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Feature search in persons with severe visual impairment

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Abstract

Feature search performance was measured in visually impaired (VI) and age-matched controls with normal vision (NV). All VI subjects were legally blind. The task was to search for a 2° × 2° square target among smaller 1° × 1° distracters. Targets and distracters were white and presented on a dark background that subtended 69° by 58°. Three field-sizes (10°, 20°, and 40°) and three set sizes (8-, 16-, and 32-items) were tested. The VI subjects searched more slowly than the NV subjects, but the reaction time of both groups of subjects did not rise with increasing number of items. The latter is consistent with a parallel search. Both groups searched more slowly when field-size increased, but the VI group was affected more by the increase than the NV group.

Keywords: Visual search; Feature search; Visual impairment; Aging

1. Introduction

In a typical visual search experiment, the subject is asked to determine the presence or absence of a target, amid various numbers of distracters. If the target and distracters differ only in one visual feature (color, for example), the target seems to "pop out" from the distracters. The search speed is fast and is not influenced by the number of distracters (set-size). Such feature search is said to be accomplished by the preattentive system, which extracts basic visual features (color, orientation, size and so on) in parallel across the visual field, and seems to have unlimited capacity (Neisser, 1967; Treisman & Gelade, 1980). If the difference between the target and distracters is the conjunction of more than one visual feature (color and orientation, for example) or the saliency of the difference between the target and distracters is low, it takes much longer to detect the presence or absence of a target and search time increases as the number of distracters increases. Such conjunction search bears the signature of the attentive system, which, guided by the preattentive system, examines visual features and preattentive object files one by one, so that visual features can be bound together, objects can be recognized, and events can be registered (Kahneman & Treisman, 1984; Wolfe, Cave, & Franzel, 1989).

Visual search is closely related to useful and important behaviors of our daily life. We look for a familiar face in a crowd, obstacles in our path, or, the color of the symbols of the stocks we hold. Many recent studies have been devoted to the change of visual search capability across the life span, especially the decay of visual search capability during normal aging, because of the potential impact of such change on life quality and well-being of the aging population. Of particular interest to us are the age-related changes of feature search. While the age-related decay of conjunction search performance may involve higher level cognitive processes such as limitations of working memory or more cautious search strategies, the decay of feature search, because of

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its supposedly unlimited capacity, is more likely to reflect age-related perceptual, sensory, or even physiological changes. A consistent finding across studies of age-related changes in feature search is that older subjects respond more slowly than younger ones (Burton-Danner, Owsley, & Jackson, 2001; Davis, Fujawa, & Shikano, 2002; Hommel, Li, & Li, 2004; Plude & Doussard-Roosevelt, 1989). Furthermore, the reaction time (RT) for feature search increases gradually over the life span (Hommel et al., 2004). Another common finding is that despite the difference in RT's between younger and older subjects neither group shows a significant effect of set-size in feature search. However, a study by Davis et al. (2002) indicates this similarity disappears if the feature search task is difficult. They used a two interval forced choice paradigm and a staircase procedure to emphasize perceptual processing and to deemphasize decision-making and psychomotor processing in feature search tasks. They had their young (mean age = 22.6) and old (mean age = 69.3) subjects search for a circle in an array of diamonds. This task was a difficult one and both young and old subject groups showed a significant set-size effect. Besides taking longer to find the target, older subjects had a stronger set-size effect. Although these observations may be explained by a number of theories of age-related loss of general resources (slowing of information processing or decline of inhibitory mechanisms or accumulated loss of information over a number of processing steps), careful analysis of other aspects of visual search (conjunction search, presence vs. absence responses, useful field of view or search efficiencies at different set-sizes) suggests that the differences in visual search between healthy younger and older adults may involve task specific processes in addition to the general-resource accounts (Burton-Danner et al., 2001; Davis et al., 2002; Hommel et al., 2004).

With increased life expectancy, more and more otherwise healthy elderly people suffer from various visual impairments. This usually results from diseases associated with age or the aging process such as age-related macular degeneration (AMD), diabetic retinopathy (DR), glaucoma, and retinitis pigmentosa (RP). Advanced AMD and DR typically involve the loss of central vision and are characterized by large central scotomata with very poor visual acuity but relatively intact peripheral vision. In contrast, retinal damage associated with glaucoma and RP usually starts in the periphery and gradually closes in on to the fovea. The result is a gradual constriction of the visual field during which time central vision often remains relatively intact. However, all vision may eventually be lost. The impact of severe visual impairment on a person's daily life, including orientation and mobility (O&M), is well documented (Geruschat, Turano, & Stahl, 1998; Marron & Bailey, 1982; Soong, Lovie-Kitchin, & Brown, 2001; Turano et al., 2004; Turano, Rubin, & Quigley, 1999; Virgili & Rubin, 2003). There are several reasons to believe that the impairment of mobility may be associated with an impairment of visual search behavior. First, severe visual impairment is usually associated with extended loss of central or peripheral visual field. Thus it is very likely that some targets of interest will fall into a scotoma, and will not be made visible without executing an eye or head movement. In advanced cases of glaucoma or RP, for example, vision is restricted to an island of a few degrees in size and many head and/or eye movements have to be made before the whole visual field can be inspected. Second, visual search performance depends on the saliency of visual features. The saliency of some visual features, such as color, orientation or shape, may depend on retinal location, being highest at the fovea, and decaying into the periphery. When the fovea is damaged by disease, visual features that are highly salient to normal persons may become much less so to visually impaired persons. Some retinal diseases also result in local perceptual distortions (metamorphopsia), which can reduce the saliency of features such as orientation or shape. Third, although attention shift is not necessarily associated with eye movements, saccades do occur during visual search, even in feature search, and the number of saccades has been found to be as useful as measurement of visual search difficulty as reaction time, at least in untrained normal subjects (Scialfa & Joffe, 1998; Zelinsky & Sheinberg, 1997). If eye movements facilitate visual search in normal subjects, then such facilitation may be reduced in some individuals who suffer from severe visual impairment. For example, when the fovea is damaged, the latency and accuracy of saccades can be adversely affected and consequently eye movement control reduced (White & Bedell, 1990; Whittaker, Cummings, & Swieson, 1991).

