse to whole-display "complexity" as a determinant of search efficiency imposes limitations similar to those that marred these earlier accounts.

Nontarget Redundancy in Experiments 1–6

To illustrate how the results of the experiments from Section 1 can be understood in terms of the efficiency of encoding of the nontargets, it is necessary to show how individual stimuli from these experiments differ in redundancy. Garner (1962, 1974) devised a crude heuristic for determining stimulus redundancy, which serves as the basis for the experiments in Section 3. This heuristic can also be applied—albeit somewhat post hoc—to the stimuli from Experiments 1–6. Using a range of converging measures, Garner and his colleagues (Garner & Clement, 1963; Sebrechts & Garner, 1981) demonstrated that the redundancy of a stimulus is correlated with the number of *R&R transformations* (reflections about the vertical and horizontal axes, and 90° rotations) that can be applied to this stimulus and that result in distinguishable shapes or patterns. Because the redundancy of a stimulus is inversely proportional to the size of its implicit set, the more transformations a stimulus permits, Garner and his colleagues reasoned, the lower will be its redundancy.

In Figure 6, the circle–line stimuli from our experiments are arranged in ascending order of redundancy (from bottom to top). The lowest degree of redundancy is associated with circle–line stimulus from Experiment 1; it permits four R&R transformations, as indicated in the rightmost column of Figure 6. The θ and *Q* stimuli are associated with a slightly greater degree of redundancy than the circle–line stimulus from Experiment 1. (Because the *Q* resists an analysis in terms of its R&R transformations, it is discussed last, as a special case.) The number of possible R&R transformations of the θ stimulus is relatively small (two, compared with four transformations for the circle–line stimulus from Experiment 1).

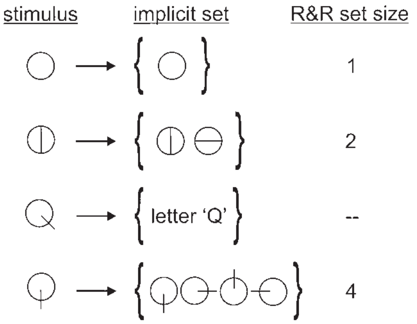

Figure 6. The stimuli from Experiments 1–6, arranged in ascending order of redundancy. R&R = reflections about the vertical and horizontal axes and 90° rotations.

The simple circle at the top of Figure 6 is associated with the highest degree of redundancy because its set contains only one item: the circle itself. Like the circle on the left side of Figure 5, the circle nontarget from the easy conditions of the experiments in Section 1 does not need to be distinguished from any alternative stimuli by way of an elaborate description. It can be described quite economically, and without ambiguity, simply as a circle. Correspondingly, the number of R&R transformations is as small as it could possibly be: Any type of rotation or reflection of the circle would be indistinguishable from the circle itself.

Finally, the *Q* should also be regarded as quite redundant. Similar considerations apply to it as to the circle: A *Q* is a *Q* is a *Q,* just like a circle is a circle is a circle. Frith (1974), who first described search asymmetries 30 years ago, already pointed out that letter schemata are quite flexible (i.e., insensitive to variations). As one of the reviewers of this article aptly put it, "Even in . . . Courier font, a *Q* isn't merely a circle with a line through it." Decisively, the concept of a *Q* redundantly encapsulates many of the visual attributes that characterize a particular circle–line arrangement as a *Q*. All subsequent attempts to explain search asymmetries have converged on much the same idea: Letters are efficiently processed because they are known, familiar, recognizable, good patterns, or, in our case, redundant.

Figure 7 summarizes the display set size functions for a number of the nontarget stimuli used in Experiments 1–6; for clarity, only target present data are shown. As can be seen from the figure, the ordering of the search slopes for the experiments shown corresponds closely to the arrangement of the nontarget stimuli in terms of their redundancy: The simple circle nontarget produces the most efficient search; the *Q* and θ stimuli produce intermediate results; and the circle–line nontargets from Experiment 1 produce the least efficient search. In other words, search efficiency is a function of the redundancy of the nontarget stimulus.

