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Flexible cue combination in the guidance of attention in visual search

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ABSTRACT

Hodsoll and Humphreys (2001) have assessed the relative contributions of stimulus-driven and user-driven knowledge on linearly- and nonlinearly separable searches. However, the target feature used to determine linear separability in their task (i.e., target size) was required to locate the target. In the present work, we investigated the contributions of stimulus-driven and user-driven knowledge when a linearly- or a nonlinearly-separable feature is available but not required for target identification. We asked observers to complete a series of standard color × orientation conjunction searches in which target size was either linearly- or nonlinearly separable from the size of the distractors. When guidance by color × orientation and guidance by size information are both available, observers rely on whichever information results in the best search efficiency. This is the case irrespective of whether we provide target foreknowledge by blocking stimulus conditions, suggesting that feature information is used in both a stimulus-driven and a user-driven fashion.

1. Introduction

In visual search experiments, observers typically search for a target among some number of distractor items (Eckstein, 2011; Wolfe, 2010). When the distractors are homogeneous and the target is defined by a salient difference in a single basic feature, search tends to be efficient with reaction times (RTs) essentially independent of the number of items presented (i.e., the set size; Neisser, 1963; Treisman, 1985; Wolfe & Horowitz, 2004). Not all feature searches are this efficient. For example, imagine a target that differs from the distractors along some continuous dimension, like size. A target is said to be "linearly-separable" from distractors if a line can be drawn in the feature space of the dimension such that the target is on one side of the line in feature space, and all the distractors are on the other (d'Zmura, 1991). When targets are linearly-separable from distractors, they are found more efficiently in a visual search task than when they are not. For example, a small target is found quickly when embedded within an array of medium and large distractors; a line can be drawn between the (small) target and the (medium and large) distractors in feature space. When, in contrast, observers search for a medium target among small and large distractors, no such line can be drawn between the target and distractors, and target search is less efficient (Hodsoll & Humphreys, 2001). Similar results have been shown for color (Bauer, Jolicoeur, & Cowan, 1996a, 1996b; Bauer, Jolicœur, & Cowan, 1998; d'Zmura, 1991), and orientation (Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992; for a different view see Vighneshvel & Arun, 2013).

Features like color, size, and orientation guide attention in two ways. Attention is attracted to salient differences between the features of items in a stimulus-driven manner (Egeth et al., 1972; Neisser, 1963; Nothdurft, 1993; Treisman & Gelade, 1980). For instance, a large item will "pop-out" from among smaller items, without the need to tell the observer to look for big items. Such effects are "stimulus-driven" in the sense that they emerge in the absence of, or even in conflict with instruction. Attention can also be guided to items in a user-driven manner (Bacon & Egeth, 1994). Thus, if observers are told to look for little red items among little green and big red distractors, they can guide their attention to "little" and "red" (or, perhaps, to the relative values "smaller" and "redder"; Becker, 2010), even though no little or red item is uniquely salient (Wolfe & Horowitz, 2004). To find the target in this case, observers must prioritize search for items matching the experimenter-defined values of the target (i.e., "little" and "red"), thus, search can be said to be "user-driven."

Linear separability effects are argued to be stimulus-driven: salient target–distractor differences allow linearly separable targets to be isolated from distractors in a way that nonlinearly separable targets cannot. However, Hodsoll and Humphreys (2001) have demonstrated that user-driven processes also influence linear separability. The authors compared the effects of foreknowledge of target size between linearly- and nonlinearly-separable search conditions within the size

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dimension. Hodsoll and Humphreys reasoned that if stimulus-driven processes alone support linear separability effects, then foreknowledge of target size should have no effect on differences between linearly-separable and nonlinearly-separable searches. When target size was known across a block of trials, search was faster and more efficient for linearly-separable targets than for nonlinearly-separable targets, replicating the standard linear separability effect. When foreknowledge of target size was removed, search for the medium-sized target was still slower and less efficient, showing that linear separability can guide attention in a stimulus-driven manner. At the same time, the switch from blocked to mixed trials slowed a linearly-separable search for big and small targets more than search for non-linearly separable medium targets, showing that linear separability effects were modulated by user-driven factors.

Hodsoll and Humphreys (2001) explained their results in the context of Duncan and Humphreys (1989) similarity theory of visual search, in which search efficiency increases when target–distractor similarity decreases and/or when distractor homogeneity increases. They argued that, in linearly separable displays, grouping of items allowed for more effective rejection of distractors. In this view, a benefit of foreknowledge of a linearly-separable target would be due mainly to the facilitation of the grouping of non-target items.

However, according to Becker (2010) the similarity account is not able to explain why it is harder to tune attention to nonlinearly separable targets than linearly separable targets. That is, it is only after a target has been identified as linearly separable that the similarity mechanism is able to group non-targets and thereby guide attention to possible targets. Instead, Becker has proposed that her relational guidance hypothesis is a more parsimonious account of linear separability effects because it depends on a single mechanism and can account for both efficient linearly-separable search and inefficient nonlinearly separable search. The relational account posits that the visual system uses the relationship between target and distractors and not absolute target features to guide visual attention. For example, in search for an odd sized item (e.g., a large target within small and medium distractors) attention is not guided by specific target features (e.g., large) but rather by the relational properties of the target relative to distractors (e.g., larger). All items that share the relational properties of the target receive higher activation than those that do not. A linearly separable search is efficient because the target, which differs from distractors in a single direction (e.g., larger), receives the most activation. Conversely, all items appearing in a nonlinearly separable search array would receive equal activation because the target (e.g., a medium sized item) differs in two opposing directions from distractors (i.e., it is both larger and smaller than the distractors). This would result in inefficient search.

Most of the work on linear separability has been conducted using search tasks in which targets and distractors differ only in one dimension (e.g. size) allowing the target to be linearly separable from the distractor in that dimension. In most real world searches, targets are more likely be defined by a conjunction of features and may be identifiable in several ways. For example, a person might locate his coffee mug on a cluttered desk by looking for an object matching its unique shape among a diverse set of other shapes (a possibly inefficient feature search). It might also be the only round, purple object on his desk (a conjunction of two features). Perhaps it is the largest item on the desk (a linearly separable size search). The specific route to the target will be constrained by the specific stimulus conditions and, perhaps, by user-driven ideas about the best way to look for this target. In the present set of studies, we examined linear separability in more complex conjunction search tasks in which linear separability can occur in a dimension that is not required for target identification. Specifically, we manipulated foreknowledge of target size in color/orientation conjunction searches.

Observers were instructed to search for a target of a given size, color, and orientation. As will be described, observers could treat the search as either a feature search (for a target of a unique size) or as a conjunction search (for a target of a particular color/orientation combination). We varied the linear separability of the size cue. Because our search task could be completed as either a feature search (using size) or as a conjunction search (using color and orientation), it was important that we first establish baseline performance in these two types of tasks using our stimuli. Thus, we asked our observers in Experiment 1 to complete a size feature search for linearly and non-linearly separable targets and in Experiment 2, we asked our observers to complete a color/orientation conjunction search in which the target and distractors were equal in size. The size feature and color-orientation conjunction cues to target presence are pitted against each other in later experiments.

