

# **Visual search and eye movements: Studies of perceptual span**

**Helena Ojanpää**

**People and Work  
Research Reports 74**

University of Helsinki, Department of Psychology  
Finnish Graduate School of Neuroscience  
Finnish Institute of Occupational Health  
2006

# Academic dissertation

- Supervisors      Professor Veijo Virsu, Ph.D.  
                         Department of Psychology  
                         University of Helsinki, Finland
- Docent Risto Näsänen, Ph.D.  
                         Brain and Work Research Centre  
                         Finnish Institute of Occupational Health
- Reviewers        Professor John M. Findlay, Ph.D.  
                         Department of Psychology  
                         University of Durham, UK
- Professor Gordon E. Legge, Ph.D.  
                         Department of Psychology  
                         University of Minnesota, US
- Opponent         Docent Kaisa Tiippana, Ph.D.  
                         Laboratory of Computational Engineering  
                         Helsinki University of Technology, Finland

To my wonderful children Juha and Saana.  
You remind me of what really is important in life.

## TABLE OF CONTENTS

TABLE OF CONTENTS .....	5
ABBREVIATIONS .....	7
ABSTRACT.....	8
TIIVISTELMÄ (SUMMARY IN FINNISH) .....	9
LIST OF ORIGINAL PUBLICATIONS.....	11
1. INTRODUCTION.....	12
1.1. Visual search and selective attention .....	13
1.1.1. Cognitive tradition of attention research.....	13
1.1.2. Feature Integration Theory and its later modifications.....	14
1.2. Eye movements in visual information processing.....	16
1.2.1. Concepts of perceptual span and visual span in reading studies.....	17
1.2.2. Visual and perceptual span in two-dimensional visual search .....	18
1.2.3. Perceptual span in visual search is two-dimensional.....	18
1.2.4. Visual span control hypothesis.....	19
1.2.5. Shrinking visual/perceptual span hypothesis.....	19
1.3. Neural basis of saccadic visual search and selective attention .....	20
1.3.1. Eye movement coordination and attention.....	21
1.3.2. Selective attention modulates neural responses to visual stimuli.....	22
1.4. What limits performance in saccadic visual search? .....	23
2. AIMS OF THE PRESENT STUDY .....	26
3. METHODS.....	27
3.1. Subjects.....	27
Psychophysical studies (I - VI).....	27
Clinical study (VII) .....	27
3.2. Stimuli .....	28
Letter search (Studies I, II, and VII).....	28
Word search (Study III).....	29
Icon search (Study IV).....	30
Face search (Studies V and VI) .....	31
3.3. Procedure.....	32
3.3.1. Visual search task.....	32
3.3.2. Staircase procedure .....	33
3.3.3. Neuropsychological tests (Study VII) .....	34
3.4. Eye movement recordings.....	34
3.5. Statistical procedure .....	35
4. RESULTS .....	37
4.1. Effects of stimulus properties on visual search performance and eye movements in normal subjects (Studies I – VI) .....	37

## CONTENTS

---

4.1.1. Luminance contrast (Studies I and IV) .....	37
4.1.2. Interaction of luminance contrast, colour contrast and size (Study II).....	40
4.1.3. Sharpness (Study IV) .....	42
4.1.4. Spatial frequency information in face search (Study V) .....	42
4.1.5. Orientation and spacing of word lists (Study III) .....	44
4.1.6. Scanning strategy .....	47
4.2. Two-dimensional perceptual span (Studies I, III, IV and VI) .....	47
4.2.1. Perceptual span for character information (Study I) .....	49
4.2.2. Perceptual span for vertical word lists (Study III) .....	49
4.2.3. Perceptual span for computer icons (Study IV).....	49
4.2.4. Perceptual span for faces (Study VI).....	50
4.2.5. Scale invariance of perceptual span .....	50
4.3. Visual search and eye movements in patients with CSE (Study VII) .....	52
4.3.1. Visual search performance and eye movements .....	52
4.3.2. Estimation of the two-dimensional perceptual span for CSE patients .....	53
4.3.3. Trail Making Test .....	54
4.3.4. Scanning strategy and oculomotor control .....	54
5. DISCUSSION.....	56
5.1. Serial and parallel information processing in saccadic search .....	56
5.1.1. Set size effect and processing within fixation .....	56
5.1.2. Search strategy .....	58
5.2. Stimulus properties and perceptual span .....	60
5.2.1. Luminance contrast and stimulus size .....	60
5.2.2. Interaction of luminance contrast and colour contrast .....	61
5.2.3. Scale invariance of perceptual span .....	62
5.2.4. Stimulus layout and perceptual span .....	62
5.2.5. Stimulus density and perceptual span .....	63
5.2.6. Stimulus type and span size .....	64
5.3. When do high-level factors affect perceptual span? .....	65
5.3.1. Effects of task complexity, learning, and allocation of attention .....	66
5.3.2. Perceptual span in CSE .....	67
6. CONCLUSIONS .....	69
7. APPENDIX: Application of the results to visual ergonomics.....	70
Size and luminance contrast .....	70
Sharpness (blur).....	71
Colours.....	71
Layout.....	71
8. ACKNOWLEDGEMENTS .....	73
9. REFERENCES.....	75
ORIGINAL PUBLICATIONS.....	85

## ABBREVIATIONS

2AFC	two alternative forced choice task
ACC	anterior cingulate cortex
ANOVA	analysis of variance
<i>C</i> or <i>c</i>	luminance contrast
<i>c/deg</i>	cycles per degree (of visual angle)
<i>c/fw</i>	cycles per face width
<i>cd/m<sup>2</sup></i>	candela per square meter
CS	contrast sensitivity
CSE	chronic solvent-induced encephalopathy
deg	degree (of visual angle)
DLPFC	dorsolateral prefrontal cortex
FEF	frontal eye field
Hz	hertz
IT	inferotemporal cortex
LGN	lateral geniculate nucleus
LED	light emitting diode
<i>L<sub>max</sub></i>	maximum luminance
<i>L<sub>min</sub></i>	minimum luminance
ms (MS)	millisecond
N	number (of subjects)
<i>ns</i>	statistically non-significant
P (or <i>p</i> )	probability
PCC	posterior cingulate cortex
PEF	parietal eye field
PPC	posterior parietal cortex
<i>r<sub>s</sub></i>	Spearman's rho, non-parametric correlation coefficient
RSVP	rapid serial visual presentation
SC	superior colliculus
<i>SD</i>	standard deviation
SEF	supplementary eye field
<i>SEM</i>	standard error of the mean
TMT	Trail Making Test
TMT-A	Trail Making Test, Part A
TMT-B	Trail Making Test, Part B
<i>U</i>	parameter for non-parametric Mann-Whitney U Test
V1	primary visual cortex
V4	cortical visual area V4

## ABSTRACT

In *visual search* one tries to find the currently relevant item among other, irrelevant items. In the present study, visual search performance for complex objects (characters, faces, computer icons and words) was investigated, and the contribution of different stimulus properties, such as luminance contrast between characters and background, set size, stimulus size, colour contrast, spatial frequency, and stimulus layout were investigated. Subjects were required to search for a target object among distracter objects in two-dimensional stimulus arrays. The outcome measure was threshold search time, that is, the presentation duration of the stimulus array required by the subject to find the target with a certain probability. It reflects the time used for visual processing separated from the time used for decision making and manual reactions. The duration of stimulus presentation was controlled by an adaptive staircase method. The number and duration of eye fixations, saccade amplitude, and *perceptual span*, i.e., the number of items that can be processed during a single fixation, were measured.

It was found that search performance was correlated with the number of fixations needed to find the target. Search time and the number of fixations increased with increasing stimulus set size. On the other hand, several complex objects could be processed during a single fixation, i.e., within the perceptual span. Search time and the number of fixations depended on object type as well as luminance contrast. The size of the perceptual span was smaller for more complex objects, and decreased with decreasing luminance contrast within object type, especially for very low contrasts. In addition, the size and shape of perceptual span explained the changes in search performance for different stimulus layouts in word search. Perceptual span was scale invariant for a 16-fold range of stimulus sizes, i.e., the number of items processed during a single fixation was independent of retinal stimulus size or viewing distance.

It is suggested that saccadic visual search consists of both serial (eye movements) and parallel (processing within perceptual span) components, and that the size of the perceptual span may explain the effectiveness of saccadic search in different stimulus conditions. Further, low-level visual factors, such as the anatomical structure of the retina, peripheral stimulus visibility and resolution requirements for the identification of different object types are proposed to constrain the size of the perceptual span, and thus, limit visual search performance.

Similar methods were used in a clinical study to characterise the visual search performance and eye movements of neurological patients with chronic solvent-induced encephalopathy (CSE). In addition, the data about the effects of different stimulus properties on visual search in normal subjects were presented as simple practical guidelines, so that the limits of human visual perception could be taken into account in the design of user interfaces.

## TIIVISTELMÄ

*Visuaalisella haulla* tarkoitetaan oleellisen tiedon tai kohteen näönvaraista etsimistä muiden ärsykkeiden joukosta. Visuaalista hakua on esimerkiksi se, kun etsitään tuttua henkilöä ihmisjoukosta, tiettyä ilmoitusta sanomalehdestä, lyijykynää työpöydältä tai vaikkapa kuvaketta tietokoneen näytöltä. Tehokas ja virheetön visuaalinen haku on erityisen keskeistä monissa eri työtehtävissä sekä liikenteessä. Visuaalinen tarkkaavaisuus ohjaa kulloinkin oleellisena pidetyn tiedon etsintää. Toisaalta visuaalisen haun tehokkuutta rajoittavat varhaisen tiedonkäsittelyn piirteet, kuten verkkokalvon ja muun näköjärjestelmän rakenne ja toiminta, jotka määräävät millaista näkö tietoa kykenemme havaitsemaan. Koska näöntarkkuus alenee ääreisnäössä voimakkaasti, visuaalinen haku tapahtuu luonnollisessa tilanteessa siten, että tarkimman näön aluetta siirretään silmiä liikuttamalla. Näitä silmänliikkeitä mittaamalla saadaan tietoa visuaaliseen hakuun vaikuttavista seikoista.

Tässä tutkimuksessa selvitettiin erilaisten monimutkaisten objektien, kuten kirjainten, kasvojen, kuvakkeiden ja sanojen visuaalista hakua, sekä rekisteröitiin visuaalisen haun aikana tapahtuvia silmänliikkeitä terveiltä koehenkilöiltä. Tutkimuksessa mitattiin psykofysiikan menetelmiä hyödyntäen, kuinka kauan tietynkokoista ärsykejoukkoa tulee esittää tietokonenäytöllä, jotta koehenkilöt löytävät kohdeärsykkeen tietyllä todennäköisyydellä. Tutkimuksessa pyrittiin selvittämään, miten erilaiset ärsykkeiden ominaisuudet, kuten ärsykkeen ja taustan vaaleus- ja värikontrasti, ärsykkeiden lukumäärä ja asettelu näytöllä, ärsykkeiden koko, paikkataajuus tai terävyys vaikuttavat visuaalisen haun tehokkuuteen ja haun aikaisten silmänliikkeiden lukumäärään ja kestoon. Erityisesti tutkittiin *havaintokentän* kokoa, eli sitä, paljonko informaatiota yhdellä katseen kohdistuksella pystytään käsittelemään. Yhdessä osatutkimuksessa selvitettiin myös liuotinaivosaivosaudesta kärsivien potilaiden visuaalista hakua ja silmänliikkeitä mainittuja menetelmiä käyttäen.

Kun ärsykkeiden määrä näytöllä kasvoi, hakuajat hidastuivat, ja katseen kohdistuksia tarvittiin enemmän. Myös etsittävien objektien monimutkaisuus vaikutti haun tehokkuuteen ja havaintokentän kokoon. Yhdellä katseen kohdistuksella monimutkainen objekti, kuten sana tai kasvokuva löydettiin 4 – 5 muun sanan tai kasvon joukosta, kun taas yksinkertaisempia objekteja, kuten kirjaimia ja kuvakkeita kyettiin prosessoimaan yhdellä katseen kohdistuksella jopa 30 – 40. Ärsykkeiden ja taustan välisen vaaleuskontrastin alentuessa havaintokenttä pieneni voimakkaasti siten, että yhdellä katseen kohdistuksella havaittiin vähemmän ärsykeitä ja samalla haku aika kasvoi voimakkaasti. Sen sijaan ärsykkeen koon muuttuessa havaintokentän koko (ärsykettä/katseen kohdistus) säilyi lähes vakiona. Liuotinaivosaivosaudesta kärsivien potilaiden havaintokenttä oli kapeutunut ja visuaalinen haku hidastunut.

Tulokset osoittavat, että visuaalisen haun tehokkuus eri tilanteissa on yhteydessä havaintokentän kokoon, joka puolestaan vaikuttaa tarvittavien katseen kohdistusten lukumäärään. Varhaiset tekijät, erityisesti verkkokalvon rakenteesta johtuva näöntarkkuuden aleneminen

## TIIVISTELMÄ

---

ääreissä, näyttävät ensisijaisesti määrävän havaintokentän koon ja siten selittävät visuaalisen haun tehokkuuden muutoksia eri tilanteissa. Myöhemmän tason tiedonkäsittely, kuten oppiminen ja kyky suunnata tarkkaavaisuutta havaintokentässä, näyttävät vaikuttavan haun tehokkuuteen välillisemmin varhaisen tason rajoitusten sallimissa puitteissa.

Eri osatutkimuksissa saatua tietoa ihmisen tiedonkäsittelyn ominaisuuksista ja rajoitteista voidaan hyödyntää mm. käyttöliittymiä suunniteltaessa. Tämän tutkimuksen liitteeksi on koottu muutamia yksinkertaisia ohjeita siitä, kuinka käyttöliittymissä tapahtuvaa visuaalista hakua voidaan tehostaa suunnittelemalla niiden visuaaliset ärsykkeet riittävän suuriksi ja selkeästi erottuviksi, jotta havaintokentän koko olisi mahdollisimman suuri.

## LIST OF ORIGINAL PUBLICATIONS

The thesis is based on the following original publications, which are referred to in the text by Roman numerals I - VII.

Article VI is reprinted with permission from Pion Ltd, London. Other articles are reprinted with permission from Elsevier.

- I Näsänen, R., Ojanpää, H., & Kojo, I. (2001). Effect of stimulus contrast on performance and eye movements in visual search. *Vision Research*, *41*, 1817-1824.
- II Ojanpää, H. & Näsänen, R. (2003). Effects of luminance and colour contrast on the search of information on display devices. *Displays*, *24*, 167-178.
- III Ojanpää, H., Näsänen, R., & Kojo, I. (2002). Eye movements in the visual search of word lists. *Vision Research*, *42*, 1499-1512.
- IV Näsänen, R. & Ojanpää, H. (2003). Effect of image contrast and sharpness on visual search for computer icons. *Displays*, *24*, 137-144.
- V Ojanpää, H. & Näsänen, R. (2003). Utilisation of spatial frequency information in face search. *Vision Research*, *43*, 2505-2515.
- VI Näsänen, R. & Ojanpää, H. (2004). How many faces can be processed during a single eye fixation? *Perception*, *33*, 67-77.
- VII Ojanpää, H., Näsänen, R., Päällysaho, J., Akila R., Müller, K., Kaukiainen, A., Sainio, M. (2006). Visual search and eye movements in patients with chronic solvent-induced toxic encephalopathy. *Neuro Toxicology*, in press.