Despite what appear to be obvious associations between visual impairment and visual search, very little is known about them. Bertera (1988) used an eye tracker to create a simulated central scotoma 20 arc min in size in normal subjects, and measured search time and eye fixation duration for detecting a target (a 20 arc min square with a small gap) from an array of distracters (20 arc min squares). Under a difficult condition (high display density and 12% contrast), the presence of a simulated central scotoma nearly doubled the search time. On the other hand, under an easier condition (low density, 30% contrast), the effect of the simulated scotoma on search time or fixation duration was not significant. Although the author did not specify, the search seemed to be a serial one, because the search times nearly tripled when set-size changed from 25 items to 100 items. Knoblauch, Mazoyer, Koenig, and Vital-Durand (2001) tested four subjects with exudative AMD and central scotomas and obtained results that suggested that these subjects could search in a parallel fashion.

In this study, two or eight discs were arranged on a virtual circle 12° in diameter. In 50% of the trials, there was one disc (the target) that had a different color from other discs (distracters). The task was to detect the presence of the target disc. When the number of discs changed from 2 to 8, reactions times did not change and the effect on set-size was not statistically significant. However, as the authors acknowledged, four subjects might be too small a number to provide a reliable description of visual search behavior of VI persons. Coeckelbergh, Cornelissen, Brouwer, and Kooijman (2002) tested 50 current drivers with visual field defects of heterogeneous origins in a visual search study. The stimulus was an "O" in an array of 19 "C's". The gap of a C was at least 0.5 log unit above the subject's acuity gap size, and was randomly located at left, right, up or down position of the ring. Although only one set-size (20 items) was tested, the search appeared to be a serial one, because the majority of search times were very long; in the range of 4–7 s. For subjects with peripheral visual field defects, search time and the number of fixations were reported to be "loosely correlated" with horizontal field extent. No search time data were reported for central field defects, although it was shown that larger central scotomata corresponded to fewer return saccades.

If visual search performance is associated with mobility it may be useful as a measure of functional visual impairment for predicting performance on other daily activities, and for estimating rehabilitation needs. It might also prove useful as a tool for facilitating mobility training. However, to establish if visual search can be used for these purposes more needs to be known about the characteristics of visual search in persons who are visually impaired. In the present study, we assessed feature search performance and its relationship to display set-size and field-size in persons who were visually impaired and compared it to results from persons who had normal vision.

2. Methods

2.1. Subjects

Three groups of subjects were recruited from the Birmingham Alabama Department of Veterans Affairs Medical Center (VAMC) and Birmingham area community support groups for persons with visual impairment. All subjects were ambulatory, willing and able to travel to the Birmingham VAMC for testing, and free of significant cognitive impairment as determined with the Short Portable Mental Status Questionnaire (Pfeiffer, 1975). All subjects who voluntarily participated signed informed consent forms approved by the Institutional Review Boards of the Birmingham VAMC. The study was conducted in accordance with the Declaration of Helsinki.

2.1.1. Subjects with normal vision

The normal vision (NV) group consisted of 24 persons between the ages of 46 and 82. They served to establish baseline performance levels, against which the performance of the visual impaired could be compared. Inclusion criteria for the NV group included: eye examination within the past six months that showed no diagnosed or apparent retinal pathology or past retinal surgery; not using medication or drugs that might affect vision; normal binocular Goldmann visual fields; and visual acuity and log contrast sensitivity better than or equal to age-adjusted median values.

2.1.2. Subjects with severe visual impairment (VI) participating in the inpatient (IN) blind rehabilitation program (VI-IN group)

The VI-IN group consisted of 26 veterans between the ages of 39 and 90 years.

2.1.3. Subjects with severe visual impairment not participating (OUT) in the blind rehabilitation program (VI-OUT group)

The VI-OUT group consisted of 23 veterans between the ages of 35 and 91.

Subjects in both of the VI groups had heterogeneous ocular pathology (macular degeneration, glaucoma, diabetic retinopathy, optic nerve disease, retinal detachment, and cataract) with vision loss to the level of legal blindness.

2.2. Vision assessment

Best-corrected visual acuity (VA) was measured binocularly using a back illuminated (95 cd/m^2) ETDRS chart. Initial viewing distance was three meters, but would be decreased to two meters and then one meter if the subject could not correctly identify at least one letter on the top line. Visual acuity was scored using a letter-by-letter procedure, and was recorded in units of log minimum angle of resolution (logMAR). Binocular Goldmann visual field (GVF) was measured along 12 meridians with a Goldmann perimeter using the III/4e target and standard background luminance (Kuyk, Elliott, & Fuhr, 1998a). The intent of the field assessment was to measure the amount of field remaining (in degrees) along each meridian, sum the values across meridians and express the result as a percent of a normal visual field with a total extent of 846°. However, visual field data are not included as part of the results because a protocol mis-interpretation resulted in only the outer boundary of the field being plotted for some subjects. In the case of subjects with macular disease, for example, scotomas lying inside the outer boundary were not consistently mapped. Contrast sensitivity (CS) was assessed using the Pelli–Robson chart (Pelli, Robson, & Wilkens, 1988) with surface luminance of the white areas at 100 cd/m^2. Viewing distance was 1 m and sensitivity was scored in log CS as the faintest triplet for which two of the three letters were named correctly. This method, rather than counting all correctly identified letters, was used because it was consistent with how we had done it in previous studies. Scanning ability (SCAN) was measured using the simple test we used in our previous studies (Kuyk and Elliott, 1999; Kuyk et al., 1998a, 1998b). In this test, the subject scanned a photograph of a street scene projected on a large screen TV and located and pointed to numbered targets scattered about the scene in sequence as rapidly as possible. Two 10 s duration trials were given.

