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Neuropsychologia 44 (2006) 1962–1977

NEUROPSYCHOLOGIA

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Visual search deficits in Parkinson's disease are attenuated by bottom-up target salience and top-down information

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Accepted 2 October 2005
Available online 31 March 2006

Abstract

Patients with Parkinson's disease (PD), a degenerative disorder primarily affecting the nigrostriatal dopamine system, exhibit deficits in selecting task-relevant stimuli in the presence of irrelevant stimuli, such as in visual search tasks. However, results from previous studies suggest that these deficits may vary as a function of whether selection must rely primarily on the "bottom-up" salience of the target relative to background stimuli, or whether "top-down" information about the identity of the target is available to bias selection. In the present study, moderate-to-severe medicated PD patients and age-matched controls were tested on six visual search tasks that systematically varied the relationship between bottom-up target salience (feature search, noisy feature search, conjunction search) and top-down target knowledge (Target Known versus Target Unknown). Comparison of slope and intercepts of the RT × set size function provided information about the efficiency of search and non-search (e.g., decision, response) components, respectively. Patients exhibited higher intercepts than controls as bottom-up target salience decreased, however these deficits were disproportionately larger under Target Unknown compared to Target Known conditions. Slope differences between PD and controls were limited to the Target Unknown Conjunction condition, where patients exhibited a shallower slope in the target absent condition, indicating that they terminated search earlier. These results suggest that under conditions of high background noise, medicated PD patients were primarily impaired in decision and/or response processes downstream from the target search itself, and that the deficit was attenuated when top-down information was available to guide selection of the target signal.

Keywords: Attention; Dopamine; Striatum; Feature search; Conjunction search

1. Introduction

1.1. Overview

Parkinson's disease (PD) is characterized by progressive degeneration of dopamine (DA) neurons in the substantia nigra pars compacta (Hornykiewicz, 1979). This degeneration leads to DA depletion within the dorsal striatum, reducing the ability of this region to effectively process corticostriatal inputs and disrupting information flow through the corticostriatal basal ganglia loops (Alexander & Crutcher, 1990). As the disease progresses, DA depletion may extend to the cells of the ventral tegmental area, site of origin for the mesolimbocortical pathway (Agid, Ruberg, Dubois, & Pillon, 1987), which comprises the dopamine neurons in the ventral tegmental area (VTA) and their projections to the nucleus accumbens (NAc), amygdala, PFC, and other forebrain regions (Alexander, DeLong, & Strick, 1986).

Although PD is primarily characterized as a disorder of motor control, a growing number of studies have found that PD patients also demonstrate impairment in various cognitive abilities, particularly the control of attention and memory (for a review, see Nieoullon, 2002). Of particular relevance to the present study are recent findings implicating DA in set-switching (Gauntlett-Gilbert, Roberts, & Brown, 1999; Rogers et al., 1998), selective attention (Crofts et al., 2001; Maddox, Filoteo, Delis, & Salmon, 1996; Redgrave, Prescott, & Gurney, 1999; Sharpe, 1990) and

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doi:10.1016/j.neuropsychologia.2006.01.037

sensory gating (Horvitz, 2002a; O'Donnell, 2003). These findings are consistent with evidence that DA plays a key role in the selection of task-relevant striatal inputs by amplifying the activity of striatal cells receiving strong glutamate excitation while attenuating the impact of those receiving weaker inputs (Horvitz, 2002a; Kiyatkin & Rebec, 1996; O'Donnell, 2003; Redgrave et al., 1999). Thus, in information-processing terms, DA may boost signal-to-noise ratios (Horvitz, 2002b; Kiyatkin & Rebec, 1996) promoting the selection of salient target stimuli for processing by response systems (Redgrave et al., 1999).

Given that salience-based models also have been highly successful in explaining visual search performance (Niebur & Koch, 1998; Rosenholtz, 1999, 2001), the present study examines the relationship between PD, selective attention, and salience using a visual search paradigm that allows manipulation of both the bottom-up salience of the target stimulus relative to the distractor field and the participant's top-down knowledge of the target identity. Previous studies of visual search in PD have exclusively manipulated bottom-up factors such as the number and composition of distractors in the search array (Berry, Nicolson, Foster, Behrmann, & Sagar, 1999; Lieb et al., 1999; Troscianko & Calvert, 1993; Weinstein, Troscianko, & Calvert, 1997). However, knowing which target to expect may be critical in determining whether search deficits will be apparent in PD patients. This type of top-down information may allow patients to facilitate target processing at multiple stages (see Section 1.2), thus reducing interference from irrelevant bottom-up information. By systematically varying top-down and bottom-up factors, our study clarifies and extends previous findings by showing that search performance in PD patients is disproportionately affected when target salience is reduced both by a lack of salient features and the absence of top-down guidance for stimulus selection.

1.2. A model of visual search: the influence of bottom-up salience and top-down information

Visual search refers to a wide range of tasks in which observers must search for a target item (whose location is uncertain) in the presence of one or more distractor items. In this section, we outline a model of information processing in visual search based on Treisman's Feature Integration Theory (Treisman & Gelade, 1980; Treisman & Sato, 1990) and Wolfe's Guided Search Theory (Wolfe, 1994, 1996; Wolfe, Cave, & Franzel, 1989). We introduce the model not as a computational simulation of search deficits in PD, but as a framework for understanding the different ways in which bottom-up stimulus salience and top-down information influence visual search behavior. Different ideas about the effects of PD on information processing lead to different sets of predictions (see Section 1.5).

In this model (see Fig. 1), a visual stimulus, such as a search array, is analyzed by the massively parallel front-end of the visual system (Fig. 1a) into a hierarchical set of feature maps (Fig. 1b), which encode a set of properties ranging from color to 3D shape (Hochstein & Ahissar, 2002). Although these properties are distributed across multiple, independent processing streams in early vision, behavior is directed to unitary objects. Thus, focal attention (Fig. 1d) is required to unify information

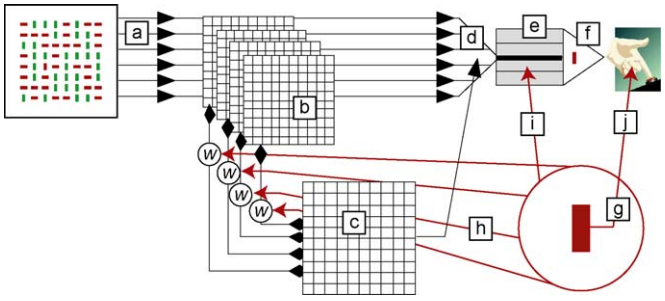

Fig. 1. Model of information flow in visual search. This example illustrates a conjunction search in which the subject is instructed (top-down information) to search for a red (dark bar) vertical target in a field of red horizontal and green (light bar) vertical distractors. The front-end early visual system (a) analyzes visual input into a hierarchy of feature maps (b). Information from the feature maps is abstracted into a salience map, (c) which directs the focus of attention (d). Attended items enter visual short-term working memory (VSTM, e) for further analysis. Items in VSTM compete for access to decision and response processes (f) that control behavior. Top-down information (g) influences processing in three ways: by weighting the input from feature maps to the salience map (h); by biasing competition in VSTM (i); by adjusting decision thresholds (j). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

from various feature maps into a single representation in visual short term memory (VSTM, Fig. 1e; (Treisman, 1996; Treisman & Gelade, 1980; Wheeler & Treisman, 2002)), where object representations are stored and consolidated (Chun & Potter, 1995; Vogel & Luck, 2002; Vogel, Woodman, & Luck, 2001). Items in VSTM then compete for access to decision and response mechanisms (Fig. 1f).

Only a single object (or perceptual grouping) can be attended at one time, keeping information from different objects segregated. In visual search tasks, attention serves as a bottleneck, restricting processing rate. Attentional deployments are controlled by a salience map (Fig. 1c; Itti & Koch, 2001; Koch & Ullman, 1985; Li, 2002), which is a representation of "interesting" locations in the visual field. In this context, "interesting" means "likely to contain a target". Functionally, the salience map serves to restrict attention to the most likely target items, reducing the effective set size.

The salience map is derived from two separate sources of information, bottom-up and top-down. Bottom-up information consists of differences between neighboring items (Julesz, 1986), along a limited set of dimensions (for a recent review see Wolfe & Horowitz, 2004). The second source of salience is top-down information (Fig. 1g), which here we will take to mean "knowing what you are looking for" (Duncan & Humphreys, 1992; Treisman & Sato, 1990; Wolfe, 1994). For example, participants will be relatively slow to find a red vertical target among green horizontal distractors in a block of trials where targets could be *unpredictably* red, blue, orange, or purple, compared to when they are *informed in advance* that the target on the upcoming trial will be red vertical (Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). The effect of top-down information is to increase the weight on information coming from objects having desired features (Fig. 1h). Of course, the effects of knowing what to look for are not restricted to weighting the salience map. Advance knowledge of the target may serve to bias competition

in VSTM (Fig. 1i; Desimone, 1998; Kastner & Ungerleider, 2001), or at decision/response stages (Fig. 1j; Cohen & Shoup, 1997).