2. Experiment 1

The purpose of Experiment 1 was to establish baseline performance in a size feature search for linearly and non-linearly separable targets using our stimuli. Search was either for a small, medium, or large red vertical line, among medium and large, small and large, or small and medium red vertical distractors, respectively. We hypothesized that search for linearly-separable targets (i.e., small and large) would be more efficient than search for nonlinearly-separable targets (i.e., medium).

2.1. Method

2.1.1. Participants

6 undergraduate students (100% female, $M_{age} = 21.4$ yrs.) from Concordia University participated in exchange for course credit. All participants reported normal or corrected-to-normal vision.

2.1.2. Stimuli and apparatus

Stimuli were presented on a 21-in. monitor (Viewsonic G225fb, 1024 × 768 pixel resolution; 100 Hz refresh rate) controlled by a Dell Precision T3400 core2 quad processor running Windows 7. Mathwork's Matlab (ver. 2011b) and the psychophysics toolbox extensions (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997) were used to create the stimuli and controlled all timing, display, and recording operations. Observers were seated 60 cm away from the screen and their head position was controlled using a mounted chinrest.

Fig. 1 shows examples of the stimuli. The stimuli were red vertical lines presented on a white background. The sizes of the lines were 25, 50, or 75 pixels. The largest line subtended a visual angle of 2.38°, and the smallest line subtended a visual angle of .79°, when viewed at a distance of 60 cm.

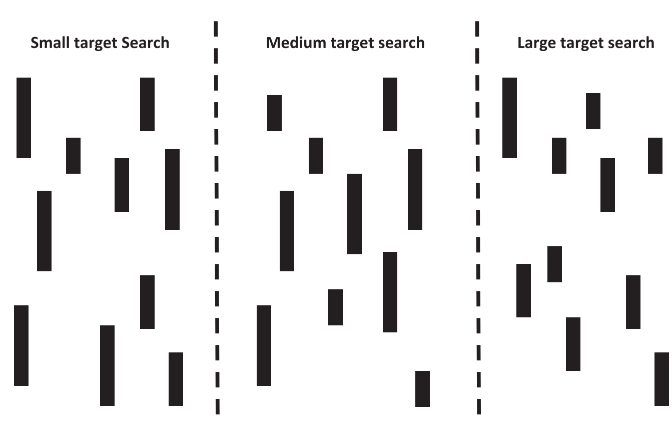

Fig. 1. Sample stimuli used in Experiment 1. Target was a small, medium, or large red vertical line (black vertical in the figure), between medium and large, small and large, or small and medium red vertical distractors, respectively.

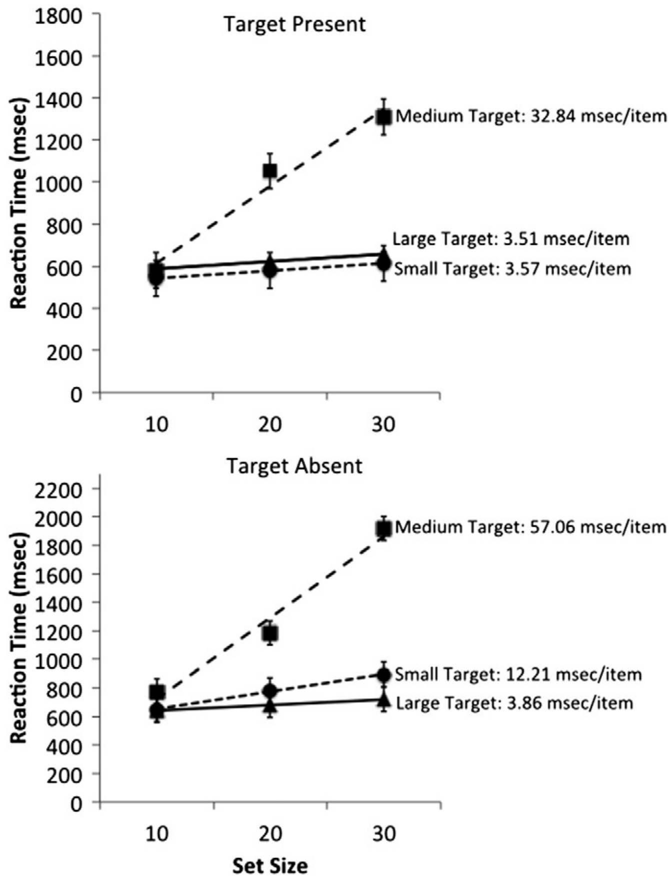

Fig. 2. RTs as a function of set size in Experiment 1. The error bars represented here, and throughout the article, are the 95% within-subject confidence intervals as described by Loftus and Masson (1994).

2.1.3. Design

The search array was comprised of 10, 20, or 30 vertical lines. For each set size there were both target present and target absent displays, for which target size was either linearly- or nonlinearly-separable from the size of its distractors. Nonlinearly-separable trials were comprised of a medium red vertical line among small and large red vertical distractors, respectively. Linearly-separable trials were comprised of either a small or large red vertical line, respectively, among medium and large or small and medium red vertical distractors. Target absent trials were created by replacing the target with a distractor of one of the two remaining sizes, chosen at random. Target size was blocked across observers, with the order of blocks chosen at random by a Matlab algorithm. The number of items in the search array and the presence of the target varied randomly on a trial-to-trial basis.

2.1.4. Procedure

An introductory screen at the beginning of each block provided a written description of the target for that block of trials. Observers were instructed to look for the small, medium, or large red vertical item as quickly and as accurately as possible (e.g., "…As quickly and as accurately as possible, please indicate whether the large red vertical item is present or absent…"). Each trial within a block was initiated with a fixation cross located at the center of the screen presented for 500 ms. The search array immediately followed offset of the fixation cross and stayed on the screen until response. We instructed observers to press the "1" key on the number keyboard as quickly as possible if they believed that the target was present, and the "2" key if they believed that the target was absent. Displaying either "correct" or "incorrect" in the middle of the screen for 250 ms provided trial-by-trial feedback. A 500 ms blank screen separated the offset of the feedback from the onset of the next fixation cross, which indicated the start of a new trial. Observers completed 30 practice trials prior to the start of the experiment. Observers completed 3 blocks of 300 trials for a total 900 trials.

2.2. Results

Mean RTs on correct trials were first submitted to a recursive outlier analysis as described by Van Selst and Jolicœur (1994); this analysis removed fewer than 1% of RTs. Results for Experiment 1 are displayed in Fig. 2. Because we were particularly interested in examining differences in search efficiency, we concentrated our analysis on search slopes rather than absolute RT measures[1]. With respect to Experiment 1, it is immediately clear that search for the medium target is less efficient than search for the large or small targets.

