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VISUAL SEARCH ASYMMETRIES IN COMPLEX GEOPHYSICAL DISPLAYS

BY

YUSUKE YAMANI

THESIS

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Adviser:

Assistant Professor Jason S. McCarley

## ABSTRACT

Electronic displays such as geophysical maps can become heavily cluttered (e.g. Lohrenz, Trafton, Beck, & Gendron, 2009), hindering operators' accurate detection of task-critical information. The use of visual search asymmetries (Treisman & Souther, 1985) in the design of display iconography might be an effective technique for prioritizing important information in such displays, but only if the asymmetry persists in the presence of clutter. The present experiments demonstrate that search asymmetries based on an additional feature (Treisman & Souther, 1985) and on stimulus familiarity (Malinowski & Hübner, 2001) persisted across varying levels of visual clutter. Results imply that iconography exploiting visual search asymmetries can support efficient search even in heavily cluttered displays.

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## CHAPTER 1: INTRODUCTION

In creating displays for high workload tasks, designers strive to ensure that operators can detect and locate critical items rapidly and accurately. An ideal display will promote *unlimited-capacity parallel processing* or ‘pop-out’ search (Treisman & Gelade, 1980), highly efficient search for a target item regardless of the number of display items. Unfortunately, electronic displays such as weather and battlefield maps often clutter and degrade human performance (Lohrenz, Trafton, Beck, & Gendron, 2009). The effects of visual clutter on human performance are more detrimental for users who make a task-critical decisions based on displayed information such as operators of battlefield displays and emergency managers. Thus, displays should be designed to minimize the effect of the clutter and facilitate operators’ access to vital information. One way to attenuate the effects of clutter is to decrease the number of items within a display, but it compromises information content in the display. An alternative possibility is to allow users to interactively de-clutter the display themselves, turning on and off display elements as they are needed. However, the response time (RT) costs of interactive de-cluttering often outweigh the benefits of reduced clutter (Yeh & Wickens, 2000). Therefore, alternative techniques are necessary to combat the adverse effects of display clutter.

One potential method to produce pop-out search in cluttered displays is a use of *visual search asymmetries* (Treisman & Souther, 1985). In a search asymmetry, searching for a target stimulus of type A among distractor stimuli of type B generates different search performance than searching for a target of type B among distractors of type A. Often, one target-distractor mapping produces parallel search without capacity limits while the reverse mapping produces search with capacity limits (Treisman & Gormican, 1988). For instance, finding a Q among Os is efficient while finding an O among Qs is inefficient (Treisman & Souther, 1985).

Coding for search asymmetries offers a potentially valuable technique to guide attention to critical information within visual displays. A critical item can be represented in iconography that the asymmetry favors, encouraging rapid target detection by putting an ‘attentional flag’ on the critical item. However, evidence suggests that the asymmetry becomes weaker in the presence of display clutter (Yamani & McCarley, 2010). In the experiments, participants searched for a target among search-relevant items with or without clutter, and effects of clutter on the asymmetry were measured. In general, search asymmetries persisted even in the presence of clutter, suggesting that the choice of iconography to produce search asymmetries may, indeed, be valuable in display design.

Even the cluttered displays of Yamani and McCarley (2010), however, were simpler than many outside-the-lab electronic displays. In their experiments, search-relevant items and clutter items were all discrete objects, distinguished either by color or luminance contrast and presented on a blank background. Outside the lab, electronic displays often fuse images of natural scenes and artificial icons to create complex geospatial displays (e.g. aerial digital maps; Davis, Tompkinson, Donnelly, Gordon, & Cave, 2006). Displays may thus contain continuous geophysical backgrounds that make search-relevant symbology difficult to perceptually segment. It remains unanswered whether the asymmetry effect is robust against such continuous natural scenes. It is well possible that such imagery will interfere with perception of iconography, compromising the strength of a search asymmetry. The goal of the present experiments was thus to test whether the effectiveness of the asymmetry persists in the presence of continuous visual clutter. If search asymmetries are robust against heavy clutter, they could be used for designing iconography that promote efficient search within complex visual displays without compromising other display content.

## CHAPTER 2: LITERATURE REVIEW

### 2.1. Models of visual search

Visual search is the behavior of looking for a target object among other objects in a scene, where the location of the target is not certain. Search is a part of many everyday activities (e.g., looking for a key on a cluttered table) and professional tasks (e.g., detecting a cancerous growth in a chest X-ray). For researchers, it has also been a valuable window on the mechanisms of attention and visual information processing. In the experimental visual search paradigm, observers search for a predefined target among non-target distractors, while the total number of items (targets + distractors) present in the search field, or *set size*, varies across trials. Analysis of response times (RTs) and error rates as a function of set size can then be used to explore underlying processing models.

Models of search are commonly classified based on two properties: *stopping rule* and *architecture* (Sternberg, 1966). The stopping rule determines whether processing in a search task is *exhaustive* or *self-terminating* (Sternberg, 1966; Van Zandt & Townsend, 1993). In an exhaustive processing model, the observer inspects all items in the search field before making a response, even if a target is found early in the search. In a self-terminating model, conversely, search ends as soon as the observer detects a target item. For target-absent trials, exhaustive and self-terminating models behave identically, since the observer will have to search the display exhaustively to confirm that no target is present even if the stopping rule is self-terminating. For target-present judgments, however, a self-terminating rule generally predicts shorter search times than an exhaustive rule.

Processing architecture determines whether items are processed in *serial* or *parallel*. Both parallel and serial models produce different predictions depending on whether the search is

exhaustive or self-terminating. One potential way to distinguish parallel and serial processing in visual search is to inspect the slopes of the linear function relating mean RT to set size. The parallel processing model holds that multiple items are processed simultaneously. Under the assumption that the mean processing rate per item remains constant as set size increases, a self-terminating parallel model therefore predicts that the mean RTs for target-present search remain constant as the number of the items increases, producing a flat search function. If processing is exhaustive, RTs still increase as set size increases because the response must wait for the slowest item to finish processing (Sternberg, 1966).

On the other hand, serial processing requires that processing of one item finish before processing of the next begins. Assuming that mean processing times for all items are equal, the serial model thus predicts a linear increase in mean RT as a function of set size. If the search is self-terminating, furthermore, the serial model predicts that the slope for target-present trials will be a half of that for target-absent condition. Wickens and McCarley (2008) formally presented these predictions of the serial search model as

$$RT = a_1 + bN^{1/2} \quad \text{for target-present search and}$$

$$RT = a_2 + bN \quad \text{for target-absent search,}$$

where  $b$  is the mean time to inspect each search item,  $N$  is the set size, and  $a_1$  and  $a_2$  are the times needed for front-end sensory processing and post-search response execution on target-present and target-absent trials, respectively.

