Visual search in Alzheimer’s disease: a deficiency in processing conjunctions of features

A. Tales , S.R. Butler , J. Fossey , I.D. Gilchrist , R.W. Jones , T. Troscianko

Abstract

Human vision often needs to encode multiple characteristics of many elements of the visual field, for example their lightness and orientation. The paradigm of visual search allows a quantitative assessment of the function of the underlying mechanisms. It measures the ability to detect a target element among a set of distractor elements. We asked whether Alzheimer’s disease (AD) patients are particularly affected in one type of search, where the target is defined by a conjunction of features (orientation and lightness) and where performance depends on some shifting of attention. Two non-conjunction control conditions were employed. The first was a pre-attentive, single-feature, ‘pop-out’ task, detecting a vertical target among horizontal distractors. The second was a single-feature, partly attentive task in which the target element was slightly larger than the distractors—a ‘size’ task. This was chosen to have a similar level of attentional load as the conjunction task (for the control group), but lacked the conjunction of two features. In an experiment, 15 AD patients were compared to age-matched controls. The results suggested that AD patients have a particular impairment in the conjunction task but not in the single-feature size or pre-attentive tasks. This may imply that AD particularly affects those mechanisms which compare across more than one feature type, and spares the other systems and is not therefore simply an ‘attention-related’ impairment. Additionally, these findings show a double dissociation with previous data on visual search in Parkinson’s disease (PD), suggesting a different effect of these diseases on the visual pathway.

Keywords: Attentional mechanisms; Dementia; Vision

1. Introduction

For appropriate environmental interaction, our visual system must be able to detect and recognise visual objects. The analysis of a complex visual scene is traditionally seen as being made up of several distinct but inter-related functional stages and anatomical regions and to be variously reliant on the need for attention. The first of these stages, feature extraction, is generally accepted to be pre-attentive or automatic in nature. At this level, local patches of the scene are encoded as a set of basic features which include size, orientation, colour, distance, brightness, position, and motion. This encoding is performed in parallel. In a subsequent feature integration stage, the sequential action of attention on different locations in the visual scene results in the binding together or conjoining of features to allow more complex processes, such as object recognition to occur. The sequential nature of this attentional process means that it cannot operate simultaneously (in parallel) on the whole visual scene; rather, the serial deployment of focused attention throughout the scene is required to conjoin the features by which the target can be defined, according to Treisman and Gelade .

The efficiency by which a particular target can be found in a natural visual scene has been emulated in the laboratory by using the technique of visual search. In a typical experiment, a participant views a display in which there is a varying number of distractor elements, and there may or may not be a pre-specified target element present. The participant is asked to indicate whether or not the specified target is present, and the reaction time (RT) is measured. Search time and accuracy systematically vary with previous data on visual search in Parkinson’s disease (PD), suggesting a different effect of these diseases on the visual pathway.

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The efficiency by which a particular target can be found in a natural visual scene has been emulated in the laboratory by using the technique of visual search. In a typical experiment, a participant views a display in which there is a varying number of distractor elements, and there may or may not be a pre-specified target element present. The participant is asked to indicate whether or not the specified target is present, and the reaction time (RT) of the response is measured. Search time and accuracy systematically vary with the type of target and the number of distractor elements.

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In the results of such an experiment, RTs are independent of \( N \) (and therefore the linear regression of RT against \( N \)) results in slope values close to zero); this is generally interpreted as indicating that the observer is not having to move their attention from one element to another. This type of search is said to be parallel and the target appears to pop-out. Such search is typically seen when the target and distractor differences are clearly discernable. This often arises when the target differs from the distractors in a single-feature (e.g. colour) and such a search is referred to as a 'feature search'. The need for very little attentional deployment therefore results in highly efficient search.

If RT increases with increasing values of \( N \) then a different situation pertains. Here, it is usually accepted that search requires focused attention which has to be serially applied to the items in the display until the target is found [37]. This type of search is often found if the target is defined by a conjunction of features present in the distractor set, e.g. search for a green T among brown Ts and green Xs (see Treisman [38] for examples). In this case the target is different from the distractors in terms of a specific combination of features. Such an outcome is also found in a single-feature search, when distractors are highly similar to the target [12]. Directing attention to each element in turn until the target is found constitutes a serial search; the more distractors present in the array, the longer the time taken to find the target.