Redundancy as a Psychological Phenomenon

Why did the participants in Experiments 1–6 not learn to impose constraints top-down on the implicit set of a given nontarget stimulus over the course of a few hundred trials? Imposing such constraints should have allowed them to increase the redundancy of the nontarget stimuli and thereby increase the efficiency of their search. It must remain as a psychological fact that observers often do not use pertinent information available to them even though this information might improve their performance. For example, Wolfe, Klempen, and Dahlen (2000) reported that subjects never learned the composition of a search display repeated over hundreds of trials. Similarly, Jonides and Gleitman's (1972) subjects, who were asked to search for a zero among other digits,

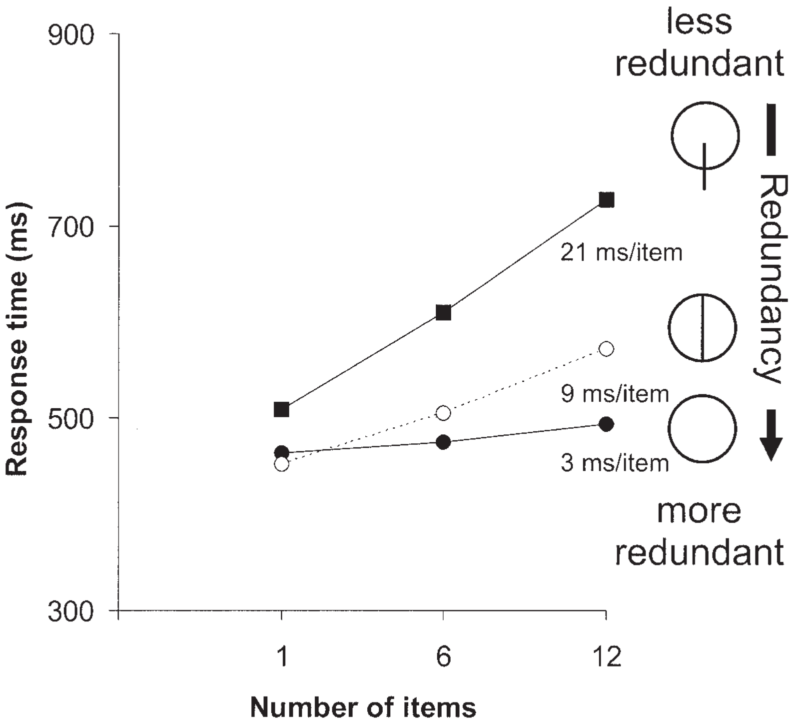

Figure 7. Display set size functions for some of the nontarget stimuli used in Experiments 1–6 (target present data only). The ordering of the functions by search efficiency corresponds to the ordering of the nontargets by redundancy, with more redundant nontargets producing more efficient search.

apparently failed to adopt a set for the letter *O* even though this switch would have facilitated their search (see, however, Duncan, 1983). More recently, Leber and Egeth (2005) found that subjects perseverated in their set even though adopting a new set could have improved their performance.

"Search Asymmetries? What Search Asymmetries?"

The emphasis on the nontargets as the determining factor for the efficiency of a given search and the inclusion of the simple circle as one of the nontarget stimuli in Figure 7 suggest a radically new account of search asymmetries. From the relationship between nontarget redundancy and search efficiency revealed in Figure 7, it becomes apparent how asymmetries could arise in search quite naturally without having to invoke some sort of special relationship between the target and nontarget stimuli based on the presence or absence of features (cf. Treisman & Souther, 1985): If a redundant stimulus produces efficient search when it serves as nontarget and a less redundant stimulus produces inefficient search when it serves as nontarget, pairing two such stimuli will result in a search asymmetry.

From this perspective, search asymmetries, however interesting they may be otherwise, are almost trivially the result of the juxtaposition of two seemingly similar yet unrelated searches: one easy (highly redundant nontargets) and one difficult (less redundant nontargets). The superficial observation that one is "simply swapping" target and nontarget should not distract from the fact that the two conditions of a search asymmetry have completely different sets of targets and nontargets. Focusing on the spurious complementary relationship between the stimuli in both "halves" of a search asymmetry has obscured the more fundamental differences between the two distinct searches involved (see also Rosenholtz, 2001). Any two searches combined within the same experiment, where one search is efficient and the other is not, will produce a "search asymmetry." This point is elaborated by the experiments presented in the next section. In these experiments, the respective target and nontarget stimuli are completely detached from any sort of description in terms of featural complementarity. They therefore reinforce the idea that search asymmetries[4] arise from a mismatch in the redundancy of the stimuli paired in a search asymmetry paradigm.