In the present study, total number of items in the display (set size) was varied from trial to trial, allowing us to derive the function relating reaction time (RT) to set size. This RT × set size function partitions RT into slope and intercept. The slope measures the cost for adding additional items to the display, while the intercept is the theoretical RT that would be observed if there were no search stage, but all other stages had to be completed. Slope is often interpreted as "search efficiency", with steeper slopes indicating slower, less efficient search. In the model, two factors influence slope: the quality of information on the salience map (how well can it distinguish the target from the distractors), and the rate of attentional shifting (how long does it take to change the locus of selection). In contrast, factors that influence early visual processes, VSTM competition, or decision and response processes will contribute to the intercept. From a neuropsychological point of view, then, we can expect that damage to salience mechanisms or to the ability to shift attention will increase the slope (thus slowing search), while damage to other stages of processing will show up in increased intercepts.

1.3. Dopamine and salience

From our cognitive model for the relationship between salience and attention in visual search, we now turn to a pharmacological model of DA's role in detection and response to salient environmental stimuli. Studies in animal models have shown that midbrain DA neurons show phasic activation in response to salient environmental change (Horvitz, 2000). For example, single-unit recordings show that salient auditory and visual stimuli of high intensity and rapid onset produce excitation of DA neurons in both the ventral tegmental area (Horvitz, Stewart, & Jacobs, 1997) and substantia nigra (Strecker & Jacobs, 1985). These midbrain DA neurons are also activated by less intense stimuli with primary or conditioned reward properties (Schultz, 1998) and by novel stimuli (Horvitz, 2000; Ljungberg, Apicella, & Schultz, 1992; Schultz, 1998). Similarly, Zink, Pagnoni, Martin, Dhamala, and Berns (2003) found that novel events (i.e., infrequently presented visual distractors), produce increased activation in the nucleus accumbens, a forebrain region which receives particularly dense VTA DA innervation.

Functionally, the strong DA response to salient events may modulate activity at striatal neurons receiving strong glutamate input from regions involved in stimulus and/or response processing. Rather than producing a general excitation or inhibition, DA appears to amplify the activity of striatal neurons receiving strong cortical glutamate input, and filter out activity at weakly activated synapses (Cepeda & Levine, 1998; Kiyatkin & Rebec, 1996; O'Donnell, Greene, Pabello, Lewis, & Grace, 1999). Thus, a disruption in striatal DA activity may interfere with corticostriatal information processing either by disrupting the transmission of strong input signals, or by permitting the transmission of weak signals that would not normally be permitted to compete for basal ganglia processing beyond the level of the striatum. Consistent with this notion, DA depletion within the dorsal striatum reduces the responsiveness of striatal neurons to auditory, visual, and tactile stimuli (Aosaki, Graybiel, & Kimura, 1994; Rothblat & Schneider, 1993; Schneider, 1991).

Extending these findings to the context of visual search, DA depletion in the dorsal striatum may result in a poorer signal-to-noise ratio, making it more difficult to filter out task-irrelevant responses and/or stimuli. This reduction could result either from a decrease in the strength of inputs from the "target" signal and/or an increase in the strength of the "noise" from weak distractors. As such, patients with Parkinson's disease may have particular difficulty detecting targets in conjunction displays, where bottom-up salience of the target is low. On the other hand, detection of targets with sufficiently high bottom-up salience, such as in "pop-out" displays may be less impaired. Indeed, even when DA in the nigrostriatal system is compromised, it appears that the organism can still select and respond to highly salient and novel information in the environment (Glickstein & Stein, 1991; Horvitz, 2000, 2002b). In accordance with this notion, PD patients have been observed to show surprisingly intact ability to locomote in response to a loud fire alarm or salient lines drawn on the ground (Jahanshahi & Frith, 1998).

As previously mentioned, however, salience in visual search is derived not only from bottom-up properties of the stimulus array, but also from top-down information that can serve to bias a particular feature or response. Several studies have demonstrated that PD patients' motor performance on tasks such as reach-to-grasp movement (Schettino et al., 2004), sequential button pressing (Georgiou et al., 1994), and finger-tapping (Frischer, 1989) can significantly improve when provided with external cues that specify a particular response. These data provide some indirect support for the view that PD patients might benefit disproportionately from top-down information about the identity of the target. For PD patients, top-down information may be an effective means of increasing target salience, even to the point of helping them compensate for what may be greater impairments in detecting stimuli with low bottom-up salience.

1.4. Visual search and Parkinson's disease

In one of the first investigations of search performance in PD, Troscianko and colleagues (Troscianko & Calvert, 1993) found that medicated PD patients exhibited an unusual non-zero slope on an easy feature search for a vertical bar among horizontal bars, but showed no difference from controls in the slope of a conjunction search task (Weinstein et al., 1997). They concluded that mechanisms to detect salience were so impaired as to render "bottom-up" salience information useless, leaving the patient to resort to a serial search. However, based on the model put forth in Section 1.2, damage to fundamental salience mechanisms would be expected to increase the slope of *both* feature and conjunction search functions.

Furthermore, these findings were not replicated by Berry et al. (1999), who found no impairment in the slope of the search function of medicated PD patients on *either* feature or conjunction search. The only difference between PD patients and controls was an increased intercept for a subgroup of PD patients identi-

fied as "frontally impaired" based on their poor Wisconsin Card Sort Test (WCST) performance. Intercepts for this subgroup were increased on both feature and conjunction search relative to controls and non-frontally impaired PD patients. Although the authors interpreted this finding as evidence of non-specific impairment associated with frontal lobe dysfunction, increased intercepts in the absence of slope effects could stem from bottleneck effects at the decision/response stage, which is past the point at which the effects of set size would exert an influence. Cormack, Gray, Ballard, and Tovée (2004), also failed to replicate the feature search deficit.

In contrast, Lieb et al. (1999), who tested search behavior in PD patients with an adaptive staircase procedure, found results suggestive of a deficit in early vision. They tested four different search tasks. Only one task yielded a reliable impairment in medicated PD patients[1]. The critical task was search for a patch of oriented line segments against a background of spatially filtered, vertically oriented noise, in which the angle of the oriented line segments was adjusted by the staircase to find the 62.5% threshold. The patients required a larger orientation difference in order to reach threshold performance, which Lieb et al. took as evidence that PD impaired preattentive orientation processes.

Yet, examining Lieb et al.'s data with the importance of bottom-up salience and top-down information in mind reveals that the orientation texture condition differs in two critical ways from the other feature search tasks tested. First, due to the Gaussian noise of the background, the salience of the texture patch was relatively low. Second, participants did not know from trial-to-trial exactly what the target stimulus would look like, because the orientation of the target patch was controlled by the staircase method. Thus, instead of (or in addition to) demonstrating a weakness in preattentive orientation processing, these data might indicate that PD patients are at a disadvantage when targets are both unpredictable from trial-to-trial and of low salience.

The sensitivity of PD patients to unpredictable trial structure has also been demonstrated in studies of set-shifting. For example, Lubow, Kaplan, and Dressler (1999) showed that, while patients and controls performed similarly on a consistent-mapping search task for novel shapes (Musen & Treisman, 1990), patients were disproportionately slowed in a varied-mapping version of the task, relative to controls. A similar finding was obtained by Hsieh, Hwang, Tsai, and Tsai (1996) using a modified odd-man out task, a type of search task. In addition, Downes et al. (1989) found that while both medicated and unmedicated PD patients were impaired on visual discrimination learning when an extra-dimensional shift was required, they were more or less unimpaired on varied-mapping visual search.

[1] Patients in the study by Lieb et al. (1999) were tested twice on each task. Deficits in detecting targets in filtered noise were present at both first and second test (unlike deficits in texton detection, which were found only at first test). Although at the time of the first test, 6 of the 16 patients were de novo and had not yet begun their medication regimen, at the time of the second test, all patients were receiving L-Dopa and/or dopaminergic agonists.

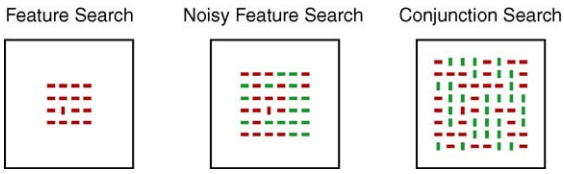

Fig. 2. Examples of stimuli from feature search (left panel), noisy feature search (middle panel), and conjunction search (right panel) displays. For illustration purposes, stimuli in the figure are depicted on a white background (actual stimuli were presented against a black computer screen) and color values have been adjusted so that red stimuli appear as darker bars and green stimuli appear as lighter bars. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

In summary, there is little agreement across previous visual search studies regarding the stage(s) of information processing impaired in PD patients. These studies have variously implicated upstream early vision (Lieb et al., 1999) and salience map (Troscianko & Calvert, 1993) processes, as well as downstream decision/responses processes (Berry et al., 1999). Yet, they converge with respect to two findings: (a) there is little evidence for a deficit in the speed of shifting attention between items (which would be evident as selectively increased slopes in an effortful/conjunction search), and (b) they are more likely to demonstrate impaired performance when there is uncertainty about the identity of the target and selection must be guided exclusively by "bottom-up" factors (Hsieh et al., 1996; Lieb et al., 1999; Lubow et al., 1999).