The traditional association of feature search with automatic visual processing and conjunction search with attention-related processing has led to the use of these two tasks in examining automatic and attention-related visual processing in both healthy individuals and in clinical populations [14,26,40]. This is particularly interesting since the two types of search appear to be associated with different functional/anatomical brain areas; conjunction search with the parietal lobe [4,8,9,34] and pop-out more with the striate and extrastriate visual areas of the brain [1,21,28,31,37,39].

The parietal cortex is an area known to be detrimentally affected by the pathological effects of Alzheimer’s disease (AD) even in its early stages [6,19,20] and one would therefore expect to find deficits in associated attention-related tasks in AD. Debate continues about the extent and effects of the involvement of the visual striate and extrastriate regions with such pathology. However, the main argument has been that the tasks most likely to be affected in AD are those that rely heavily on the spatial shifting of attention such as typical conjunction searches and attentional cueing [17,29,32,33].

In a previous study, Foster et al. [14] used the visual search technique to investigate attention-related and automatic processing capacities in AD and found that for a typical conjunction task (with slope values in healthy people of 24.5 ms per item) people with AD were significantly poorer than age-matched controls, whereas there was no significant difference in performance in a typical pop-out task (in which slope values for healthy people were 0.53 ms per item). The results may therefore be interpreted as supporting the idea that it is the tasks requiring attentional deployment that are performed inefficiently by people with Alzheimer’s disease.

However, researchers have now identified numerous types of visual search in which certain target and distractor combinations result in a wide range of search efficiencies. In studies with healthy individuals it is clear that some conjunction searches can be performed very efficiently, while some feature searches are performed very inefficiently. The results from such studies imply that there is not a strict dichotomy between automatic and attention-related visual processing, but rather a continuum. In addition, the need for attention also appears to be dependent upon the outcome and efficiency of other aspects of visual processing such as stimuli similarity, stimulus dimensions, the ability to group and segment; the ability of the visual system to use visual information extracted pre-attentively to guide shifts of attention during search, the inherent noise in visual processing and other low-level factors [15,18].

The aim of the present study was to further characterise how visual search could be affected by AD. The results from the study by Foster et al. [14] have already indicated that typical conjunction tasks, resulting in inefficient search (i.e. high search slope values), are performed worse in AD compared to controls. We ask whether it is the attentional load in the conjunction tasks, or the presence of the conjunction itself, that caused the observed deficit. Our aim was therefore to investigate this issue by comparing performance when the attentional requirements (search difficulty) of a single-feature search and a conjunction search were similar (for the control group, at least).

We therefore used three visual search tasks: a conjunction task, a single-feature task whose difficulty is similar to the conjunction task, and an easy, "pop-out" single-feature task.

For the conjunction condition a set of stimulus parameters was chosen which in our previous pilot studies on both young and older adults had indicated slope values well below 10 ms per item. This forms a type of efficient conjunction search in which strategies based on early visual processing, such as perceptual segmentation and grouping, can be employed in order to reduce the need for the serial application of attention [11,15,18,43]. In this task, the target, a black vertical bar, was surrounded by distractors composed of black horizontal bars and white vertical bars. Healthy people appear to be able to segment or group the different distractors and restrict search to just one type, e.g. by grouping together the black elements, and the vertical elements, rather than having to search through all the elements.

For the pop-out feature condition, the target was a black vertical bar surrounded by black horizontal bars. The homogenous nature of the distractors is thought to facilitate their grouping and therefore the pop-out of the target. For the ‘attention-requiring’ single-feature condition, a task was chosen in which the target was a black bar that was only very slightly longer than otherwise identical distractors. We refer to this as the “size” task. Previous studies with such stimuli [12] had shown that some serial deployment of attention
is necessary in order to detect the when distractor and target similarity is great. Pilot experiments were carried out on groups of both young and older healthy adults drawn from the general population (as part of an exhibition of Bristol University’s research interests) to establish the precise degree of size difference required to match the attention requirements (search difficulty) of this task to those of the conjunction task. These experiments determined the parameters for the rest of the study. Specifically, we found that a size ratio of 0.7 (distractor-to-target) in the “size” task matched the search difficulty of this task and the conjunction task. Thus, any differences between these two tasks for the AD group would not be expected to arise from different attentional requirements of the two tasks.