Section 3: Testing the Redundancy Account

The experiments in Section 1 led us to assert that search efficiency is determined by nontarget redundancy. However, because Garner's (1962, 1974) R&R heuristic was applied to our stimuli post hoc, we lack independent evidence for our claim that the nontargets in question were indeed redundant. Garner and colleagues (Clement & Varnadoe, 1967; Garner & Clement, 1963; Sebrechts & Garner, 1981) suggested methods for measuring redundancy that are not based on visual search performance (e.g.,

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[4] Any occurrence of "search asymmetry" in the text should henceforth be read with implied quotation marks. We continue to use the term merely to make contact with previous discussions of this phenomenon in the literature.

grouping task; speeded same–different task; speeded classification task). These measures therefore offer an index of redundancy that avoids the circularity inherent in our first set of experiments. The stimuli for which Garner and colleagues obtained measures of redundancy are five-dot patterns like the ones illustrated in Figure 8. These stimuli have the additional advantage that they are difficult to describe in terms of elementary visual features.

Experiments 7 and 8: Nontarget Redundancy

Experiments 7 and 8 tested the basic prediction that nontarget redundancy should have a decisive effect on the efficiency of search. Experiment 7 pitted two items at opposite ends of the redundancy spectrum against one another (Patterns 11 and 87 from Garner & Clement, 1963; see Figure 8); Experiment 8 used items matched for redundancy (Patterns 85 and 87). We predicted a large search asymmetry in the first case but not in the second.

Method

Ten new participants (3 men, 7 women) were tested in Experiment 7, and 12 (5 men, 7 women) in Experiment 8. The participants' ages ranged from 19 to 22 years ($M = 20.1$ years) in Experiment 7 and from 18 to 21 years ($M = 19.0$ years) in Experiment 8. The same design was used as before. The stimuli were dot patterns taken from Garner and Clement (1963; see Figure 8) that were composed of five dots arranged in a virtual 3×3 grid. The patterns were scaled to match the size of the circle–line stimuli in Experiments 1–6. They were placed in the same random positions as the stimuli in the previous experiments.

Results and Discussion

The results of Experiments 7 and 8 are presented in Figure 9 (left panel). The error data for this and all subsequent experiments in Section 3 are presented in Table 2. As predicted, there was a very clear search asymmetry in Experiment 7, whereas there was very little indication of a search asymmetry in Experiment 8. In Experiment 7, search slopes were substantially lower for the condition in which the nontargets were highly redundant than for the condition in which they were less so. Without having to invoke a relationship between the stimuli that is based on the presence or absence of a single feature, the redundancy of the items fully accounts for the observed search asymmetry (in Experiment 7), or the absence thereof (in Experiment 8).

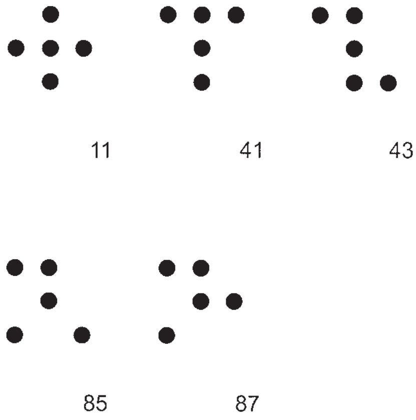

Figure 8. Dot patterns used in Experiments 7–10. Adapted from *Journal of Verbal Learning and Verbal Behavior, 2,* Garner, W. R., and Clement, D. E., Goodness of pattern and pattern uncertainty, 446–452, Copyright 1963, with permission from Elsevier. The number to the bottom right of each stimulus provides a rough indication of the relative redundancy associated with that stimulus—the larger the first digit in that number, the lower the redundancy of the corresponding pattern. All patterns with the same first digit are roughly comparable in redundancy.