2.3. Visual search stimulus

White target and distracters were displayed on a black background. The target was a 2° × 2° square and the distracters were 1° × 1° squares. Size difference between the target and homogeneous distracters is a basic visual feature, which leads to very efficient search (Wolfe, 2000). It is less influenced by retinal eccentricity, and is robust against metamorphopsia that is often associated with macular disease. A target or a distracter could appear at one of the 36 locations of a 6 × 6 virtual square grid, with a small positional jittering to avoid edge alignment of the neighboring items. To study the effect of field-size on visual search, the 6 × 6 grid had three sizes, 10° × 10°, 20° × 20°, and 40° × 40°. In all field-sizes, the sizes of the target and distracters remained the same, only the separation between items changed. To study the effect of display set-size, 8-, 16- and 32-items were used with each field-size. Therefore, there were a total of nine field-size and set-size combinations, each of which was tested in a separate experimental session. In our manipulation of field-size and set-size, there were inevitable changes of display density. Cohen and Ivry (1991) showed that for normal subjects, display density change did not affect simple feature search RT. It would be informative if visually impaired subjects perform differently.

Each visual search session contained two types of trials. In a target-present trial, the display contained one target and 7, 15 or 31 randomly positioned distracters, and in a target-absent trial, the display contained no target and 8, 16 or 32 randomly positioned distracters.

Subjects were instructed to look at the center of the display screen. This was not particularly difficult for individuals with central scotomas because they could use the geometry of the screen and the projected image to locate the center of the display. A crosshair was provided in the center of the display at the onset of a series of trials to aid persons with field restrictions to find the center of the display. However, because the target and the distracters were highly visible even in the very far periphery, and because the difference between the target and distracters was conspicuous enough that discrimination could be made without foveating, precise fixation at the center of display and strict control of eye movements were not necessary (Wolfe, 2000; Zelinsky & Sheinberg, 1997).

The stimulus array was generated on a desktop computer. The video signal was fed to an Epson multimedia projector, which projected the image to a 75 × 120 cm semi-transparent screen (Stewart Filmscreen Corporation). The subject sat on the opposite side of screen from the projector and viewed the display binocularly from a distance of 92 cm from the screen. The luminance of the target and distracters was 20.1 foot-lamberts, and the background was 2.9 foot-lamberts. The experiment was conducted in a dimly lit room and the target and background light levels were measured in that condition.

2.4. Visual search procedure

Prior to the experiment, each subject was given a demonstration of the task. The subject's task was to detect as fast as possible the presence or absence of a target in each display of an array of items. The subject initiated the onset of the first display by pressing a key. If the subject decided that there was a target in the display, he/she pressed one key on the computer keyboard. If the subject found no target in the display, he/she pressed another key. The computer timed the duration between the onset of the display and the key-press, and recorded it as the reaction time (RT) for the display. The key-press also trigged the display of the next array of items.

Each experimental session contained 36 target-present trials so that the target appeared once on each of the 36 possible positions of the 6 × 6 grid. Because RT may depend on the eccentricity of the target in the display (Carrasco, McLean, Katz, & Frieder, 1998), the evenly distributed target positions helped to avoid system errors associated with eccentricity. There were also nine target-absent trials in each session (25%) for a total of 45 trials in each session. The choice of 25% blank trials rather than 50% was made to reduce testing time. The results reported here are only part of what each subject completed in a larger study of the effects of visual search training on mobility performance.

Each subject completed all nine feature search conditions (3 field-sizes × 3 set-sizes) each day for five days. It is known that feature search performance improves with practice (Ahissar & Hochstein, 1993, 1996; Sireteanu & Rettenbach, 1995). The number of trials required to reach the asymptotic performance level ranged from several dozens to several hundreds. We also noticed that most of our subjects' RT shortened with practice and reached asymptotic level around the fifth day. Therefore, to provide a description of steady state visual search performance of VI subjects', we used the data collected from the fifth day. In other words, each subject had had $4 \times 45 = 180$ trials of practice for each field-size/set-size combination before their feature search performance was measured.

Four measurements were obtained from each feature search session for each subject. Percentage of hits (reporting a target on a target-present trial, PHIT) and percentage of false alarms (reporting a target on a target-absent trial, PFA) are measures of the accuracy of the search. Reaction time on correct target-present trials (RT for a hit, RTHIT) and reaction time on correct target-absent trials (RT for correct rejection, RTCR) are measures of the speed of the search.