2. Method

2.1. Participants

Two groups of individuals were tested: those with probable Alzheimer’s disease and age-matched healthy controls. The Alzheimer’s disease group consisted of 15 individuals (7 males), mean age 78.5 years, S.D. 3.9 years, range 71–87 years. The individuals included in the Alzheimer’s group all had a recently determined diagnosis of probable Alzheimer’s disease based on medical and neuropsychological examination, Mini-Mental State Examination (MMSE) [13], family interview, laboratory screening and neuroimaging, according to DSM III-R and NINCDS-ADRD A criteria [27] and were free from any other neurological or psychiatric disorder. Individuals with a suspected vascular component to their probable AD were excluded. The mean MMSE score for the individuals with AD was 20.2. Although medication could not be controlled in the AD group participants who used neurotropic drugs were excluded from the study.

The elderly healthy adult group consisted of 15 individuals (9 males), mean age 76.7 years, standard deviation 4.4 years, ranging from 66 to 87 years. They were known from previous cognitive and clinical screening investigations to have no neurological deficit or significant medical disorder and were not dementing. Both groups had normal or corrected-to-normal vision. All participants gave informed consent obtained according to the local Research Ethics Committees.

2.2. Stimmuli

The stimuli were generated on an IBM PC system. The display was presented on a colour monitor on which just the green phosphor was activated. The area used to display the stimuli subtended 17.3 × 10.6° at a viewing distance of 80 cm in front of the display monitor. The participant’s eye level was at that of the centre of the display. The luminance of the uniform green screen was 5.6 cd m⁻² (all luminances measured with a Minolta Spot Chroma Meter, model CS-1).

For the pop-out task the target was a vertical dark bar, the distractors were horizontal dark bars (Fig. 1a). For the size task, the target was a vertical dark bar, the distractors were vertical light bars and horizontal dark bars (Fig. 1c). The luminance of the dark bars (in the pop-out, conjunction and size conditions) was 4.3 cd m⁻². The luminance of the light bars in the conjunction condition was 7.3 cd m⁻² (giving a Michelson contrast of 13% for both light and dark stimuli). Each bar in the pop-out and conjunction task subtended 0.3 × 0.7°.

For the size task in which the target was a dark vertical large bar the target subtended 0.3 × 0.7° and the distractors were dark vertical bars which had 70% of the height and width of the target bar—see Figs. 1a–c for examples of the target present stimuli. Each bar was located in an imaginary grid box but with a random internal perturbation and no bars touched each other. The target could appear at any location amid three possible arrays of items (containing 16, 36, or 81 elements). There were 30 trials for each of the six
conditions, i.e. 16, 36 and 81 items with the target present and the same for the target absent. The conditions appeared in a random order of presentation.

2.3. Procedure

For the pop-out, conjunction and size conditions, partici-
pants were instructed to initially fixate on the central fixation
disk (coloured bright red) which appeared 100 ms before the
onset of each stimulus array. For all conditions, participants
were asked to respond to the presence or absence of the tar-
get as quickly but as accurately as possible. Responses to the
presence or absence of the targets were made by the partici-
 pant pressing one of two hand held buttons (if a button had
not been pressed for more than 10 s the computer ignored
that trial and the screen displayed an ‘out of time’ message).
The buttons were large (approximately 5 cm²) and designed
to be easy to press. One was red, the other yellow. The run
was restarted by pressing one of the buttons and that par-
ticular trial was repeated later. The order of the conditions
was approximately counterbalanced.

After a description of the task requirements the partici-
pants were asked to perform a practice block of trials to
ensure that they could understand the task, could identify
the presence and absence of the target and were able to use
the buttons to respond appropriately. The participants were
told that there would be a target present on 50% of trials. To
reduce the likelihood of individuals (particularly those with
AD) forgetting the task instructions, and thus failing to re-
spond to the target in the time allocated, several breaks were
given throughout the procedure during which the task in-
structions were repeated. Auditory feedback was given both
in the training phase and the test phase of the experiment,
to allow optimal performance levels to be attained.