It is important to note that prediction of flat search functions from the parallel model holds only under the assumption that mean processing rate per item does not change as set size increases. More formally, this is known as an assumption of *unlimited processing capacity*. When parallel processing capacity is limited, meaning that the mean processing rate per item

decreases with set size, the parallel and serial models can perfectly mimic each other in their predictions of mean RT and error rates (Townsend, 1971; Townsend & Ashby, 1983). Under capacity limits, that is, increasing set size will increase RTs even in a parallel processing model. Therefore, a flat search function is diagnostic of *unlimited-capacity parallel processing*, but a positive search function does not distinguish limited-capacity parallel processing from serial processing.

## 2.2. Perception, Attention, and Search

One of the most influential theories of visual search has been Treisman's *Feature Integration Theory (FIT)* (Treisman & Gelade, 1980; Treisman & Sato, 1990), a model that postulates both parallel and serial search mechanisms. According to FIT, elementary visual features are processed in parallel without focused attention at a *preattentive* processing stage, and focused attention is used in a subsequent processing stage to integrate multiple features to produce complex object representations. A search target that is defined by a distinctive elementary feature can therefore be detected in parallel among any number of distractors, producing a flat search function. Colloquially, this effect is described as *pop-out search*. Conversely, a target that is defined by a conjunction of basic features requires serial search, with a spotlight of focused attention shifting from location to location to bind the features into object representations (Treisman & Gelade, 1980). Unlike feature search, therefore, conjunction search produces a positive RT slope. Importantly, this two-stage architecture allows researchers to examine what features are considered as elementary in the visual system (Treisman & Gelade, 1980; Treisman & Gormican, 1988). Target-present RTs that are flat across set sizes imply that the target possesses a unique perceptual feature that is processed preattentively.

FIT established a valuable framework for explaining visual search, but in its original form

did not include an explicit top-down component. Later models of visual search incorporated mechanisms for the top-down regulation of visual attention. Most notably, the Guided Search model (GSM)(Wolfe, Cave, & Franzel, 1989; Wolfe, 1994) posited that attention is steered toward likely target locations in visual search. GSM assumed preattentive parallel processing of feature maps, like that in FIT, but proposed further that the top-down processes could modulate activity in the feature maps. A final activation map integrates the outputs of the feature maps to determine which items within the search field are prioritized by attention. GSM explains some data that the original FIT (Treisman & Gelade, 1980) could not easily account for, such as the finding that search for a conjunction of three target features is more efficient than search for a conjunction of two features (Wolfe, Cave, & Franzel, 1989; also see Treisman & Sato, 1992 for an update of FIT proposing a top-down mechanism that allows feature inhibition on the location map, functionally similar to the top-down component in GSM). Nonetheless, FIT and GSM share the notion that basic features are processed early and in parallel and that focused attention processes stimuli in serial a later stage. The modern view of visual search therefore does not assume exclusively parallel or serial processing, but rather a hybrid framework of parallel and serial mechanisms (Wolfe, 1998).

### 2.3. Visual search asymmetry

An intriguing finding in the visual search literature is the search asymmetry. A search asymmetry results when finding a target stimulus of type A among distractors of type B is more efficient than finding a target stimulus of type B among distractors of type As (Treisman & Gormican, 1988; Wolfe, 2001). In many asymmetries, one target-distractor mapping produces pop-out search while the reversed mapping produces slow and effortful search. For instance, finding a target Q among Os is effortless while finding a target O among Qs is slow and clearly

capacity-limited (Treisman & Souther, 1985). Asymmetries have been found with a variety of stimulus sets including longer vs. shorter line segments, off-vertical vs. vertical line segments, curved vs. straight segments, Cs vs. Os, orange vs. red objects (Treisman & Gormican, 1988), familiar vs. non-familiar objects (e.g. Ns vs. reversed Ns, Wang, Cavanagh, & Green, 1994; Malinowski & Hübner, 2001; Shen & Reingold, 2001), and “dead” vs. “live” elephants (Wolfe, 2001).

Theorists have offered a number of accounts of the search asymmetry effect. Treisman (Treisman & Gormican, 1988; Treisman & Souther, 1985) has argued that a search asymmetry sometimes results when the object favored by an asymmetry possesses a basic visual feature that is absent from the distractors. When a target item possessing the feature is present among distractors without the feature, the target engenders above-baseline activity in the relevant feature detectors while the distractors do not. Any above-baseline level of activation in the relevant feature detectors therefore indicates that the target is present in the display, and a baseline level of activation indicates that the target is absent. Conversely, when multiple distractors possess the feature, activity in the relevant feature detectors will be well above baseline whether or not the display contains a target. To determine whether the target is present, the searcher will therefore be forced to attend to stimulus items in serial (either singly or in small groups; Pashler, 1987) in order to locate a single item that does not possess the feature. Phrased more simply, the signal-to-noise (SNR) level of a target display relative to a target-absent display within a bank of relevant feature detectors is larger when the target contains a feature that the distractors do not than when the distractors contain a feature that the target does not. Consider the Q-O asymmetry. Presumably, both items will activate a feature detector of curvature. However, an extra line segment in the Q will selectively activate an additional detector for

straightness, producing a greater level of activation for the Q than that for the O. When searching for a Q among Os, therefore, one can simply check an item with above-baseline activation produced by the line segment, which result in parallel search. In contrast, when searching for an O among Qs, an observer cannot simply check an item with the highest activation because a target O has activation below the Q distractors due to the lack of the line. This condition thus requires more effortful search.

Search asymmetries are possible even with stimuli that do not differ in inherent feature content, however, most notably, canonically-oriented and reversed characters (e.g., Malinowski & Hübner, 2001; Shen & Reingold, 2001; Wang, Cavanagh, & Green, 1994). For instance, an N is difficult to find among reverse Ns, but a reverse N pops out from among canonically oriented Ns (e.g. Frith, 1974). In this case, the novelty of the reverse N relative to the canonical N appears to engender asymmetrical search efficiency (Treisman & Gormican, 1988). Treisman explains these asymmetries with the prototype-deviation hypothesis (Treisman & Gormican, 1988), which states that an item deviating from a prototype presentation produces higher activation than do prototypical, or more familiar, stimuli. Therefore, in her framework, an unfamiliar item will produce higher activation than familiar items, leading a familiarity-based search asymmetry.

Recently, Rauschenberger and Yantis (2006) have generalized Treisman's basic account of the search asymmetry, arguing that any differences in the perceptual encoding efficiency of target and distractor stimuli can produce an asymmetry. This model presumes that encoding efficiency can increase with either the figural regularity (e.g., symmetry) of visual items or stimulus familiarity (Attneave, 1954; Garner & Clement, 1963). It therefore explains both the aforementioned feature-based and familiarity-based search asymmetries. That is, extra features or non-familiarity of distractors can decrease the perceptual encoding efficiency of a search

display, producing an inefficient search for a target.