## 1. INTRODUCTION

This study concerns a form of visual behaviour that is essential in everyday life. In *visual search* we select the relevant visual target (object, face, item etc.) among other items that are irrelevant to our actions at that given time. Visual search is done every time we try to find a pencil on the desk, look for a certain advertisement in a paper, a friend we are supposed to meet in a crowded railway station, or a certain icon on the computer desktop. Visual search is a tool for selective visual attention, and it is controlled by our goals, previous experience and current needs. On the other hand, many factors at the relatively early stages of visual information processing, such as the anatomical structure of the visual system, or stimulus processing mechanisms at the retina or in the input levels of the visual cortex set limits to visual perception. These limits are here called as *low-level factors*, since they are related to the information processing at relatively early levels of the visual system in comparison to the information processing at higher cortical areas, such as object identification in inferotemporal cortical areas (e.g. Allison et al., 1999; Haxby, Hoffman, & Gobbini, 2000), or attentional, decision making, response selection and inhibition processes probably controlled by parietal and frontal areas (e.g. Corbetta et al., 2000; Corbetta & Shulman, 2002; Leonards et al., 2000; Ungerleider, Courtney, & Haxby, 1998). Successful low-level information processing is a prerequisite for high-level information processing, and thus, all levels together affect the performance in complex visual tasks.

Traditionally visual search has been studied with simple stimuli, and with experimental tasks in which eye movements were restricted. However, in natural situations eye movements are intimately linked to visual search, because the visual resolution decreases steeply with eccentricity (Wertheim, 1894), and therefore the retinal area of the highest resolution must be turned towards the current region of interest by moving the eyes. Nearly all visual information is gathered during *eye fixations*, relatively short moments when the eyes stay fixed at a certain location, before they jump into the next location by a fast *saccadic eye movement*. During the last 25 years, there has been growing interest in studying eye movements and their role in information processing, especially in reading, visual search and scene perception (for review, see Rayner, 1998).

We investigated the effects of different stimulus properties, such as size, stimulus type (face, word, character, or computer icon), luminance contrast, colour, and spatial frequency on performance in visual search task, in which stimuli were arranged as a two-dimensional array and eye movements could be made freely as in natural situations. We investigated how eye movement parameters were related to visual search performance, and we paid special attention to *perceptual span*, i.e., the area from which visual information can be gathered during a single eye fixation. The effects of low- and high-level factors on visual search performance and eye movements are discussed.

Since visual search is highly essential for everyday life, the research on this area has many practical applications. The results are discussed in relation to visual ergonomics, especially to the design of user interfaces. The knowledge of the limits that normal humans have in visual information processing can help design user interfaces so that the salience and clarity of the relevant information is supported, and the effectiveness of visual search is enhanced. This could save a substantial amount of time by increasing the rate by which the information is searched for, by decreasing error rate, and by increasing satisfaction of the users. Most important is the clarity of the user interfaces in safety-critical areas such as traffic, health care or aviation.

### **1.1. Visual search and selective attention**

Attention is a label given to a set of cognitive processes that include "selectivity of perception, voluntary control over this selectivity, and capacity limits in mental functioning that cannot be attributed to mere limitations of our sensory or motor systems" (Pashler, 1998, p. 3). It is often divided into selective, sustained and divided attention. This review is limited to visual focused or selective attention, which is strongly related to visual search, and can be described as "the capacity to highlight the one or two important stimuli or ideas being dealt with while suppressing awareness of competing distractions" (Lezak, Howieson, & Loring, 2004, p. 34).

#### **1.1.1. Cognitive tradition of attention research**

Selective attention is related to the limited capacity of information processing. The amount of information that is constantly acquired by our senses is overwhelming, and only a small part of it can be analysed, and probably an even smaller part of it ever reaches our consciousness. The concept of selective attention is one of the key concepts in psychology, but since it is very difficult to define precisely, it is susceptible to many different, even conflicting, interpretations. However, its importance has been addressed as early as in 1890, when William James wrote in *Principles of Psychology* (see e.g. Wilshire, 1984, p. 77 - 79):

“Consciousness...is always interested more in one part of its object than in another, and welcomes and rejects, or chooses, all the while it thinks. The phenomena of selective attention and deliberative will are of course patent examples of this choosing activity. [...] Accentuation and emphasis are present in every perception we have. [...] But we do far more than emphasize things, and unite some, and keep others apart. We actually *ignore* [original italics] most of the things before us. Let me briefly show how this goes on. To begin

at the bottom, what are our very senses themselves but organs of selection? [...] [...] Attention, on the other hand, out of all the sensations yielded, picks out certain ones as worthy of its notice and suppresses all the rest. [...] [...] That industry goes on to deal with the things thus given in perception. A man's empirical thought depends on the things he has experienced, but what these shall be is to a large extent determined by his habits of attention. A thing may be present to him a thousand times, but if he persistently fails to notice it, it cannot be said to enter into his experience."

The cognitive studies that have had a large influence on modern views of selective attention date from the decades of the 1950's, when Cherry (1953) and Broadbent (1958), among others, studied auditory selective attention using the method of dichotic listening (for review see, e.g., Pashler, 1998; Driver, 2001). They played two concurrent auditory streams, one to each ear of the subject, and asked the subject to repeat back one stream, i.e., to "shadow" it. They studied which physical differences in the two streams made shadowing easy, and what people could report from the other stream they were told to ignore. Broadbent (1958) stated in his Filter Theory that, since only superficial properties could be reported from the ignored auditory stream, the selective attention works like an early filter that protects the later systems from overload by preventing all the non-attended information from being further processed. This is called "early selection" theory, since he thought that the parallel pre-attentive stage consists only of the extraction of simple physical stimulus properties, in contrast to the later attentive stage, where all further information processing was thought to occur.

After numerous exceptions to the original results were found, an opposing view was formulated (e.g. Deutsch & Deutsch, 1963; Duncan, 1980). In "late selection" theories all stimuli were thought to be processed in a parallel way quite thoroughly, and a later serial stage was thought to be related to the limited access of unattended information into memory or awareness. Broadbent's student Anne Treisman formulated an intermediate view in her Attenuation Theory (Treisman, 1960), where she proposed that most of the ignored information is attenuated in the early stages, and thus receives only limited further processing. On the other hand, some of the ignored information may be primed, for example due to the semantic relatedness to currently attended material, or due to the long-term learning (such as one's own name). These items come into awareness more easily even from the ignored stream.

### **1.1.2. Feature Integration Theory and its later modifications**

Later Treisman started to study the visual modality by using the visual search paradigm. She used simple stimuli (such as bars or circles of different colours and orientations etc.)

## INTRODUCTION

---

and measured reaction times for targets differing from distracter stimuli in one feature or in conjunctions of several features. Many themes from earlier theories, like distinction between a fast parallel pre-attentive stage and later serial attentive stage with limited capacity, came to theories of visual selective attention. The Feature Integration Theory (Treisman & Gelade, 1980; Treisman, 1986) stated that visual focused attention binds the individual stimulus features, such as form and colour together in a certain spatial location, and helps to form the perception of a single unitary object. In unattended regions of the visual field the features that are only pre-attentively coded may be “free-floating”, and do not form coherent wholes, or may be combined inappropriately to “illusory conjunctions”. Thus, she offered selective attention as a solution to the binding problem, as a means to group together the features that belong to the same object but are processed separately in different brain regions (see e.g. Treisman, 1998). Treisman and Gelade (1980) showed that the search for feature conjunctions becomes slower when the number of stimuli increases (set size effect), and interpreted this as a sign of the serial covert attentional processing.

It should be noted that Feature Integration Theory was conceived so that the eyes were fixed to one location, and therefore, all search was done as covert shifts of attention. Feature Integration Theory postulated that only targets that differed from distracters in one stimulus feature (e.g. vertical bar among horizontal ones, or blue bar among red bars) could be searched in a parallel way, almost without capacity limitations. Treisman has received a substantial amount of criticism, and conflicting results (see e.g. McLeod, Driver, & Crisp, 1988; Nakayama & Silverman, 1986; Theeuwes & Kooi, 1994) have been used to formulate further theories (e.g. Duncan & Humphreys, 1989; Wolfe, Cave, & Franzel, 1989; Wolfe, 1992, 1994, 1998).

Duncan and Humphreys (1989) showed that difficulty of search increases with increasing similarity of targets to distracters (nontargets), and with decreasing similarity between distracters. Thus, slopes of the search times in different tasks form a continuum rather than two distinct groups of parallel and serial search tasks. They proposed that a parallel stage of visual feature coding and object segmentation is followed by a stage of competitive interaction between inputs, which guides the selective access to awareness and visual short-term memory. They also proposed that similar stimuli are grouped together, and the grouping affects the weights of the individual elements in competition. The structural unit (stimulus) that matches the internal description of the target best, is the first location of attention during serial visual search.

Wolfe (Wolfe et al., 1989; Wolfe 1994) proposed a Guided Search model as an alternative to Feature Integration Theory. He found that some targets which were defined by three features were actually easier to find than ordinary conjunctions defined by only two features. Wolfe explained this by stressing the role of the pre-attentive parallel processes in guiding the location of selective attention in a later serial stage. Since three processes guide selective attention to potential target locations more effectively than two, the new

results made sense. Wolfe proposed that information from parallel processes are summed together as activation maps, which consist of both bottom-up activations of each item determined by its difference to neighbour items (saliency), as well as the top-down activations determined by each feature's match with target properties. According to Wolfe, the activation map is used in a serial stage to guide attention so that at first the location of the highest activation is attended, after that the next best location etc. until target has been found. Efficiency of search is related to the amount of guidance the parallel processes can give. When guidance is very strong, the serial stage can be omitted and the search is parallel. He considered visual search as a signal-detection task, where the efficiency of the search is determined by a relation between signal that draws attention, and signals from distracters (Wolfe, 1994).

A recent development is the Load Theory of Attention, which proposes that the location of a “bottleneck” in visual system is affected by perceptual load of the task, which modulates the degree to which the irrelevant distracter stimuli can be processed (Lavie, 2005). If the task is perceptually demanding, e.g., contains distracters that are similar to targets, or requires demanding identification of targets, the capacity for information processing is filled with the task and irrelevant distracters receive very limited amount of processing. On the other hand, when the primary task is not perceptually demanding, a part of the information processing capacity involuntarily “spills over” to the irrelevant items, which causes increasing interference by task-irrelevant distracters. Thus, according to Lavie (2005), the issue of early vs. late selection depends on the cognitive and perceptual demands of the current task.

### **1.2. Eye movements in visual information processing**

The visual search studies reviewed so far concern only covert movements of attention, which are possible if eyes are unnaturally kept fixed at some location. However, when eyes move freely, as in saccadic visual search, the shifts of visual attention are thought to be coupled to eye movements (Hoffman, 1998), as covert attention and eye movement programming are related to, at least partially, overlapping neural processes (e.g. Cutrell & Marrocco, 2002; Pierrot-Deseilligny, Milea, & Müri, 2004; see also Rizzolatti et al., 1987). Therefore, since eye movements are made constantly in natural viewing, studies in which eye movements are allowed may have a higher ecological validity than studies of covert attention.

Because the retinal cell density and visual resolution decrease steeply towards the peripheral visual field (Curcio & Allen, 1990; Curcio et al., 1990; Wertheim, 1894), the retinal area of the highest resolution, the fovea, is usually turned towards the current region of interest by means of moving the eyes. These fast foveating eye movements are called saccades and they last only few tens of milliseconds depending on their amplitude (35 - 50 ms for 5 deg saccades, see Ciuffreda & Tannen, 1995). In normal individuals, the

duration and velocity of saccades are nearly linearly related to saccade amplitude. During a saccade, the detection thresholds are elevated (Ross et al., 2001), probably to prevent the visual perception of retinal movement. Thus, visual information is mostly gathered during eye fixations.

In a relatively simple visual search task, the average duration of eye fixations between saccades in a healthy individual is 200 - 300 ms, although there is considerable variation depending on the task and stimuli. Therefore, fixations take most of the time during visual search. A scan path consists of a sequence of saccades and fixations. Scan paths are closely related to the global strategy of visual search. The number of fixations needed to find the target depends on the number of items that can be processed during a single fixation. The area from which various types of visual information can be gathered during a single fixation is variously called the *perceptual span* or *visual span* (Legge et al., 1997; O'Regan, Lévy-Schoen, & Jacobs, 1983; Rayner, 1998).

### **1.2.1. Concepts of perceptual span and visual span in reading studies**

In studies investigating eye movements in reading, several different concepts have been used to refer to the amount of different kinds of information available around the fixation point. Concepts of *perceptual span* (McConkie & Rayner, 1975; Rayner, 1975), *visual span* (Jacobs, 1986; Legge et al., 1997; O'Regan, 1990), *conspicuity area* (e.g. Motter & Belky, 1998), *span of the effective stimulus* (Bertera & Rayner, 2000), *effective visual field* (McConkie & Rayner, 1975) and *word identification span* (Rayner, 1998; Underwood & McConkie, 1985) all resemble each other.

Originally the concepts of *perceptual span* and *effective visual field* were used to refer to the region from which readers pick up various types of information during a fixation in reading. It includes information about letters that can be recognised, some partial information about letters, contextual linguistic information and information about spaces between words. Several studies indicate that, for readers of alphabetical orthographies, the size of the perceptual span is about 14 - 15 character spaces to the direction of reading, and about 3 - 4 character spaces to the opposite direction (see Rayner, 1998 for review). However, specific information about individual letters is acquired from no further than 6 - 8 characters to the right or 3 - 4 letters to the left of the fixation point (Underwood & McConkie, 1985; Rayner & Fisher, 1987). Perceptual span has been shown to be considerably smaller for more densely packed languages. For example, for Japanese it is about 5 - 7 character spaces to the vertical or horizontal direction of reading (Osaka & Oda, 1991; Osaka, 1992).

The concept of *visual span* describes the number of letters of a given size that are visible during a single eye fixation without the help of any contextual or linguistic information

(O'Regan, 1990; Jacobs, 1986). The size of the horizontal visual span has been estimated with isolated letters or meaningless strings of letters (O'Regan et al., 1983; Jacobs, 1986). O'Regan et al. (1983) found that the size of the visual span was about 5 letters to the left and right from the fixation point when the required response accuracy was 90%. Legge et al. (1997) have estimated the *visual span in reading*. They used isolated words presented with the RSVP (rapid serial visual presentation) method. Reading speed (words/min) was calculated, and the reading time (ms/word) was determined. They found that horizontal diameter of the *visual span in reading* in fovea was about 10.6 characters for text of normal size (character size of 1 deg).

### **1.2.2. Visual and perceptual span in two-dimensional visual search**

As reviewed above, in reading the concepts of perceptual span and visual span refer to different things. However, unlike in reading, in two-dimensional visual search the two concepts can be used nearly synonymously, particularly when simple stimuli are used, because stimuli are independent of each other and contextual information does not affect the identification of targets, as in reading. In this study we have used the concept of *perceptual span* to refer to the area of the visual field from which the target item in visual search can be found during a single fixation. This is because the more general concept of perceptual span includes both “top-down” and “bottom-up” factors that might affect the size of the span in visual search, whereas the concept of visual span is limited to low-level factors by definition. While reviewing previous studies, the concepts of visual span and perceptual span are used here as the authors of the original articles have done. Although the usage may be confusing in some instances, we did not want to violate the authors' terminology.