One featural difference quite clearly describes the difference between the stimuli in Experiments 7 and 8, however: the presence or absence of symmetry. Symmetry is often regarded as a basic feature (e.g., Olivers & van der Helm, 1998; Wagemans, 1995; Wenderoth, 1994; Wolfe & Friedman-Hill, 1992). Whereas Pattern 11 is symmetric about four axes as well as its central point, Patterns 85 and 87 contain no symmetry. In Experiment 8, therefore, the two halves of the would-be search asymmetry are both characterized by the absence of a feature. Neither FIT nor AET would consequently predict an asymmetry in search efficiency, and this is in accord with our results. By contrast, in Experiment 7, the target in one half of the search asymmetry possesses symmetry, whereas in the other half, it does not. Accordingly, FIT and AET would predict a search asymmetry. Our results do reveal an asymmetry, but it is in the opposite direction to the one predicted by FIT and AET: The presence of symmetry is detected less efficiently than its absence (cf. Olivers & van der Helm, 1998, p. 1111).

Similarity Ratings

On inspection of the stimuli used in Experiments 7 and 8, it is tempting to conclude that a difference in T-NT similarity (a crucial factor according to AET) could have been responsible for the different outcomes of the two experiments. To investigate this possibility, similarity ratings were obtained from 20 observers, who were asked to complete a pencil-and-paper questionnaire after participating in another, unrelated experiment. None of the raters had participated in any of the experiments reported here. Participants were asked to rate pairs of dot patterns presented in random order for similarity on a 10-point scale (0 denoting *no similarity* and 9 *complete similarity*) by writing their numerical rating next to each pair of patterns. They were presented with all possible permutations of pairings between Items 11, 42, 43, 85, and 87 (see Figure 8; Item 42 not shown), for a total of 20 separate ratings. Ratings were averaged across observers and proved quite stable. A separate group of 20 participants was asked to rate the interitem similarity in the same manner for pairings between Items 41, 42, and 87, as well as their 90°, 180°, and 270° rotations (see Experiment 10), for a total of 32 separate ratings. These ratings were used for Experiment 10, presented below.

The two stimuli in Experiment 8 were judged to be significantly more similar to each other than the two stimuli in Experiment 7, $t(39) = 6.51$, $SE = .04$. This difference in similarity represents a confound in that high T-NT similarity is correlated with highly inefficient search in Experiment 8, as AET would predict, and that low T-NT similarity is correlated with efficient search in Experiment 7. However, an account in terms of T-NT similarity fails on two counts. First, it fails to explain the search asymmetry in Experiment 7, because the T-NT similarity is the same in both conditions; the target and nontarget items merely exchange roles (as discussed above). Second, an account based on T-NT similarity

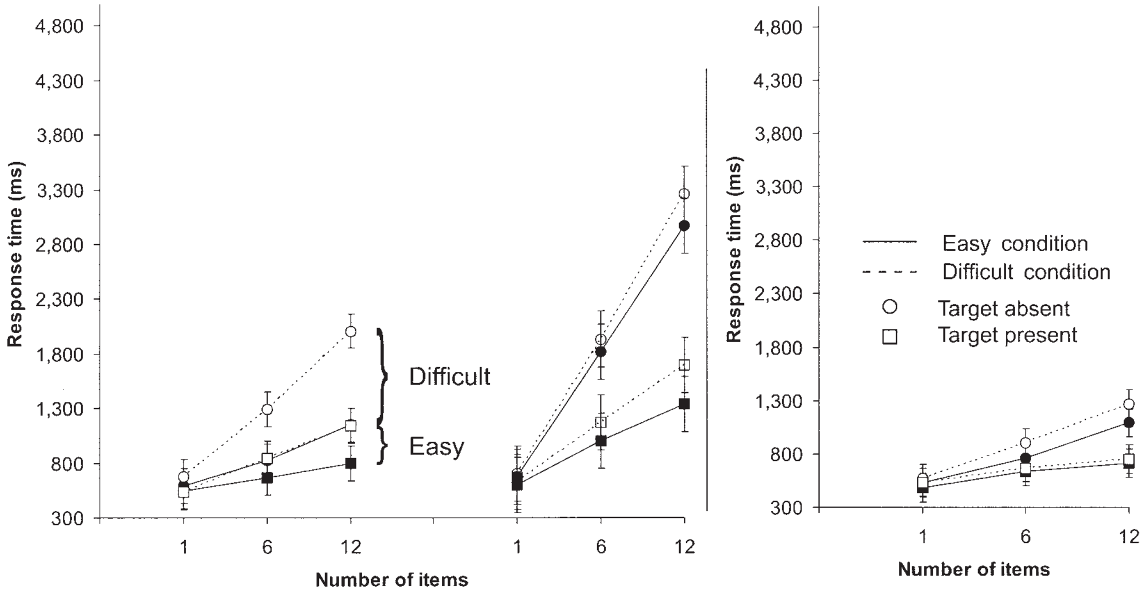

Figure 9. Response time data from Experiments 7 and 8 (left panel) and 9 (right panel). Error bars denote the within-subject confidence intervals for each condition.