1.5. The present experiment

We compared medicated moderate-to-severe PD patients to matched controls on visual search tasks in which both bottom-up salience and top-down knowledge were manipulated to produce higher or lower levels of stimulus salience. We chose to test patients while "on" medication in order to allow for direct comparison with previous studies of visual search in PD. Although the use of medicated patients has implications for conclusions about the direct contribution of DA to any observed dysfunction, we note that medication often fails to fully restore DA function in moderate-to-severe patients (Antonini, Schwarz, Oertel, Pogarell, & Leenders, 1997; Torstenson, Hartvig, Langstrom, Westerberg, & Tedroff, 1997), and will return to this issue in the discussion. Bottom-up salience was varied across task by increasing distractor heterogeneity and target-distractor similarity (see Fig. 2). In the feature search task, distractors were homogenous (e.g., red horizontal bars), such that the target (e.g., red vertical bar) would easily pop-out from the background. In the noisy feature search task, there were two types of distractors, but the target differed on a basic feature dimension (e.g., red vertical target with red and green horizontal distractors). In the conjunction search task, there were two types of distractors, each sharing one feature with the target (e.g., a red vertical target with red horizontal and green vertical distractors). The availability of top-down information was manipulated by including both Target Known and Target Unknown target conditions. In Target Known conditions, participants were informed that the target

(red vertical or green horizontal) would be held constant for a block of 36 trials. In Target Unknown conditions, the target varied randomly from trial to trial, and participants had to find the odd item.

A replication of previous studies of feature search (Berry et al., 1999; Troscianko & Calvert, 1993; Weinstein et al., 1997) and conjunction search (Berry et al., 1999; Weinstein et al., 1997) is thus embedded in our design. However, the addition of the noisy feature search condition allows us an intermediate level of salience between standard feature search and conjunction search. Finally, the Target Known versus Target Unknown manipulation allows us to observe the effect of top-down information on both intercept and slope measures across these varying levels of salience.

We can anticipate five possible outcomes from this experiment, depending on where PD disrupts the flow of information processing. Outcomes are presented in order from low-level to high-level deficits.

1. There may be no PD-specific effect. Since all previous studies have obtained some effect of PD on search (for at least a subset of patients), we rate this outcome as unlikely.
2. The salience map (Fig. 1c) may be impaired in PD. In this case, we should see increases in search slope for all conditions. Again, non-zero slopes in the feature search condition would be strong evidence for this scenario. Additionally, effects on RT should be proportional to salience. This outcome would be compatible with the conclusions of Troscianko and his colleagues (Troscianko & Calvert, 1993; Weinstein et al., 1997).
3. Shifts of attention may be slowed (Fig. 1d). In this case, we would expect that feature searches would remain efficient (i.e., near zero slopes), but conjunction search should be noticeably slowed. Another way to describe this would be as a multiplier on the slope, relative to the elderly controls. This would be a surprising outcome, given previous studies.
4. PD patients may have a deficit in VSTM processing or at the decision and response stages (Fig. 1e and f). These effects would be present in the intercepts, rather than the slopes of the search functions. However, since these stages are after the computation of salience (Fig. 1b and c), we would expect their deficits to be proportional to salience.

It is of course possible that the effects of PD would manifest at more than one level, producing more complicated patterns in the data. However, the key features to look for are non-zero feature slopes, changes in conjunction slopes relative to elderly controls, and changes in intercept that are independent of, or proportional to, salience. The conflicting results of the existing literature make it difficult to predict an exact pattern, however they suggest that there may be an interaction with the presence of top-down information: when participants do not know which target to expect, patients should be more severely impaired relative to elderly controls than when the target is known.

2. Method

2.1. Participants

Ten patients with Parkinson's disease and 10 age- and education-matched elderly controls participated in the experiment. All patients had received a diagnosis of idiopathic PD from neurologist and author L.C. (i.e., at least two of the following signs with progressive onset: akinesia, resting tremor, rigidity, or postural instability, and the absence of any other condition that may produce signs of Parkinsonism, including Progressive Supranuclear Palsy [PSP]). Patients had no known history of other significant medical disease such as diabetes, thyroid disease or major psychiatric disorder, substance abuse or additional neurological events (e.g., head injury, stroke, tumor). PD patients were in the moderate-to-severe range of the disease, as confirmed by the Hoehn & Yahr (range 2–4, $M = 3.1$, S.D. = 0.16) and the total score on the UPDRS (Unified Parkinson's Disease Rating Scale) taken while patients were "on" medication (range = 10–60; $M = 35.9$, S.D. = 4.94). Mean duration of illness at the time of testing was 8.0 years (range: 2–13 years).

All patients were also tested in the visual search tasks while "on" medication, 1–2 h after daily dose, which means that they were tested at approximately their peak medication level. This ensured that the level of motor impairment experienced during the task was representative of the level indicated by the UPDRS, which was conducted at a similar medication level during their most recent office visit to physician L.C. Nine patients were taking L-Dopa medication (Sinemet). The one patient who was not taking Sinemet was taking Selegiline and the anticholinergic medication Norflex. Removal of this patient did not change the pattern of the data. Seven other patients were also taking Selegiline, and six were additionally taking a DA agonist (Permax [$n = 2$], Requip [$n = 1$], Mirapax [$n = 4$]). One other patient was taking Norflex.

Patients and elderly controls were screened for dementia using a modified version of the Mini-Mental State Examination (mMMSE cut-off = 50/57, Folstein, Folstein, & McHugh, 1975; Stern, Sano, Paulson, & Mayeux, 1982), and for depression using the Beck Depression Inventory-II (BDI-II cut-off = 17, Beck, Steer, & Brown, 1996). There were no significant differences between the elderly controls and patients on the mMMSE ($t[9] < 1$). Although a significant difference on the BDI-II was found between the patients and elderly controls ($t[9] = 5.63$, $p < .0005$), the average scores of both groups were well within the normal range (see Table 1). All participants also demonstrated normal visual acuity and contrast sensitivity as tested by a computerized version of the Freiburg Visual Acuity Test (Bach, 1996).

All participants gave informed consent before participating in the experimental session in accordance with Columbia University Medical Center and Morningside Institutional Review Board regulations.

2.2. Apparatus and stimuli

The experiment was run on an Apple Powerbook G3 laptop computer with a 21.6 cm × 28.6 cm LCD screen. Screen resolution was set to 1024 × 768 pixels, color depth to 24 bits. The refresh rate was 60 Hz. Stimulus presentation and response collection were controlled by Matlab 5.2.1 software (MathWorks) using routines from the Psychophysics Toolbox (Brainard, 1997). Participants responded using a PsyScope three-button box.

Stimuli were presented on a black background. The fixation cross was a plus sign drawn in 48-point Arial font and measuring roughly 1.12° × 1.12°. Search stimuli consisted of red and green bars, which could be either vertical

Table 1
Participant demographics

	PD patients		Elderly controls	
	Mean	S.D.	Mean	S.D.
Age (years)	67.9	10.0	66.3	8.5
Education (years)	17.6	2.3	16.8	2.9
BDI-II	7.6	2.6	2.3	2.5
mMMSE	54.3	2.8	54.7	2.0

(.42° visual angle [°] × 1.12°) or horizontal (1.12° × .42°). Display density was controlled by presenting search arrays on 4 × 4, 6 × 6, and 8 × 8 grids for set sizes of 16, 36, and 64 items, respectively. Inter-item center-to-center distance was 1.68°. The 4 × 4 grid thus subtended 6.73° × 6.73°, the 6 × 6 grid subtended 10.09° × 10.09°, and the 8 × 8 grid subtended 13.45° × 13.45°. The 8 × 8 grid defined the possible stimulus area. Smaller grids were displaced randomly within the larger grid. Thus, targets could appear at any location within the display area, independent of set size. This allowed us to hold the range of target eccentricity from initial fixation constant across set size.

2.3. Protocol

Participants were tested individually. The majority of patients were tested in their homes, as it was often difficult for them to travel to the laboratory. Elderly controls were tested either in their homes or in the laboratory, depending on which was more convenient. After consent, but prior to testing on the visual search task, participants were given the mMMSE, BDI, and asked some questions about their mental and physical health.

Target Known and Target Unknown conditions were tested in a counterbalanced order. Six of the elderly controls and two of the patients performed both conditions on the same day. The remaining participants performed these tasks in separate test sessions, conducted at least 10 days apart for the elderly controls and patients. When testing was done in separate sessions it was to minimize fatigue reported by the participant. In addition, for patients, separate sessions ensured that the start time of the tasks was controlled with regard to time since last dose of medication.