One-sample t-tests revealed that all slopes in Experiment 1 were statistically significantly different from zero: all *ts* > 4.0 and all *ps* < .01. Search efficiency was analyzed by entering slope values into 2 (Target Presence) × 3 (Target Size) repeated measures analyses of variance (ANOVA). There was a significant main effect of Target Presence, $F(1,5) = 28.32$, $p < .003$, $\eta_p^2 = .85$. Search was less efficient

[1] We conducted parallel RT analyses for all search slope analyses reported in the four experiments. The RT results corroborated the slope comparisons, but did not add any substantial contributions to the understanding of search behavior. As such, we report only the search slope comparisons.

on target absent displays ($M = 24.37$; $SD = 9.77$) than on target present displays ($M = 13.31$; $SD = 5.01$). There was also a significant main effect of Target Size, $F(2, 10) = 49.17$, $p < .001$, $\eta_p^2 = .91$. A calculation of Tukey's HSD revealed that a difference of 25.13 was significant at alpha = .05. By this criterion, medium target search ($M = 45.95$; $SD = 18.27$) was less efficient than small ($M = 7.89$; $SD = 4.09$) and large ($M = 3.69$; $SD = 1.47$) target searches. Slopes were not statistically different between small and large targets. The Target Presence × Target Size interaction was also significant, $F(2, 10) = 44.22$, $p < .001$, $\eta_p^2 = .89$. Looking at Fig. 2, it is clear that small target search ($M = 12.21$; $SD = 7.41$) was less efficient than large target search ($M = 3.86$; $SD = 1.85$) on target absent displays, $t(5) = 3.31$, $p < .021$. There was no significant difference between small ($M = 3.57$; $SD = 4.09$) and large target searches on target present displays ($M = 3.51$; $SD = 1.47$), $t(5) = .075$, $p > .943$.

2.2.1. Accuracy

Accuracy was analyzed using the signal detection measure, d' (Table 1). Overall, accuracy was high with an average d' value of 3.5 (average hit rate = 89.4% and average false alarm rate = 2.2%). We entered d' values into a 3 (Target Size) × 3 (Set Size) repeated measures ANOVA. There was a significant main effect of Trial Type, $F(2, 10) = 14.90$, $p < .001$, $\eta_p^2 = .75$, but neither the main effect of Set Size, $F(2, 10) = 2.64$, $p > .121$, $\eta_p^2 = .35$, nor the Target Size × Set Size interaction, $F(4, 20) = .58$, $p > .723$, $\eta_p^2 = .094$, was significant. Accuracy was worse for medium targets ($M = 2.89$; $SD = 0.44$) than for both small ($M = 3.81$; $SD = 0.62$) and large ($M = 3.88$; $SD = 0.46$) targets (Tukey's HSD = .90; $\alpha = .05$). There was no difference between small and medium target searches.

2.3. Discussion

In Experiment 1, we replicated Hodsoll and Humphreys (2001) result that a nonlinearly-separable search was both less efficient and less accurate than linearly-separable search along the size dimension. Furthermore, search slopes for both target present and target absent displays in Experiment 1 were consistent with those reported by Hodsoll and Humphreys, yielding an approximately 1:2.5 target present/absent slope ratio. It is interesting to note that the linear separability effect occurs even when there are no targets. It took observers longer to confirm that a medium target was not present than to confirm that a big or small target was not present, suggesting that observers were using the structure of the task as a cue to target presence. In a linearly separable block, it would take less time to become confident that a target was *not* present.

3. Experiment 2

The goal of Experiment 2 was to obtain baseline measures of search behavior in a color/orientation conjunction search, without the benefit of size information. The target was a small, medium, or large red vertical line, among small, medium, or large horizontal red and green vertical distractors.

Table 1
d′ values in Experiment 1.

Target	Set Size		
	10	20	30
Small	3.86 (0.72)	3.99 (0.66)	3.59 (0.43)
Medium	2.92 (0.45)	2.96 (0.39)	2.81 (0.51)
Large	3.86 (0.52)	3.93 (0.44)	3.85 (0.46)

3.1. Method

3.1.1. Participants

10 undergraduate students (70% female, $M_{age} = 20.02$ yrs.) from Concordia University participated in return for partial course credit. All participants reported normal or corrected-to-normal vision.

3.1.2. Stimuli, apparatus, design and procedure

The stimuli, apparatus, design, and procedure in Experiment 2 were the same as in Experiment 1, with the following exception: stimuli were red and green vertical and horizontal lines appearing on the same white background as in Experiment 1. Sample stimuli for Experiment 2 are shown in Fig. 3. Search was either for a small, medium, or large red vertical target, among an equal number of small, medium, or large horizontal red and green vertical distractors, respectively. Thus, Experiment 2 differs from Experiment 1 in that all items in a given display were of the same size; however and similar to Experiment 1, target size varied across blocks. Furthermore, as in Experiment 1, observers were asked to locate the small, medium, or large red vertical item as quickly and as accurately as possible. The results of Experiment 2 thus provide a baseline measure of color/orientation conjunction search for each of our target sizes.

3.2. Results

Similar to Experiment 1, a recursive outlier analysis removed fewer than 1% of RTs. Results for Experiment 2 are displayed in Fig. 4. In this case, it is the small targets that are more difficult to find. All slopes in Experiment 2 were statistically significantly different from zero: all $ts > 4.0$ and all $ps < .002$. There was a significant main effect of Target Presence, $F(1, 9) = 8.1$, $p < .019$, $\eta_p^2 = .47$. Search was less efficient on target absent displays ($M = 17.37$; $SD = 13.35$) than on target present displays ($M = 8.86$; $SD = 5.07$). The main effect of Target Size was also significant, $F(2,18) = 10.73$, $p < .001$, $\eta_p^2 = .54$. Search for small targets ($M = 16.8$; $SD = 8.67$) was less efficient than search for medium ($M = 10.19$; $SD = 7.21$) and large ($M = 12.3$; $SD = 8.45$) targets (Tukey's HSD = 4.31; $\alpha = .05$). There was no significant difference between large and small targets. The Target Presence × Target Size interaction was not significant, $F(2,18) = 1.18$, $p > .331$, $\eta_p^2 = .12$.

3.2.1. Accuracy

Overall, accuracy was comparable to Experiment 1 with an average d' value of 3.6 (average hit rate = 90.2% and average false alarm rate = 2.2%). Neither the main effect nor the interaction was significant, $F(4,36) = 1.93$, $p > .06$, $\eta_p^2 = .31$. d' prime values in Experiment 2 are displayed in Table 2.