#### 2.4. Search asymmetries in complex displays

The theoretic and empirical study of human search behavior has also been extended to applied tasks such as medical image scanning (e.g. Kundel & Lofollete, 1972), baggage screening (e.g. McCarley, Kramer, Wickens, Vidoni, & Boot, 2004), air traffic control (e.g. Remington, Johnston, Ruthruff, Gold, & Romera, 2000), and electronic map reading (e.g. Yeh & Wickens, 2001). Non-optimal search performance for operators in such environments can have dire consequences. Therefore, it is important for researchers to provide display design guidelines that support optimal search performance. Ideally, a visual search display should support unlimited-capacity parallel processing in which a searcher can rapidly detect and locate to a target item regardless of the number of display items.

The phenomenon of the search asymmetry, interestingly, may offer a straightforward technique for improving display design. Because search for the target favored by an asymmetry tends to be highly efficient, the practice of tailoring iconography to produce asymmetries might allow designers to prioritize a visual object for immediate attention. Typically, however, displays outside the lab are far more complicated than the simple stimuli frequently used for study of visual search. An asymmetry will thus be useful in display design only if it is robust against in the presence of clutter and other visual objects irrelevant to the search task. In fact, the current models of visual search suggest that the asymmetries may not hold in heavy display clutter. FIT (Treisman & Gelade, 1980) predicts that discriminability of a target and distractors might decrease due to extraneous features embedded within the clutter, producing spurious activation within feature detectors that otherwise allow target feature pop-out. Similarly, Rauschenberger and Yantis' model (2006) predicts that heavy clutter may increase the perceptual irregularity

within a display, degrading search efficiency and reducing the strength of a search asymmetry.

Preliminary evidence (Yamani & McCarley, 2010) suggests that a search asymmetry may survive the presence of clutter, at least within some display formats. Building on basic research (Friedman-Hill & Wolfe, 1995; Wolfe et al., 1989), applied scientists have shown that the practice of *color-* or *intensity-coding* can facilitate perceptual segregation of visual items within a complex display, allowing observers to search for a critical item more efficiently (Remington, Johnston, Ruthruff, Gold, & Romera, 2001; Wickens, Alexander, Ambinder, & Martens, 2004). Within a color- or intensity-coded display, different categories of display items are distinguished either by hue or by contrast. For instance, aircraft within different altitude bands might be rendered in different hues within a color-coded air traffic display, or rendered at different levels of luminance contrast within an intensity-coded display (Remington et al., 2001). Color- or intensity-coding can thus allow selective search through a relevant category of items within the coded display, improving search performance. However, even within a color- or intensity-coded subset of display items, a designer may often wish to prioritize a small number of specific objects. Experiments by Yamani and McCarley (2010) implied that coding for a search asymmetry can be used for this purpose, demonstrating that a search asymmetry between a spoked circle and a circle persisted at full strength within color-coded displays and within intensity-coded displays in which search-relevant stimuli were presented in higher contrast than the surrounding clutter. However, the same study also found that the asymmetry was attenuated when the clutter was depicted in a higher contrast than the search-relevant items. Thus, search asymmetries can be exploited within displays containing color- or intensity-coded clutter, but may be of limited value when clutter is more salient than search-relevant information.

In practice, unfortunately, operators must often search for target embedded within complex

geospatial display imagery. Such complex displays—synthetic vision system in aerial vehicles (Calhoun, Draper, Abernathy, Delgado, & Patzek, 2005), radar data visualization over terrain images (James, Brodzik, Edmon, Houze, & Yuter, 2000) and aerial digital maps (Davies, Tompkinson, Donnelly, Gordon, & Cave, 2006) for example—can contain continuous geophysical backgrounds that make search-relevant items difficult to separate. Indeed, recent research found that RT and fixation duration systematically increased as clutter in a search field increased when observers searched through a set of discrete items on real-world scenes (Henderson, Chanceaux, & Smith, 2009). It remains unanswered whether search asymmetries will persist within complex displays involving cluttered, continuous natural images.

## 2.5. Purpose of the current study

Visual search asymmetries might be a useful technique to prioritize a target items within complex displays and to support highly efficient search, or unlimited-capacity parallel processing. However, the effect of continuous geophysical images background clutter on search asymmetries remains untested, and empirical data as well as search theory suggest that clutter might in fact compromise the search asymmetry effect. To test this possibility, the present two experiments investigated whether the asymmetry between a circle and a spoked circle (Yamani & McCarley, 2010) and that between Ns and mirror-reversed Ns (Frith, 1974; Malinowski & Hübner, 2001) are robust within heavy clutter imposed by the geophysical images.

## CHAPTER 3: EXPERIMENT 1

### 3.1. Introduction

Experiment 1 examined whether a search asymmetry would persist against heavy, spatially continuous visual clutter. Participants searched for a predefined target (a circle or a spoked circle) among distractors (spoked circles or circles, respectively) against a background of a low- or high-clutter simulated geophysical display.

### 3.2. Methodology

#### 3.2.1. Participant

Twenty-five participants (12 male, 13 female, mean age = 20.12 years) were recruited from the community of the University of Illinois at Urbana-Champaign. All reported normal or corrected-to-normal visual acuity and normal color vision. They received \$8 per hour or course credit for participation.

#### 3.2.2. Apparatus

Stimuli were presented on a 17'' CRT monitor with a frame rate of 75 Hz and a resolution of 1024 x 768 pixel. Stimulus presentation and response recording were controlled by E-Prime 1.1 (Psychology Software Tools, Pittsburgh, PA). Responses were made by mouse. Participants viewed the display from a distance of approximately 57 cm. Experimental sessions were conducted in a quiet room with dimmed light.

#### 3.2.3. Stimuli

Stimuli were circles either with or without a single horizontal spoke. The radius of all circles was  $1.08^\circ$  of visual angle; the spokes were horizontal segments drawn from the center of

the circle to the vertical midpoint of the right side. Each item was positioned at one of 49 possible locations in a 7 x 7 imaginary grid, with a minimum center-to-center- distance of 3.20° between items, and randomly jittered between 0° to 0.27° both horizontally and vertically. Items were drawn in black and presented on background images (17.4° x 17.4°) in the center of the screen. Colored background images were downloaded from the Google Earth (<http://earth.google.com>), and the images were transformed to grayscale to produce achromatic images of the same spatial content. The images were classified into two groups by levels of clutter (high vs low) for images with and without colors (Color- High Clutter, Color- Low Clutter, No Color- High Clutter and No Color- Low Clutter). Levels of clutter were measured by the subband entropy (SE), which gauges efficiency of encoding an image while maintaining its perceptual quality (Rosenholtz, Li & Nakano, 2007). Data in Rosenholtz et al. (2007) show a reliable correlation between the SE measure and log-transformed RTs in the visual search task. SE was chosen over other reliable measures of clutter (e.g., feature congestion; Rosenholtz, Li, Mansfield, & Jin, 2005) because it is applicable both chromatic and achromatic images (<http://dspace.mit.edu/handle/1721.1/37593>). The SE values are presented in Table 1.