2.4. Design and procedure

Examples of the displays used in the feature, noisy feature and conjunction search tasks are shown in Fig. 2.

There were four stimuli: red horizontal bars, red vertical bars, green horizontal bars, and green vertical bars. Each stimulus could potentially serve as target or distractor. In order to reduce the number of possible combinations, each participant was assigned two stimuli as targets; all stimuli served as distractors at one point or another for all participants. Targets were randomly assigned such that half of the participants in each group searched for red vertical and green horizontal bars, while the other half searched for red horizontal and green vertical bars.

The experiment consisted of two sessions, the Target Known session and the Target Unknown session. Each session consisted of 12 blocks of 36 trials preceded by 6 practice trials, for a total of 1008 correct trials in the experiment. Each session was in turn divided into two sets of six blocks each. In the Target Known condition, the red bar (vertical or horizontal, depending on which targets had been assigned to that participant) was the target for the first set of six blocks, and the green bar (horizontal or vertical) for the second set. In the Target Unknown condition, targets were picked randomly from trial to trial in both sets. Within each set, there were two blocks of each search type (feature, noisy feature, and conjunction). There were six possible orders of the three search types, counterbalanced across participants in each group[2]. The order in the second set within each session was always the reverse of the order in the first set. For example, if a participant experienced two blocks of feature search, followed by noisy feature search, followed by conjunction search in the first set, in the second set she would start with conjunction search, then noisy feature search, and finish with feature search.

Within a block, there were six trials at each level of set size and target presence, randomly intermixed. Since there were two blocks of each search type per set, collapsing across sets there were 24 trials per cell.

In feature search, all distractors were identical. For example, if the target was a red vertical bar, distractors might be all green vertical bars (color search) or all red horizontal bars (orientation search). In noisy feature search, there were two types of distractors, but the target was distinct from both distractors along a single dimension. Thus, distractors for a red vertical target might be green vertical and green horizontal bars, or red horizontal and green horizontal bars. In the conjunction search condition, there were two types of distractors, each sharing a different feature with the target. Again with a red vertical target, distractors would be red horizontal and green vertical. Note that the same distractors would be used for a conjunction search with a green horizontal target.

In the Target Known sessions, each block began with the target for that block (e.g., a red vertical bar or a green horizontal bar) presented in the center of the screen along with the text "This will be your target". Participants then advanced to practice trials by pressing the middle button on the button box. When a block of trials was complete and the target changed, a new example was shown.

In the Target Unknown sessions, participants were told that on some trials there would a single bar in the display that was different from all the rest of the bars and that this was the "oddball" target. Their task was to determine, as quickly and accurately as possible, whether an "oddball" was present or not.

In the Target Known sessions, the first block within each set of feature search and noisy feature search trials was an orientation search, and the second block was a color search. In the Target Unknown sessions, however, targets varied randomly from trial to trial, so any trial in a feature or noisy feature block could be color or orientation search with equal likelihood. In these sessions, distractors did not provide any information about the target. That is, within an "unknown" feature search block, green horizontal distractors could mean a search for a green vertical target or a search for a red horizontal target with equal likelihood. Targets and distractors in the two blocks of conjunction search were identical under both Target Known and Target Unknown sessions.

Each trial began with a screen instructing the participant to hold down the yellow middle button on the button box. Controls were asked to use the index finger of their dominant hand. Patients used the index finger on the side that was first or most impaired. Once this button was pressed, the fixation cross was presented at the center of the screen for 833 ms, followed immediately by the search array. At this point, the computer checked to make sure that the participant was still holding down the center key. If not, the trial was aborted.

Participants responded by moving their index finger to the green button on the right of the button box to indicate that they saw a target, or the red button on the left to indicate that they did not see a target. As soon as the response button was pressed, the search array was replaced with a feedback display, indicating trial number, RT in ms, and whether or not the response was correct. If there was no response within 10 s, the trial was declared a time out. Participants were informed if the trial was aborted or if they did not respond before the time out limit.

Any errors, time outs, or aborted trials were recycled, so that the same number of correct responses was obtained for each condition, regardless of the error rate in that cell. Participants were informed that if they made an error, that trial would be repeated. We added this feature in anticipation of the possibility that there might be differences in the errors, time outs or aborted trials across the three groups, either overall or as a function of condition. Given that RT was our primary measure, this recycling reduced the possibility that group differences in RT would be influenced by greater variability stemming from fewer trials in groups with higher error rates. Thus, there were always 24 correct trials per cell for all groups. We also recorded error rates.

2.5. Data analysis

RT is typically measured from stimulus onset to the depression of the response button. We partitioned the total RT into response initiation time (RT_i) and movement time (MT), where RT_i was the time from stimulus onset to the release of the start button, and MT the remainder. We used RT_i as our primary dependent measure, rather than RT_{total}, on the assumption that RT_i is a more direct measure of cognitive processing time, eliminating variability associated with motor implementation. There is also some suggestion in the literature that movement times in this population do not accurately reflect processing times (Downes et al., 1989). However, we did analyze RT_{total}, and the statistical conclusions were identical.

All analysis of variance (ANOVA) results were subjected to Mauchly's Test of Sphericity. The Huynh-Feldt correction was applied when violations of sphericity were observed. In these cases, the corrected degrees of freedom are reported. Where appropriate, we also report partial eta-squared ($\hat{\eta}^2$) as a measure of effect size.

[2] Two PD patients initially included in the counterbalancing scheme were later found not to meet our inclusion criteria.

Both slope and intercept of the RT × set size functions were computed based on the medians of correct responses after responses faster than 250 ms had been eliminated as anticipations. Planned comparisons tested slopes against zero using one-tailed *t*-tests.

Error data were converted to the signal detection measures d' and c, representing sensitivity and criterion, respectively. High d' values indicate a better ability to discriminate between the presence of the target and its absence. Positive c values denote a more conservative criterion (more likely to say the target is absent), negative scores a more liberal criterion (more likely to say the target is present) (Macmillan & Creelman, 2004). Sensitivity and criterion are theoretically independent quantities.

3. Results

3.1. Overview

Fig. 3 illustrates the mean of the median RT data for both groups as a function of search task (feature, noisy feature, and conjunction), Target Known versus Unknown, target presence versus absence, and set size (16, 36, and 64). From these data we extracted slopes of the RT × set size functions, which are shown in Fig. 4, and intercepts, which are shown in Fig. 5. The first analysis (Section 3.1.1), compares our results directly with those of previous studies of search behavior in PD (Berry et al., 1999; Troscianko & Calvert, 1993; Weinstein et al., 1997); this analysis involves only the Target Known data for feature and conjunction search (top left and bottom left panels of Figs. 3–5). Next, we analyze the effect of known versus unknown targets on the two groups across all three search types, looking first at slope (Section 3.1.2) and then at intercept (Section 3.1.3). Next, since PD patients are known to have troubles with set-shifting, we tested whether they would be more impaired than controls in

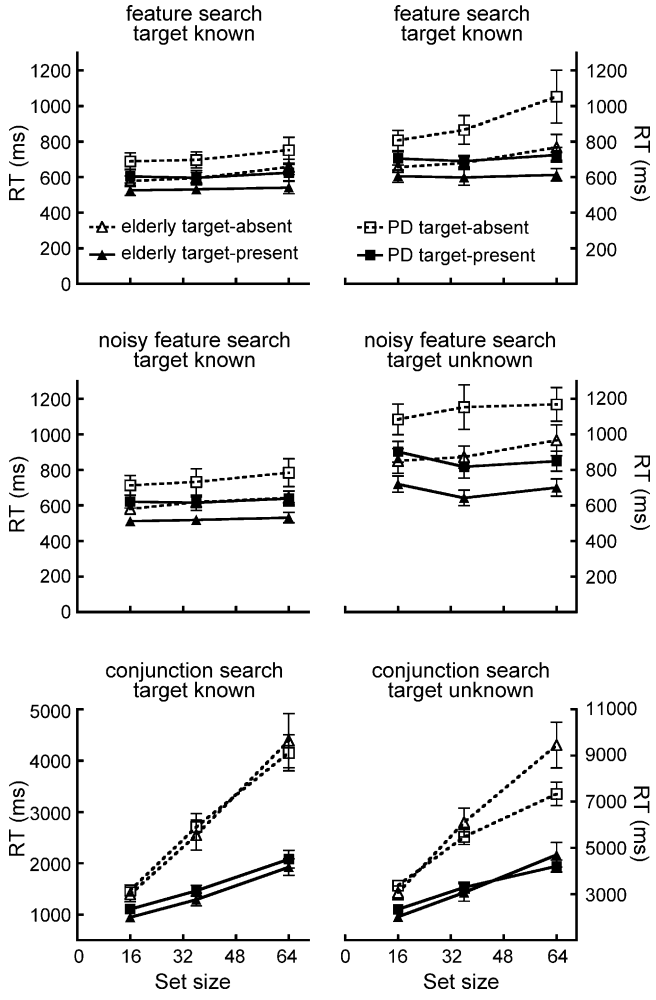

Fig. 3. Median RT by set size. Data from elderly control participants are plotted as triangles (▲), data from PD patients as squares (■). Open symbols denote target-absent conditions, filled symbols target-present. Left-hand panels plot data from the Target Known conditions, while right-hand panels plot data from the Target Unknown conditions. Top panels show data from the feature search condition, middle panels show data from the noisy feature search condition, and bottom panels show data from the conjunction search condition. Note that the vertical scale is different for the conjunction data. Error bars in this and all subsequent figures denote the standard error of the mean.