In Study III, in which real words were used as visual search stimuli, we used the concept of *word identification span*, because words can sometimes be identified on the basis of partial letter information, and therefore, the span estimate may there be slightly different from the visual span for isolated letters or objects. Here we have followed the definition of Rayner (1998, p. 380) for *word identification span* as “area from which words can be identified on a given fixation”. This concept does not include information about character spaces or sentence structure as the perceptual span in reading, and is, therefore, narrower. For further discussion on different concepts related to the perceptual and visual span, see the Introduction section in Study III.

### **1.2.3. Perceptual span in visual search is two-dimensional**

The perceptual span estimated for reading is asymmetrical and strongly elongated to the direction of reading (Rayner, 1998), and subjects seem to obtain little information from

lines below the fixated line (Pollatsek et al., 1993). The asymmetry is probably related to allocation of attention, because subjects in these studies are instructed to search or read the rows in horizontal order. Because visual acuity depends on retinal receptor cell and ganglion cell densities (Rovamo & Virsu, 1979; Virsu & Hari, 1996, Figs. 4 and 5), which drop nearly symmetrically (although vertically more steeply) towards the periphery (Curcio and Allen, 1990; Curcio et al., 1990), the perceptual span should actually be more or less round or elliptical, and not as heavily elongated as previous reading studies suggest. To clarify these questions, we have investigated the perceptual span in visual search of two-dimensional stimulus matrices for different stimulus types and layouts in Studies I, III, IV and VI.

#### **1.2.4. Visual span control hypothesis**

*The visual span control hypothesis* (O'Regan et al., 1983) for reading postulates that eye movements are controlled mainly in relation to the size of the visual span. Jacobs (1986) found that in a simple horizontal letter search, about 80% of the variance of mean saccade sizes and about 45% of the variation in fixation durations could be explained by the changes in visual span measured in psychophysical experiments manipulating viewing distance, letter spacing, and target-distractor similarity. When the target item was hard to discriminate (i.e., the visual span was considered to be small), saccade amplitudes were short and constant, whereas fixation durations were long and variable. When the target item was easy to discriminate (i.e., the visual span was considered to be large), saccade sizes were variable, but fixation durations were relatively short and constant. However, since these tasks were strictly one-dimensional, there is no information how well the hypothesis accounts for the search tasks with two-dimensional stimuli, or for more complex objects.

#### **1.2.5. Shrinking visual/perceptual span hypothesis**

Since visual span by definition strongly reflects the sensory acuity limitations of the retina, the size of the span varies as a function of viewing conditions. Legge et al. (1997) have shown that, in reading, changes in visual span affect both reading speed and eye movements. They showed that when the luminance contrast decreased, visual span shrank, resulting in a reduction of reading speed. With decreasing contrast, reading speed became increasingly dependent on word length because, with decreasing span, longer words needed to be fixated more than once. In the results of Legge et al. (1997), longer reading times at low contrast were partitioned about equally between prolonged fixation times and an increased number of fixations.

In the periphery, the visual span for isolated words measured with RSVP is only on average 1.7 letters at 15 deg eccentricity in comparison to at least 10 letters in the fovea

(Legge, Mansfield & Chung, 2001). This is in good agreement with the reduction of reading speed observed with increasing eccentricity (Chung, Mansfield, & Legge, 1998). Recently it has been also shown that the patients using eccentric fixation due to central field loss following macular disease have a small perceptual span in peripheral vision, and the changes in reading speed as the disease progresses are related to changes in the size of their peripheral span (Crossland & Rubin, 2006; see also Déruaz et al., 2005).

These studies show that visual span is an important determinant of reading performance in the fovea as well as in the periphery. Further, perceptual learning has been shown to increase the visual span in peripheral vision (Chung, Legge, & Cheung, 2004), which opens up new possibilities of rehabilitation for patients with central visual field loss. It also suggests that the size of the visual span in reading is not completely determined by low-level factors such as spatial resolution. In Study I, the effect of stimulus contrast on perceptual span in two-dimensional visual search was investigated.

### **1.3. Neural basis of saccadic visual search and selective attention**

Visual saccadic search requires joint functioning of many brain areas, for example, areas responsible for early visual information processing, object recognition, eye movement coordination, selective attention, long-term memory, and possibly working memory (e.g., Chelazzi et al., 1993, 1998; Desimone & Duncan, 1995; Leonards et al., 2000; see also Ungerleider et al., 1998).

Classically visual system for object recognition is seen as a hierarchy of cortical areas, where neurons of low-level cortical areas (V1, V2) receive visual input from the retina mostly via the lateral geniculate nucleus (LGN) of the thalamus and represent simple features such as lines and edges of specific location and orientation. The output of the low-level cortical areas is integrated and further processed in higher cortical areas, which represent increasingly complex physical stimulus characteristics. The highest visual cortical levels (inferotemporal cortex, for example) integrate the information and represent abstract forms, complex objects and different categories. For example, the identification of faces has been shown to occur in inferotemporal areas distinct from those for letter identification (e.g. Allison et al., 1999; Haxby et al., 2000; see also Vuilleumier et al., 2003). Objects are also recognised independently of lighting conditions (Vogels & Biederman, 2002) or contrast (Avidan et al., 2002). Retinal location plays a minor role at higher cortical levels since receptive fields are very large (see e.g. Kandel, Schwartz, & Jessell, 2000, p. 564). Lesions in the specialised cortical areas result in highly specific deficits of object recognition called agnosias (see Farah, 1990). Prosopagnosia, an inability to identify familiar faces, is one example of them.

### **1.3.1. Eye movement coordination and attention**

The cortical co-ordination of eye movements takes place via the superior colliculus (SC) in the midbrain that specifies the desired change in eye position. SC receives input directly from the retina as well as from the middle temporal and parietal cortices and the frontal eye fields (FEF). Some neurons in SC respond to visual stimuli, some control motor neural circuits responsible for eye movements, and some inhibit eye movement neurons and are active during fixations (McPeck & Keller, 2004; Krauzlis, Liston, & Carello, 2004). The eye movement signal is transformed in the brain stem into velocity and position instructions further organized by areas in the paramedian pontine reticular formation (horizontal components), and the mesencephalic reticular formation (vertical components). The accuracy of saccades is also affected by cerebellar areas. For a recent review, see Leigh and Kennard (2004).

Top-down control of SC takes place via the frontal and parietal areas that modulate visual attention, the parietal eye field (PEF) involved in the programming of reflexive saccades, as well as FEF that primarily provides excitatory motor commands for all types of voluntary saccades (Leigh & Kennard, 2004; Pierrot-Deseilligny et al., 2004; Rivaud et al., 1994; Schall, 2004b). FEF also participates in visual search without eye movements, and has been proposed to mediate covert and overt attention (Muggleton et al., 2003; Schall, 2004a, b; Thompson, Biscoe, & Sato, 2005; but see Paus, 1996). In addition, other frontal areas connected to FEF, such as the dorsolateral prefrontal cortex (DLPFC) and the supplementary eye field (SEF) participate in saccade control. SEF is involved in motor programming of rapid sequences of saccades, and DLPFC is involved in cognitive saccade control, such as inhibition, anticipation, and saccadic short-term memory (Kennard et al., 2005; Pierrot-Deseilligny et al., 2004). Frontal lesions in FEF or DLPFC cause difficulties in suppressing unwanted saccades to salient stimuli (Leigh & Kennard, 2004; Pierrot-Deseilligny et al., 2004). Functions of different parietal areas are less well known, but the posterior parts (PPC) around the intraparietal sulcus are involved in the control of both saccades and attention (see below). In the primate PPC, a plain shift of spatial attention, or an actual saccade was generated depending on the magnitude of electrical stimulation (Cutrell & Marrocco, 2002). Cingulate cortex (ACC/PCC) in the parietal lobe seems to be related to intentional motivational control of saccades, and is thought to control the frontal area DLPFC (Pierrot-Deseilligny et al., 2004). Parietal lesions have been shown to cause both eye movement abnormalities, as well as disorders of spatial attention (neglect) (see e.g., Kennard et al., 2005; Mort & Kennard, 2003). For a recent review of cortical eye movement control, see Pierrot-Deseilligny et al. (2004).

### **1.3.2. Selective attention modulates neural responses to visual stimuli**

Many neuroimaging studies show that an extensive system of overlapping brain areas is activated by both overt (saccades) and covert attention (e.g. Fink et al., 1997; Nobre et al., 2000; Pierrot-Deseilligny et al., 2004). These areas consist of the superior frontal cortex, including FEF, and the superior and inferior parietal cortex, including the intraparietal sulcus. This *fronto-parietal network* has been suggested to especially control spatial selective attention, and also nonspatial orienting of attention to some extent (Giesbrecht et al., 2003; Hopfinger et al., 2001). One “attentional system” including the intraparietal cortex and the superior frontal cortex (the putative FEF) seems to be involved in maintaining attention in a location *before* the presentation of visual stimuli, whereas the other system including the temporoparietal cortex and the inferior frontal cortex seems to direct attention to salient events at previously unattended regions (Corbetta et al., 2000; Corbetta & Shulman, 2002). These areas, especially FEF, have been suggested to form the neural basis of the selection of successive fixation points during visual search, guided both by the salience of stimuli, as well as by the top-down influences related to search stimuli, such as memory representations or training (Schall, 2004b; Thompson & Bichot, 1999).

It has been suggested that frontal and parietal control of attention can act by biasing the competition of visual stimuli for representation in the extrastriate cortical areas (Chelazzi et al., 1998; Desimone, 1996, 1998; Desimone & Duncan, 1995; Peers et al., 2005, see also Hamker, 2005). Selective attention has been shown to modify neural responses to visual stimuli at several different levels of the visual system, including the inferotemporal areas (IT) (Chelazzi et al., 1993, 1998; Desimone & Duncan, 1995), V4 (Mazer & Gallant, 2003), V1 (Roelfsema, Lamme, & Spekreijse, 1998; Somers et al., 1999) and the LGN (O’Connor et al., 2002). In these brain areas, neural responses to attended stimuli within receptive field were enhanced, responses to ignored stimuli were attenuated, and the baseline activity in the absence of visual stimuli was increased, when stimuli were anticipated soon to appear at the attended location.

In addition to cortical top-down control, also subcortical neural systems may modulate the neural representations of sensory information. For example, rapid detection via the amygdala of visual stimuli with recognised emotional relevance, such as those related to fear or threat, has been shown to modify neural processing of visual information in the ventral stream, as well as to interact with cortical control of selective attention (Vuilleumier, 2005; Vuilleumier et al. 2001, 2003, 2004; Vuilleumier & Schwartz, 2001). In summary, attention and other top-down processes affect several levels of visual information processing in a complex way, and, in a sense, low-level (“bottom-up”) and high-level (“top-down”) information processing become intertwined in the neural processing of stimuli.

## **1.4. What limits performance in saccadic visual search?**

As discussed in Section 1.1., traditional visual search theories (e.g. Treisman & Gelade, 1980; Wolfe et al., 1989) considerably emphasize high-level cognitive processing, especially attentional mechanisms. However, many low-level factors, such as the normal physiological properties of the eye (e.g., optics, cell density, and the properties of the receptive fields in the retina), signal transmission and information processing at early stages of the visual system, as well as the amount of information available in the stimulus itself, may strongly affect performance in visual tasks. Although higher cortical levels are increasingly independent of many stimulus properties, such as the retinal size or luminance contrast of the stimuli (Avidan et al., 2002), the low-level factors may in some cases limit the amount of information available to high-level information processing, and/or affect the temporal characteristics of signal transmission (see Näsänen et al., 2006).

One particularly important low-level factor is the decreasing spatial resolution with increasing retinal eccentricity (Rovamo, Virsu, & Näsänen, 1978; Virsu & Rovamo, 1979), which results primarily from decreasing ganglion cell density with increasing eccentricity (Curcio & Allen, 1990). This dramatically affects the stimulus information available above the level of ganglion cells (see demonstration in Geisler & Chou, 1995, p. 360). This is particularly important in visual search tasks with multiple stimuli, where peripheral discrimination is essential for performance. One consequence of the decreasing retinal resolution is that the available stimulus information with increasing eccentricity is dependent on spatial frequency content of the stimuli, because the contrast attenuation increases with eccentricity more rapidly for high than low spatial frequency information.

On the other hand, psychophysical studies have shown that different spatial frequencies are selectively utilised in the recognition of different objects. According to these studies, the critical spatial frequency information used in static face recognition task is mainly limited to a band of mid spatial frequencies, mostly between 8 – 16 c/face width (Costen, Parker, & Craw, 1996; Fiorentini, Maffei, & Sandini, 1983; Gold, Bennett, & Sekuler, 1999; Harmon & Julesz, 1973; Näsänen, 1999; Peli et al., 1994; Tieger & Ganz, 1979; see also Vuilleumier et al., 2003). For characters, the critical frequencies are 2 - 3 c/character height (Solomon and Pelli, 1994; but see Chung, Legge, & Tjan, 2002; Majaj et al., 2002). Therefore, the effect of retinal eccentricity on the availability of critical stimulus information may be different for different objects and stimulus sizes used in visual search tasks. However, it is unclear whether the selective use of spatial frequency information also applies to tasks that require eye movements and fast object recognition as in natural situations. This was investigated in Study V for saccadic visual search for faces.

Some stimulus properties related to low-level visual information processing, such as luminance contrast or stimulus size have been investigated in psychophysical studies of

## INTRODUCTION

---

complex visual tasks, such as reading (Legge et al., 1985; Legge, Rubin, & Luebker, 1987; Knoblauch, Arditi, & Szlyk, 1991). Maximum reading rates were achieved at character sizes between 0.25 - 2 deg, and reading rates decreased for both increasing and decreasing character sizes. Within the optimal range of character sizes, reading rate was quite tolerant of the reduction of luminance contrast - a tenfold reduction in luminance contrast only resulted in a twofold reduction in reading speed. However, for characters smaller than 0.25 deg or larger than 2 deg, reading rate decreased more rapidly with decreasing luminance contrast. These effects are probably related to the contrast sensitivity of the human visual system, which decreases towards small or very large spatial frequencies (see e.g. Campbell & Robson, 1968). For very small stimuli the effect is also related to the optical contrast attenuation of high spatial frequencies in the eye, which results in the decrease of retinal contrast even near the fovea (see Navarro, Artal, & Williams, 1993). In Studies I, II, IV and VI the effects of luminance and colour contrast and stimulus size were investigated for two-dimensional visual search for complex objects (characters, computer icons and faces).

Legge et al. (2001) investigated letter recognition and RSVP reading performance in central and peripheral vision. Their model using information about human visual span, i.e., the number of individual letters recognised within fixation, together with a simple lexical matching rule, could account for the reading speed in central vision. Thus, the reading speed in central vision may be limited only by the low-level spatiotemporal limits of letter recognition. However, in peripheral vision, humans outperformed the simple model using also some kind of lexical inference to compensate for the reduced size of their visual span.

Different low-level factors may actually explain a considerable proportion of variance also in visual search performance, at least for simple stimuli. Geisler and Chou (1995) estimated the effect of low-level factors by measuring discrimination performance in a 2AFC task as a function of eccentricity. This task was designed to minimise high-level demands and did not include any spatial uncertainty. The discrimination performance was expressed as the size of the accuracy window within which the target was detected, and was compared to visual search performance for the same stimuli. Most of the visual search time variance in simple tasks was accounted for by the discrimination performance, i.e., by the contribution of low-level factors. Further, some specific effects like decreasing performance with increasing number of stimuli (set size effect), decreased performance for conjunction stimuli, and the effects of search asymmetry were shown to be related to low-level rather than high-level factors. Similarly, Palmer, Verghese, and Pavel (2000) have shown that in search tasks with simple feature stimuli, signal detection models using only low-level information could account for many phenomena of visual search previously attributed to limited attentional capacity or serial processing. These included the effects of set size, multiple targets and distractor heterogeneity. Further, Carrasco and Frieder (1997,

## INTRODUCTION

---

see also Carrasco et al., 1998) have shown that the eccentricity effect in covert visual search is eliminated when peripheral stimuli are magnified in relation to cortical magnification factor (Rovamo & Virsu, 1979; Virsu & Rovamo, 1979). Thus, the eccentricity effect that had previously been attributed to covert attention may be explained by the reduced spatial resolution with increasing eccentricity.