#### 3.2.4. Procedure

The participants' task was to make a speeded judgment each trial of whether or not a target was present. Each display contained 4, 8, or 12 items for search. Half of all trials contained a single target (target-present trials) and the other half contained only distractors (target-absent trials). Participants were instructed to focus on the search items, while ignoring the background images. Target type (a circle or a circle with a spoke) alternated between blocks, with the order of alternation counterbalanced across participants. The search items were presented with the background images with or without colors. Therefore, the experiment consisted of four different

blocks, target O – Colored background, target Q – Colored background, target O – Achromatic background, and target Q – Achromatic background. Participants provided responses with the mouse by their right hand, clicking the left button to report that the target was present and the right button to report that the target was absent.

Each trial started with a 400 ms blank screen that was followed immediately by the stimulus. The stimulus display remained visible until a response was detected or timeout duration of 5,000 ms had elapsed. Participants were instructed to respond as quickly as possible on each trial while minimizing errors. Trials that ended without a response were considered as errors. A 750 ms feedback screen followed each trial, displaying a gray '+' to indicate a correct response and a gray 'X' to indicate an error. The subsequent trial began automatically after a 400 ms delay. Participants were allowed to rest between blocks.

Prior to experimental trials, the participants received 4 randomly-chosen practice trials from each of the four different blocks, and were given an opportunity to ask questions to the experimenter. They performed 8 blocks of 48 experimental trials. A message at the start of each block indicated which target to search for. Trials within a block were comprised all combinations of search set size, target presence, and levels of clutter, and each type of trials was repeated 4 times in a block. Order of trials within a block was random.

### 3.3. Results

The purpose of Experiment 1 was to investigate whether continuous clutter in a search display would affect the strength of a feature-based visual search asymmetry. Participants searched for a target among distractors embedded on continuous aerial imagery. Figure 1 presents a sample display of the low-clutter condition and Figure 2 presents that of the high-clutter condition in Experiment 1. While some empirical data suggest that the asymmetry might

persist in clutter (Yamani & McCarley, 2010), several theories of visual search suggest that heavy clutter might disrupt the asymmetry.

Incorrect responses were excluded from analysis of RTs. For analysis, linear regression equations were fit to the RT by set size and error rate by set size functions in each experimental condition (Wolfe, 1998), and slopes and intercepts of the regression equations were analyzed separately. Linear functions accounted for 77.21% of the variance in relationship between RTs and the set size, averaged across participants and conditions. Preliminary analyses revealed a highly reliable interaction indicating that the effects of increasing clutter were stronger in achromatic displays than in color displays ( $p = .002$ ), but showed no interactions involving color and target type. To simplify exposition, therefore, the analyses below excluded Color as a factor.

The slopes (Table 2) and intercepts (Table 3) for RTs and error rates were submitted to separate 2 x 2 x 2 analyses of variance (ANOVA) with Clutter (Low vs. High), Target Type (Circle vs. Spoke) and Target Presence (Present vs. Absent) as within-subject factors. Figure 3 presents mean RTs and error rates for Experiment 1.

### 3.3.1. RT slopes

RT slopes were reliably larger when the target was a circle than when it was a spoked circle [ $F(1, 24) = 90.178, p < .001, MSE = 869.958, \eta_p^2 = .790$ ], confirming a search asymmetry. Heavy display clutter reduced search efficiency, as evidenced by larger slopes in the high clutter condition [ $F(1, 24) = 34.281, p < .001, MSE = 659.688, \eta_p^2 = .588$ ], and, as expected within a self-terminating search model (Sternberg, 1966), slopes were significantly larger when target was absent than when present [ $F(1, 24) = 40.873, p < .001, MSE = 1555.207, \eta_p^2 = .630$ ]. A two-way interaction of Target Type by Target Presence indicated that the effect of Target Type was larger in the target-absent trials than in the target-present trials [ $F(1, 24) = 7.448, p = .012, MSE$

= 1001.744,  $\eta_p^2 = .237$ ], an effect again consistent with a self-terminating search rule.

Interestingly, a two-way interaction of Target Type by Clutter was significant [ $F(1, 24) = 10.649$ ,  $p = .003$ ,  $MSE = 902.542$ ,  $\eta_p^2 = .307$ ], indicating that the asymmetry effect was weaker in heavy clutter. The three-way interaction was statistically significant [ $F(1, 24) = 7.282$ ,  $p = .013$ ,  $MSE = 612.95$ ,  $\eta_p^2 = .233$ ], indicating that the interaction of clutter by target type differed between target-present and target-absent trials. However, post hoc t-tests revealed that in the asymmetry was significant or borderline significant both in low clutter [paired-samples  $t(24) = 11.684$ ,  $p < .001$  for target-absent trials; paired-samples  $t(24) = 6.062$ ,  $p < .001$  for target-present conditions] and in high clutter [paired-samples  $t(24) = 3.482$ ,  $p = .002$  for target-absent trials; paired-samples  $t(24) = 1.977$ ,  $p = .06$  for target-present trials]. The two-way interaction of Clutter by Target Presence was not significant [ $F < 1$ , n.s.].

### 3.3.2. RT intercepts

Display clutter reliably increased RT intercepts [ $F(1, 24) = 265.456$ ,  $p < .001$ ,  $MSE = 48849.351$ ,  $\eta_p^2 = .917$ ]. The intercepts were higher when target was absent [ $F(1, 24) = 32.729$ ,  $p < .001$ ,  $MSE = 31245.485$ ,  $\eta_p^2 = .577$  for main effect], and the increase was larger for High clutter than Low clutter [ $F(1, 24) = 25.513$ ,  $p < .001$ ,  $MSE = 54728.554$ ,  $\eta_p^2 = .515$  for interaction]. The two-way interaction of Clutter and Target Type was marginal [ $F(1, 24) = 3.424$ ,  $p = .077$ ,  $MSE = 49768.710$ ,  $\eta_p^2 = .125$ ], indicating a trend toward bigger clutter effects for a circle targets ( $M = 567$  ms) than for a spoked targets ( $M = 450$  ms). The remaining effects were not reliable [ $ps > .217$ ].