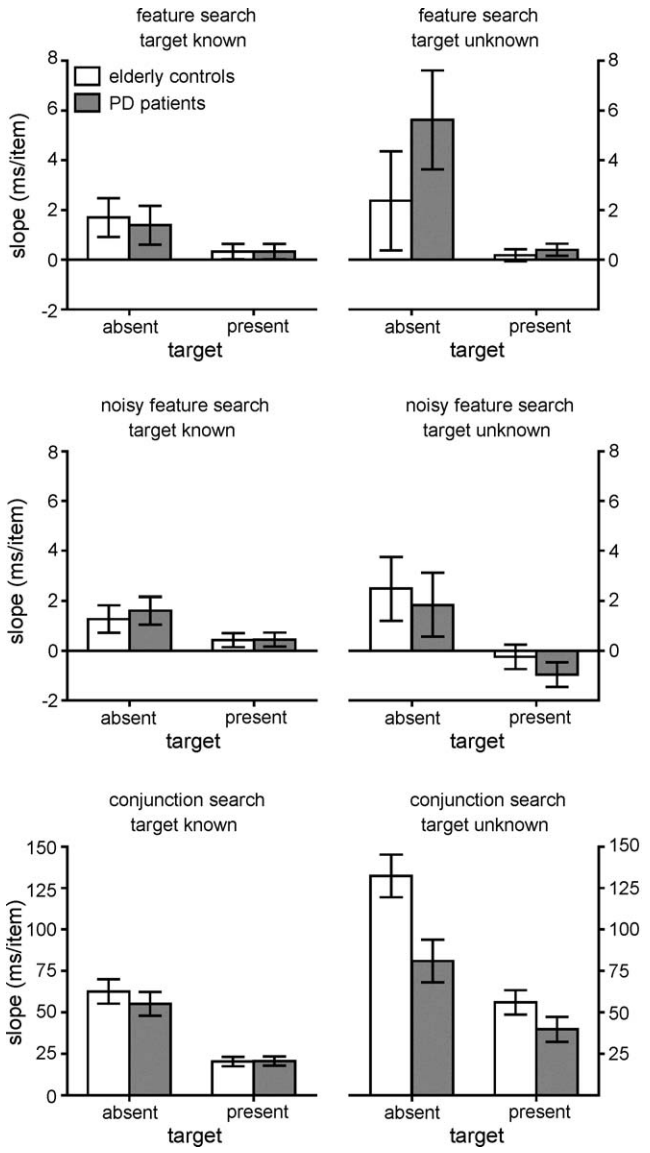

Fig. 4. Slopes of the median RT × set size functions. Open bars denote elderly control data, and dark gray bars denote PD patient data. Left-hand panels plot data from the Target Known conditions, while right-hand panels plot data from the Target Unknown conditions. Top panels show data from the feature search condition, middle panels show data from the noisy feature search condition, and bottom panels show data from the conjunction search condition. Note that the vertical scale is different for the conjunction data.

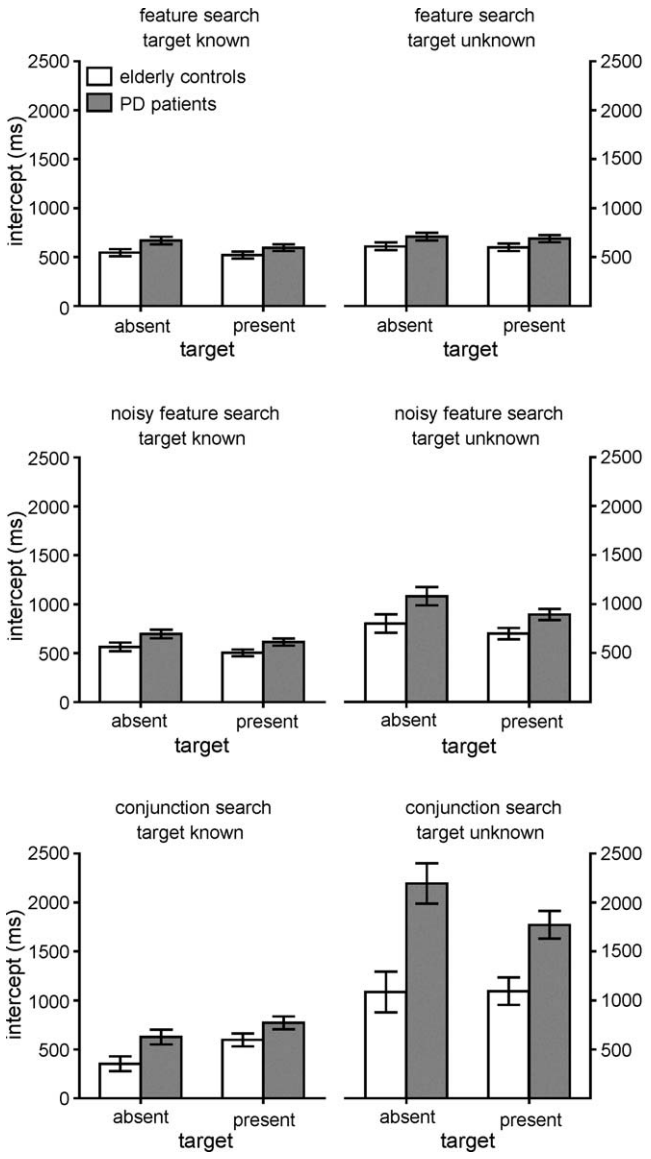

Fig. 5. Intercepts of the median RT × set size functions. Open bars denote elderly control data, and dark gray bars denote PD patient data. Left-hand panels plot data from the Target Known conditions, while right-hand panels plot data from the Target Unknown conditions. Top panels show data from the feature search condition, middle panels show data from the noisy feature search condition, and bottom panels show data from the conjunction search condition.

the Target Unknown conditions when the target changed from trial to trial (Section 3.1.4).

Throughout these analyses, we found many within-subject effects of search type and condition that were expected and easily predictable from the literature (e.g. Wolfe, 1998a). Specifically, target-absent trials produced steeper slopes and higher intercepts than target-present trials, and conjunction search produced steeper slopes and higher intercepts than feature search trials. When the target was known, search was more efficient and responses were faster than when it was unknown. Therefore, in the interest of simplifying presentation of our results and given the specific emphasis of the current report on the effects of PD on search behavior, we report below only the effects that involved the group variable.

3.1.1. Comparison to previous studies of search in PD (Target Known)

The first question is whether our PD patients demonstrated a pattern of results that replicate the impaired feature search performance found by Troscianko and colleagues (Troscianko & Calvert, 1993; Weinstein et al., 1997) or the intact feature search observed by Berry et al. (1999). The known target conditions of feature search and conjunction search correspond to the experiments conducted by these two groups.

For feature search, slopes for both groups were flat. Target-present slopes did not differ from 0.0 for either the PD patients ($t[9] < 1$) or the elderly controls ($t[9] = 1.1$, $p > .10$). Target-absent feature slopes were greater than 0.0 for the elderly controls ($t[9] = 3.3$, $p < .01$) and marginally greater for the PD patients ($t[9] = 2.1$, $p = .06$). Nonetheless, both slopes were still quite shallow (1.7 ms/item and 5.6 ms/item, respectively). As expected, conjunction search slopes for both groups all differed from 0.0 (all $p < .00001$).

When slope data were entered into a three-way mixed ANOVA with Group (elderly controls versus PD patients), search type (feature versus conjunction) and target present versus absent as factors, there was no main effect of Group, nor did Group interact with any other factor (all $F[1,18] < 1$, $p < .05$).

3.1.2. Target Known versus Unknown: slopes

Overall, slopes were marginally greater for the patients than for controls ($F[1,18] = 6.9$, $p = .06$, $\hat{\eta}^2 = .18$). Looking at Fig. 4, it is clear that patients and controls were producing very similar slopes in the feature and noisy feature conditions, but something quite different was going on for the conjunction condition. This impression is supported by a four-way interaction (Group × Target Known versus Unknown × Search Type × Target-present versus Target–absent: $F[1.2,22.1] = 8.0$, $p < .01$, $\hat{\eta}^2 = .31$), and by separate ANOVAs on each search type.

In the feature and noisy feature search conditions, there were no slope differences between patients and elderly controls (all $F[1,18] < 1$). Nor did Group interact significantly with any other variable (all $p > .10$, $\hat{\eta}^2 < .15$).