The computer program controlling the experiments and
recording the data was designed not to exclude trials which
resulted in a wrong response. However, to exclude wrong
responses due to anticipation of the stimulus, any trial giving
a reaction time of less than 100 ms was rejected and replaced
subsequently. Similarly, any trial giving a reaction time of
more than 10 s was rejected as a time-out and testing was
only resumed after an additional confirmatory button-press.
This time-out facility which allowed breaks to be taken at
any time. The pilot experiments revealed that, with suitable
training, error rates could be kept low (especially the excludi-
one of anticipatory responses).

3. Results

The mean RTs for each condition (pop-out, size and con-
junction; target (target present [TP], target absent [TA]);
display size (16, 36, 81) and for groups (Alzheimer’s dis-
ease [AD], control) are displayed in Fig. 2.

A mixed design analysis of variance (ANOVA) was

carried out on these RT data. There was a significant
effect of condition—F(2, 52) = 31.0, P < 0.01; target—
F(1, 26) = 47.6, P < 0.01; display size—F(2, 52) = 38.2,
P < 0.01 and group—F(1, 26) = 12.1, P < 0.01. The
following interactions were also statistically reliable: condi-
tion by target by group—F(2, 52) = 3.75, P < 0.05; target
by display size—F(2, 52) = 9.95, P < 0.01; condition by
display size—F(4, 104) = 20.0, P < 0.01; condition by
display size by group—F(4, 104) = 3.21, P < 0.05 and
condition by target by display size—F(4, 104) = 7.85,
P < 0.01.

Since the condition by display size by group interaction
was significant, clearly search rates differed between the
two groups differentially in the three different conditions.
To investigate further which condition differed between the
two groups we carried out planned sub analyses of variance
comparing each pair of conditions, i.e. we asked which con-
ditions contributed to the significant interaction. Comparing
the conjunction and size conditions, the following interac-
tions were reliable: condition by display size by group—
F(2, 54) = 4.17, P < 0.05, and target by condition by
display size—F(2, 54) = 12.76, P < 0.01. Comparing
the pop-out and size conditions, the following interactions
were reliable: target by condition by group—F(1, 26) =
4.97, P < 0.05, and condition by display size—F(2, 52) =
13.15, P < 0.01. However, there was no significant target
by condition by display size interaction in this comparison.
Finally, we compared the pop-out and conjunction condi-
tions. Here, the following interactions were reliable: target
by condition by group—F(1, 27) = 5.23, P < 0.05, and
target by display size—F(2, 54) = 17.52, P < 0.01; condi-
tion by display size—F(2, 54) = 32.87, P < 0.01; condi-
tion by display size by group—F(2, 54) = 4.16, P < 0.05;
and target by condition by display size—F(2, 54) = 6.14,
P < 0.01.

The results show that search rates on the pop-out and
size tasks were similar for both the AD and control groups,
whereas people with AD searched significantly more slowly
compared to the control group on the conjunction task.

A linear regression of reaction time (RT) against the num-
ber of items (N) was also performed for each participant
within each group for each search, and the resulting slope
and intercept data were analysed by ANOVA. (Note that it
is possible to analyse visual search data as either raw RT
scores or search slopes; for completeness, we give both types
of analysis here.)

A three-factor, one between- and two within-subjects fac-
tors ANOVA on the slope data indicated that there was no
significant main effect of group, F(1, 26) = 1.03, P > 0.05.
There was a significant main effect of condition, F(2, 52) =
3.6, P < 0.0001. There was a significant main effect of
Target, F(1, 26) = 9.49, P < 0.01. There was a signifi-
cant group by condition interaction, F(2, 52) = 3.57, P <
0.05. There was a significant condition by target interaction,
F(2, 52) = 12.29, P < 0.0001. There was no significant
three-way interaction.