### 3.3.3. Error rate slopes

Error rates ranged from a low of 1.0 % in the spoked target absent, low clutter, set size 12

condition to a high of 25.1% in the unspoked target present, high clutter, set size 12 condition, reaching values far higher than those generally observed in RT studies of visual search (Figure 3). The slope of the error rate by set size function was reliably higher within heavy clutter than within low clutter [ $F(1,24) = 17.358, p < .001, MSE = .0002, \eta_p^2 = .420$ ], and was higher when the target was a Circle than when it was a Spoked Circle [ $F(1,24) = 17.358, p = .014, MSE = .0002, \eta_p^2 = .226$ ], evincing an asymmetry in the same direction as that seen in RTs. Slopes were also larger for target-present trials than for target-absent trials [ $F(1,24) = 6.782, p = .016, MSE = .0002, \eta_p^2 = .220$ ]. No interactions reached the significance [all  $p$ s  $> .410$ ]. Data thus gave no evidence of a speed-accuracy tradeoff in search slopes.

#### 3.3.4. Error rate intercepts

Error rate intercepts were reliably higher for target-present trials than for target-absent trials [ $F(1,24) = 4.854, p = .037, MSE = .015, \eta_p^2 = .168$ ], which indicates a speed-accuracy tradeoff in search intercepts. All the remaining effects were not significant [all  $p$ s  $> .262$ ].

#### 3.4. Discussion

Consistent with the findings of Yamani and McCarley (2010, Experiment 3), the asymmetry between spoked and unspoked circle targets in the present experiment was attenuated in heavy clutter, but was not eliminated. Data thus extend earlier findings by demonstrating that a search asymmetry can persist even in the presence of continuous and relatively dense visual clutter. Perhaps more remarkably, the present results demonstrate a search asymmetry in high clutter despite error rates substantially greater than zero, and far higher than those observed in typical visual search experiments. Assuming that accuracy levels were near asymptote, these findings imply that the asymmetry can persist even under conditions of

severe stimulus degradation.

## CHAPTER 4: EXPERIMENT 2

### 4.1. Introduction

Experiment 2 examined whether the N-mirrored N asymmetry would persist in the cluttered displays identical to those in Experiment 1. Participants searched for a target (an N or a mirror-reversed N) among distractors (mirror-reversed Ns or Ns, respectively). Methodology for Experiment 2 was identical to that of Experiment 1 except for the following.

### 4.2. Methodology

#### 4.2.1. Participant

Twenty-three participants (13 male, 10 female, mean age = 19.13 years) were recruited from the community of the University of Illinois at Urbana-Champaign. All reported normal or corrected-to-normal visual acuity. They received course credit for participation.

#### 4.2.2. Stimuli

Search stimuli were Ns and mirror-reversed Ns,  $1.08^\circ \times 1.08^\circ$  of visual angle, drawn with straight strokes.

### 4.3. Results

Experiment 2 extended the findings of Experiment 1 by measuring the strength of a familiarity-based search asymmetry (N vs. reversed N; see, e.g., Malinowski & Hübner, 2001) in the presence of display clutter. Figure 2 illustrates a sample display of Experiment 2.

Statistical analyses for Experiment 2 were identical to those for Experiment 1. Table 4 presents mean slopes for RTs and error rates and Table 5 presents mean intercepts in Experiment 2. Linear functions accounted for 66.58% of the variance in relationship between RTs and the set

sizes averaged across participants and conditions. Again, the color factor was excluded from the following analyses. Figure 4 illustrates mean RTs and error rates for Experiment 2.

#### 4.3.1. RT Slopes

The main effect of Target Type was significant [ $F(1,22) = 42.961, p < .001, \text{MSE} = 936.628, \eta_p^2 = .661$ ], confirming the N-reversed N search asymmetry. Slopes were larger for target-absent trials than target-present trials [ $F(1,22) = 47.608, p < .001, \text{MSE} = 1092.494, \eta_p^2 = .684$  for main effect]. Furthermore, heavy clutter reduced target-absent slopes more than target-present slopes [ $F(1,22) = 8.317, p = .009, \text{MSE} = 1137.792, \eta_p^2 = .274$  for interaction]. Unexpectedly, search slopes were lower within heavy clutter ( $M = 27.99$  ms/item) than within low clutter ( $M = 50.36$  ms/item) [ $F(1,22) = 15.178, p = .001, \text{MSE} = 1517.353, \eta_p^2 = .408$ ], though as discussed below, this effect seems to reflect a speed-accuracy tradeoff. No remaining effects were significant [ $ps > .223$ ]. Of most importance, data showed no reliable interaction of clutter level by target type [ $F(1,22) = .014, p = .907, \text{MSE} = 838.361, \eta_p^2 = .001$ ], and thus suggest that the N-reversed N asymmetry held even under heavy clutter.

#### 4.3.2. RT intercepts

Increased display clutter produced reliably higher RT intercepts [ $F(1,22) = 69.856, p < .001, \text{MSE} = 346941.684, \eta_p^2 = .760$ ], and intercepts were significantly higher when a target was absent than when it was present [ $F(1,22) = 30.682, p < .001, \text{MSE} = 165876.510, \eta_p^2 = .582$  for main effect]. Further, the effect of target presence was larger in heavy clutter than in low clutter [ $F(1,22) = 30.565, p < .001, \text{MSE} = 144327.713, \eta_p^2 = .581$  for interaction]. All remaining effects were not reliable [ $ps > .301$ ].

#### 4.3.3. Error slopes

Mean error rates were again greater than those generally seen in RT studies of visual search, ranging from a low of 3.4% in the N target present, low clutter, set size 4 condition to a high of 34.8% in the N target absent, high clutter, set size 12 condition condition (Figure 4). Error slopes were significantly larger in heavy clutter [ $F(1,22) = 4.901, p = .038, MSE = .0002, \eta_p^2 = .182$ ], indicating a speed-accuracy tradeoff with the RT slopes; that is, the RT search slopes for heavy clutter conditions would presumably have been greater if error rates were equivalent across set size. However, the slopes were reliably greater when target was an N rather than a mirror-reversed N [ $F(1,22) = 29.682, p < .001, MSE = .0001, \eta_p^2 = .574$ ], an asymmetry consistent with that of the RTs. Slopes were larger for target-absent than for target-present trials [ $F(1,22) = 12.131, p = .002, MSE = .0004, \eta_p^2 = .355$ ], and the two-way interaction of Target Type by Target Presence also reached significance [ $F(1,22) = 5.452, p = .029, MSE = .0002, \eta_p^2 = .199$ ], indicating that the asymmetry was larger in the target-present condition than the target-absent condition. Remaining effects were not significant [all  $ps > .276$ ].

#### 4.3.4. Error intercepts

Intercepts were higher when target was a reversed N than when it was an N [ $F(1,22) = 7.230, p = .013, MSE = .015, \eta_p^2 = .247$ ], (though, because of differences in slope, mean error rates for the reversed N targets were equal to or lower than those of the N targets at all of the set sizes tested). The effect of Target Presence reached the significance [ $F(1,22) = 4.589, MSE = .018, p = .043, \eta_p^2 = .173$ ], indicating the intercepts were higher when the display contained a target than when it did not. The remaining effects were not significant [all  $ps > .440$ ].