(derived from subjective ratings) would predict a difference between those conditions of Experiments 7 and 8 that use Item 87 as nontarget: This item was judged significantly more similar to the target used in Experiment 8 than to the target used in Experiment 7. Although there was a slight trend in the predicted direction (55 vs. 67 ms/item for target present trials), this effect did not reach significance ($F < 1$).

Experiment 9: Target Contribution

A comparison between Experiments 7 and 8 suggests that the contribution of the target stimulus to search efficiency was minimal, at best. One condition in each experiment used Stimulus Pattern 87 as nontarget, but the targets differed between these two respective conditions. Even so, as discussed above, there was only a slight nonsignificant difference between these two conditions. At the same time, one condition in each experiment used Stimulus Pattern 87 as target, and the nontargets differed between experiments. In this case, there was a substantial and significant difference between the conditions (23 vs. 97 ms/item for target present trials). Experiment 9 examined this difference in the effects of target and nontargets on search efficiency more systematically, within the same experiment. In this experiment, two different targets were used (which differed in their redundancy), but the nontarget stimulus was kept the same between conditions.

Table 2
Error Data for Experiments 7–10 in Percentage Error

		Target present			Target absent		
Experiment	Condition	1	6	12	1	6	12
7	Easy	3.1	1.2	6.0	1.8	0.7	0.6
	Difficult	2.8	7.2	11.1	0.5	0.3	0.8
8	Easy	1.2	1.1	5.0	1.3	1.0	4.8
	Difficult	1.9	4.5	10.5	1.3	0.5	0.6
9	Easy	1.3	3.3	5.7	1.1	0.9	0.2
	Difficult	2.4	2.6	4.2	0.9	0.7	0.9
10	Easy	2.0	3.6	6.6	0.9	0.0	0.2
	Difficult	1.3	11.4	17.7	1.0	0.2	0.7

Method

Twelve new participants (4 men, 8 women) were recruited for Experiment 9. These participants ranged in age from 18 to 21 years ($M = 19.3$ years). The experiment used Pattern 11 as nontarget and Patterns 85 and 43 as targets. Pattern 43 is significantly more redundant than Pattern 85 (Garner & Clement, 1963). Because we wanted the displays in Experiment 9 to differ only in the redundancy of their targets, we equated the targets for their similarity to the nontargets (at least in terms of their subjective similarity). According to participants' ratings (as described above), the two target patterns do not differ in their similarity to the nontarget pattern (Pattern 11 vs. Pattern 43: $M = 3.25$, $SD = 1.78$; Pattern 11 vs. Pattern 85: $M = 2.88$, $SD = 1.86$), $t(39) = 1.20$, $p = .21$. (Given these values, on the order of 300 subjects would have been required to achieve even moderate power [.8].)

Results and Discussion

As can be seen from Figure 9 (right panel), Experiment 9 failed to show an effect of the target on search efficiency. In both conditions of the experiment, the nontargets were the same, and only the target differed. An ANOVA revealed no significant interaction between target pattern and display set size, $F(2, 22) = 1.03$, $MSE = 11{,}446.72$, $p = .37$, and no significant main effect of target, $F(1, 11) = 3.50$, $MSE = 241{,}162.84$, $p = .09$. (To achieve even moderate power [.8] for the interaction, given the tiny effect size, well over 500 subjects would have been required. We are therefore quite confident that the effect of target on search efficiency is negligible.) A separate analysis for the target present trials found no significant interaction either ($F < 1$), nor was there a significant main effect for the type of target, $F(1, 11) = 1.72$, $MSE = 33{,}153.13$, $p = .22$. The absence of a discernable difference between conditions underscores the idea that the target is not as important in determining search efficiency as are the nontargets.