Post-hoc t-tests on the slope data revealed a significant
difference between the AD and control slope values in the
Fig. 2. Experimental results. The mean reaction time is shown as a function of the number of items on the screen, for each of the experimental conditions. "TA": target absent; "TP": target present; "cont": control group; "alz": Alzheimer's disease group.
conjunction, target present condition, \( r(13) = 2.18, P < 0.05 \). There were no significant differences between AD and controls in any other individuals conditions (pop-out, size, target present or target absent). Thus, the cause of the significant interaction was a particularly marked increase in search slope for the AD group in the conjunction task, when the target was present on the screen.

The slope values are assumed to represent the attentional demand of the search task. The intercepts provide a measure of baseline RT (for zero elements on the screen) and relate to (a) the basic time to press a button, and (b) any fundamental difficulty in remembering the required response. Table 1 summarises these results.

A mixed design ANOVA was carried out on the intercept data in order to see whether the AD group might have a global impairment in the conjunction condition, for example a difficulty in remembering the more complex definition of the target in that condition. There was a significant effect of condition—\( F(2, 52) = 15.4, P < 0.0001 \); a significant main effect of group, \( F(1, 26) = 11.85, P = 0.005 \), but no significant group by condition interaction, \( F(2, 52) = 1.86, P > 0.05 \), and no significant group by target interaction, \( F(1, 26) = 0.7, P > 0.05 \). There was one significant three-way interaction: group by condition by target, \( F(2, 52) = 4.77, P < 0.05 \).

The results of the intercept data indicate that the AD group did not find the basic conjunction task hard to remember—since a difficulty in remembering would be expected to give high reaction times even with few elements on the screen (a non-visual aspect of task difficulty) and therefore a high intercept value. Therefore, there is no suggestion that having to remember a target defined by two features, rather than one, poses a particular problem for this group.

3.1. Error data

The software which recorded the data was designed not to remove error trials; however, it counted the incidence of such trials. The mean percentage accuracy for each condition summarises these results.

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with the results of Foster et al. [14], we found that people with AD were significantly impaired overall (main effect of group in the reaction time analysis). The results show that search rates on the pop-out and size tasks were similar for both the AD and control groups, whereas people with AD searched significantly more slowly compared to the control group on the conjunction task.

Unlike Foster et al. [14], our conjunction task was one in which healthy people are able to perform an efficient search, and thus are thought to require less serial application of attention in order to find the target. So, even though our conjunction task required less in the way of attention-related processing, people with AD were still significantly impaired in its performance in relation to healthy controls. This impairment is therefore not due to the conjunction task simply requiring more attention than the single-feature, “size” task. The conjunction and size tasks were approximately matched for mean (target absent and target present) performance, for the control group. However, the AD group showed impaired searching in the conjunction task. There seem to be several possible interpretations of this result.

One possibility is that the visual system of AD patients has a problem with “feature binding”—namely, it is unable to establish efficient communication between different feature descriptions of each patch of stimulus—for example, the orientation and colour of an element. Since features are typically analysed in functionally and anatomically separate cortical areas, an impairment of “binding” would result from an impaired ability to compare across these features. For this explanation, attention may be unimpaired and segmentation and grouping processes may be working well.

There is a second possibility that may account for these findings. In our conjunction search, healthy people are thought to employ segmentation or grouping strategies among the distractors in order reduce the need for attention shifting, thus improving search efficiency. “Grouping” is distinct from “binding”. Grouping is an ability to jointly represent similar members of a set distributed across space (e.g. “all black items”) whereas binding is an ability to jointly represent the different characteristics of a single item or patch of visual space (e.g. “black and vertical”). It may be the case that people with AD have a reduction in the efficiency of basic visual processing, such as segmentation or grouping necessary to form a grouping strategy, or in the application of such a strategy. This would therefore result in a greater need for attention shifting in order to detect the target.

Thirdly, the result may arise because there is some damage to general attentional mechanisms in AD, and thus any attention-related task is affected.

The neurophysiological evidence may support the first interpretation. There is evidence that the binding of features may be mediated by areas such as the temporal and parietal cortex [36,41], areas known to be affected by AD-related pathology [2,3,16]. In AD, such problems with aspects of basic visual processing, for example the ability to successfully conjoin features, may also be associated with or underlie the problems in object recognition and other higher level visual problems often encountered in the disease [10,23,35]. Importantly, it appears that such problems are not the result of retinal or optical detriment, but appear to be due to problems at other stages [35].