#### 4.4. Discussion

The familiarity-based search asymmetry between N and reversed N targets persisted in

heavy clutter, generalizing the results of Experiment 1 to indicate that a search asymmetry can be robust against heavy clutter even when target and distractor stimuli do not differ in perceptual features. This was again true, moreover, despite that mean error rates were substantially greater than zero for both target types. Thus, the data indicate once more that an asymmetry in search efficiency can persist despite severe degradation of perceptual stimulus quality.

## CHAPTER 5: GENERAL DISCUSSION

Two points below can summarize the present results. First, heavy clutter significantly degraded search performance in the two experiments, as measured by slopes and intercepts of both RTs and error rates. Experiment 1 found highly efficient parallel search for the spoked circle target in low clutter, with RT slopes near zero (7.6 ms/item), indicating parallel processing without capacity limits. In heavy clutter, however, performance deviated from unlimited-capacity, with RTs slopes increasing nearly 5 times (35.9 ms/item). Slopes for circle targets were inefficient in low clutter (39.4 ms/item) and became even larger in high clutter (58.9 ms/item). At the same time, average intercepts of Experiment 1 increased by over 500 ms between low and high clutter conditions. In Experiment 2, although RT slopes were lower in heavy clutter than in low clutter, the error rate slopes increased significantly in high clutter suggesting a decrease in overall search performance that was masked in the RT data by an SAT. That is, the RT slopes with heavy clutter could have been larger if the error rates were equal, leaving a possibility that display clutter may reduce search efficiency for the reversed N target. RT intercepts were higher in heavy clutter than in low clutter, increasing by an average of over 700 ms. Thus, as expected, increasing clutter dramatically hindered search performance in both experiments.

Second, despite the overall performance decrements seen in heavy clutter, both of the search asymmetries persisted. These results extend previous findings (Yamani & McCarley, 2010) that an asymmetry can hold up in heavy clutter composed of discrete objects. The present data indicate that asymmetries can be robust against continuous clutter as well. In addition, while Yamani and McCarley (2010) measured the strength of a feature-based search asymmetry, the present data from Experiment 2 indicate that a familiarity-based asymmetry can also persist

against heavy clutter, generalizing the previous findings. In general, the visual system can often process a target item favored by a search asymmetry in parallel without capacity limits (Treisman & Gormican, 1988). However, the present results suggest that visual search for the favorable item, both feature-based and familiarity-based asymmetries, may become more effortful in the presence of heavy clutter. Within the clutter, the spoke target in the feature-based asymmetry was found less efficiently. On the other hand, the reversed N target in the familiarity-based asymmetry was found less accurately. Nonetheless, performance continued to favor these target forms over the unspoked circle and N targets, showing the same asymmetry that obtained in low clutter.

The results in Experiment 2 can be viewed as inconsistent with earlier findings of experiments that involved letter recognition. Previous research on stimulus identification (Pasher & Badgio, 1985) showed that the effects of imposed visual noise were additive with the effect of set size. Furthermore, Wolfe, Oliva, Horowitz, Butcher, and Bompas (2002) also reported a similar result, demonstrating an additive effect of clutter and set size, which produced an intercept change in RT search functions but no slope changes without significant difference in accuracy across set sizes. They interpreted the effect as evidence of observers' ability to segment out the display information (background noise) irrelevant to the task (finding an T among Ls) during front-end processing, before search itself began. In the current experiments, the same filtering process might have operated to segment out search items. In heavy clutter, however, the system may not have been capable of perfectly filtering the noise. Within the noisy search field, the stimuli in both experiments could not have been clearly differentiated, which might have decreased search performance.

For real-world application, the current results would provide two implications for using

search asymmetries to facilitate target detection in complex displays. First, either a feature-based or familiarity-based search asymmetry can produce efficient search for the favored items, even in cluttered displays (see Table 2 and 4). Search for a spoked circle target appeared to operate in parallel without capacity limits in displays with light clutter, suggesting that display elements with a distinct additional feature might be helpful for guiding one's attention to a particular critical item.. Similarly, search for a reversed N target was highly efficient in low-clutter displays, approaching the level of unlimited capacity processing. Second, and more remarkably, these asymmetries hold even in heavy display clutter. Here, RT slopes for the targets favored by an asymmetry remained more efficient than search for the unfavored targets, even when high clutter displays reduced search efficiency well below the point of unlimited capacity. Moreover, the asymmetries were evident in error rates as well as RTs, suggesting that coding for an asymmetry can not only speed search through clutter displays, but can improve asymptotic target detection levels. From the perspective of the human factors practitioner, ensuring greater accuracy of target detection is vitally important.

All in all, heavy clutter affected search slopes in RTs (Experiment 1) and error rates (Experiment 2), eliminating unlimited-capacity parallel processing of the targets favored by the asymmetries. However, both the feature-based and the familiarity-based asymmetries persisted within clutter. In application, iconography designers could utilize a variety of search asymmetries to support rapid and accurate detection of a critical item, but selecting either feature-based or familiarity-based asymmetry should depend on how much clutter a display should contain.

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APPENDIX A: FIGURES AND TABLES

Figure 1. A sample low-clutter stimulus from Experiment 1.



Figure 2. A sample high-clutter stimulus from Experiment 1.