3. Results

3.1. Age and visual function: NV vs. VI groups

Age and vision test data are summarized in Table 1. The mean age of the subjects with normal vision was 67 ± 12.71. The mean ages for the in-house and out patients with visual impairment were 73.38 ± 11.84 and 73.43 ± 11.64, respectively. An ANOVA showed that there was no significant age difference among these three groups ($p = 0.111$). Therefore, they can be considered as samples from the same age population. As shown in Table 1, subjects with normal vision had significantly better visual acuity, higher contrast sensitivity and better scanning ability than subjects with visual impairment. A series of t tests showed that there were no significant differences in the means of visual acuity, contrast and scanning ability between the VI-IN and VI-OUT groups ($p = 0.998$ for age, $p = 0.287$ for visual acuity, $p = 0.229$ for contrast and $p = 0.153$ for scan). Therefore, in-house and out patients with visual impairment were samples from the same population and their results in visual search tests are subsequently analyzed as one VI group ($N = 49$). As noted previously, the VI group was a heterogeneous sample with respect to cause of vision loss. However major cause of vision loss was macular disease and this was reflected in the breakdown by type of vision loss. Sixty-nine percent of the sample was qualified as legally blind based on an acuity loss, 16% by a peripheral field restriction, and 14% of the sample had both and would have qualified as legally blind by either criterion.

3.2. Overall visual search performance: NV vs. VI

Visual search performance was averaged over all field-size/set-size combinations. Nonparametric tests were used to compare mean PHIT and PFA, because distributions of these measures were highly skewed. The means of hit rate for the NV and VI groups are 99.12 ± 0.74 and 96.27 ± 7.45, respectively. Although the PHIT difference between groups is significant ($p = 0.003$, two-tailed Kolmogorov–Smirnov test), the rates are very high indicating neither group had difficulty performing the feature search task. This is supported by low false alarm rates for each group. The means of false alarm rate for the NV and VI groups were 1.56 ± 1.99 and 4.56 ± 6.72, respectively. Kolmogorov–Smirnov test showed that the PFA difference between the two groups was not significant ($p = 0.110$, two-tailed).

Table 1
Summary of vision assessments

Group	Visual acuity (VA)	Contrast (CS)	Scan (SCAN)
NV	.025 ± 0.217	1.600 ± 0.201	7.89 ± 1.50
VI-IN	.838 ± 0.296	0.733 ± 0.291	3.25 ± 0.87
VI-OUT	.927 ± 0.282	0.600 ± 0.461	3.79 ± 1.66

Fig. 1 illustrates that on average, the VI group took more time to detect the target in a target-present trial than the NV group (RTHIT were 1440.4 ± 515.1 ms vs. 915.2 ± 130.1 ms, $t = -4.903$, $p < 0.0005$). The VI group also took more time to reject a target-absent trial than the NV group (RTCR were 2968.0 ± 1556.4 ms vs. 1346.2 ± 370.6 ms, $t = -5.019$, $p < 0.0005$). Subjects of the NV group took more time to reject a target-absent trial than to detect the target in a target-present trial. Their RTCR over RTHIT ratio was 1.45 ± 0.23. For subjects of the VI group, this ratio is 2.00 ± 0.59. The difference between these ratios was significant ($F = 15.790$, $p < 0.0005$).

For both NV and VI groups, the measurements of search speed, RTCR and RTHIT, were highly correlated (Spearman's $\rho = 0.860$ for NV and $\rho = 0.829$ for VI, $p < 0.0005$ for both). For the NV group, search speed was not correlated with search accuracy. The Spearman's ρ for PHIT and RTHIT was −0.148 ($p = 0.491$). However, for the VI group, PHIT and RTHIT were correlated. Spearman's ρ was −0.383 ($p = 0.007$). The negative correlation suggested that subjects who searched faster usually searched more accurately. It also suggested that our VI subjects did not

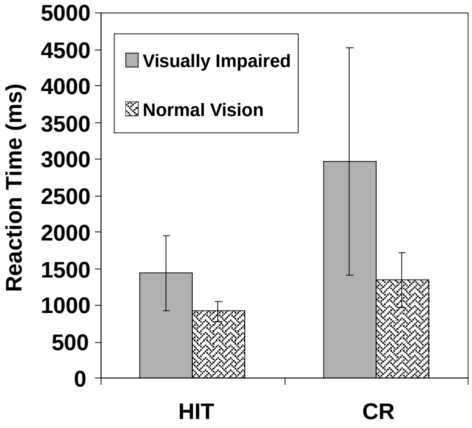

Fig. 1. Reaction times for hits and correct rejections (RTHIT and RTCR) averaged across all viewing conditions.

trade search speed for accuracy. This tendency, however, did not seem to exist in target-absent trials, because PFA and RTCR, were not correlated (Spearman's $\rho = 0.264$, $p = 0.067$).

Therefore, except for false alarm rate (PFA), all feature search performance indicators are significantly different between the NV and VI groups. Visually impaired subjects on average made no more errors than subjects with normal vision, but they took more time to detect a target. They also took a disproportionably longer time than normal controls to reject a target-absent trial.

3.3. Set-size effect at different field-sizes: NV vs. VI

Fig. 2 shows changes of reaction time with display set-size. Open and solid symbols are data from NV and VI groups, respectively. Circles and squares represent results from target-absent and target-present trials (RTCR and RTHIT), respectively. A repeated measures procedure was used to analyze visual search performance at the three set-sizes. In this analysis, subjects' performances at 8-, 16- and 32-item set-sizes were entered as within-subjects variables, and group (NV or VI) was entered as the between-subjects factor. The analysis revealed that there was no set-size effect in terms of search accuracy. Both PFA and PHIT main effects were not significant. There was no difference between NV and VI groups in these measurements (Group main effects were not significant), except for PFA at 10° field-size and PHIT at 40° field-size. There were no significant interactions between Set and Group factors in search accuracy measurements.