In summary, the studies discussed here suggest that low-level physiological properties of the visual system should be taken into account more carefully in interpreting visual search data. However, the contribution of high-level control may be larger for more complex visual search tasks or stimuli. In the present study, we investigated one complex visual task, saccadic search for complex objects. We were especially interested in stimulus properties related to low-level information processing, and their effect on search performance and eye movements. Since perceptual span has been shown to be important in reading and in simple one-dimensional search, we investigated the two-dimensional span for different complex objects and for different stimulus contrasts.

## 2. AIMS OF THE PRESENT STUDY

In the present study, we investigated the performance in a saccadic visual search task, where complex objects of different types (characters, faces, computer icons, or words) were required to be identified in a two-dimensional stimulus array. The effects of different stimulus properties, such as size, luminance contrast, colour contrast, spatial frequency, sharpness, layout, and stimulus set size on visual search performance and eye movement parameters were investigated. Especially, the size of the two-dimensional perceptual span was estimated for different object types, such as characters (Study I), words (Study III), computer icons (Study IV), and faces (Study VI). In addition, we investigated whether visual search and eye movement measurement can give useful information for characterising visual perception in patients with chronic solvent encephalopathy.

In contrast to traditional visual search studies, the performance was measured by using a psychophysical method (adaptive staircase algorithm) that allows the estimation of the time used for stimulus processing separately from the confounding factors of manual reaction speed or time used for decision-making before responses. In addition, the method allowed the estimation of visual search performance and eye movements near or at threshold level for pre-determined accuracy without any effect of speed-accuracy trade-off.

Specific aims of each individual study were:

Study I: To investigate the effect of luminance contrast on visual search for characters and estimate the perceptual span for character information.

Study II: To investigate the effects of colour contrast, luminance contrast and character size on visual search.

Study III: To investigate the effects of stimulus layout and set size on visual search for words and estimate the perceptual span for vertical word lists.

Study IV: To investigate the effects of luminance contrast and sharpness (blur) on visual search for computer icons.

Study V: To investigate the effect of spatial frequency information on visual search for faces.

Study VI: To estimate the perceptual span for faces and investigate the effect of retinal stimulus size.

Study VII: To investigate visual search performance and eye movements in patients with chronic solvent encephalopathy (CSE).

## 3. METHODS

### 3.1. Subjects

#### Psychophysical studies (I - VI)

Each study had 3 - 5 volunteer subjects. All subjects had normal or corrected to normal vision and were native speakers of the Finnish language. In addition, 16 voluntary subjects participated in a reading experiment in Study II.

#### Clinical study (VII)

Study VII had 13 volunteer patients (12 male). Their mean age was 56.2 (SD 4.8, range 45 - 65) years. They had, on the average, 8.7 (SD 1.4) years of education. All patients had previously received a diagnosis of chronic solvent-induced toxic encephalopathy (CSE) caused by a long-term occupational exposure to mixtures of several organic solvents. The CSE patients participated in the study when they came to their regular yearly follow-up visit at the Finnish Institute of Occupational Health during the year 2002. The diagnostic procedure consisted of medical investigations, a careful examination of the visual function and a neuropsychological investigation (see details in Study VII). The exclusion criteria were the following: other main diagnoses such as major depression or other psychiatric diagnosis, major sleep disorder, previous heavy alcohol consumption, current strong medication with central nervous system effects, and any disease or condition affecting eyes or visual system (unrelated to CSE, such as glaucoma or cataract).

There were two groups of healthy controls. One group (N = 14, 2 female, later referred to as *controls*) was matched with the patient group for gender, age, and years of education. The other control group (N = 8, 1 female, later referred to as *educated controls*) was also matched for age and gender, but had about 8.5 years more education (mean 18 years, SD 1.9). The highly educated controls were included in order to study the effect of education on performance in the visual search task used in this study. The vision of all subjects was carefully examined. The patients were investigated as a part of their medical examinations, and the controls were recruited among people participating in a normative project for clinical vision tests. Thus, all subjects participated in tests for visual acuity, contrast sensitivity, colour vision, and visual field sensitivity, as well as in clinical ocular examination, and assessment of basic oculomotor functions. All subjects filled in a comprehensive symptom and health questionnaire (see Chouanière et al., 1997, Kaukiainen et. al., 2004).

## 3.2. Stimuli

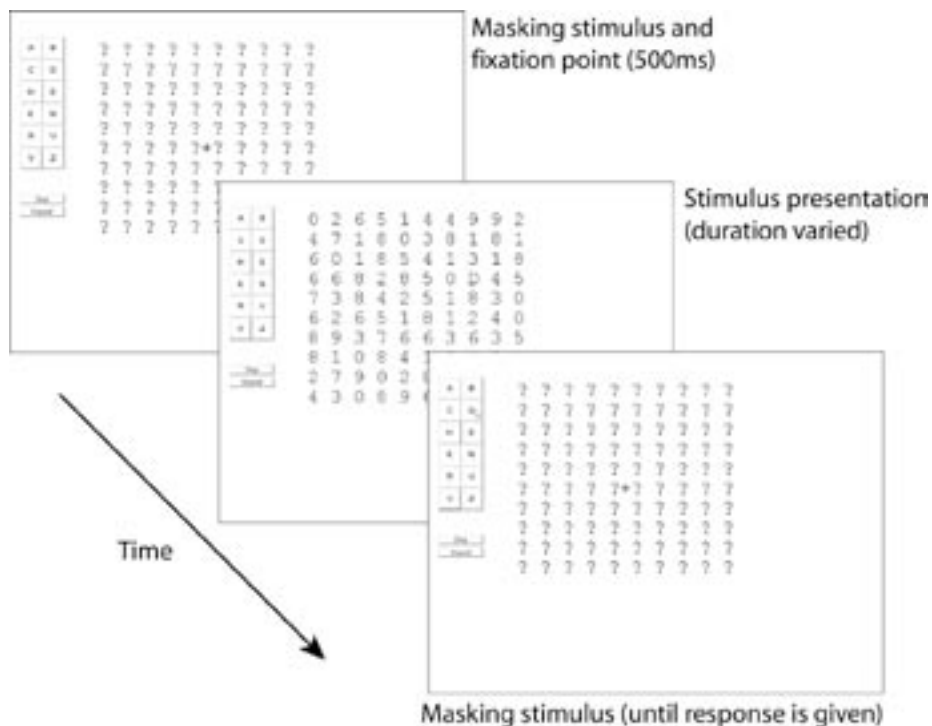
All stimuli were presented on a computer screen. The nonlinear relationship between grey level and luminance was taken into account in generating stimuli (gamma correction). The greyscale resolution of the displays used was eight bits (256 grey levels). In colour stimuli the bit resolution was eight bits per colour channel (“true colour”).

### Letter search (Studies I, II, and VII)

In Studies I, II, and VII, subjects searched for a target letter among numerals in a rectangular matrix (see Fig. 1). The target could be any of the 12 (or 14 in Study I) alternatives: A, B, C, D, E, H, K, N, R, (S,) U, V, (X,) or Z. Distracters were numerals (0 - 9). Letter height in Studies I and VII was 0.9 and 1 deg, respectively. Three character sizes (0.17, 0.37, and 1.26 deg) were used in Study II. In Studies I and VII, letters and numerals were black on a grey or white background, respectively. In Study I, luminance contrast was varied. Luminance contrast ( $c$ ) was expressed as Michelson contrast:  $c = (L_{max} - L_{min}) / (L_{max} + L_{min})$ , where  $L_{max}$  is the background luminance and  $L_{min}$  is the character luminance). Contrasts in different conditions were 0.037, 0.07, 0.15, 0.29, and 0.58.

In Study II, the colours of the characters and background were varied in different experiments. In the first experiment, background was grey and stimuli were green (moderate colour difference). In two experiments with high colour difference, background was either blue or red, and stimuli were yellow, or green, respectively. In Study II, the luminance difference between stimuli and background was systematically varied in each experiment, while stimulus colours were kept constant within each experiment.

## METHODS



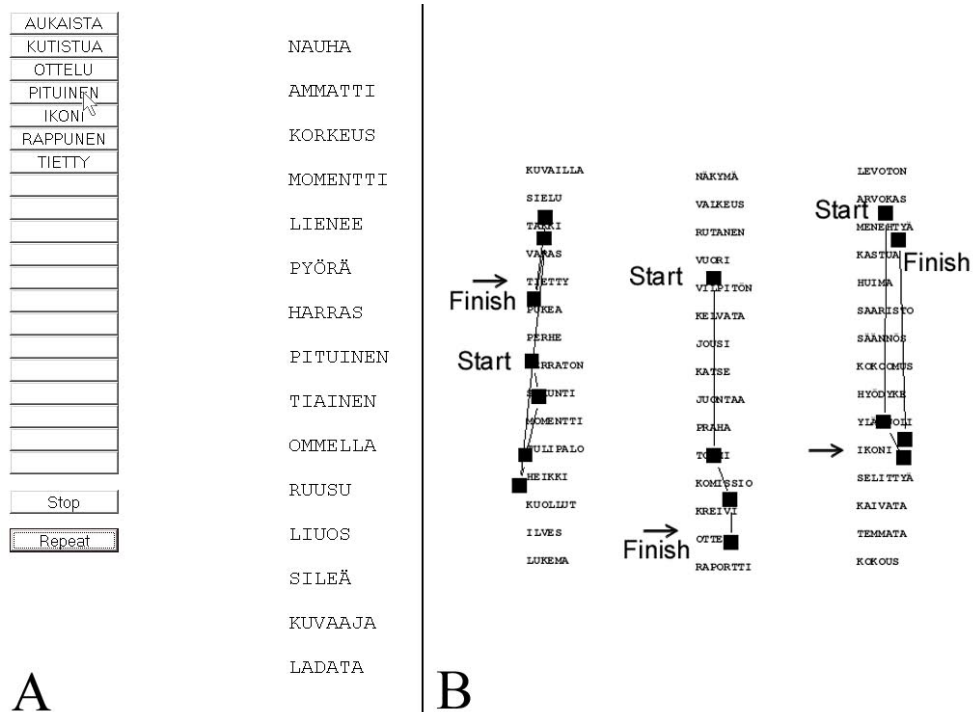
**Figure 1.** Visual search procedure used in all studies. The presentation duration of stimulus array (middle) varied adaptively in relation to the correct and incorrect answers of the subject by using a staircase algorithm (see Fig. 5). After about 50 search trials the threshold search time estimate with a fixed probability of correct answers (0.79) was obtained. The estimate is independent of the speed of manual reactions. Eye movements were measured during stimulus presentation. An example of stimuli in Study VII is shown.

### Word search (Study III)

Subjects were required to search for the target words (any of the following: AUKAISTA<sup>1</sup>, KUTISTUA, OTTELU, PITUINEN, IKONI, RAPPUNEN, TIETTY) among distracter words (see Fig. 2). Distracter words were common Finnish words of 6 – 8 characters, and were randomly selected from a set of 2640 words. The set was selected from a frequency dictionary (Saukkonen et al., 1979). Target words had similar length and mean frequency. Words were presented in black on a white background. The list length (3 – 8 in experiment 1, and 5, 10, 15, or 20 in experiment 3), layout (horizontal/vertical), and line spacing (0 – 4 spaces between vertical lines) were manipulated. Letter height was about 0.4 deg, and width 0.24 deg.

<sup>1</sup> In English AUKAISTA = to open, KUTISTUA = to shrink, OTTELU = game/match, PITUINEN = length, IKONI = icon, RAPPUNEN = step/stair, TIETTY = certain.

## METHODS



**Figure 2.** A: An example of vertical word lists used in Study III. Response buttons with target words are shown on the left. B: Examples of scanning paths to vertical lists. Target words are marked with arrows.

### Icon search (Study IV)

In Study IV computer icon was searched in an array of 13 x 13 icons (Fig. 3 A). Two different target icons of different conspicuity were used in different conditions (Fig. 3 B). Distracters were other computer icons selected randomly among 18 different alternatives. The stimulus arrays were filtered by using a circularly symmetric Gaussian low-pass filter with different cut-off frequencies (1, 1.4, 2, 2.8, 4, 5.6, 8, and 11 c/icon width) to obtain different levels of blur. In the contrast condition, Michelson luminance contrasts of the stimuli were 0.062, 0.125, 0.25, 0.5 and 0.99.

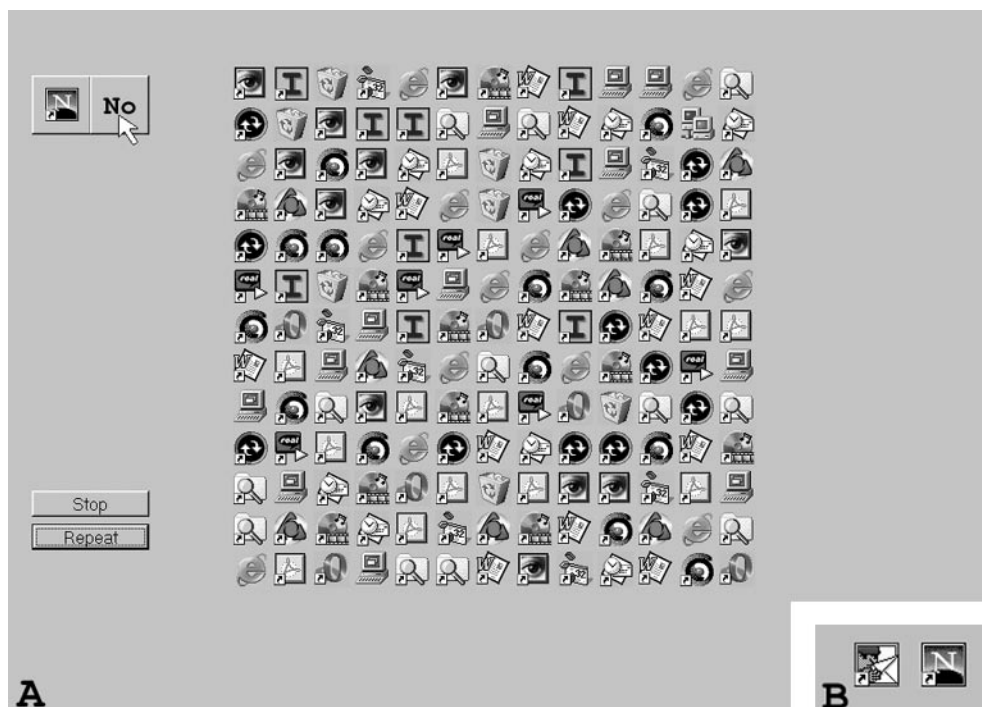
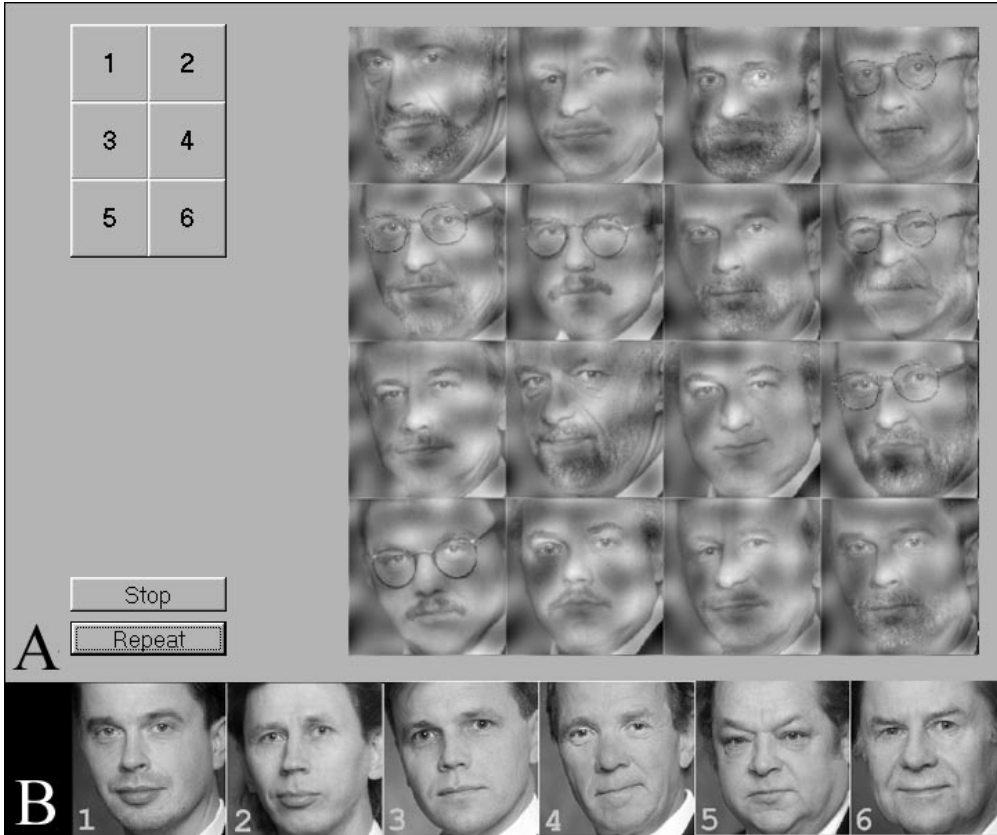