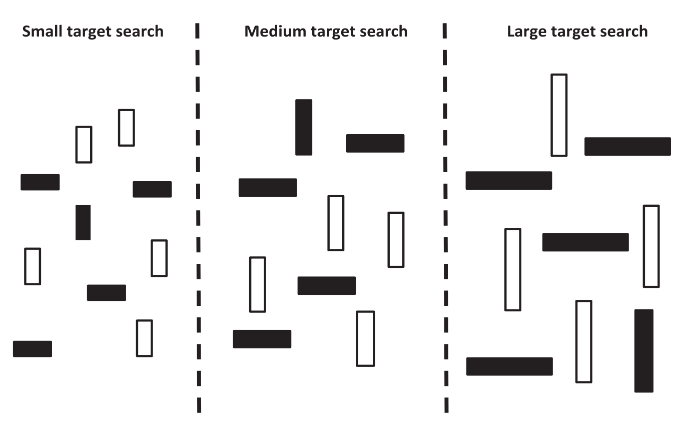

Fig. 3. Sample stimuli used in Experiment 2. Target was a small, medium, or large red vertical line (black vertical in the figure), between small, medium, or large horizontal red (black horizontal) and green vertical (white vertical) distractors, respectively.

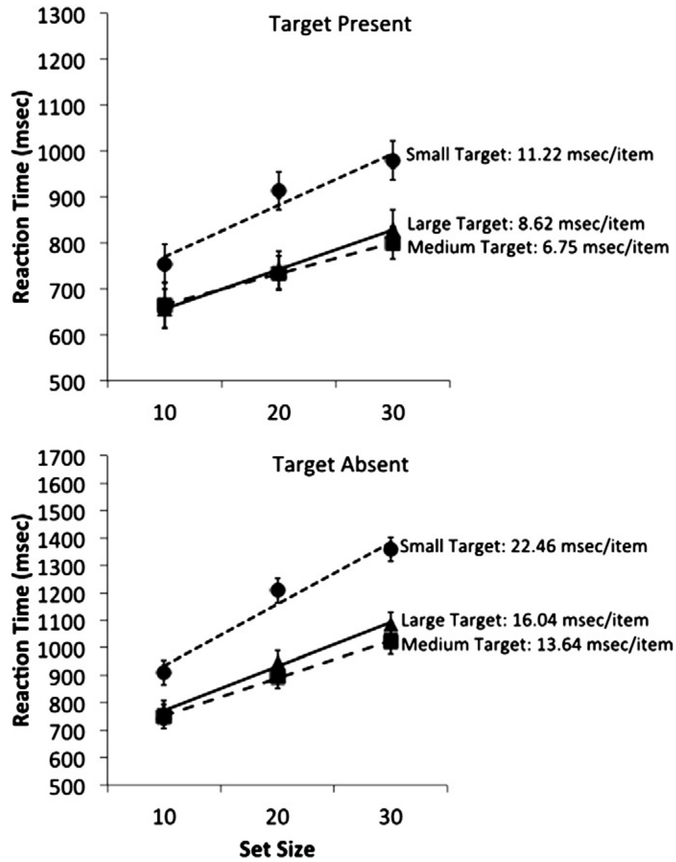

Fig. 4. RTs as a function of set size in Experiment 2.

3.3. Discussion

Although target present slopes were reasonably shallow in Experiment 2, they were all significantly different from zero and consistent with previously published color/orientation conjunction data (e.g., Friedman-Hill & Wolfe, 1995). Small target search was the least efficient. The present/absent ratio was approximately 1:2 for all target sizes. Fig. 5 summarizes the data for purposes of comparison across all four experiments on target present trials. Reaction time × set size functions for small target searches are displayed in the first panel, medium target searches in the next, and large target searches in the final panel. For present, looking only at Experiments 1 and 2, it is clear that size feature search is easier than conjunction search for large and small targets, while conjunction search is easier for medium sized targets. In the remaining experiments, we combine these two sources of information.

4. Experiment 3

In Experiment 3, the target-defining cues in Experiments 1 and 2 are combined in a manner that allows observers to use either or both cues.

Table 2
d′ values in Experiment 2.

Target	Set Size		
	10	20	30
Small	3.67 (0.77)	3.51 (0.97)	3.27 (0.84)
Medium	3.68 (0.81)	3.82 (0.48)	3.93 (0.68)
Large	3.88 (0.66)	3.81 (0.57)	3.24 (0.56)

The target item was uniquely defined by a color/orientation conjunction, and also by a target size that was either linearly- or nonlinearly-separable from distractors. Observers searched for a small, medium, or large red vertical target, among medium and large, small and large, or small and medium red horizontal and green vertical distractors, respectively (see Fig. 6). Target size was held constant over a block of trials. Observers knew the target size. It was unique and potentially useful in the search array. Observers were given instructions identical to those in Experiments 1 and 2. Thus, observers, in principle could have performed the task as a conjunction search, a size-feature search or some combination of the two.

4.1. Method

4.1.1. Participants

15 undergraduate students (60% female, $M_{age} = 24.2$ yrs.) from Concordia University participated in return for partial course credit. All participants reported normal or corrected-to-normal vision.

4.1.2. Stimuli, apparatus, design and procedure

The stimuli, apparatus, design, and procedure in Experiment 3 were the same as in Experiment 1, with the following exception: nonlinearly-separable trials were comprised of a medium red vertical line embedded within small and large red horizontal and green vertical distractors. Linearly-separable trials were comprised of either a small or large red vertical line embedded within medium and large, or within small and medium red horizontal and green vertical distractors, respectively. Sample stimuli for Experiment 3 are displayed in Fig. 6. Critically, all other procedures were identical to Experiments 1 and 2; we provided observers with the same task instructions and target size was held

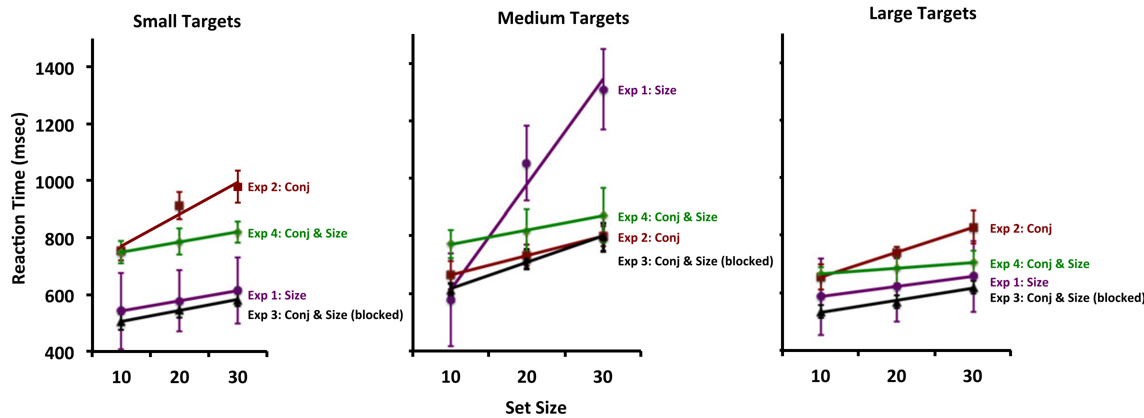

Fig. 5. Comparison across all four experiments on target present displays with all small target RT × set size functions in one panel, all medium in the next and all large in the final panel. Because Fig. 5 compares search performance between experiments, the 95% confidence intervals here are not based on a within-subjects calculation.

constant in a block of trials. Because the target was unique in size, the target could be found by size alone, but observers were not told this.