Experiment 10: Redundancy and NT-NT Similarity

The final experiment pitted stimuli of different redundancy against one another under conditions of nontarget heterogeneity. In our proposal, there is no question that display heterogeneity can negatively affect search efficiency (as discussed in Part 2). However, beyond the prediction that display heterogeneity may generally decrease the efficiency of search, our proposal can further make differential predictions for different types of heterogeneous displays. In Experiment 10, for example, the displays in both conditions of the experiment were heterogeneous. Because of the nature of the stimuli, there is no straightforward objective way of determining which display has greater NT-NT similarity (e.g., overlap in features; see Duncan & Humphreys, 1992; Treisman, 1992) other than relying on search performance. This approach, however, is circular, because the goal is to predict search performance from NT-NT similarity. At the same time, whereas it is difficult to determine which of the two displays used in Experiment 10 has greater NT-NT similarity, it is possible to determine which of the two has the more redundant nontarget stimuli.

On the basis of this difference in nontarget redundancy, our theoretical framework predicts that the display with the more redundant nontarget stimuli should produce the more efficient search. Furthermore, because the two conditions are combined into the same experiment, one should observe a search asymmetry. As discussed in Section 2 of Part 1 of this article, it is our contention that search asymmetries are the result of juxtaposing two seemingly similar yet fundamentally different searches, and that search asymmetries in general arise from differences in nontarget redundancy between the two halves of the asymmetry. In Experiment 10, we emphasized this point by loosening the concept of search asymmetries entirely from the complementary (featural) relationship between the two halves of the asymmetry.

The ratings of similarity we obtained for the dot pattern stimuli in Figure 8 (as described above) were intended to minimize the possibility that the displays in Experiment 10 differed systematically in terms of their (subjective) T-NT similarity. (Recall that, according to Duncan & Humphreys, 1989, T-NT similarity has a larger effect when NT-NT similarity is low, as in the case of Experiment 10, where the nontargets in both conditions are heterogeneous.) On the basis of these ratings, a similarity-based account would make the opposite prediction to the one made by our theoretical framework: The condition in which the target is (subjectively) more similar to its nontargets includes nontarget stimuli that are associated with a greater degree of redundancy. According to T-NT similarity, this condition should produce less efficient search; according to nontarget redundancy, the same condition should produce more efficient search.

Method

Twelve participants (8 men, 4 women) took part in Experiment 10. The participants' ages ranged from 18 to 22 years, with a mean of 19.6 years. The design was the same as in the previous experiments.

The stimuli were Items 41 and 87 from Garner and Clement (1963) and their 90°, 180°, and 270° rotations (as instances of set members; see above). The stimuli at 0° rotation (see Figure 10) served as target, and the transformed versions served as nontargets. Participants rated the nontargets for Item 41 to be substantially more similar to their respective target (a mean rating of 6.68, $SD = 2.14$) than the nontargets for Item 87 to their respective target (a mean rating of 5.63, $SD = 2.48$). This effect was statistically significant, $t(59) = 2.31$, $SE = 0.45$.

Results and Discussion

Figure 10 depicts the results from Experiment 10. Search slopes for the less redundant nontarget stimuli were more than three times as steep as those for the more redundant nontarget stimuli (173 vs. 48 ms/item for target present trials), although T-NT similarity (based on subjective item–item ratings) was significantly greater in the latter case. This result supports our claim that search asymmetries are largely driven by differences in the redundancy of the nontargets and not the presence or absence of features (or an otherwise complementary relationship between the two halves of the search asymmetry). Moreover, it demonstrates that it is possible to derive differential predictions for different search displays that are heterogeneous—beyond the categorical prediction that