Figure 3. A: The display during icon search in Study IV. B: Two targets used (OM and NS, see Fig. 6).

### Face search (Studies V and VI)

In Studies V and VI, the stimuli were black-and-white facial images of men (Fig. 4 A). The target in each search array could be any of six alternatives that were learned before the experiment (Fig. 4 B). Distracters were facial images of 15 different persons with similar pose, clothing, and lighting conditions. Distracters in each search array were selected randomly from the set of 15 faces. The persons were not previously known to the subjects. In Study VI the stimulus set size ( $2 \times 2 - 8 \times 8$ ) and viewing distance were varied.

In Study V the set size was  $4 \times 4$  faces, and spatial frequency information available in the facial images was manipulated by using Fourier phase randomisation (Oppenheim & Lim, 1981; Piotrowski & Campbell, 1982), in which a phase spectrum within a certain band of spatial frequencies is replaced with random numbers between 0 and 360 (see Fig. 4; more examples in Study V). This results in the total absence of useful spatial frequency information within the randomised band without changing the contrast or the natural Fourier amplitude spectrum of the image. Nine one-octave wide bands with centre frequencies of 2, 2.8, 4, 5.6, 8, 11, 16, 23, and 32 c/face width were used. In the control condition no randomisation was done.



*Figure 4.* A: The display during face search in Study V. Stimuli with phase randomisation of one-octave band with centre frequency of 2.8 c/face width are shown. B: Six target faces used in Studies V and VI. The numbers associated to each face and response button were learned before the experiments.

### 3.3. Procedure

#### 3.3.1. Visual search task

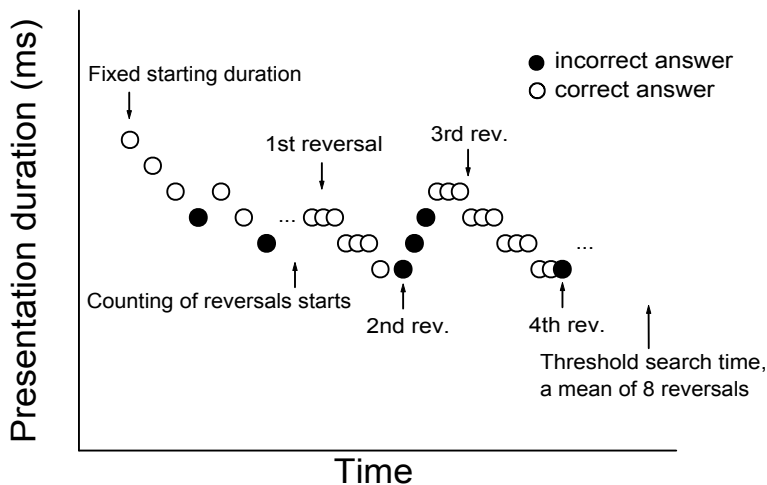
The task of the subject in all studies was to search for and identify one of the pre-learned targets from a set of distracters in a stimulus array (Fig. 1). The presentation duration of stimulus array was varied adaptively depending on the correct and incorrect answers of the subject (see Fig. 5 for details). Close to the left-hand edge of the stimulus screen was an array of graphical buttons, one button for each target. Buttons were either numbered (in Studies V and VI), or the image of the target was in the button. In all studies, except

## METHODS

VII, subjects responded by selecting the graphical button corresponding to target with the mouse. In Study VII, subjects spoke out their response and the experimenter used the mouse. All tasks were non-speeded, i.e., responses were given after the stimulus presentation had ended. A forced-choice procedure was used. After each non-speeded response, there was a delay of 500 ms before the next stimulus array was presented. The subjects were allowed to move their eyes freely over the screen while searching the target.

### 3.3.2. Staircase procedure

The duration of stimulus presentation was adaptively varied to estimate the *threshold search time*, that is, the time required to find the target with a certain probability (see Fig. 5). Therefore, the error level of all subjects was equated by the procedure, and the performance could be expressed solely as a function of search time. In addition, the procedure allowed exclusion of the effects of the speed of the manual reactions from search time estimates. The mean number of stimulus presentations needed for a single threshold estimate was around 50. The measurement for each condition was repeated 3 – 6 times with a counter-balanced order of different conditions in each study. Therefore, each data point includes about 150 – 300 search trials per subject.



**Figure 5.** The duration of stimulus presentation was controlled by an adaptive staircase algorithm (Wetherill & Levitt, 1965) in the following way. Initially the stimulus array was visible for a pre-determined time (4000 ms usually, and 6000 ms in Study VII). After each correct response, the presentation duration of the next stimulus array was reduced by a factor of 1.26, and after each incorrect response the presentation duration was correspondingly increased. The counting of actual reversals started after two incorrect responses. After that, the duration of stimulus presentation was shortened only after three consecutive correct responses, and it was increased after each incorrect response (i.e., three-down-one-up algorithm). Thus, the duration was automatically adjusted close

to a level at which the probability of responding correctly ( $P$ ) three times consecutively ( $P^3$ ) is equal to that of not responding correctly over three trials ( $1 - P^3$ ). It follows from this that at threshold the probability of responding correctly three times consecutively is equal to 0.5, and the probability of correct responses is  $P = 0.5^{1/3} = 0.79$ . A resulting threshold search estimate was calculated as a mean of eight reversals.

### **3.3.3. Neuropsychological tests (Study VII)**

The Trail Making Test, Parts A and B (originally part of Army Individual Test Battery, 1944) was presented as a traditional paper-and-pencil version. In Trail Making Test, Part A (later referred to as TMT-A) the stimuli consist of encircled numbers from 1 to 25 printed in a pseudo-random order on a paper sheet (see Lezak et al., 2004). The subject is required to connect the successive numbers as fast as possible but without making errors. In Trail Making Test, Part B (later referred to as TMT-B), the stimuli consist of numbers from 1 to 13, and letters from A to L, and the subject is required to connect them in an alternating order (1 - A - 2 - B etc.). The total completion time and the number of errors were measured. In the procedure applied, a subject's errors were not corrected during the task by the experimenter. TMT is considered to measure visual scanning, motor speed, shifting of attention, and cognitive flexibility (Lezak et al., 2004, p. 372).

## **3.4. Eye movement recordings**

Eye movements during visual search were recorded simultaneously with stimulus presentation by using an EyeLink video eye tracker manufactured by Sensomotoric Instruments Inc. The sampling rate of the system was 250 Hz. The gaze position was recorded with miniature infra-red video cameras attached to a headband worn by the subject. Two infra-red LEDs in each camera illuminated the eyes. The eye tracking system was controlled by a separate computer, which was interfaced with the stimulus presentation computer via an Ethernet link. A chin rest was used to stabilise the observer's head and to set the viewing distance.

The registration of eye movements started simultaneously with stimulus presentation and was automatically switched off when the subject made an eye movement to the response buttons, when stimulus presentation ended, or when the mouse button was pressed for response. The observers were instructed to make a saccade to the response buttons as soon as possible after finding the target. The purpose of these measures was to ensure that the collected data reflect actual search performance and not eye movements made after the target was found. The collection of eye movement data started after the subject had made two errors in her/his responses. Thus, the eye movement data represent the behaviour at or near threshold level. The saccades and fixations were detected automatically by using software

provided by the manufacturer of the eye tracker. A sample was regarded as belonging to a saccade if either the acceleration or velocity exceeded their respective thresholds for that sample. Other samples were considered to belong to a fixation. Viewing was binocular in all studies, and eye movement data for both eyes were measured.

### 3.5. Statistical procedure

The eye movement data for left and right eyes were highly correlated. Therefore, the eye position data for the dominant eye of the subjects (Studies II, IV, V, VI and VII) or the mean of left and right eye values (I and III) were used in statistical analyses. However, the oculomotor eye movement data in Study VII was analysed for both eyes separately. The threshold search times, and the mean values of the eye movement measures across trials for each separate threshold measurement were used in further analysis. Therefore, there were 3 – 6 measurements for each experimental condition and subject.

In Studies I – VI, the differences between experimental conditions were statistically analysed and each subject acted as his/her own control in a counter-balanced setting. In most of the studies, all the assumptions of parametric testing were not met due to relatively small number of subjects or measurements and positively skewed distributions of search times and eye fixation data. Therefore, non-parametric statistical tests were used. The differences between conditions were analysed by using the non-parametric Friedman test (Howell, 2002), which corresponds to the repeated measures analysis of variance. The Friedman's chi-square ( $\chi^2_{\text{F}}$ ) tests the null-hypothesis that ranked scores come from the same population, i.e., they do not differ from their expected value. Correspondingly, non-parametric Spearman's correlation coefficient ( $r_s$ ) or Kendall's coefficient were used when bivariate correlations were calculated. However, in Studies I and III we used a parametric Pearson's correlation coefficient, as well as a repeated measures ANOVA and Huyhn-Feldt correction of degrees of freedom for small sample size.

In Study VII, we studied the differences between three groups of subjects. Main effects between the patients, controls, and educated controls were investigated by using the non-parametric Kruskal-Wallis Test, which corresponds to ANOVA for  $k$  independent samples. In pairwise post hoc comparisons we used the Mann-Whitney U test (or Wilcoxon's Rank Sum Test). The effect of multiple comparisons between three groups on post hoc tests was corrected by setting the criterion for statistical significance for these tests to 0.0166 instead of 0.05 (the Bonferroni procedure).

Statistical values ( $p$ -values, degrees of freedom etc.) for the data presented in the Results section are presented in original studies.

## METHODS

---

---

## 4. RESULTS

### 4.1. Effects of stimulus properties on visual search performance and eye movements in normal subjects (Studies I – VI)

Main results of Studies I, III, IV, and VI are shown in Figs. 6A (search time), B (number of fixations), C (fixation duration), and D (saccade amplitude). Data are presented as a function of set size. Data for different stimulus types, as well as luminance contrast levels, are presented as separate curves.

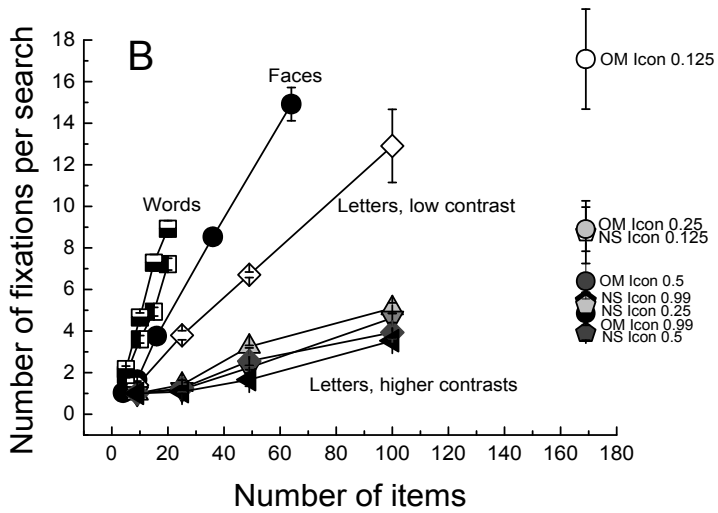
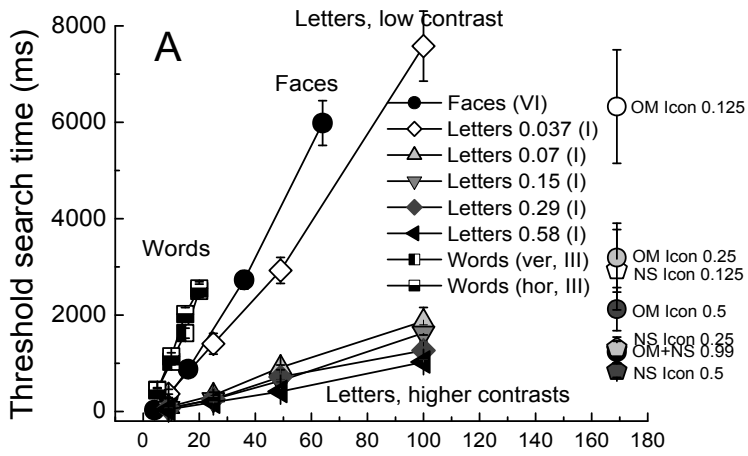
#### 4.1.1. Luminance contrast (Studies I and IV)

In Fig. 6, data for different luminance contrast conditions are plotted as separate curves for characters (Study I) and as separate data points for icons (Study IV). Contrast values corresponding to the different symbols are shown in Fig. 6A.