4.2. Results

As in Experiments 1 and 2, an outlier analysis was performed on the RT data and removed 1.6% of RTs. Results for Experiment 3 are displayed in Fig. 7. As can be seen in Fig. 7, medium targets are somewhat harder to find than small or large targets. The explanation for this can be found by comparing these results to those of Experiments 1 and 2, as shown in Fig. 5. When the target is uniquely large or small, observers can take advantage of the size information to make search as fast and efficient as the large or small size targets in Experiment 1. When the target size is medium, the intermediate size information is not useful and observers rely on the color and orientation information to make search only as efficient as the color × orientation search of Experiment 2. However, before reporting the between experiment results, we first report the report the within experiment results for Experiment 3.

4.2.1. Search slopes

All search slopes in Experiment 3 were statistically different from zero: all *ts* > 5 and all *ps* < .001. As in the previous experiments, we analyzed search efficiency using a 2 (Target Presence) × 3 (Target Size) repeated measures ANOVA. There was a significant main effect of Trial Type. As in Experiment 1, medium target search ($M = 9.62$; $SD = 4.78$) was less efficient than small target search ($M = 4.74$; $SD = 1.91$) and large target search ($M = 3.87$; $SD = 2.16$) (Tukey's HSD = 3.36, α = .05).

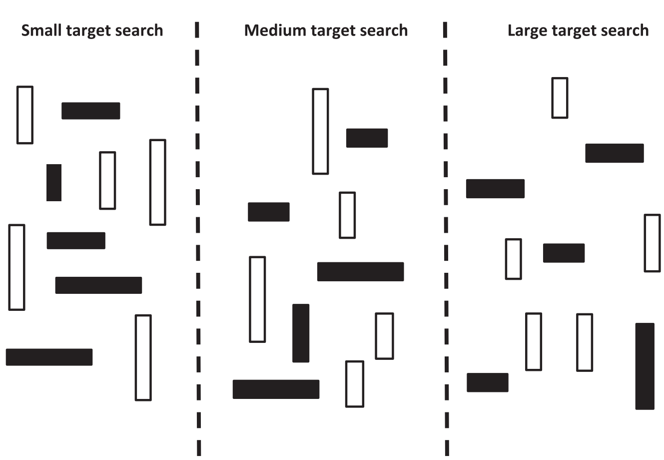

Fig. 6. Sample stimuli used in Experiments 3 and 4. Nonlinearly-separable trials (medium target search) were comprised of a medium red vertical line between small and large red horizontal and green vertical distractors. Linearly-separable trials (small and large target searches) were comprised of either a small or a large red vertical line between medium and large or small and medium red horizontal and green vertical distractors. Target absent trials were created by replacing the target with a distractor of one of the two remaining sizes, chosen at random.

4.2.1.1. Accuracy.

d′ values for Experiment 3 are displayed in Table 3. Overall, accuracy was comparable with Experiments 1 and 2, with an average *d′* value of 3.4 (average hit rate = 88.3% and an average false alarm rate = 3.1%). A 3 × 3 repeated measures ANOVA revealed a significant main effect of Trial Type, $F(2, 28) = 12.18$, $p < .001$, $\eta_p^2 = .47$. Small target search ($M = 3.65$; $SD = 0.54$) was less accurate than medium target search ($M = 3.11$; $SD = 0.27$). Accuracy did not statistically significantly differ between small target search and large target search ($M = 3.37$; $SD = 0.26$), or between medium target search and large target search (Tukey's HSD = .49, α = .05). There was also a significant Set Size main effect, $F(2, 28) = 11.74$, $p < .001$, $\eta_p^2 = .46$. Search was less accurate on 30-item search arrays ($M = 3.10$; $SD = 0.69$) than 10-item search arrays ($M = 3.55$; $SD = 0.58$). There was no significant difference in accuracy between 30-item arrays and 20-item arrays ($M = 3.47$; $SD = 0.74$), or between 20-item arrays and 10-item arrays (Tukey's HSD = .41, α = .05). The Target Size × Set Size interaction was also significant, $F(4,56) = 6.43$, $p < .001$, $\eta_p^2 = .32$. Although accuracy decreased with increasing set size, this decrease was largely attributable to medium target search, with smaller effects of set size on small and large target searches, respectively.

4.2.2. Comparison between Experiments 1 and 3

In order to compare search behavior between Experiments 1 and 3, we entered slope values into a series of 2 (Experiment) × 2 (Target Presence) × 3 (Target Size) repeated measures ANOVAs. Because we were interested in the differences between the two studies, we concentrated our interpretation on the effects of Experiment, and its interaction with the other factors.

There was a significant main effect of Experiment. Search was less efficient in Experiment 1 ($M = 18.84$; $SD = 7.39$) than 3 ($M = 6.08$; $SD = 4.09$), $F(1,19) = 54.68$, $p < .001$, $\eta_p^2 = .74$. There was also a significant main effect of Target Presence, $F(2, 38) = 39.62$, $p < .001$, $\eta_p^2 = .68$ and a significant Target Presence × Experiment interaction, $F(1, 19) = 54.47$, $p < .001$, $\eta_p^2 = .74$. Search was less efficient on target absent displays in Experiment 1 and there was no difference in search efficiency between target present and target absent displays in Experiment 3, as confirmed by the non-significant Target Presence main effect reported in the within experiment ANOVA. There was also a significant main effect of Target Size, $F(2, 38) = 133.82$, $p < .001$, $\eta_p^2 = .87$, and a significant Target Size × Experiment interaction, $F(2, 38) = 85.55$, $p < .001$, $\eta_p^2 = .82$. Medium target search was least efficient in both Experiments;