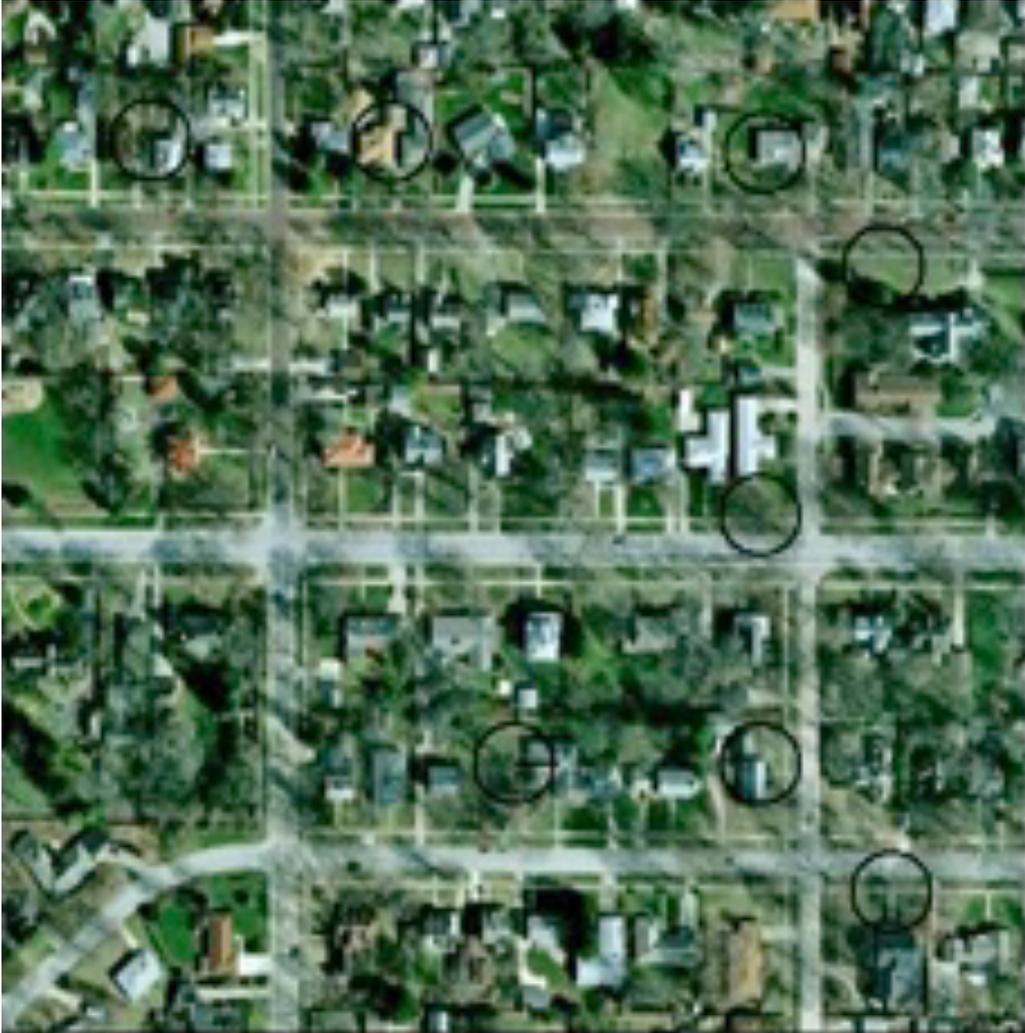


Figure 3. Mean RTs and error rates in Experiment 1. Error bars in all figures represent 95% within-subject confidence intervals (Loftus & Masson, 1994), which are calculated based on the two-way interaction among target type and set size, and they are calculated separately for the low- and high-clutter conditions.