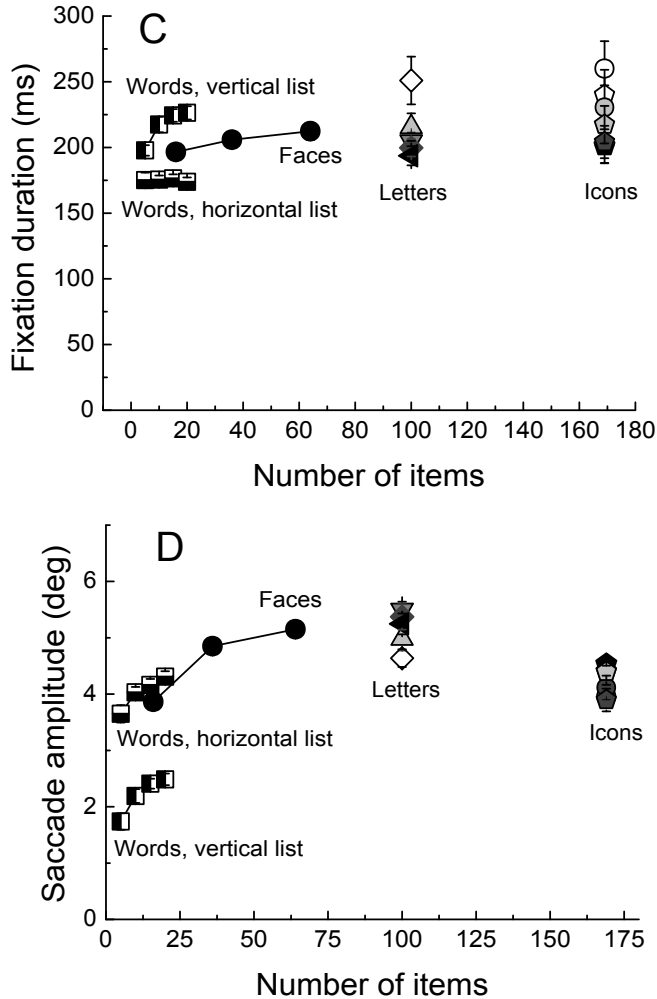
In Study I investigating characters, search times were longer for larger stimulus set sizes across contrast conditions, but the set size effect was largest for the smallest contrast. Within each set size (3 x 3 - 10 x 10), threshold search time decreased when luminance contrast between characters and their background increased. At first the decrease was very steep, but it levelled off for moderate and high contrast values. The number of fixations behaved very similarly (6B). Fixation duration decreased (6C) and saccade amplitude increased (6D) slightly with increasing contrast, more clearly for low contrast conditions.

In Study IV investigating icons, one set size of 13 x 13 and two different targets were used. One target icon was more and one less conspicuous (see Fig. 3B, right and left, respectively). The less conspicuous target icon was generally harder to find, especially at very low luminance contrast. No measurements for the less conspicuous target and the lowest luminance contrast (0.062) could be made, because the subjects could not find the target at all. As for characters in Study I, search time and the number of fixations both decreased with increasing luminance contrast, more steeply at low contrast values. Fixation duration first decreased and then levelled off with increasing contrast. Saccade amplitude was close to the value of 4 deg for all contrast values and for both target icons.

# RESULTS



## RESULTS

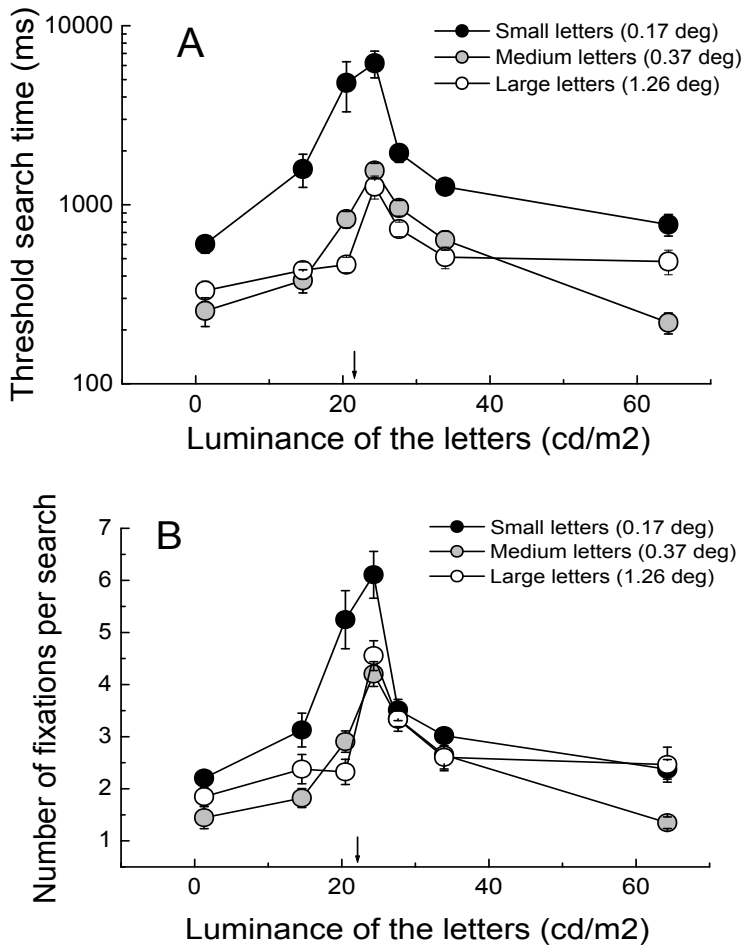


**Figure 6.** Main results of Studies I, III, IV, and VI. A: The effects of stimulus type (faces, words, icons, letters) and luminance contrast (letters, icons) on threshold search times for different stimulus set sizes. Study numbers are in parenthesis. Numbers correspond to the Michelson luminance contrasts between stimuli and background in Studies I and IV. "Ver" and "hor" correspond to the vertically and horizontally arranged word lists in Study III. Error bars represent  $\pm 1$  SEM across subjects. Individual data for each subject are plotted in the original studies. Circles refer to OpenMail icon, and pentagons to Netscape icon (Fig. 3B, on the left and right, respectively). B: The average number of eye fixations during stimulus presentation. C: The average fixation duration. D: The average saccade amplitude. Other symbols as in A. The squared correlation coefficients (i.e., the ratio of explained to total variance) between the corresponding data points of search performance (Fig. 6A) and eye movement data (Figs. 6B - D) were 0.92 for the number of fixations, 0.43 for fixation duration, and 0.07 for saccade amplitude.

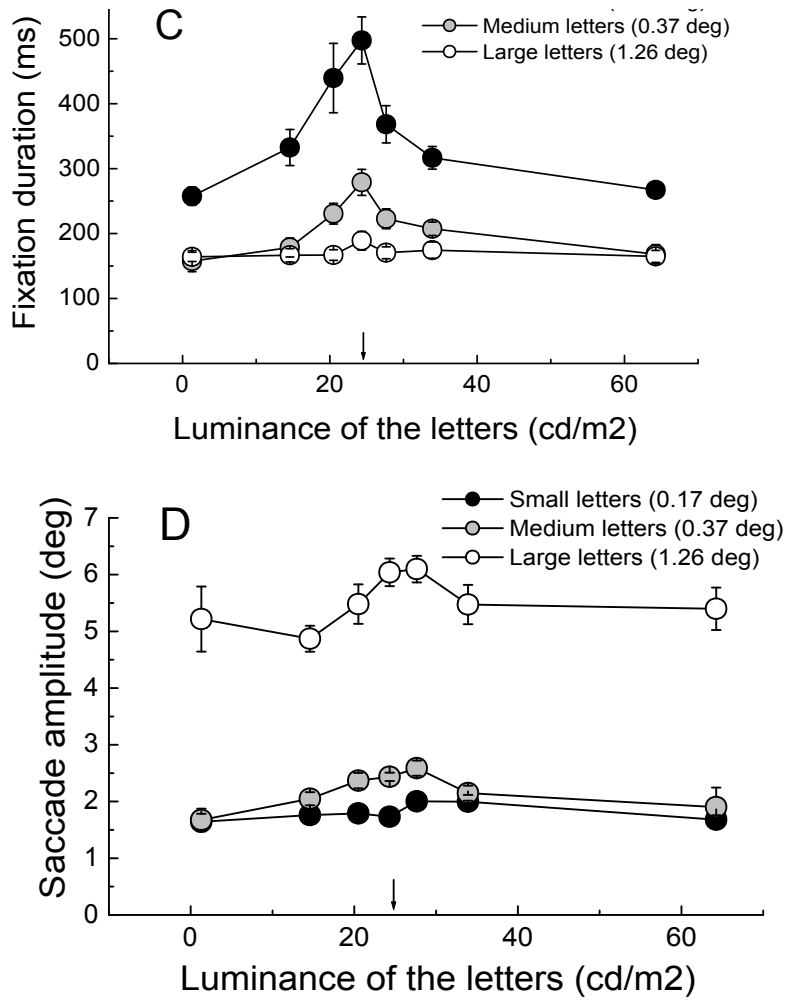
## RESULTS

### 4.1.2. Interaction of luminance contrast, colour contrast and size (Study II)

In Study II, the effect of luminance contrast was studied when there was a colour difference between characters and background. In particular we were interested in the situation, where there was almost no luminance contrast and information was mediated by colour difference. Data are presented in Fig. 7. The search times for all three character sizes differed statistically significantly as a function of character luminance. Maximum search times were found for the smallest luminance contrast between characters and background, i.e., when the characters and background were approximately equiluminous (see Fig. 7A, vertical arrow). Thus, the search performance depended on the magnitude of luminance difference between characters and background, not on the moderate colour difference.



## RESULTS



**Figure 7.** Effects of character luminance on visual search and eye movements for three different character sizes in an array of 7 x 7 stimuli (Study II). Green characters were presented on a grey background (moderate colour contrast). Luminance of the background, which was held constant, is shown with a vertical arrow. Error bars represent the  $\pm 1$  SEM. A: Threshold search time. B: Mean number of fixations per search. C: Mean fixation duration. D: Mean saccade amplitude.

For all stimulus sizes, the number of fixations increased strongly when luminance contrast between text and background was small (Fig. 7B). The effect of luminance contrast on fixation duration was different for different character sizes. Fixation durations increased with decreasing luminance contrast when character size was small or medium, but there was no significant increase for the large character size (Fig. 7C). Saccade amplitudes were not affected by the variation of luminance contrast for small or large characters, but rather reflected the angular size of the search array, which depended on character size (Fig. 7D). However, for the medium character size the small but consistent increase of saccade amplitude with decreasing luminance contrast was statistically significant. In the additional experiments with very high colour difference (blue-yellow or red-green) between characters and background, the luminance contrast still had a strong main effect on search times for small characters, and in some colour combinations for large characters too. Eye movements were not investigated in these experiments. See Study II (Figs 8 – 9, p. 176) for the data.

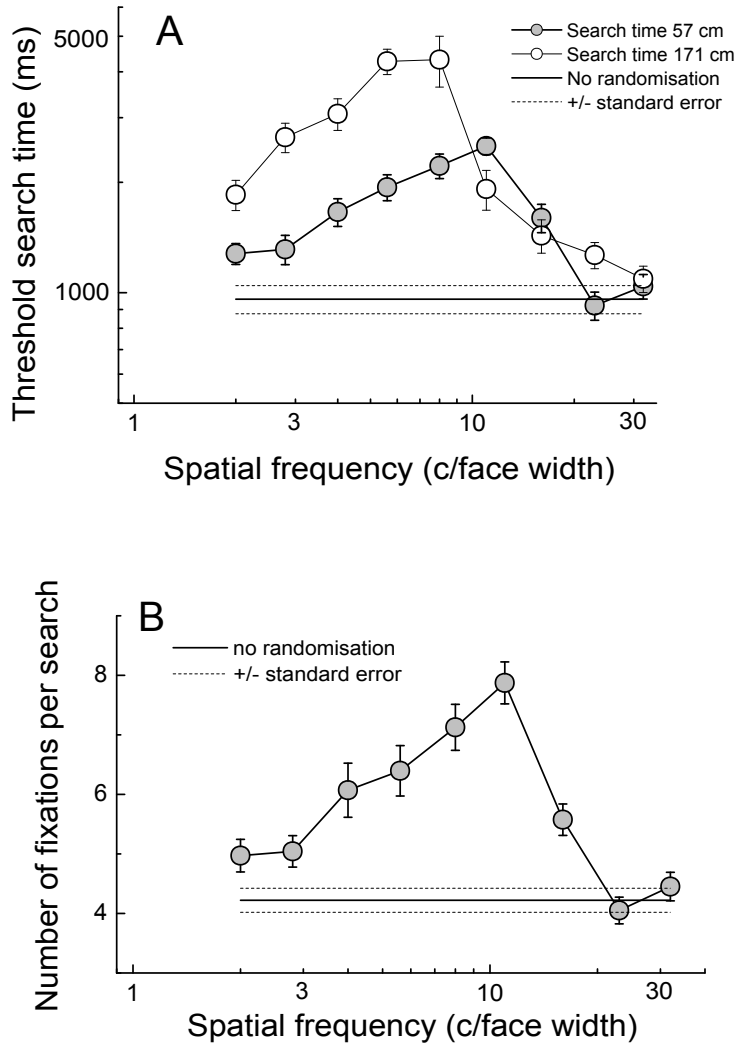
### **4.1.3. Sharpness (Study IV)**

In Study IV, the sharpness of the computer icon array was manipulated by low-pass filtering the images using a Gaussian Fourier filter of different cut-off frequencies (1, 1.4, 2, 2.8, 4, 5.6, 8, and 11 c/icon width). Blurring the stimulus array only had a small effect on threshold search times and the number of fixations, when cut-off frequency of the filter increased above 2 c/icon width. The effect was slightly larger for the less conspicuous target icon (Fig 3B). Fixation duration and saccade amplitude were nearly constant across different conditions (for details, see Figs. 5 and 6 in Study IV).

### **4.1.4. Spatial frequency information in face search (Study V)**

In Study V we investigated whether the selective utilisation of spatial frequency information previously observed in static object recognition tasks (e.g., Gold et al., 1999; Näsänen, 1999) also takes place during visual search. This was investigated by using Fourier phase randomisation. Data are presented in Fig. 8. Threshold search time was an inverted U-shaped function of the centre spatial frequency of the phase randomisation band (Fig. 8 A, grey symbols). The effect was statistically highly significant for all subjects, although the location of the maximum varied slightly. The maximum occurred at 8 - 11 c/face width, which indicates that the randomisation of mid spatial frequencies makes the visual search less efficient.

## RESULTS



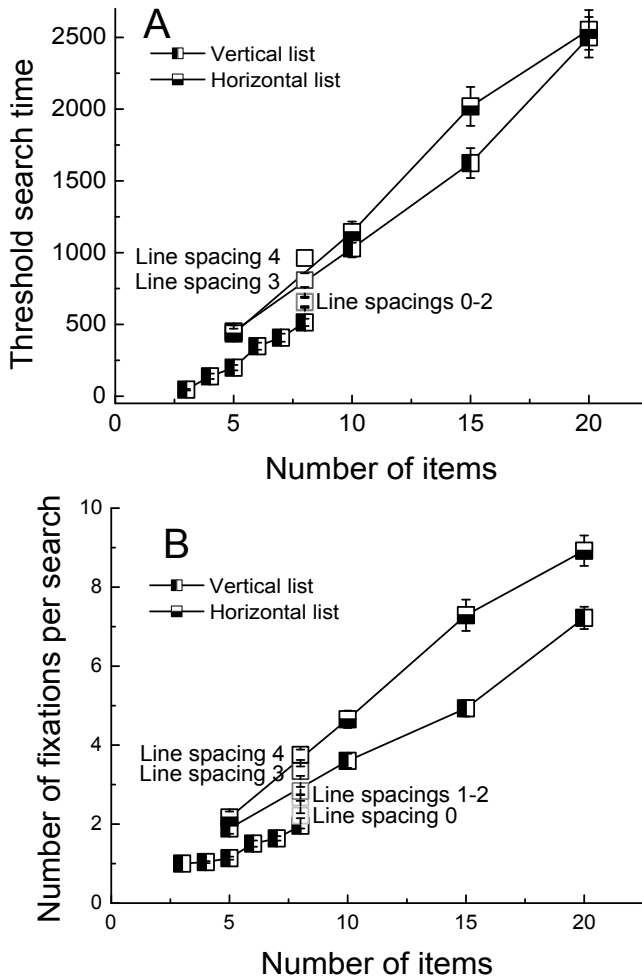
**Figure 8.** Effect of Fourier phase randomisation of spatial frequency information (centre frequency of the randomised one-octave band) on threshold search times (A) and on the number of fixations (B) in face search (Study V). Error bars indicate  $\pm 1$  SEM across subjects. Horizontal lines represent the control condition without randomisation  $\pm 1$  SEM. Open symbols in A represent the data for control experiment with three-fold viewing distance. The search time in corresponding control condition without randomisation (lines not shown) was 1350 ms (SEM 207 ms).