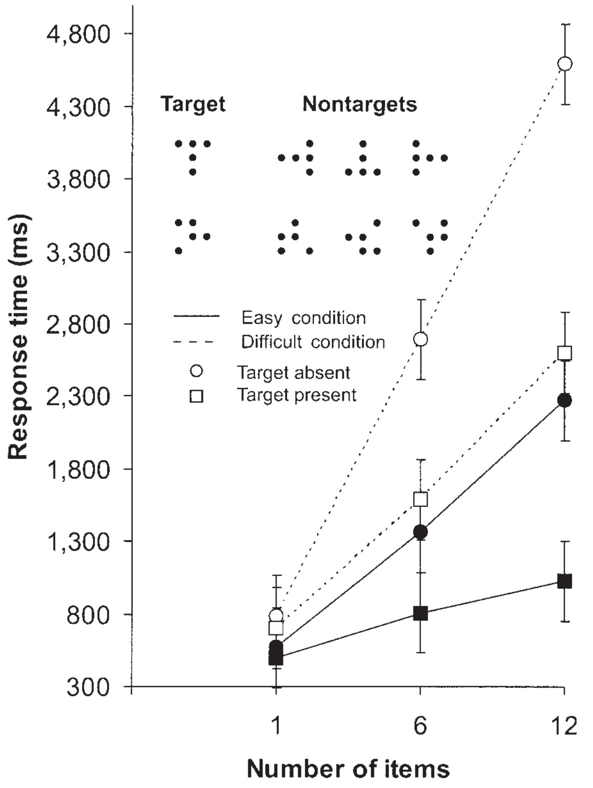

Figure 10. Stimuli and response time data from Experiment 10. Error bars denote the within-subject confidence intervals for each condition.

heterogeneous displays should produce less efficient search than homogeneous displays.

PART 2: A THEORETICAL FRAMEWORK FOR VISUAL SEARCH

In the previous sections of this article, we have reported evidence that nontarget redundancy can have a large effect on the efficiency of search and that both feature-based and similarity-based models of visual search cannot fully account for visual search performance. In the following, we provide a more detailed description of the theoretical framework that we used to predict search efficiency for the experiments in Section 3 of Part 1, on the basis of the results of the experiments from Section 1 of Part 1.

At the center of our proposal is the idea that search is performed on the basis of a representation of the visual scene and that the quality of this representation influences the efficiency of search. This representation is similar in spirit to Duncan and Humphreys's "perceptual description" (Duncan & Humphreys, 1989, p. 445). The quality of the representation is determined by two factors. First, there is a limit to the amount of information that can be processed by the visual system at any given point in time. Limited processing capacity at some level is assumed by almost all theories of attention (e.g., Broadbent, 1958; Bundesen, 1990; Chun & Potter, 1995; Duncan & Humphreys, 1989; Treisman & Gelade, 1980; see, however, Schumacher et al., 2001). The more redundant the stimuli are, the more efficiently they can be encoded and the better is the resulting representation achieved in a given amount of time. Second, to augment the occasionally sparse information available to construct the representation, the visual system relies extensively on default assumptions, memory, and expectations to fill in missing or scanty information (cf. Pessoa, Thompson, & Noe, 1998).

The quality of the representation is furthermore governed by the principle of parsimony: The representation will always be only as good as it needs to be for the present behavioral goals of the organism, and not better (Attneave, 1954; Garner, 1962, p. 200). Many tasks, such as the detection of a singleton target, may be performed without requiring much detail about the display. Consequently, nontarget redundancy will play a relatively small role in determining search efficiency in these cases. For example, in search for a red item among green items, the shape redundancy of the nontargets will be largely irrelevant.

As dictated by the principle of parsimony, to make maximum use of the information it has available, the visual system extrapolates this information across the entirety of the representation. This filling-in on the one hand serves to reduce the information load on the system (especially given the intrinsic capacity limitations), but on the other hand, it may obscure the presence of a target in visual search (see Rauschenberger, Peterson, Mosca, & Bruno, 2004): The more nontargets are present in the display, the more information suggests that all of the items in the display are nontargets. The majority status of the nontargets in most visual search displays in part accounts for the disproportionately large effect of the nontargets in our experiments, relative to that of the target.

Relationship to FIT and AET

Even though the experiments in Section 1 of Part 1 were devoted to illustrating some of the limitations of FIT and AET, there are some similarities between these theories and our theoretical framework. This section is devoted to discussing a number of features and characteristic predictions of FIT and AET, and to illustrating how our theoretical framework deals with these.

FIT

In our proposal, the fact that an item's implicit set comprises alternatives that are as probable as the stimulus itself has similar consequences as the fact that conjunction items are unbound in FIT. In both cases, different (re)combinations of the same features are considered as alternatives to the actual target: in FIT because attention may be unavailable to bind the features correctly and in our proposal because an inaccurate display representation is generated, on the basis of an equally likely but incorrect alternative member of the implicit set. Our theoretical framework therefore accommodates the illusory conjunctions predicted by FIT (see Treisman & Schmidt, 1982). Illusory conjunctions arise for stimuli associated with low redundancy because the set induced by these stimuli may be quite large. Because every item in the set of alternatives is equally likely, the probability that one of the alternative stimuli will replace the actual stimulus in the representation is likewise quite large. Under these conditions of uncertainty, the "wrong" set members are just as (statistically) appropriate a representation of the display items as the actual stimuli.