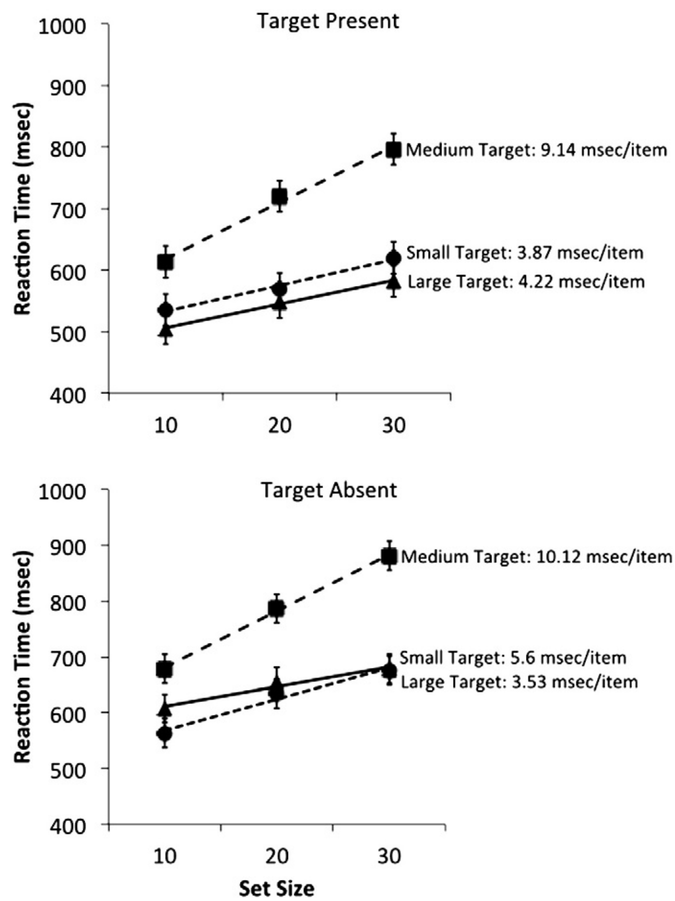

Fig. 7. RTs as a function of set size in Experiment 3.

however, it was more efficient in Experiment 3 ($M = 9.62$; $SD = 4.78$) than in Experiment 1 ($M = 44.95$; $SD = 18.27$). In order to confirm this interpretation, we compared search slopes between Experiments 3 and 1 using a series of independent samples *t*-tests. The greatest benefit was for medium target search, $t(19) = 5.29$, $p < .001$. Small target search did not differ significantly between Experiment 1 ($M = 7.89$; $SD = 4.09$) and Experiment 3 ($M = 4.73$; $SD = 1.9$), $t(19) = 1.51$, $p > .183$. Furthermore, large target search was equally efficient between Experiment 1 ($M = 3.69$; $SD = 1.47$) and Experiment 3 ($M = 3.87$; $SD = 2.2$), $t(19) = .19$, $p > .850$.

4.2.3. Comparison between Experiments 2 and 3

In Experiment 2, all items in a display are of equal size, so a comparison with Experiment 3 provides a test of whether stimulus driven size information was used to find the color/orientation target in Experiment 3. Similar to above, we compared search efficiency between Experiments 2 and 3 using a 2 × 2 × 3 repeated measures ANOVA.

Table 3
d′ values in Experiment 3.

Target	Set Size		
	10	20	30
Small	3.73 (0.52)	3.72 (0.65)	3.48 (0.61)
Medium	3.62 (0.53)	3.09 (0.78)	2.61 (0.72)
Large	3.31 (0.61)	3.59 (0.61)	3.22 (0.64)

There was a significant main effect of Experiment. Search was less efficient in Experiment 2 ($M = 13.11$; $SD = 8.59$) than Experiment 3, $F(1,23) = 10.06$, $p < .004$, $\eta_p^2 = .31$. There was also a significant main effect of Target Presence, $F(1,23) = 12.98$, $p < .001$, $\eta_p^2 = .36$, and a significant Target Presence × Experiment interaction, $F(1,23) = 9.46$, $p < .005$, $\eta_p^2 = .29$. Search was less efficient on target absent displays than on target present displays in Experiment 2. There was no difference in search efficiency between target absent and target present displays in Experiment 3. The main effect of Target Size, $F(2, 46) = 5.03$, $p < .011$, $\eta_p^2 = .18$, and the Experiment × Target Size interaction was significant, $F(1,23) = 23.29$, $p < .001$, $\eta_p^2 = .51$. Whereas small target search was least efficient in Experiment 2, medium target search was the least efficient in Experiment 3. The three-way Experiment × Target Size × Target Presence interaction was not significant, $F(2, 46) = .811$, $p > .451$, $\eta_p^2 = .34$.

4.3. Discussion

Experiment 3 shows that observers can adjust the guidance of search, even without explicit instructions, to make use of whatever source of guidance is most useful. When the targets are uniquely small, or large, observers can (and do) use size information, as in Experiment 1, to produce more efficient search than would be produced by searching for a small, or large red vertical item on the basis of its color and orientation. Having turned the task into a size search, observers do not appear to be distracted by the now-irrelevant color and orientation information. On the other hand, when the target is uniquely medium in size, observers are not limited by the inefficiency of medium-size search, as in Experiment 1. Instead, they can use the color × orientation guidance, observed in Experiment 2, to produce search results comparable in efficiency to the medium-size condition of that experiment. These results rule out a class of less flexible guidance strategies (e.g., always search by color first). In Experiment 3, this flexibility is occurring on a blocked basis. Experiment 4 asks whether observers can demonstrate similar flexibility in guidance if the size information is changing from trial to trial and, thus, is available only in a stimulus-driven, bottom-up form.

5. Experiment 4

In Experiment 4 observers searched for the red vertical item. The target was always of unique size but the specific size varied from trial to trial, so the task could be performed as an odd-man-out size search. If so, the medium sized targets should be severely penalized as in Experiment 1. If observers ignored the size information and treated the search as a color/orientation conjunction search, then we might expect the small targets to be penalized as in Experiment 2. If size differences facilitate search in an essentially stimulus-driven, flexible manner then performance in Experiment 4 should resemble that in Experiment 3 even though observers cannot set themselves to look for a specific size in a user-driven manner.

5.1. Methods

5.1.1. Participants

13 undergraduates (80% female, $M_{age} = 21.3$ yrs.) from Concordia University participated in exchange for partial course credit. All participants reported normal or corrected-to-normal vision.

5.1.2. Stimuli, apparatus, design and procedure

Experiment 4 was identical to Experiment 3 with the exception that target size was allowed to vary on a trial-to-trial basis and observers were instructed to locate the red vertical item, if present, with no information about the target's size provided. For the purposes of analysis, target absent trials were categorized according to the size of the distractors appearing in the display; for example, a trial with only small and large distractors would be classified as a medium target absent trial.

5.2. Results

As in previous experiments, RTs were first analyzed for outliers, which eliminated fewer than 1% of RTs. Experiment 4 results are displayed in Fig. 8. All slopes are quite shallow, reflecting a relatively efficient search. As can be seen in Fig. 5, RTs are systematically slower in Experiment 4 than in Experiment 3, as is generally the case when one compares blocked and mixed versions of the same search conditions. Nevertheless, the effects of stimulus-driven size information can be indexed by comparing the RT × set size functions to Experiment 2 (conjunction search). As can be seen in the figure, when the target is uniquely small or large, search is somewhat easier than it would be in the absence of size information. A uniquely medium-sized target is not particularly effective in guiding search because, as shown in Experiment 1, it is not easy to find. Similar to previous experiments, we analyzed slope values between the experiments using 2 × 2 × 3 repeated measures ANOVAs, but, first, we report the within experiment results of Experiment 4.