## RESULTS

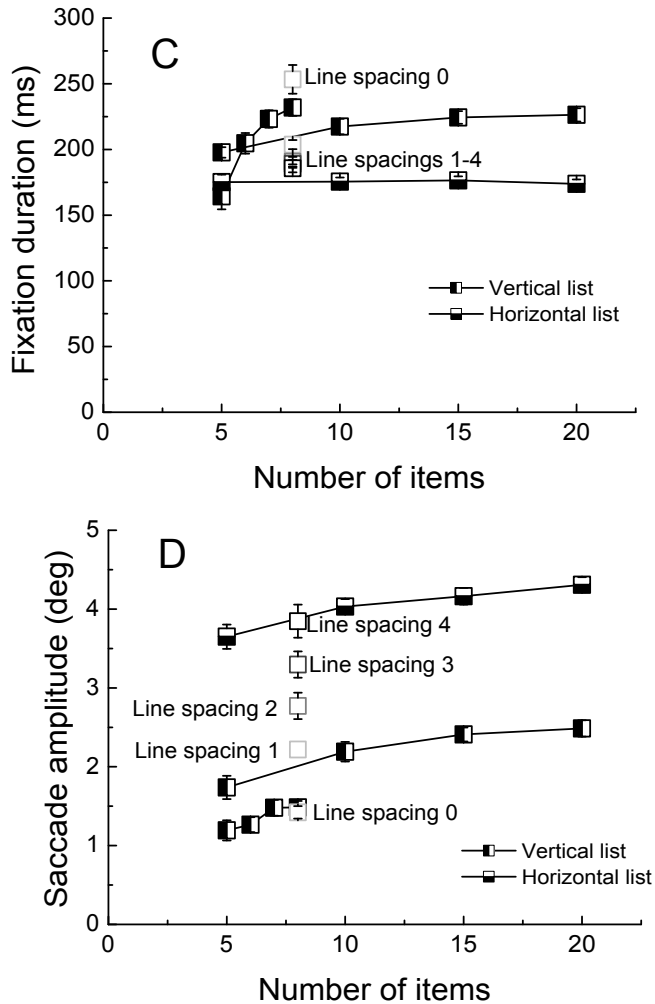
The changes in search performance were mainly reflected in increased number of fixations (Fig. 8 B). The correlation between threshold search time and the number of fixations was high ( $0.75 - 0.95$ ,  $p < 0.001$ , two-tailed). Effects for fixation duration were less consistent between subjects, and saccade amplitudes were not affected (see Figs. 5 - 6 in Study V for data).

### 4.1.5. Orientation and spacing of word lists (Study III)

Figures 9 A - D show the data for word search experiments (Study III). 9 A shows search performance, 9 B number of fixations, 9 C fixation durations, and 9 D saccade amplitudes.



## RESULTS



**Figure 9.** Effects of stimulus layout (horizontal vs. vertical), list length and list spacing in visual word search task (Study III). A: Search performance. B: Number of fixations. C: Fixation duration. D: Saccade amplitude. Open isolated symbols refer to the vertical 8-word lists (exp. 2 in Study III). Other details as in Fig. 6.

## RESULTS

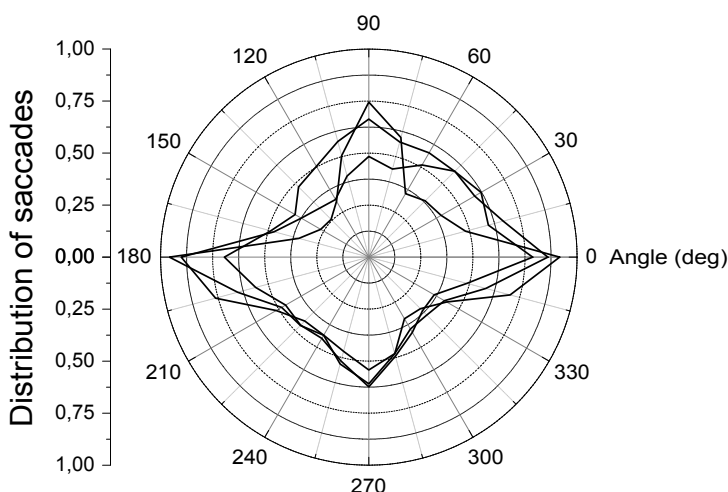
---

In experiment 3 of Study III, we manipulated list orientation (vertical vs. horizontal) and list length (5, 10, 15 or 20 words). With increasing list length, threshold search time and the number of fixations increased linearly. Threshold search times for vertical and horizontal lists did not differ statistically significantly. This was due to a longer mean fixation duration for vertical lists, which compensated for the effect of the increased number of fixations in horizontal lists. Saccade amplitudes were clearly longer for horizontal lists. Both mean fixation duration and saccade amplitude increased slightly with increasing list length. There was no statistically significant interaction between list length and list type. Thus, eye movement patterns depend also on stimulus layout.

In experiment 2 of Study III we manipulated line spacing of vertical eight-word lists by adding 0 – 4 empty lines (0.6 deg each) between words. With increasing line spacing, threshold search time, mean number of fixations per search and mean saccade amplitude increased. Mean fixation duration did not change statistically significantly with increasing line spacing, although the smallest line spacing showed a trend towards longer fixations. The results indicate that the subjects used more fixations and longer saccades to examine the list when the same number of items was spread over a wider spatial area. The increase in search times with increasing line spacing can be explained by an increase in the number of fixations since in all experiments, the number of fixations and search time were highly correlated.

#### 4.1.6. Scanning strategy

Polar plots of the distributions of saccades made to different angular directions during face search (Fig. 10) and letter search (Study VII, Fig. 5) reveal that subjects typically made more saccades in horizontal and vertical than in oblique directions. The differences in scanning strategies between subjects can be seen as different shapes of the plots. None of the subjects in Studies I -VII used any strictly systematic scanning strategy, such as in reading, which is also shown as the relatively irregular scan paths of individual search trials. For examples of scanning paths in word search, see Fig. 2 B and original Study III (Figs. 7 – 8, p.1510), and for examples of letter search, see Figs. 14 A - B (normal subjects) and 14 C – D (CSE patients), as well as Fig. 6 in Study I (p.1823).



*Figure 10.* Probability density distributions for angular directions of saccades made during face search by three subjects (Study VI). Differences in the absolute number of saccades between subjects are normalised by making the area of the plot equal to unity. Subjects made more horizontal and vertical than oblique saccades. Individual differences in search strategy are shown as different shapes of the plots.

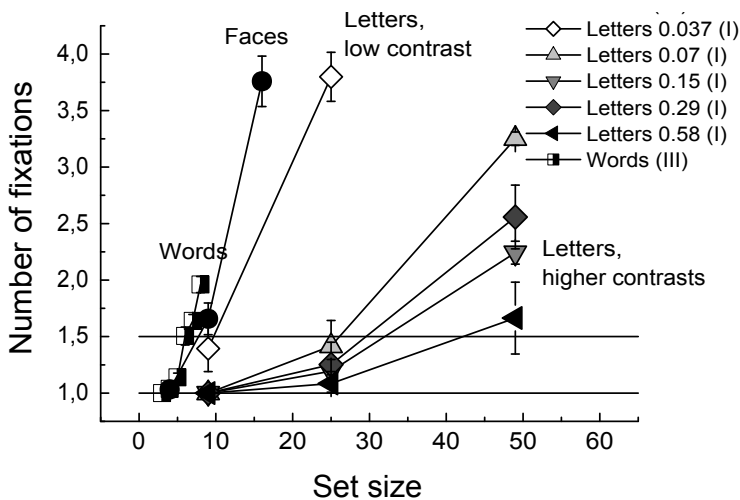
#### 4.2. Two-dimensional perceptual span (Studies I, III, IV and VI)

The limit of perceptual span was estimated as the number of items among which the target was found by using only 1 to 1.5 fixations per search trial (i.e., only one fixation in half or more of the individual trials). Fig. 11 shows the part of the data for Studies I, III, and VI, where the number of fixations for different stimulus types increases from one to two.

## RESULTS

However, for icons in Study IV (see section 4.2.3.) and for characters in low contrast condition in Study I (section 4.2.1.), there were always more than one fixation. To estimate the span for these few cases, where the primary method could not be used, we calculated the span estimate by dividing the number of fixations by the total number of items in array. However, the supplementary method is less accurate, because the areas investigated within each fixation are not assumed to overlap, and all items are assumed to be investigated before finding the target.

Because of the irregular scanning paths, the saccade amplitude does not allow an accurate estimate of perceptual span in two-dimensional visual search, unlike in reading or one-dimensional visual search tasks, where material is scanned in a relatively orderly fashion. Therefore, saccade amplitudes were not used, and all estimates were based on eye fixation data. The two-dimensional estimates represent the total number of items within the perceptual span, not the horizontal or vertical diameters of the span. However, for words we have separately estimated the number of words identified in vertically arranged word lists and compared it to the previous estimates for horizontally presented words, which allows us to investigate the shape of the two-dimensional span.



**Figure 11.** Two-dimensional perceptual span for different object types (words, faces, and characters), and for different contrast conditions for letters. The limit of the perceptual span is estimated as the number of items among which the target is found by using on average 1 – 1.5 fixations, i.e., the number of items within span can be read from the abscissa value at the intersection of each data curve and horizontal line of  $Y = 1$  or  $Y = 1.5$ . For vertically arranged words, the span is 4 - 5 words (28 – 35 characters). For faces the span is between 4 and 7 faces (slightly more than  $2 \times 2$  faces). For low contrast characters the span lies at or below 9 items ( $3 \times 3$ ), and for high contrast characters between 25 and 40 items depending on luminance contrast (above  $5 \times 5$ , below  $7 \times 7$  items). For other data labels, see Fig. 6A.

### **4.2.1. Perceptual span for character information (Study I)**

The number of items processed during a single eye fixation depends on luminance contrast between characters and background (Figs. 6 and 11). The perceptual span for characters was at least 3 x 3, i.e., 9 items for all contrast conditions ( $c = 0.073, 0.146, 0.292,$  and  $0.584$ ) except for the smallest luminance contrast ( $0.0365$ ), for which the span was 7 or 8 characters (number of items divided by the average number of fixations). For the highest luminance contrast, the estimated number of items within perceptual span was between 25 and 49 characters (Fig. 11), because 5 x 5 items could be processed within single fixation, whereas for array size of 7 x 7 items, more than 1.5 fixations were always necessary to find the target. Thus, the upper limit of the characters within the perceptual span seems to be around 40 (estimated from Fig. 11). Individual data for each subject is plotted in Study I, p.1821. See also Table 1 (top) and Fig. 13B for the span in the clinical Study VII.

### **4.2.2. Perceptual span for vertical word lists (Study III)**

In Study III we estimated the perceptual span for vertical word lists by increasing the length of the list from 3 to 8 words (see Figs. 9 A – D and 11), and by measuring the number of fixations needed to find the target word on the list. Threshold search time and mean number of fixations increased with increasing list length. The perceptual span for vertically listed words was around 4 - 5 words, i.e., 28 - 35 characters, because for the lists of 4 - 6 words, subjects had on average 1.04, 1.14, and 1.51 fixations per search, respectively. With longer lists there was clearly more than one fixation. Supplementary estimates calculated from longer word lists (data in Fig. 9B) yielded estimates that varied between 2 and 4.4 words within a fixation depending on stimulus layout. Data in Fig. 9B show that the perceptual span for horizontally arranged word lists, as well as for vertical lists with large line spacing, are clearly smaller than the span for densely packed vertical words. For example, for horizontal lists of five words about 3.5 fixations are needed, whereas for corresponding vertical lists less than two fixations are needed.

### **4.2.3. Perceptual span for computer icons (Study IV)**

Because only one set size (13 x 13) was used in Study IV, there was always more than one fixation, and the perceptual span for icons was estimated by dividing the average number of fixations by the total number of stimuli. On average, 5.14 fixations were needed for finding the target icon in the high luminance contrast condition, i.e., the span for icons was on average 33 items (on average 34.8 for OM target, and 31.1 for NS, see Fig. 6B). In low contrast condition ( $c = 0.125$ ), the span for icons was on average 13 items (9.9 for OM target, and 19.3 for NS, see Fig. 6B).

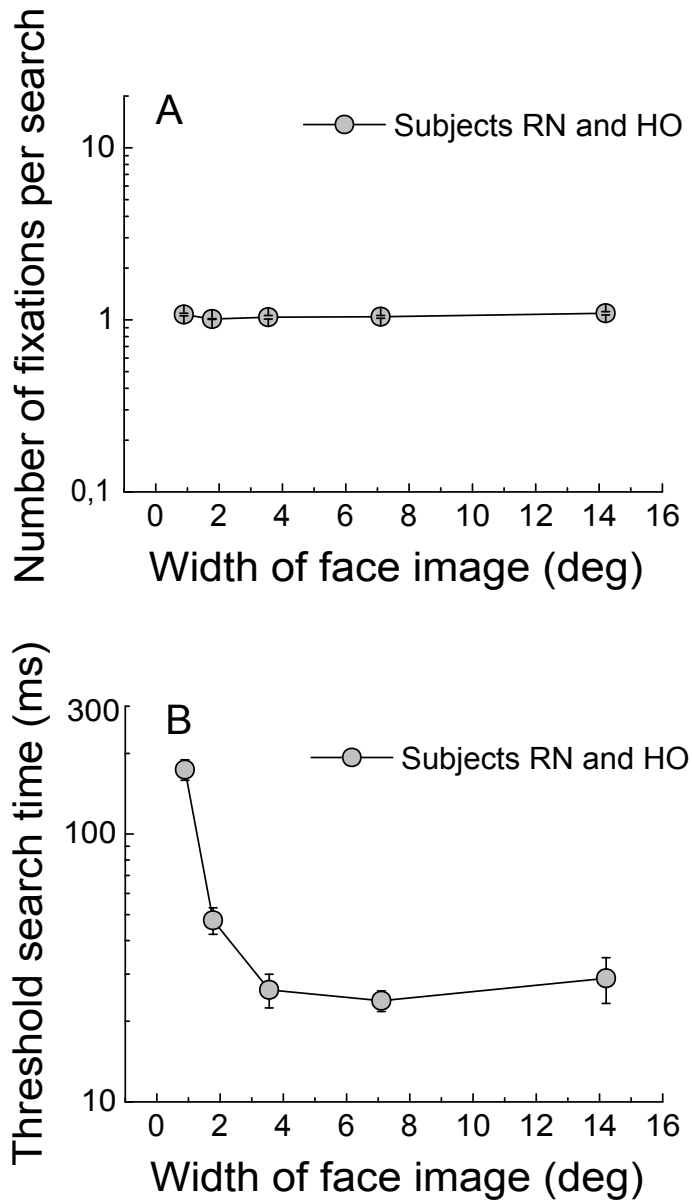
#### 4.2.4. Perceptual span for faces (Study VI)

In Study VI (see Figs. 6 A - D and 11), the size of the array of facial images was varied (2 x 2, 3 x 3, 4 x 4, 6 x 6 or 8 x 8 faces). Threshold search times and number of fixations increased with increasing set size. Two-dimensional perceptual span for faces was above 4 faces, but clearly below 9 faces, because for the smallest set size (2 x 2 faces, each face image 3.6 deg), only a single eye fixation was needed, whereas for the set sizes of 3 x 3 faces and 4 x 4 faces, on average 1.66 and 3.76 fixations were needed to find the target, respectively. When calculated from all set sizes (4, 9, 16, 36, and 64), the span estimates were 3.9, 5.4, 4.3, 4.2, and 4.9 faces/fixation, respectively. Thus, perceptual span for faces was around 4 to 5 faces.