Reaction time on target-present trials (RTHIT) showed no significant set-size effect at 10° and 20° field-sizes, but showed significant set-size effect at 40° field-size ($F = 4.68$, $p = 0.011$). In contrast, reaction time on target-absent trials (RTCR) showed significant set-size effects at all field-sizes (p's < 0.01). The Group main effects were significant for both RTCR and RTHIT at all field-sizes (p's < 0.001), indicating significant slowing in search speed in VI subjects. Set * Group interaction was not significant under three conditions and only marginally significant under the other three conditions.

To quantify the set-size effect on search speed, linear regression was performed on each subject's data. The mean RTHIT slopes for the NV group were 0.468, 1.151, and 0.963 ms/item for 10°, 20°, and 40° field-sizes, respectively. The mean RTHIT slopes for the VI group were slightly steeper than corresponding slopes for the NV group but were still very shallow, being 2.284, 4.658, and 9.293 ms/item for 10°, 20°, and 40° field-sizes, respectively. These shallow slopes, in combination with the results of the repeated measurements ANOVA, indicate insensitivity of search time to the number of search items, and thus suggest parallel search of the display. The RTCR slopes were steeper than RTHIT slopes. Although RTCR slopes for the NV group were still shallow enough to indicate parallel search, the RTCR slopes for the VI group exceeded the 13 ms/item criterion for parallel search (Wolfe, 2000), and thus suggested the existence of a serial component when VI subjects searched target-absent displays. Our results confirmed previous observations that NV subjects searched for

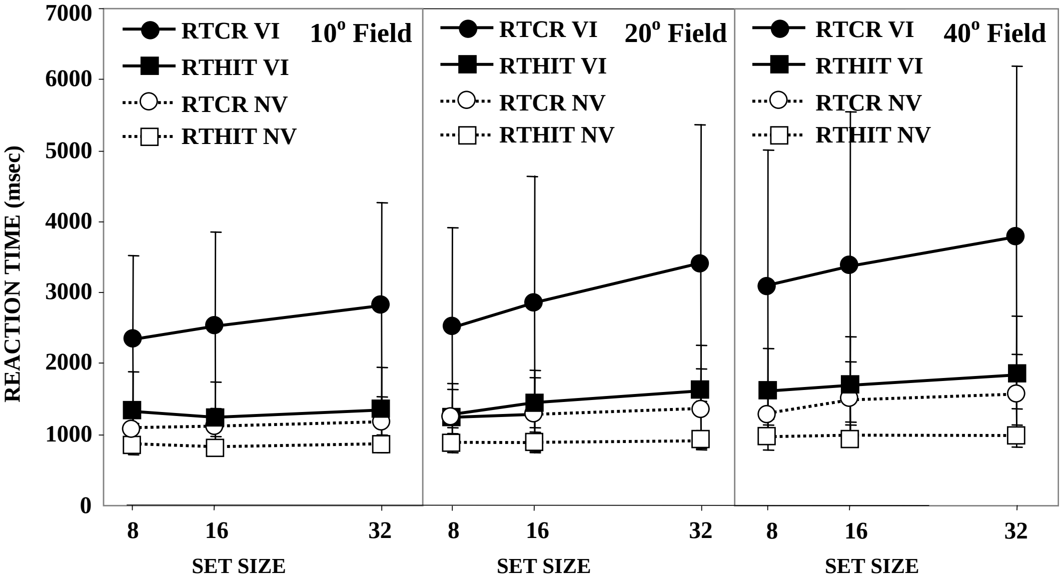

Fig. 2. Set-size effects at 10°, 20°, and 40° field-sizes. Solid symbols were data points from the VI group. Open symbols and dotted-lines were data from the NV group. Squares were reaction time for correctly rejecting target-absent trials (RTCR), and circles were reaction time for correctly detecting the target in target-present trials (RTHIT). The three panels show data from 10°, 20° and 40° field-sizes.

features in a parallel fashion. However, feature search of VI subjects showed a peculiar pattern. While target-present trials appeared to be search in a parallel fashion, target-absent trials were not.

3.4. Field-size effect at different set-sizes: NV vs. VI

Fig. 3 shows changes of reaction time with display field-size. Open and solid symbols are data from NV and VI groups, respectively. Circles and squares represent results from target-absent and target-present trials (RTCR and RTHIT), respectively. A repeated measures procedure was used to analyze subjects' visual search performance at the three field-sizes. In this analysis, subjects'' performance at 10°, 20°, and 40° field-sizes were entered as within-subjects variables, and subject group (NV or VI) was entered as the between-subjects factor. Most PFA and PHIT field main effects were not significant, with the exception of PHIT at 8- and 16-item set-sizes. There were only marginal differences between NV and VI groups in PFA at 8- and 16-item set-sizes. There were no significant interactions between Field and Group factors in search accuracy measurements. In contrast, both measurements of search speed, RTCR and RTHIT, showed significant field-size effects at all set-sizes (p's < 0.0001). As expected, all Group main effects were significant, reflecting the slower search by VI subjects. Field-size × Group interactions did not show a consistent pattern and were significant for RTCR for 8 and 32 items, but not 16 and were significant for RTHIT for 8- and 16-item set sizes but not 32.

The repeated measure procedure did not allow post hoc analyses on within-subjects factor to specify how the three field-sizes differed from each other. Subsequent pair-wise comparisons showed that most reaction time/field-size relationships fell into one of the two patterns. The first is a significant increase of RT from 10° field-size to 20° field-size and a weak or no increase of RT from 20° field-size to 40° field-size. The second pattern is the opposite, with the largest increase in RT occurring between 20° and 40° field-sizes. As shown in Table 2, four of the twelve RT/Field-size relationships were of the first type, and seven were of the second type. The only exception was NV group's RTHIT at 16-item set-size, which showed significant increase from 10° to 20° field-size, and from 20° and 40° field-size.