It was not possible in the present study to be certain which, if any, of these factors could account for the significantly impaired search performance on the conjunction task in AD. However, performance on the single-feature “size” task, in which the AD group is unimpaired on search rate measures, suggests that the first or second explanations are more likely than the third. In other words, the impairment in the conjunction search may arise as a result of an impairment of a “binding” process, or to a failure to group different elements efficiently. It is not likely to be due exclusively to a generalised failure of attentional processes since, if anything, the “size” task may require such processes slightly more than the conjunction task (for controls; even though the mean search slopes are matched across the two conditions, there are more errors in the “size” task, suggesting that it is more demanding). In spite of this, the “size” task is unimpaired in AD whereas the conjunction task is impaired. Thus, further work is required to be able to decide whether a failure of grouping processes, or of binding processes, may be responsible for our present results.

We asked whether our results on the conjunction task could have been caused by a failure to remember that, in conjunction search, the target is defined by two features rather than a single-feature, i.e. we asked whether the difficulty with detecting the conjunction target is due to the added difficulty of remembering a more complex definition of the target (e.g. dark and vertical). If so, we would predict that such a difficulty would persist independently of the number of items on the screen—even when that number is low. If there were a memory problem, we would expect the intercepts in the conjunction condition to be particularly high, since they relate to the “base” reaction time in a highly sparse display. There is no indication in the data that these intercepts are abnormally high and we may be able to discount this type of explanation. Another possible way in which a memory impairment might manifest itself in the AD group is to suppose that, as the number of elements increases, so the patients spend longer searching and need to retain the memory for target features longer. However, the data (shown in Fig. 2) do not support such an interpretation since the RTs in the conjunction and size tasks for the AD group are broadly similar, even for high numbers of elements. Therefore, this type of memory impairment becomes less likely. We should point out, however, that the intercepts of the AD group are uniformly higher than those of the controls; therefore, there may be a raised level of difficulty across all tasks (or a more severe motor problem). However, there is no additional impairment of intercept in the critical conjunction condition.

Another possible problem with the RT dataset, particularly since error trials are included, is the effect of speed-accuracy trade-offs. We compared the results of
the five highest-error AD subjects with the results of the whole group and found evidence of a global speed-accuracy trade-off in that the RTs of the high-error group were always faster than the whole-group means. However, there was no interaction with the number of distractors in any of the conditions, and therefore there is little likelihood that the main RT effects can arise from speed-accuracy trade-offs.

Traditionally the emphasis on the effects of AD on visual processing has been more concerned with the attention-related aspects of such processing [7]. The present results provide some evidence that this may not be the only factor. AD is associated with multi-focal pathological changes affecting many areas of visual processing [5,22,25] which may therefore affect many more aspects of visual function in addition to those related to the attention-related aspects of visual search. For example, recent fMRI data [24] do not clearly point to a dissociation between conjunction and single-feature search in visual cortex but do reveal differential activity in relation to the solution of the “binding problem”. Thus, the differences found in our study may relate to aspects of vision not particularly related to visual search, but rather to “binding” difficulties or a failure of inhibition of responses to heterogeneous distractors.

Finally, we would like to draw attention to an interesting double dissociation of which the present results are a contributory part. Earlier work [40,42] was carried out on patients with Parkinson’s disease (PD) using exactly the same equipment and testing procedures. In those studies, evidence was found of impairment in PD on the pop-out task, and no evidence of impairment on the conjunction task (the “size” task was not tested). Here, we have precisely the opposite set of results: normal performance on the pop-out task, but impairment on the conjunction task. Whatever the neurophysiological basis for these results, the double dissociation provides evidence that PD and AD differentially affect the visual pathway, and that the pop-out task and the conjunction task are differentially processed within that pathway.

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[12] Duncan-Jones P, Humphreys GW. Attention and single-feature search in visual cortex but do reveal differential activity in relation to the solution of the “binding problem”. Thus, the differences found in our study may relate to aspects of vision not particularly related to visual search, but rather to “binding” difficulties or a failure of inhibition of responses to heterogeneous distractors.

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