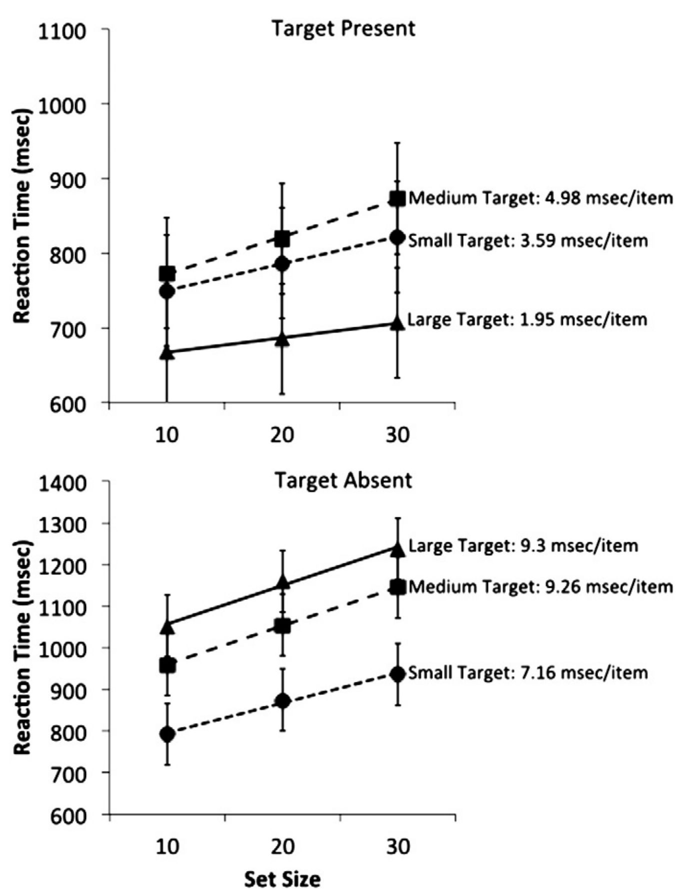

Fig. 8. RTs as a function of set size in Experiment 4.

5.2.1. Search slopes

Search slopes in Experiment 4 were all statistically greater than zero: all $ts > 2.0$ and all $ps < .05$. There was a significant main effect of Target Presence, $F(1,12) = 11.09$, $p < .006$, $\eta_p^2 = .48$. Search was less efficient on target absent trials ($M = 8.58$; $SD = 5.38$) than on target present trials ($M = 3.51$; $SD = 4.15$). Neither the main effect of Trial Type, $F(2,24) = 1.49$, $p > .245$, $\eta_p^2 = .11$, nor the Trial Type × Target Presence was significant $F(2, 24) = 3.42$, $p > .089$, $\eta_p^2 = .22$.

A key difference between Experiments 3 and 4 is the possibility of *intertrial effects*. The impact of intertrial bottom-up effects can be determined by comparing RTs in Experiment 4 as a function of whether target size repeated or changed from one trial to the next. We separated trials into those on which target size repeated across successive trials (repeat trials) and those on which target size did not (nonrepeating trials). For each of these trials, the mean search slope was computed for each target size on target present displays. Mean slopes are displayed in Fig. 9. A 2 (repeat versus nonrepeating) × 3 (Target Size) repeated measures ANOVA revealed no significant effect of Target Size, $F(2, 24) = 2.14$, $p > .13$, $\eta_p^2 = .15$, no main effect of repetition, $F(1, 12) = .110$, $p > .74$, $\eta_p^2 = .009$, and no interaction between the two factors, $F(2, 24) = .233$, $p > .79$, $\eta_p^2 = .019$.

5.2.2. Comparison between Experiments 3 and 4

The main of effect of Experiment was not significant, $F(1, 26) = .001$, $p > .970$, $\eta_p^2 < .001$. Search was equally efficient between Experiments 3 and 4. The main effect of Target Presence, $F(1, 26) = 5.08$, $p < .033$, $\eta_p^2 = .16$, and the Target Presence × Experiment interaction was significant, $F(1, 21) = 7.68$, $p < .011$, $\eta_p^2 = .23$. Search was less efficient on target absent displays in Experiment 4; there was no difference in search efficiency between target absent and target present displays in Experiment 3. The main effect of Target Size, $F(2, 52) = 6.91$, $p < .002$, $\eta_p^2 = .21$, and the Target Size × Experiment interaction was significant, $F(2, 52) = 4.37$, $p < .018$, $\eta_p^2 = .14$. Medium target search was least efficient in Experiment 3; there was no difference in search efficiency between target sizes in Experiment 4. The Target Presence × Target Size × Experiment interaction was significant, $F(2,52) = 6.05$, $p < .004$, $\eta_p^2 = .19$, corroborating the significant two-way interactions.

5.2.3. Comparison between Experiments 2 and 4

There was a significant main effect of Target Presence, $F(1, 21) = 5.39$, $p < .031$, $\eta_p^2 = .21$, but Target Presence × Experiment interaction was not significant, $F(1, 21) = 1.21$, $p > .285$, $\eta_p^2 = .05$. Search was slower on target absent trials than on target present trials. There were also significant main effects of Experiment, $F(1, 21) = 8.53$, $p < .008$, $\eta_p^2 = .29$, and Target Size, $F(2, 42) = 13.36$, $p < .001$, $\eta_p^2 = .39$. The Target Size × Experiment interaction was also significant, $F(2, 42) = 11.09$, $p < .001$, $\eta_p^2 = .34$. Overall, small target search was least efficient in Experiment 3 and there was no difference in target search efficiency between target sizes in Experiment 4. No other interactions were significant.

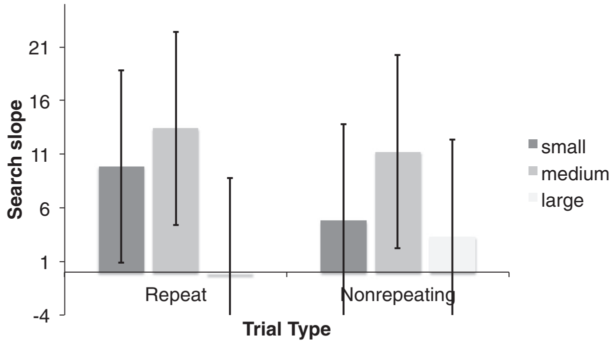

Fig. 9. Mean slope values for repeat and nonrepeating trials in Experiment 4.

Table 4
d′ values in Experiment 4.