To further explore the differential field-size effects between NV and VI groups, RTHIT and RTCR at 10° field-size were used to normalize corresponding measures at 20° and 40° field-sizes, and the results are shown as pairs of curves in Fig. 4. A star between two vertical datum points indicates that the vertical difference is significant. While increasing field-size slowed down feature search for all subjects, it had a much stronger impact on subjects with visual impairment, especially when the field-size was greater than 20°. For example, when the set-size was 8 items, increasing field-size from 10° to 40° increased RTHIT by 10% in the NV group, but 30% in the VI group. The VI group RTHIT was slowed down 18–27% more than the NV group RTHIT when field-size was increased from 10° to 40°. For 8 items set-size, VI group RTCR was slowed down 19% more than NV group RTCR when field-size was increased from 10° to 40°, but there were no significant differential field-size effects for 16 items and 32 items set-sizes.

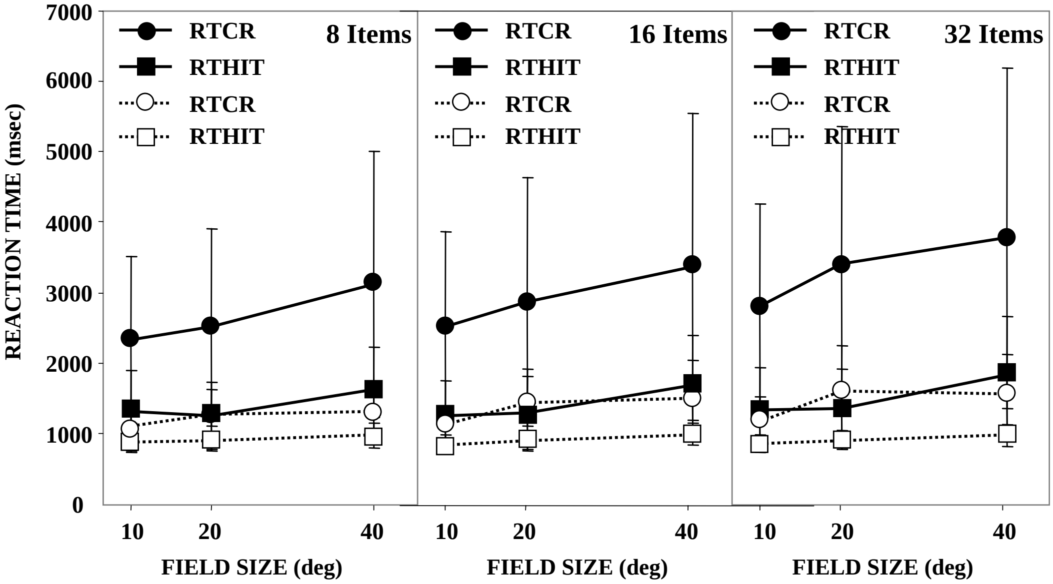

Fig. 3. Field-size effects at 8-, 16- and 32-item set-sizes. Solid symbols were data points from the VI group. Open symbols and dotted-lines were data from the NV group. Squares were reaction time for correctly rejecting target-absent trials (RTCR), and circles were reaction time for correctly detecting the target in target-present trials (RTHIT). The three panels show data from 8-, 16-, and 32-item set-sizes.

Table 2
Field-size effect: pair-wise comparison

	Set-size 8 items				Set-size 16 items				Set-size 32 items			
	10 and 20		20 and 40		10 and 20		20 and 40		10 and 20		20 and 40	
	F	Sig.	*F*	Sig.	*F*	Sig.	*F*	Sig.	*F*	Sig.	*F*	Sig.
VI												
RTCR	1.527	0.223	24.525	0.000	4.655	0.036	9.983	0.003	14.974	0. 000	3.695	0.061
RTHIT	2.024	0.161	52.363	0.000	0.470	0.496	55.800	0.000	0.037	0.847	50.586	0.000
NV												
RTCR	11.984	0.002	0.293	0.593	29.360	0.000	0.943	0.342	34.650	0. 000	0.293	0.594
RTHIT	0.319	0.578	19.577	0.000	29.309	0.000	23.154	0.000	2.873	0.104	15. 458	0.001