In conjunction search, however, PD patients produced marginally shallower slopes overall than elderly controls ($F[1,18] = 4.4$, $p = .05$, $\hat{\eta}^2 = .20$), and Group interacted with both Known versus Unknown ($F[1,18] = 7.1$, $p < .05$, $\hat{\eta}^2 = .28$), and present versus absent ($F[1,18] = 5.2$, $p < .05$, $\hat{\eta}^2 = .22$). However, these effects were subsumed under a significant three-way interaction ($F[1,18] = 7.1$, $p < .05$, $\hat{\eta}^2 = .28$). In the Target Known case, slopes were nearly identical for the two groups, but when the target was unknown, the elderly controls produced steeper slopes than the patients, particularly on target-absent trials. This unexpected result will be discussed further in Section 4.4.

3.1.3. Target Known versus Unknown: intercepts

Intercepts are shown in Fig. 5. Intercepts were higher overall for patients than for elderly controls ($F[1,18] = 20.7$, $p < 0005$, $\hat{\eta}^2 = .54$). This was true for both the Known ($F[1,18] = 7.6$, $p < .05$, $\hat{\eta}^2 = .30$) and Unknown ($F[1,18] = 22.5$, $p < .0005$,

$\hat{\eta}^2 = .56$) conditions, consistent with the expectation that more advanced PD patients will show motor slowing even when medicated. More interestingly, however, the data in Fig. 5 illustrate that the difference between Known and Unknown conditions increased from feature to noisy feature to conjunction search, and that this effect was more dramatic for patients than for controls. This impression is supported by a Group × Known versus Unknown × Search type interaction ($F[1.3,23.4] = 7.3$, $p < .01$, $\hat{\eta}^2 = .29$), and further confirmed by separate analyses of the Group × Known versus Unknown interaction for the three search types.

The difference between known and unknown targets did not vary between groups for feature search ($F[1,18] = 0.0$, $\hat{\eta}^2 = 0.00$). Although for noisy feature search, the cost for unknown targets was somewhat greater for the patients, the effect was not significant ($F[1,18] = 2.5$, $p = 0.13$, $\hat{\eta}^2 = .12$). There was a significant interaction for conjunction search ($F[1,18] = 10.1$, $p < .01$, $\hat{\eta}^2 = .36$), indicating that not knowing the target caused a substantial increase in these intercepts for the patient group, relative to the elderly controls.

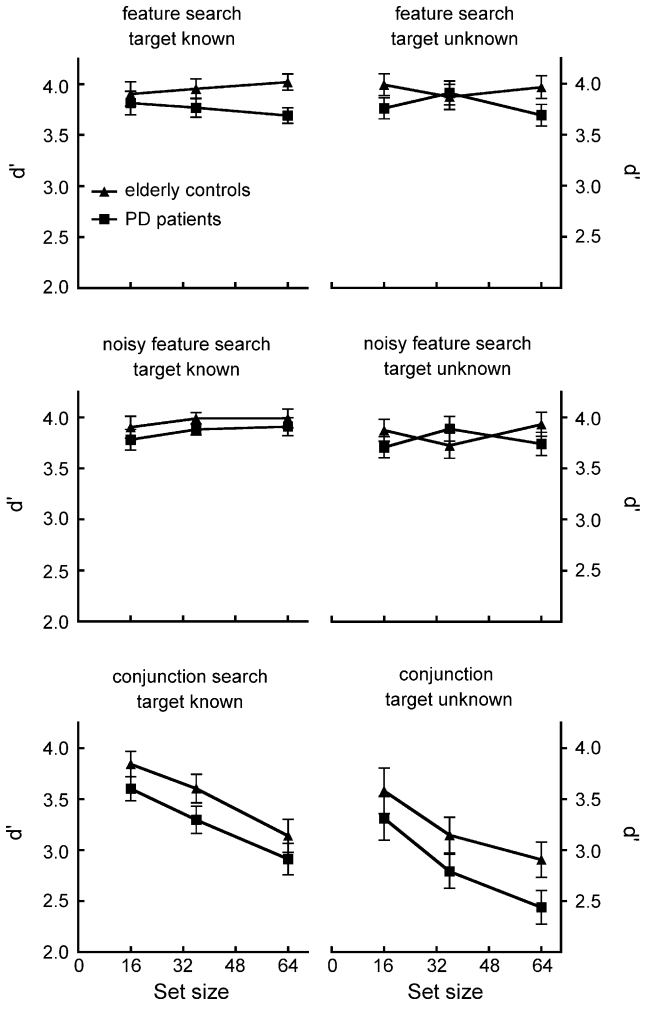

Fig. 6. Sensitivity. d' ("d prime"), a signal detection theory measure of sensitivity computed from the error data, is plotted against set size. Greater d' values indicate higher sensitivity to target presence/absence. Data from elderly control participants are plotted as triangles (▲), data from PD patients as squares (■). Left-hand panels plot data from the Target Known conditions, while right-hand panels plot data from the Target Unknown conditions. Top panels show data from the feature search condition, middle panels show data from the noisy feature search condition, and bottom panels show data from the conjunction search condition.

3.1.4. Target Unknown: repeated target analysis

Given the possibility that the increased switching demands in the Target Unknown condition might have contributed to the observed intercept increases in our medicated PD patients, we sorted target-present trials on the basis of whether the target on the previous target-present trial had been the same or different, then submitted median repeated and unrepeated RTs for each search type to a three-way mixed ANOVA. Although we did observe a sizeable advantage for repeated trials ($F[1,18] = 13.6$, $p < .005$, $\hat{\eta}^2 = .43$), Group did not enter into any interactions (all $p > .10$, all $\hat{\eta}^2 < .05$). Thus, these data do not point to switching deficits in our PD patients.

3.2. Error data

d' Scores (see Fig. 6) were analyzed using a four-way ANOVA with Group, Target Known versus Target Unknown, search type, and set size as factors. PD patients showed marginally worse discriminability overall than elderly controls ($d' = 3.5$ versus 3.7, respectively; $F[1,18] = 4.3$, $p = .05$, $\hat{\eta}^2 = .20$). However, Group did not interact with any of the within-subject factors (all $p > .10$, $\hat{\eta}^2 < .15$). In the criterion analysis, participants were just slightly conservative (more likely to say that the target was absent than present, $c = .07$). Criterion did not differ by subject group, nor did Group interact with any within-subject variables (all $F < 1$, $\hat{\eta}^2 < .10$).

4. Discussion

4.1. Overview

When target identity was made explicit and consistent from trial to trial (Target Known), medicated PD patients and age-matched controls performed similarly on all three visual search tasks (i.e., feature, noisy feature, conjunction). However, important differences between patients and controls emerged in the Target Unknown conditions. While both groups paid some cost (in intercept terms) for not knowing the target in advance, this cost was significantly elevated for patients compared to elderly controls. These differences were exacerbated by increasing levels of bottom-up noise.

In terms of the hypotheses presented in Section 1.5, we can decisively rule out the first hypothesis—that PD and aged-matched controls show identical performance across conditions. Flat search functions in the feature and noisy feature conditions are also sufficient to eliminate the strong form of the second hypothesis (damage to the salience map). Finally, given that there was no increase in the conjunction search slope, we can also eliminate the third hypothesis (impaired attentional shifting).

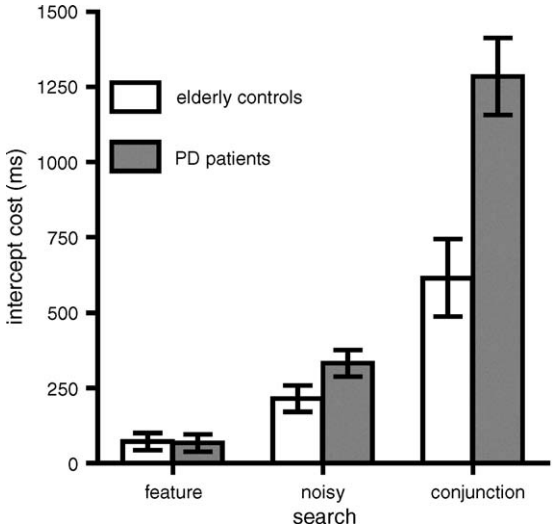

Fig. 7. Cost of unknown targets. Unknown target intercept–known target intercept plotted as a function of group and search task. Open bars denote elderly control data, and dark gray bars denote PD patient data.

We are left with the fourth hypothesis. There were significant changes in intercept, and these varied systematically according to stimulus salience, strongly suggesting that the locus of the effect was after salience computation. We conclude that search behavior of these medicated moderate-to-severe PD patients is influenced by a deficit at either the VSTM or decision and response processing stages, although further experimentation will be necessary to more precisely identify the source of the deficit. In any case, it is clear that without target foreknowledge, patients were at a severe disadvantage, particularly as bottom-up information decreased in salience. Moreover, these results indicate that PD patients greatly benefit from the ability to constrain and facilitate decision/response selection using top-down information, consistent with the view that external cues or other information that serves to limit decision or response options can serve to compensate for performance deficits in this group.