AET

Of the currently existing theories of search, our theoretical framework is perhaps most compatible with AET; in fact, it may be construed as an elaboration of AET. Unlike FIT, but much like our proposal, AET assumes that search is based on a highly processed representation. Another idea central to AET is that T-NT and NT-NT similarity determine the efficiency of search. Our proposal does not deny that nontarget heterogeneity can have a profound effect on search in some cases; however, the link between NT-NT similarity and search efficiency is not a direct one, as AET proposes. Rather, the effects of nontarget heterogeneity on search efficiency are mediated by nontarget redundancy. Inefficient search as the result of low NT-NT similarity is only a special case of the more general effects of nontarget redundancy on search. According to our proposal, the reason why nontarget heterogeneity can (albeit not inevitably) decrease search efficiency is that it decreases the redundancy associated with the nontargets. Heterogeneity has an effect on stimulus redundancy because it is capable of inducing a larger implicit set for individual display items than might be generated either in isolation or in homogeneous displays. On the one hand, heterogeneous stimuli share features with one another, suggesting that they could originate from the same (superordinate) set of alternatives. On the other hand, they are sufficiently different from one another to indicate substantial variability within this potential shared set, thereby effectively increasing the size of the implicit set and consequently reducing the redundancy of each individual item.

In Experiment 3, the effects of heterogeneity were seen solely as a (nonsignificant) trend in target absent slopes. In visual search, the default hypothesis is that all of the display positions are occupied by nontargets. The visual system will therefore hold on to the assumption that there are no targets present until it receives evidence to the contrary. Target present slopes may not immediately be affected by decreased redundancy, because a rejection of the hypothesis that all items are nontargets will unambiguously indicate a target present trial. On target absent trials, however, the added uncertainty of a less redundant display may cause a participant to be more reluctant to “accept” the current hypothesis because of the general difficulty in “proving” a null hypothesis.

Whereas NT-NT similarity may affect redundancy in our proposal, T-NT similarity has possible influences on the filling-in process. The more similar the target is to the nontargets, the more likely it is to be camouflaged by an overly zealous filling-in process. In this regard, the treatment of T-NT similarity by both AET and our proposal is quite similar: In both, the target is drawn into an intimate association with the nontargets—in one case because of grouping and in the other because of an overgeneralization. The experiments reported here demonstrate, however, that T-NT similarity, like NT-NT similarity, does not always produce an effect. Like NT-NT, it should therefore be regarded as a particular example of more general mechanisms operating in search.

Conclusions

In the first part of this article, we presented data that challenge the predictions of FIT and AET in their current formulations. Some of the results could be explained by incorporating auxiliary assumptions into both theories or by reinterpreting our displays in ways that are more favorable to both theories. However, when taken as a whole, in particular in conjunction with the experiments presented in Section 3 of Part 1, the data we present here pose distinct problems for both FIT and AET. To account for those aspects of our data that are troublesome for both theories, in Part 2 we proposed some perceptual principles that emerge from our results, from recent findings in the literature, and from classic information theoretic notions articulated by Garner and others, emphasizing the importance of the efficiency with which nontargets can be encoded. In Section 3 of Part 1, we tested the predictions of this proposal directly by using a new set of stimuli that were derived independently of visual search.

Although our theoretical framework represents a distinct departure from FIT and AET, it shares some assumptions and predictions with them. Ultimately, for example, decisions about the presence or absence of a target are made on the basis of—sometimes minute—featural distinctions between the target and the nontargets, as they would be in FIT. Furthermore, there is a logical relationship between nontarget heterogeneity and nontarget redundancy. It may be possible to find a common denominator for our theoretical framework and AET by examining the potential relationship between stimulus redundancy and the facility of grouping. Indeed, such a relationship would further our understanding not only of visual search but of one of the most fundamental processes of midlevel vision: perceptual grouping. The most fruitful avenue for future research will be to refine the theoretical principles that provide the greatest explanatory traction in accounting for observed perceptual phenomena.

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Received September 23, 2004
Revision received July 19, 2005
Accepted July 28, 2005 ■