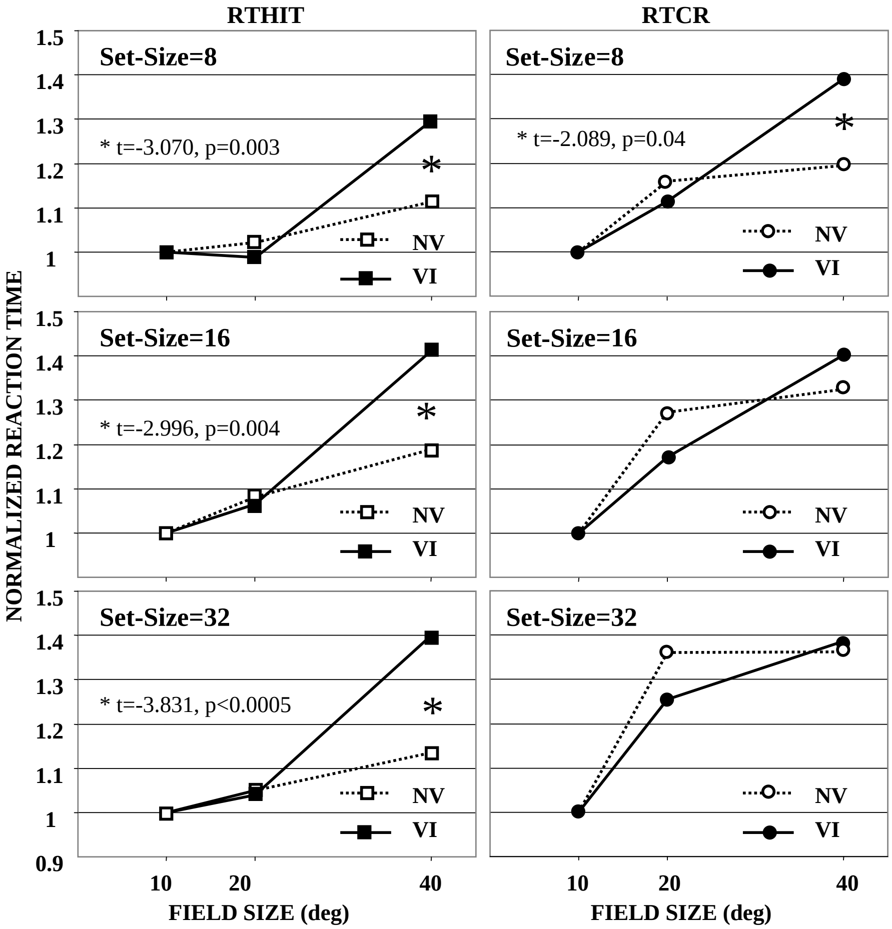

Fig. 4. Comparing field-size effect between NV and VI groups for 8-, 16-, and 32-item set-sizes. Reaction times for each set-size are normalized with the reaction time at 10° field-size. Therefore, the plots show proportion of reaction time change at different field-sizes comparing to that at 10° field-size. A "*" between two vertically separated symbols indicates that the difference between these two data points is significant, and the corresponding *t* test results are shown in the panel. The first column shows reaction time for correctly detecting a target in target-present trials (RTHIT), and the second column shows reaction time for correctly rejecting target-absent trials (RTCR). Open and solid squares are data from the NV and the VI groups, respectively.

4. Discussion

4.1. Parallel or serial?

Our visually impaired subjects are unique in the study of visual search because, due to their retinal defects, there is always the chance that some items in the display fall into scotomata. Pre-attentive processes that provide the basis for visual search have no access to these elements, and shifting focus of attention cannot bring them back. Whether eye movement is necessary in feature search in normal subjects is debatable, but there is no question that eye movement must be used by subjects with severe visual impairment to do feature search. Other difficulties in peripheral mechanisms that may affect visual search include impaired processing in the functioning part of the retina that may reduce the saliency of visual features, poor eye movement control, and no preferred retinal locus, or multiple preferred loci that substitute for the damaged fovea as the center(s) of attentive vision.

Thus, it is not surprising that subjects in the VI group were much slower than subjects in the NV group in feature search. However, the time required for VI subjects to search for a feature in a target-present display did not seem to be affected by the number of items in the display. This is true for all three field-sizes we tested. For example, at the largest field-size (40°), where the set-size effect was the strongest, the slope of RTHIT × Set-size curve was less than 10 ms/item (from 1619 ms for 8 items to 1842 ms for 32 items). The shallow slope suggests that, despite all the functional impairments, VI subjects did not search for a feature item-by-item. On the other hand, the time spent confirming the absence of a target in a target-absent trial was much longer and was related to the number of items in the display. Did VI subjects inspect the display item-by-item in a target-absent display? This is unlikely for several reasons. First, a subject would not know whether a display contained a target until a target was detected or until the whole display was examined. Therefore, it is impossible for the subject to choose a parallel strategy for a target-present trial or a serial strategy for a target-absent trial before the display started. Second, we want to emphasize that although the RTCR × Set-size slopes were steeper than the 13 ms/item criterion for parallel search, the set-size effect was very weak in comparison to the general slowness of VI subjects in performing the task. In the most significant case of RTCR set-size effect, that is, at 20° display size, RTCR were 2511, 2865, and 3419 ms for 8, 16, and 32-item set-sizes, respectively. The slope was about 38 ms/item. However, for a three-fold increase in set-size (from 8- to 32-item), the RT increment was a mere 36%. It was clearly not a serial search in the classical sense, but consisted instead of several consecutive parallel searches executed on different areas of the stimulus field until a target was detected.

Many visual search studies show consistent search patterns for target-present and target-absent trials. They are either all parallel, as in cases of typical feature search, or all serial, as in cases of typical conjunction search. Differential dependence of RT on set-size, however, has been reported before. Treisman and Gelade (1980) showed that when a small ellipse was searched for among larger ellipses, the RT × Set-size slope for target-present trials was about 16 ms/item while the slope for target-absent trials was more than 60 ms/item. In the same paper, the authors also showed that when searching an R among P's and B's, or a T among I's or Y's, the slopes for target-present trials were 5.3 and 9.7 ms/item while the slopes for target-absent trials were 18.1 and 40.5 ms/item. Treisman (1982) also showed differential set-size dependence when a feature was searched in a sparse display. Treisman (1982) believed that "Subjects may have been less confident that the target was absent when the distracters were peripheral than when they were centrally located." And she observed that "It appears to be a typical strategy with feature search under difficult or confusable conditions." (Treisman, 1982). These conditions were definitely met in the population we tested. However, increased cautiousness has also been used (Hommel et al., 2004) to explain the longer RT for target-absent trials observed in elderly normal subjects. Currently, we agree with the explanation that our VI subjects were performing a parallel search under difficult conditions.