Target	Set Size		
	10	20	30
Small	3.57 (0.51)	3.22 (0.58)	3.53 (0.71)
Medium	3.65 (0.53)	3.55 (0.57)	3.18 (0.63)
Large	4.13 (0.65)	4.06 (0.48)	3.91 (0.65)

5.2.4. Accuracy

Overall accuracy was comparable with previous experiments with a d′ of 3.65 (hit rate = 90% and false alarm rate = 1.9%; Table 4). There was a significant main effect of Target and Set Size, and a significant interaction between the two, $F(4, 48) = 2.48$, $p < .05$, $\eta_p^2 = .17$. Overall, large target search was the most accurate and medium target search became less accurate with increasing set size. We confirmed this conclusion by removing medium target trials from the ANOVA analysis. The main effect of Target Size was significant, $F(1, 12) = 18.07$, $p < .001$, $\eta_p^2 = .61$. Neither the main effect of set size, $F(2, 24) = 2.88$, $p > .075$, $\eta_p^2 = .19$, nor the Set Size × Target Size interaction was significant, $F(2, 24) = 1.46$, $p > .253$, $\eta_p^2 = .11$.

5.3. Discussion

As can be seen in Fig. 5, RTs in Experiment 4 are slower than in Experiment 3. Both target present and absent slopes are shallower and show no effect of linear separability, although medium target search remains the slowest. Comparing search slopes to Experiment 3 reveals that removing trial-to-trial certainty about target size had no effect on the efficiency of finding small and large targets, but paradoxically, increased the efficiency of finding medium targets. This result can be readily understood, however, by assuming that relying on size penalizes detection of medium targets (as suggested by the results in Experiment 1), so a shift toward using color and orientation information actually increases the efficiency of searching for medium targets. However, although search is overall slower in Experiment 4 than in Experiment 3, the presence of salient target–distractor size differences allows for small and large target searches to be more efficient than in Experiment 2, suggesting that size facilitated search for linearly-separable targets in a stimulus-driven manner. Further, medium target search was equally efficient in Experiments 2 and 4, providing further support that observers used color/orientation information (the only information available in Experiment 2), rather than size information, when searching for nonlinearly-separable targets in Experiment 4. Finally, there was no evidence of intertrial priming in Experiment 4. If search had benefited from such priming, shallower slopes would have been expected when subjects searched for the same size target on the current trial as on the preceding trial. The absence of such effects provides additional evidence that subjects did not make use of size information even as an implicit priming cue to locate the target in Experiment 4; nevertheless, the presence of salient target–distractor size differences facilitated search for small and large targets in an essentially bottom-up fashion.

6. General discussion

This paper examines linear separability effects when the linearly-separable feature of the target is not required to perform the task. We are able to quantify the relative contributions of target–distractor size differences and knowledge of target size by comparing the results in Experiment 3 to Experiments 2 and 4, respectively. Experiment 3 shows that when color, orientation, and size information are all available in a top-down manner, observers use the feature that will yield the most efficient search. When searching for linearly-separable targets (i.e., small and large), observers use a size search strategy, producing search behavior comparable to the efficient size feature search slopes in Experiment 1.

Conversely, when searching for nonlinearly-separable targets (i.e., medium), observers adopt a color × orientation conjunction search strategy, producing efficient search slopes that are similar to medium target trials in Experiment 2. Further, we are able to quantify stimulus-driven effects by comparing Experiment 4 to Experiments 3 and 2. Removing knowledge of target size in Experiment 4 had little effect on search for small and large targets relative to Experiment 3, but the stimulus-driven contribution of salient target–distractor size differences made search more efficient for small and large targets compared to Experiment 2, in which the size of the target and distractors is the same.

The results appear to be generally consistent with the relational guidance framework, with the caveat that subjects can flexibly switch between relational guidance and feature-based guidance depending on which will yield more efficient search. Given that the displays were identical in Experiments 3 and 4, but search for a non-linearly separable target was more efficient in the latter than in the former, a simple version of similarity theory would seem unable to account for our findings. Specifically, similarity theory posits that search will be efficient when distractors are similar enough to each other (and different enough from the target) to be grouped together and discarded from consideration. Yet in Experiment 4, search for medium targets was as efficient as for small and large targets despite the fact that distractors were neither especially similar to each other (given they differed in size, color, and orientation) nor saliently different from the medium target.

To our knowledge, the present work is the first to describe conjunction search behavior within the relational guidance framework. Target search in Experiment 1 was a size feature search; thus, observers were strongly encouraged to adopt a relational search strategy, which resulted in an efficient search for small and large targets, and an inefficient search for medium targets. In contrast, Experiment 2 was a color/orientation conjunction search with targets and distractors of equal size, which not only discouraged a relational search strategy, but also effectively made it difficult for color/orientation combinations and impossible for size. Not surprising, search was equally efficient across all target sizes, although small target search was overall the slowest. Although target size was not required to locate the target in Experiment 3, observers were nevertheless implicitly encouraged to attend to target size because it was held constant across a block of trials. Thus, on linearly-separable trials, size information was useful, perhaps because size information guided attention and/or reached awareness more rapidly than the color × orientation information. The size-based strategy would be less useful on medium target trials and, thus, search for medium targets was less efficient than for small or large targets in Experiment 3 though this condition was still far more efficient than search for medium targets in Experiment 1, where search by size was the only strategy possible. In contrast, in Experiment 4 the target varied from trial to trial, thereby discouraging a relational search strategy. Instead, observers were encouraged to adopt a feature-based approach—an efficient strategy no matter what size the target was. Thus, the results suggest that the mere availability of a relational strategy doesn't mandate that such a strategy be used.

This conclusion converges with Harris, Remington, and Becker's (2013) finding that in search for size, observers adopt a relational search strategy when both feature and relational strategies are available. In a modified version of Posner's (1980) attention cueing paradigm, observers indicated the orientation of a medium target line among small, or large distractors, respectively. The target/distractor relation was either blocked (Experiment 1), or allowed to vary from trial-to-trial (Experiment 2). Prior to onset of the search array, observers were presented with a cue display in which uninformative spatial cues appeared at all possible target locations. The display was constructed such that the cue appearing at either the target location (valid trials) or a non-target location (invalid trials) matched the relational property of the target, or the target's specific feature value. When the target/distractor relationship was blocked, only cues that matched the relational property of the target yielded significant validity effects, suggesting that observers preferred a relational search strategy. When, in contrast, the target/distractor relationship was allowed to vary in Experiment 2, only cues that matched the target's specific feature value produced significant validity effects, suggesting that observers adopt a feature-specific search strategy when the target/distractor relation is unreliable. Thus, as in Harris et al.'s experiments, observers in the present study appear to have been able to identify whether conditions were more favorable for relational or feature search, and adjust their strategy accordingly.

Hodsoll and Humphreys (2001) investigation provided an early indication that the seemingly-primarily bottom-up process of linear separability was perhaps more strongly governed by top-down search strategies than previously believed. Here, we show that indeed size information is not always used in a bottom-up manner, and the presence of the linear separability effect depends on foreknowledge of target size and whether a relational search set can be applied. Observers use size information when the size of the target is known in advance, but only when searching for a linearly separable target. Our findings thus corroborate Becker's (2010) suggestion that linear separability effects are due to relational guidance of attention in visual search in response to stimulus characteristics and task demands.

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