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Flexible cue combination in the guidance of attention in visual search

John Brand [a,*], Chris Oriet [b], Aaron P. Johnson [a], Jeremy M. Wolfe [c]

[a] Department of Psychology, Concordia University, Canada
[b] Department of Psychology, University of Regina, Canada
[c] Visual Attention Lab, Harvard Medical School and Brigham and Women's Hospital, United States

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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

* Corresponding author.
E-mail address: jo_bra@live.concordia.ca (J. Brand).

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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.

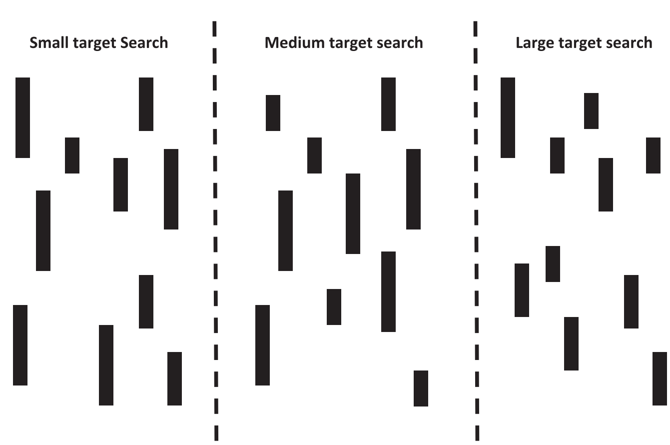

Fig. 1. Sample stimuli used in Experiment 1. Target was a small, medium, or large red vertical line (black vertical in the figure), between medium and large, small and large, or small and medium red vertical distractors, respectively.