4.2. The cost of unknown targets

Our findings in the slope domain were primarily negative, however a robust and systematic pattern of effects emerged in the intercept analyses. First, intercepts increased as salience decreased. This was true for both groups (see Fig. 5). However, this pattern was greatly exaggerated in PD patients relative to elderly controls. Specifically, the intercept difference between conjunction and feature search for PD patients is three times what it is for the elderly controls. Second, this pattern was aggravated in the Target Unknown, compared to the Target Known case. We can measure this effect in terms of the cost of not knowing the target in advance (see Fig. 7). In the feature search condition, elderly controls are slower by about 72 ms in the Target Unknown condition, relative to the Target Known condition. For the PD patients, the cost is a nearly identical 67 ms. In the noisy feature condition, the elderly controls are slowed by 215 ms when the target is unknown, while their PD counterparts are slowed by 332 ms. In conjunction search, the cost is 616 ms for the elderly controls, compared to 1285 ms for the PD patients.

How do we interpret this effect? As noted in the introduction, intercept is typically held to index "non-search" aspects of the task. Here "search" is metonymy for the cognitive processes specific to the visual search task: computing salience and shifting attentional focus accordingly. We can think of information processing as flowing "downstream" from early vision to action, as in Fig. 1. Intercept effects can occur either upstream from search, in the massively parallel system we have abbreviated as "early vision", or downstream, after the attentional bottleneck.

There is some evidence in the literature suggesting that PD impairs processing upstream from search. For example, Lieb et al. (1999) observed an impairment of preattentive orientation processing in PD. If so, we should have seen steeper slopes in the feature search conditions due to impaired pop-out for orientation targets, which we did not observe. Previously (see Section 1.4), we re-interpreted the Lieb et al. finding as a product of PD patients' difficulties with unknown targets, since their staircase procedure changed the target on each trial. However, even if there were some impairment to early visual processing that did not disrupt salience computations (imagine, for example, that orientation information was not degraded, but merely arrived late), this could not explain why the patients were more impaired with unknown targets than with known targets. The stimulus, and therefore the input from early visual processing, is exactly the same in these two conditions, but the magnitude of the intercept depends on top-down information. Furthermore, as we have noted, both the general PD impairment and the cost of not knowing the target in advance vary inversely with target salience. An effect that is modulated by salience must logically be downstream from the salience map[3]. In other words, it is what observers do with the output of the search process that differs between patients or controls.

The output of the search process (i.e., the candidate target representation) enters VSTM, then is passed to decision and response processes. Any of these stages may be the source of the increased intercepts that we observed. As we noted in the Introduction (see Section 1.2), top-down information can modulate processing at the level of the salience map, at the level of competition in VSTM, or at the decision/response level. Furthermore, if we think of DA as serving to modulate the flow of information through corticostriatal basal ganglia circuits, boosting task-relevant signals and inhibiting task-irrelevant noise (Horvitz, 2002a), then we might speculate that DA is playing a role in biasing competition in VSTM for access to decision and response mechanisms (Desimone & Duncan, 1995). This would predict that PD patients should show a greater second-target impairment in the attentional blink paradigm (Broadbent & Broadbent, 1987; Chun & Potter, 1995; Raymond, Shapiro,

[3] Of course, salience computations may feedback onto early "preattentive" processing (Di Lollo, Kawahara, Zuvic, & Visser, 2001; Hochstein & Ahissar, 2002). However, if re-entrant processes were impaired in PD patients, we would again expect effects on slope, rather than intercept.

& Arnell, 1992). PD patients may also have problems at the level of decision or response processing, either in addition to or instead of at the VSTM competition level. Impaired response competition processing has been blamed for PD patients' set-shifting difficulties (Ravizza & Ciranni, 2002). Variations on the flanker task may serve to parse further these possibilities (Botella, 1996).

4.3. Comparison to previous studies

As discussed in the Introduction, most of the prior work on visual search in PD indicates that medicated patients produce slope data similar to those of age-matched controls in tasks where the target is known in advance (Berry et al., 1999; Lieb et al., 1999; Lubow et al., 1999). The exception is the work of Troscianko and his colleagues (Troscianko & Calvert, 1993; Weinstein et al., 1997), who argued that PD patients were intact on conjunction search but impaired at feature search. Our data replicate Berry et al. rather than those of Troscianko and colleagues, in that when the target was known in advance, there were no significant differences in slope between PD patients and elderly controls on either search type.

It is not obvious why we observe different results than Troscianko and colleagues (Troscianko & Calvert, 1993; Weinstein et al., 1997). One methodological difference between our study and those of Troscianko and colleagues is that we used RT_i rather than RT_{total} as our primary dependent measure. If RT_i was not a valid substitute for RT_{total}, then our data might be suspect. We think this is unlikely for two reasons. First, the elderly control group produced RT data that closely match what we would expect from previous studies using RT_{total} (Greenwood & Parasuraman, 1999; Humphrey & Kramer, 1997; Plude & Doussard-Roosevelt, 1989; Zacks & Zacks, 1993). Second, we ran the same experiment on a group of young controls (data not shown) and obtained the standard results that have been obtained with these tasks numerous times before in the literature (see Wolfe, 1998a).

With only ten participants in each group in our study, it is also possible that we simply lacked the power to detect group differences. However, the effect sizes of the group factor in the known target conditions were extremely small, both in terms of $\hat{\eta}^2$ and in absolute terms; target-present slopes differed by less than 0.5 ms/item. In addition, we should note that the Berry et al. study (1999), whose results were similar to ours in this respect, was methodologically more similar to the Troscianko (Troscianko & Calvert, 1993; Weinstein et al., 1997) studies, and had a larger sample size than either our study or Troscianko's.

One effect that we expected to see in the unknown target condition, but did not, was some sort of elevated cost in the PD group for switching targets. Since PD patients in other tasks have some difficulty switching sets (Gauntlett-Gilbert et al., 1999; Hsieh et al., 1996; Lewis, Slabosz, Robbins, Barker, & Owen, 2005; Lubow et al., 1999; Rogers et al., 1998), we predicted that it would be more difficult for them to switch targets. This was not the case. There were target-switching costs, proportional to target salience, but they did not differ between the patients and elderly controls. One possibility is that, in the Target Unknown conditions, participants entered a singleton detection mode (Bacon & Egeth, 1994; Lamy & Egeth, 2003), as opposed to the feature search mode used in the Target Known conditions. By this view, no active set switching would be required in the Target Unknown situation, as the attentional control mode would remain constant throughout a session. The switching "costs" that we did observe would then be reclassified as priming for repeated targets (see Hillstrom, 2000; Maljkovic & Nakayama, 1994).

Berry et al. (1999) found that a frontally impaired (according to the WCST) subset of Parkinson's patients produced greater intercepts in visual search, while the non-frontally impaired subset performed similarly to age-matched controls. Based on this finding, they suggested that slowed RTs associated with PD would be observed only when proper functioning frontal lobes was compromised by the disease. We did not acquire WCST data on our patients. However, in Berry et al. the average UPDRS score for the "non-frontal" subgroup was 15.0, compared to 24.0 for the "frontal" subgroup, suggesting that motor dysfunction was more advanced in the latter subgroup. By comparison, our patients had an average score of 35.9, making them more similar to the "frontal" subgroup with regard to the severity of their motor symptoms. Thus, the intercept increases observed in Berry et al.'s "frontal" PD subgroup in and in our moderate-to-severe patients might both have resulted from DA dysfunction in the dorsal striatum. Indeed, although the majority of patients in both studies were tested while "on" medication, by the time that the disease is more advanced, L-Dopa treatment may restore DA in the cortex to levels comparable to age-matched controls (Scatton, Javoy-Agid, Rouquier, Dubois, & Agid, 1983), while failing to restore normal DA functioning in the dorsal striatum (Antonini et al., 1997; Torstenson et al., 1997). In contrast, the less impaired "non-frontal" subgroup may have had DA levels in the nigrostriatal pathway more fully restored by the medication.

We should also note that our patients were, on average, more depressed than elderly controls. Clinically depressed patients have more difficulty with search for conjunctive (Beats, Sahakian, & Levy, 1996; Hammar, Lund, & Hugdahl, 2003) or low salience (Hammar, 2003) targets. Although our patients' scores on the BDI were far from the threshold for clinical depression, it is not implausible that subclinical individual differences in depressive affect might be related to search performance. However, while self-reported depression and group membership were somewhat confounded in our study, we do not think that this should undermine our conclusions. First, the effects of depression do not seem to be modulated by top-down information, as our effects were; recall that we observed no differences between groups when the target was known. Second, while Hammar (2003) observed an increase in slopes for depressed patients as search became less efficient, our inefficient conjunction condition produced a slope *advantage* for patients (see next section). Finally, an analysis of the patient group did not reveal any correlations between BDI score and measures of search performance.