4.2. *Why slower?*

In studies of age-related change in visual search, most authors found that aged normal subjects performed feature search in a parallel fashion. Some authors found an age-related slowing of feature search (Burton-Danner et al., 2001; Humphrey & Kramer, 1997; Oken, Kishiyama, & Kaye, 1994; Plude & Doussard-Roosevelt, 1989). This age-related difference was attributed to two factors, generalized slowing and age-related shrinking of the useful field of view (Burton-Danner et al., 2001; Humphrey & Kramer, 1997). These two age-related factors, however, are not quite effective in explaining why our VI group searched much slower than the NV group, since they both belonged to the same age group. The useful field of view explanation, however, might be applied to the slowing we observed in VI subjects with one difference. The difference is that the key concept is not a *useful* field of view, which is defined as the extent of the visual field that attention can be deployed, but a *usable* field of view, which is the field corresponding to the intact parts of the retina. The slow search was not due to the inability to deploy attention in a large area of the visual field, but due to the fact that some items of the display, target or distracters, fell on parts of the retina where functioning had either stopped or was severely impaired. Thus, the field defects of VI subjects prevented them from processing the entire stimulus array in one inspection, they had no choice but to move their eyes and to make several inspections, each directed to a different area of the display. We assume that parallel feature search was performed within the area of each inspection. This pseudo-parallel search is self-terminating, that means that the inspection of different parts of the display continues until either a target is detected or the whole display area is inspected. Because the number of inspections is determined by the size of the display area, not by the number of items in the area, when the display field-size is fixed, the amount of time required to inspect the field should not be related to the number of items in the field, in other words, the search appears to be parallel. This prediction agrees with our results.

Pashler (1987) proposed a "molar serial search process" for conjunction search, in which a capacity-limited parallel self-terminating search mechanism serially searches subsets of the display. If the display contained more items than the proposed capacity of parallel search (8 items), then more than one parallel search would be needed. The difference between Pashler's models and the pseudo-parallel search explanation of VI-related slowing is that Pashler's model is driven by capacity overflow, and thus search time is still related to the set-size, while our explanation is based on the area of useable vision, and thus is independent of the set-size, as long as all items are displayed in a field of the same size. Treisman and Gormican (1988) suggested a serial scan of groups of items to explain a wide range of search rates observed under less discriminable feature search conditions. In Treisman's suggestion, grouping was necessary because a wide beam of attention might not have the resolution to discriminate less discriminable items; the width of the attention beam might be adjustable, and the mechanism of the scan, though not specified, was likely to be attention shifts. In the pseudo-parallel search explanation, serial scan is a necessity, no matter how discriminable the items are, and serial scan is accomplished by moving the eyes so that the intact part of the retina can be directed to a different part of the display.

The pseudo-parallel search explanation predicts that the time spent on rejecting a target-absent trial (RTCR) should be roughly twice as long as the corresponding time spent on detecting the target in a target-present trial (RTHIT). This is because the pseudo-parallel search is self-terminating. For example, assume, due to a loss of retinal sensitivity in an area, a subject needs to make n inspections to cover the entire display area. On average, only $n/2$ inspections are needed to detect a target in a target-present trial, because the target has an equal chance to appear at any of the 36 positions in the display, and the subject has a 50% chance to encounter the target before all n inspections are made. In a target-absent trial, on the other hand, a responsible subject has no choice but making all n inspections before indicating the absence of a target. We divided the RTCR with the corresponding RTHIT. The mean ratios for 10, 20, and 40° field-sizes are 1.95 ± 0.71, 2.21 ± 0.91, and 1.89 ± 0.60, respectively. It seems that VI subjects did spend approximately twice as long to search a target-absent display than a target-present display, and they seemed to have adopted a pseudo-parallel search strategy.

The pseudo-parallel search explanation also predicts that the ratio of 2.0 should stay constant throughout all set-sizes for a given field-size, because the number of parallel searches performed is not determined by the number of items, but only by the size of the field needing to be searched. However, the RTCR/RTHIT ratio increased with increasing set-size at all three field-sizes, and this type of set-size effect is significant (repeated measurement analysis, $p = 0.006$, $p < 0.0005$, and $p = 0.001$ for 10°, 20°, and 40° field-sizes, respectively). This type of set-size effect is mainly due to the increase of RTCR with set-size. As explained in Section 4.1, a set-size sensitive RTCR is common in feature search under difficult or confusable conditions

4.3. Field-size effect

Because the number of serial inspections depends on the ratio of the size of the display and the usable field of view, the pseudo-parallel search explanation makes two predictions concerning display field-sizes: search time should be correlated with usable area of vision, and search time should increase with the increase in display field-size. Due to the lack of good visual field data, the first prediction could not be verified. For the second prediction, a display field-size related slowing of visual search was found in our NV subjects, which confirmed the finding of Burton-Danner et al. (2001). However, the field-size effect for the VI subjects was much stronger than for age-matched normals. This was true for all set-sizes. The most significant differences between NV and VI groups occurred when field-size changed from 20° to 40° (see Fig. 4). The differential field-size effect may be explained by the fact that while normal subjects can largely rely on faster attention shift to perform feature search (Scialfa & Joffe, 1998), VI subjects have to rely on much slower eye movements even in feature search (Coeckelbergh et al., 2002).

5. Conclusions

Visually impaired subjects perform feature search at a much slower speed than age-matched normal controls. However, their feature search is parallel, indicated by the shallow slope of their RT × Set-size lines. VI persons show a much stronger field-size effect than NV subjects. A pseudo-parallel search across the display provides a reasonable explanation of the feature search performance observed in VI subjects.

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