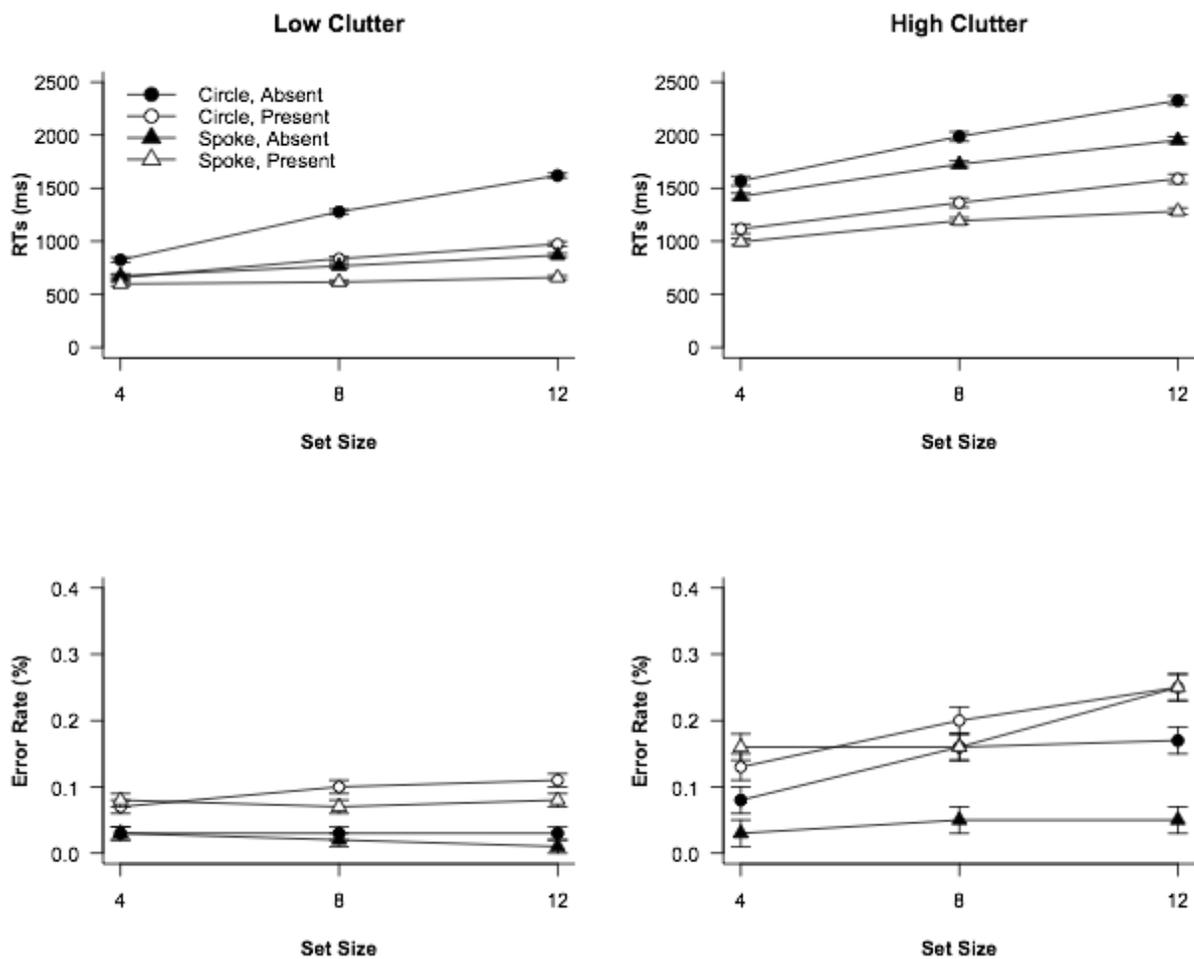


Figure 4. Mean RTs and error rates in Experiment 2

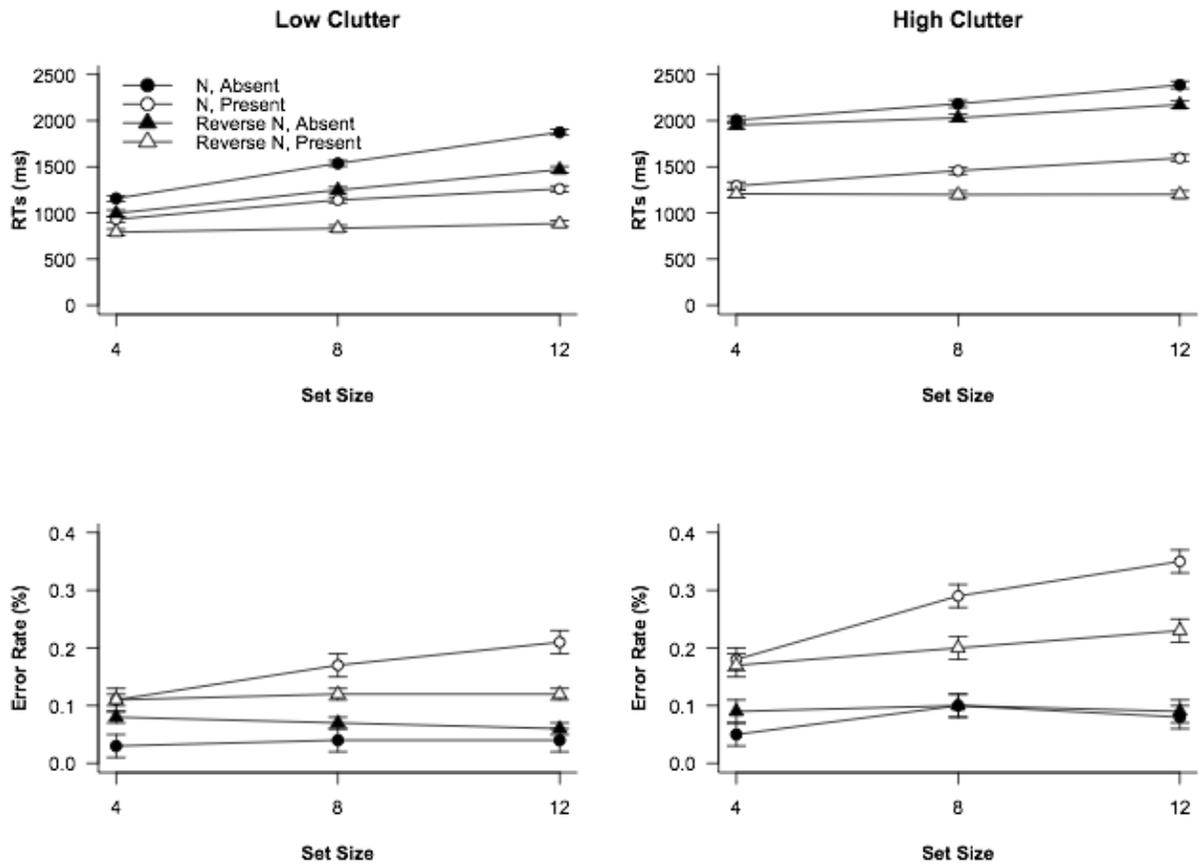


Table 1. Summary of SE measures of the background images. Standard deviations are presented within parentheses.

	Colored	Gray-scaled
High clutter	4.18 (.04)	4.35 (.03)
Low clutter	3.48 (.12)	3.58 (.09)

Table 2. Mean slopes of RTs and error rates in Experiment 1.

Trial Type	RT Slope (ms/item)	Error Slope (%/item)
<i>Low Clutter</i>		
Circle, Present	39.4	0.5
Circle, Absent	99.4	0.1
Spoke, Present	7.6	0
Spoke, Absent	24.3	-0.3
<i>High clutter</i>		
Circle, Present	58.9	1.5
Circle, Absent	94.7	1.1
Spoke, Present	35.9	1.1
Spoke, Absent	66.2	0.2

Table 3. Mean intercepts of RTs and error rates in Experiment 1.

Trial Type	RT Intercept (ms)	Error Intercept (%)
<i>Low Clutter</i>		
Circle, Present	506.4	5.1
Circle, Absent	445.5	2.3
Spoke, Present	562.7	7.6
Spoke, Absent	575.5	4.3
<i>High clutter</i>		
Circle, Present	884.4	6.9
Circle, Absent	1202.8	5.3
Spoke, Present	869	-10.3
Spoke, Absent	1170.9	2.8

Table 4. Mean slopes of RTs and error rates in Experiment 2.

Trial Type	RT Slope (ms/item)	Error Slope (%/item)
<i>Low Clutter</i>		
N, Present	41.1	1.2
N, Absent	89.7	0.1
Reversed N Present	11.6	0
Reversed N Absent	59	-0.3
<i>High clutter</i>		
N, Present	37.5	2.1
N, Absent	47.6	0.4
Reversed N Present	-0.8	0.8
Reversed N Absent	27.7	0

Table 5. Mean intercepts of RTs and error rates in Experiment 2.

Trial Type	RT Intercept (ms)	Error Intercept (%)
<i>Low Clutter</i>		
N, Present	781.3	6.3
N, Absent	805	3
Reversed N Present	743	11.4
Reversed N Absent	765.1	9.1
<i>High clutter</i>		
N, Present	1148.8	10.5
N, Absent	1811	4.1
Reversed N Present	1207.8	13.8
Reversed N Absent	1830.2	8.9

APPENDIX B: INSTITUTIONAL REVIEW BOARD APPROVAL LETTER

UNIVERSITY OF ILLINOIS  
AT URBANA-CHAMPAIGN

Office of the Vice Chancellor for Research  
Institutional Review Board  
528 East Green Street  
Suite 203  
Champaign, IL 61820



September 22, 2009

Jason McCarley  
Institute of Aviation/Psychology  
Beckman Institute  
M/C 251

RE: *Behavioral Studies of Attention*  
IRB Protocol Number: 09122

Dear Jason:

Your response to stipulations for the continuing project entitled *Behavioral Studies of Attention* has satisfactorily addressed the concerns of the University of Illinois at Urbana-Champaign Institutional Review Board (IRB) and you are now free to proceed with the human subjects protocol. The IRB approved the protocol as described in your IRB-1 application, by expedited continuing review. The expiration date for this protocol, UIUC number 09122, is 09/14/2010. The risk designation applied to your project is *no more than minimal risk*. Certification of approval is available upon request.

Copies of the enclosed date-stamped consent forms must be used in obtaining informed consent. If there is a need to revise or alter the consent forms, please submit the revised forms for IRB review, approval, and date-stamping prior to use.

Under applicable regulations, no changes to procedures involving human subjects may be made without prior IRB review and approval. The regulations also require that you promptly notify the IRB of any problems involving human subjects, including unanticipated side effects, adverse reactions, and any injuries or complications that arise during the project.

If you have any questions about the IRB process, or if you need assistance at any time, please feel free to contact me or the IRB Office, or visit our Web site at <http://www.irb.illinois.edu>.

Sincerely,

Sue Keehn, Director, Institutional Review Board

Enclosures

c: Jibo He  
Kelly Steelman