4.4. Explaining the conjunction search data

One unexpected finding of our study was that elderly controls actually had steeper target-absent slopes than the PD patients in

the Target Unknown conjunction condition. This effect was not driven by a few outliers, as only three of the elderly controls had Target Unknown conjunction target-absent slopes of less than 100 ms/item, whereas only two of the PD patients had slopes greater than this value. Although this finding was not predicted, some speculation on its source seems appropriate.

Interpretation is more difficult for target-absent data than for target-present data. Early theories of search assumed a simple exhaustive processing rule (Treisman & Gelade, 1980; Wolfe et al., 1989), which predicts a 2:1 absent:present slope ratio. However, this assumes that the brain has some way of knowing which items have been attended and which have not (Klein, 1988). This assumption no longer seems tenable, as the capacity for keeping track of attended items appears to be quite small (Chan & Courtney, 1998; Horowitz & Wolfe, 1998; Horowitz & Wolfe, 2003; McCarley, Wang, Kramer, Irwin, & Peterson, 2003). Furthermore, slope ratios are often reliably greater than 2:1 (Wolfe, 1998b). Therefore, participants must set some sort of threshold (Cousineau & Shiffrin, 2004; Hong, 2005), either in terms of the amount of time to search or the number of items to examine before concluding that no target is likely to be found. This threshold is probably determined adaptively; participants slow down after errors and speed up after correct responses (Chun & Wolfe, 1996).

Within this framework, one possibility is that elderly controls were using an excessively conservative threshold when they did not know which target to look for, searching much longer than necessary. We allowed up to 10 s for participants to respond, and it is clear from Fig. 3 that the elderly controls were unwilling to commit to a target-absent response before most of that window had elapsed. Against this argument is the fact that the observed absent:present slope ratios (2.4 and 2.1 for elderly controls and PD patients, respectively) are well within the normal range for searches of this degree of difficulty (see Fig. 4 of Wolfe, 1998b). The slopes themselves are comparable to those obtained by Zacks and Zacks (1993) in a similar task with an elderly population. Thus RTs > 7 s could simply be the result of slow search through a very large array. On the other hand, "normal" behavior may be excessively conservative. Using a forced-choice staircase method, which measured the exposure time necessary to reach a fixed accuracy, Zacks and Zacks found that slope estimates were reduced, compared to the standard, unlimited exposure RT method. Thus, had we forced our participants to respond within a shorter time window, we might have obtained faster RTs and shallower slopes in the conjunction condition without loss of accuracy.

This may explain the long RTs for the elderly controls. However, why were the PD patients' slopes shallower? Paradoxically, the patients may have performed somewhat better in this condition because they had difficulty sustaining task-relevant performance over long periods (Rogers et al., 1998; Stern, Horvitz, Côté, & Mangels, 2005); overly conservative thresholds require too much time per trial from the patients. Note that the patients pay no additional cost in discriminability for their impatience, possibly because both groups are already operating at the asymptote of their respective speed-accuracy trade-off functions (Dosher, Han, & Lu, 2004; McElree & Carrasco, 1999).

Given that we did not monitor eye movements or enforce fixation in any way, it is likely that participants made eye movements during search of large arrays in the conjunction condition. There is ample evidence that gaze control is affected by PD (Chan, Armstrong, Pari, Riopelle, & Munoz, 2005; Hodgson, Tiesman, Owen, & Kennard, 2002; Kingstone et al., 2002), so differences in gaze patterns may have produced the patterns we observe in the data. Of particular relevance to our result, there is some evidence, for example, that PD patients show stronger inhibition of return (Briand, Hening, Poizner, & Sereno, 2001), a reduced tendency to revisit attended locations. This might have produced more efficient gaze strategies in the patients than controls, allowing them to quit the search earlier.

In summary, the apparent advantage for PD patients in conjunction search, at least for target-absent trials, is an intriguing finding. Although our current data do not allow a definitive explanation, clearly a number of avenues are open for subsequent research.

4.5. Conclusions

How does PD impair visual search behavior in patients? Given the importance of DA in modulating salience, we might expect that moderate-to-severe PD patients, who suffer from compromised striatal DA transmission even when medicated (Antonini et al., 1997; Torstenson et al., 1997), would have difficulty using visual feature information to guide attention. As a result, search tasks of varying difficulty would all be treated by the PD visual system as inefficient searches. However, the few experiments on the issue have generally found that PD patients display the normal pattern of "pop-out" for an easy feature search task. Here, using a set of highly controlled studies, we have replicated that finding. However, we suggest that the typical procedure of using a constant, known target throughout the search task may mask patients' real difficulties with visual search when target salience is decreased by the presence of increasing distractor noise. We demonstrate that when target identity is unpredictable from trial to trial, patients show striking, systematic deficits.

The fact that these deficits showed up in intercept rather than in slope leads us to argue that DA does not play a role in the basic computation of visual salience. If we consider only target-present trials, search is equally efficient in patients and elderly controls, and patient behavior varies in the expected fashion with the salience of the search array. Thus, instead of disrupting visual input salience per se, PD seems to interfere with the conversion of a salient visual signal into action. This is consistent with the view of DA as a gatekeeper for the transmission of signals in corticostriatal processing loops (Horvitz, 2002a).

Our findings raise a new set of questions. First, where does the intercept effect arise? A different set of paradigms will be required to parse the downstream impairment into VSTM, decision and response components. Second, what are the neural mechanisms by which high "bottom-up" stimulus salience and "top-down" instructional guidance operate to mitigate the difficulties that medicated PD patients face in this task? Targets with high stimulus salience may boost DA within the nigrostriatal

system to acceptable levels, allowing striatal DA to increase signal-to-noise ratio more effectively. Alternatively, these targets may possess sufficient salience at the input level such that this modulation is less critical for gating responses. Top-down knowledge may further improve the salience of the signal such that modulation by DA is less critical for normal behavior.

As with any study of medicated PD patients, we must exercise caution in concluding that this pattern of results is due solely to DA dysfunction in the nigrostriatal pathway (Gordon & Reilmann, 1999; Kulisevsky, 2000) Although in more severe patients, medication is less likely to completely restore DA function in the dorsal striatum (putamen and dorsal caudate nucleus) or to overmedicate parts of the ventral striatum and mesocorticolimbic system (as may be the case with more mild PD patients, Cools, Stefanova, Barker, Robbins, & Owen, 2002; Gotham, Brown, & Marsden, 1988; Swainson et al., 2000), with the more advanced patient it is also more difficult to isolate nigrostriatal DA depletion from dysfunction in the mesocorticolimbic DA pathway, as well as in non-dopaminergic systems (Agid et al., 1987). In order to better understand the direct contribution of DA to the pattern of results shown here, future studies should assess patients in the earlier stage of the disease both "on" and "off" L-Dopa medication.

In the present task, top-down knowledge may operate via a network involving prefrontal regions, similar to that which has been shown to be involved in top-down biasing of task-relevant features or objects (Corbetta & Shulman, 2002; Desimone & Duncan, 1995; Pessoa, Kastner, & Ungerleider, 2003). In addition, given that participants were only shown the target at the start of the block, one might expect frontal regions to be necessary for the maintenance of target identity in working memory throughout the subsequent block of trials. Therefore, it may at first seem surprising that PD patients demonstrate such a dramatic benefit from top-down information, given ample evidence for working memory deficits associated with frontostraital dysfunction in PD (e.g. Cools et al., 2002; Lange et al., 1992; Lewis, Dove, Robbins, Barker, & Owen, 2003). However, impairments are generally greatest for working memory tasks that have high demands on manipulation of information, with simple maintenance being relatively unimpaired in mild-to-moderate PD, regardless of medication status (Lewis et al., 2005). The demands on working memory capacity in this task are relatively low, given that there is only one target per block. In addition, top-down information can be obtained not only directly from instruction (Wolfe et al., 2004), but also indirectly, from having found the same target several times in a row (Wolfe, Butcher, Lee, & Hyle, 2003). In the Target Known conditions in the present study, explicit and implicit top-down information were working in concert, making it difficult to separate out the relative contribution of each to the improved performance of the PD patients.

In summary, our study demonstrates that the decision and response components of visual search in PD are strongly influenced by the interaction of bottom-up stimulus salience and top-down information. Not only do these results serve to clarify inconsistencies in the literature on visual search in PD, they also provide support for implementation of therapeutic interventions that increase stimulus salience either through bottom-up or top-down mechanisms.

Acknowledgement

This research was supported by grants to J.A. Mangels from the National Institute of Mental Health (R21-MH066129), to J.C. Horvitz from the National Institute of Drug Abuse (R29-DA11653), and to Columbia University from the W.M. Keck foundation. We thank Emily Stern, Gillian Diercks, and Emily Voigt for their assistance in testing patients and controls. We would also like to thank Shlomo Bentin and three anonymous reviewers for constructive criticism of the manuscript. Portions of this study were presented at the 2003 Cognitive Neuroscience Society Meeting, New York, NY.

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