#### 4.2.5. Scale invariance of perceptual span

Fig. 12A shows that when the size of the 2 x 2 face array was varied over a sixteen-fold range (0.9 -14.4 deg) by changing the viewing distance (Study VI, experiment 2), the number of fixations remained constantly one. This suggests that the perceptual span was scale invariant, that is, it was independent of viewing distance. However, search times started to increase clearly when face width decreased below 3.6 deg (Fig. 12B), which probably reflects the contrast attenuation of high spatial frequencies at early stages of visual processing. In Study VI (control experiment, data not shown), also an array of 6 x 6 faces was used, and search times or number of fixations were not affected by a two-fold difference in viewing distance. Study II (see Fig. 7) showed that very small characters (0.17 deg) require longer search times and more fixations than larger characters (0.37 or 1.26 deg) when luminance contrast is very low, but that for larger luminance contrasts (tails in 7 B) character size is not systematically related to the number of fixations. Thus, perceptual span seems to be roughly scale invariant for stimulus sizes that are large enough to pass the limits of the early stages of visual processing.

An increase in search times with increasing viewing distance was also found in Study V investigating critical spatial frequencies in face search (Fig. 8A, white symbols). The overall effect of phase randomisation of spatial frequency bands on the visual search was similar to the main experiment (Fig. 8A, grey symbols), but for the three-fold increase in viewing distance, the randomisation of highest spatial frequencies did not interfere with search performance as much as in the original data, which suggests that the information (and phase randomisation) at high spatial frequencies was not visible from the longer viewing distance. The maximum search times were considerably longer for the longer viewing distance, and the maximum was slightly shifted towards lower object spatial frequencies, being between 5.6 and 8 c/face width. Eye movements were not measured in this experiment.

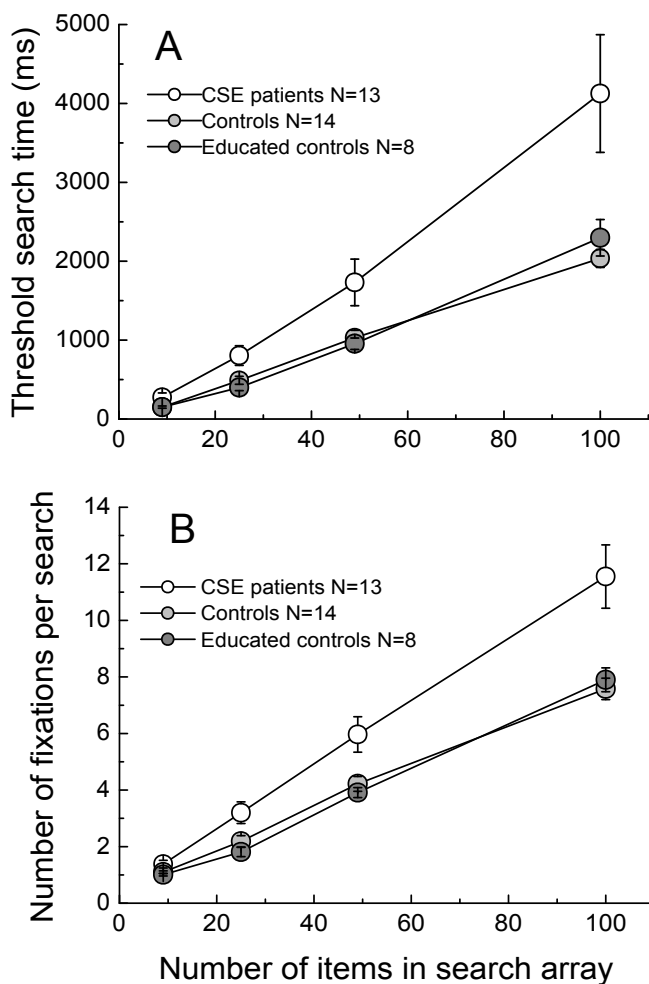


*Figure 12.* A: The effect of viewing distance on the number of fixations (A) and threshold search time (B) for 2 x 2 array of faces in Study VI. The mean for two subjects  $\pm$  SEM is presented.

### 4.3. Visual search and eye movements in patients with CSE (Study VII)

#### 4.3.1. Visual search performance and eye movements

In Study VII subjects were required to search for target letters among numerals (Fig. 1). Set sizes of 3 x 3, 5 x 5, 7 x 7, and 10 x 10 were used. Controls and CSE patients differed in threshold search time and in the number of fixations (Figs. 13A and B). Groups did



*Figure 13.* Threshold search times (A) and number of fixations (B) in letter search for controls and patients with CSE (Study VII).

## RESULTS

not differ statistically significantly in fixation duration or saccade amplitude (see Fig. 3 in Study VII for data). The two control groups did not differ from each other statistically significantly in performance nor in the eye movements. Thus, performance in the letter search test does not seem to be dependent on the level of education.

### 4.3.2. Estimation of the two-dimensional perceptual span for CSE patients

Perceptual span was estimated from eye fixation data for each subject (Table 1, above on the left) as a set size where 1.5 fixations or less per array were needed to find the target. Thus, if the subject needed only one fixation on a half or more individual trials to perform the task, the matrix was considered to be within the span. Four patients out of 13 had a span of 3 x 3 items or smaller in the letter search task, and 9 patients had a perceptual span of at least 3 x 3 but below 5 x 5 items. None of the patients had a span of 5 x 5 or above. On the other hand, only 1 of the 22 controls had a span of about 3 x 3 (1.52 fixations), whereas 5 of 22 controls had a span larger than 5 x 5 items. None of the subjects had a span larger than 7 x 7 items.

*Table 1.* Perceptual span and Trail Making Test performance in CSE patients and controls.

Groups	N			Trail making test (time/s)	
	Patients	Controls	Educated controls	Part A ( <i>SEM</i> )	Part B ( <i>SEM</i> )
span* ≤ 3x3	4	1	-	68.20 (8.67)	200 (33.57)
3x3<span<5x5	9	10	6	45.32 (3.44)	107.96(11.53)
5x5<span<7x7	-	3	2	28.4 (2.54)	87.60 (24.28)
All patients	13			57.54 (5.46)	162.27(24.77)
Controls <sup>†</sup>		14		41.71 (4.81)	107.21(11.98)
Educated controls <sup>‡</sup>			8	35.5 (4.33)	67.88 (6.26)

<sup>†</sup> Controls matched by age and education.

<sup>‡</sup> Controls matched by age, on average 8.5 years more education.

\* The size of the span (characters) was estimated from the number of fixations needed in letter search

### 4.3.3. Trail Making Test

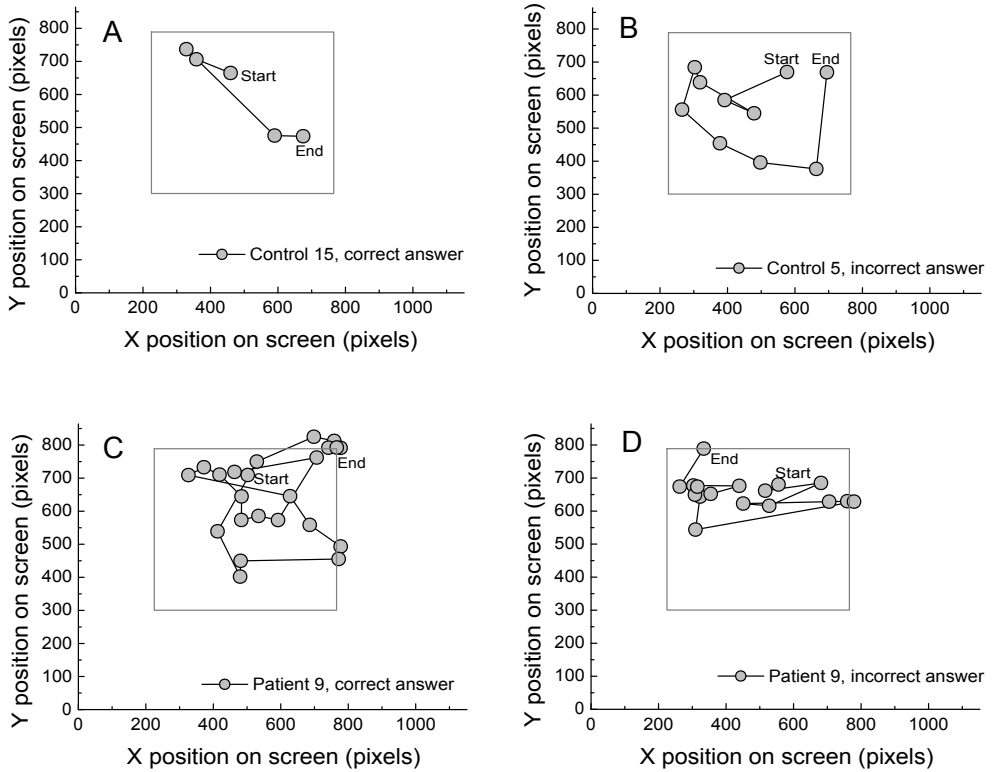
The performance of CSE patients and controls in the neuropsychological Trail Making Test, Parts A and B was investigated (Table 1, bottom section). A main effect was found for completion times but not for the number of errors. Pairwise post hoc tests revealed that CSE patients were slower in TMT-A than either of the control groups. The two control groups did not differ in TMT-A. In TMT-B, the controls and patients did not differ statistically significantly due to large variability, but the educated controls were faster than patients or other controls. When all subjects were grouped into three groups according to the increasing size of their perceptual span in letter search (span  $\leq 3 \times 3$  items,  $3 \times 3 < \text{span} < 5 \times 5$ , and  $5 \times 5 < \text{span} < 7 \times 7$  items), the TMT-A and TMT-B performance between groups differed statistically significantly (Table 1, above on the right). All three groups with different span sizes differed from each other with respect to TMT-A, whereas performance in TMT-B differed statistically significantly only between the two groups with the smallest span.

### 4.3.4. Scanning strategy and oculomotor control

Typically the subjects scanned the stimulus arrays in a relatively irregular fashion (Fig. 14). To further investigate the strategy, we determined the angular distribution of saccades for visual search (for details, see Figs. 4A and B in Study VII). The CSE patients, who needed the largest number of eye movements also tended to show the strongest trend towards using more horizontal saccades during search. This was investigated by calculating the ratio between sums of horizontal and vertical saccades for each subject. This ratio averaged 2.3 for patients and 1.7 for controls. The larger average of the patients differed statistically significantly from the value of controls.

In addition, we investigated the *main sequence*, that is, the relationship between average saccade amplitude and peak velocity (see Fig. 3 in original Study VII), which is considered to measure the overall neurologic integrity of saccadic eye movement system (Ciuffreda & Tannen, 1995). We found that CSE patients and controls did not differ with respect to these basic oculomotor processes.

## RESULTS



**Figure 14.** X and Y coordinates of eye positions (filled circles) and scan paths (lines) relative to the area of the stimulus array in Study VII. Examples for controls (A, B) and CSE patients (C, D).

## 5. DISCUSSION

We found that search performance depended on stimulus set size and object type (characters, words, computer icons or faces), as well as on stimulus properties such as size, luminance contrast, and spatial frequency information (Figs. 6A, 7A, 8A). The increase in search times with increasing set size was clearly steeper for more complex objects (faces, words) than for simpler objects (characters).

Three eye movement parameters were investigated. We found that search time was correlated with the *number of eye fixations*, whereas the effects of *fixation duration* or *saccade amplitude* were smaller (6B - D). Average fixation durations were moderately increased in conditions with very low luminance contrast, and/or small stimulus size (6C, 7C), and when the availability of the most relevant spatial frequency information was restricted. Density of the stimuli (Study III) also had a small effect on average fixation duration in word search. Average saccade amplitudes reflected most strongly the layout and angular size of the stimulus array (Study III, Fig. 9D), and were only slightly affected by other stimulus properties, except that the amplitudes decreased slightly with decreasing luminance contrast of the characters (Fig. 6D).

The correlation between the number of fixations and threshold search time, which were measured by using independent methods, suggests that the *perceptual span* (number of items that can be processed during a single fixation) was the best eye movement measure for explaining the performance in saccadic search. The size of the two-dimensional perceptual span was estimated for different object types (characters, words, facial images, and computer icons). Clearly more than one complex object could be processed during a single eye fixation regardless the object type. Perceptual span was smallest for words and faces (4 - 5 items within fixation), and clearly larger for characters (about 9 - 40 items within fixation depending on stimulus contrast) and icons (about 10 - 35 items depending on luminance contrast).

### 5.1. Serial and parallel information processing in saccadic search

#### 5.1.1. Set size effect and processing within fixation

It has been acknowledged increasingly that mere deterioration in visual search performance with increasing stimulus set size ("set size effect") does not guarantee that the capacity-limited attentional processes limit search (e.g. Carrasco & Yeshurun, 1998; Carrasco et al., 1998; Eckstein, 1998; Geisler & Chou, 1995; Palmer et al., 2000). Our eye movement data show that visual search for complex objects in two-dimensional stimulus arrays is performed

## DISCUSSION

---

as a serial sequence of eye fixations, when the number of items exceeds the perceptual span. It has been shown that the oculomotor planning and execution of a saccadic eye movement requires, at least a limited amount of, focal attention (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler et al., 1995; McPeck, Maljkovic, & Nakayama, 1999). Thus, a multiple fixation visual search is a serial process in that sense and requires the presence of at least some kind of overt attention.

An interesting question is, whether the processing within each eye fixation (i.e., within the perceptual span) is serial or parallel. Traditional visual search theories (e.g. Treisman & Gelade, 1980) assume that visual search without eye movements is performed as fast serial shifts of covert attention. A similar situation could arise within each fixation in saccadic search. Another plausible possibility is that within the perceptual span all stimuli are processed in a more or less parallel way before overt attention and the line of sight are shifted to the next spatial location. In a recent study by Näsänen et al. (2006), the temporal resolution of object identification in human vision was investigated by using a rapid serial visual presentation (RSVP) method. The identification of high contrast target letters among distracter numbers in the RSVP sequence took about 40 ms per stimulus (threshold frequency of 25 Hz) with a fixed accuracy of 79%. The temporal resolution was contrast and size invariant for medium and high contrasts and medium and large character sizes. In our data the corresponding threshold search time for high contrast characters in an array of 3 x 3 stimuli was on average 41 ms, which shows that at least for relatively small set sizes the processing within single eye fixation is parallel. It is possible that the search is also parallel for larger stimulus arrays within perceptual span (e.g. 5 x 5 characters). However, this can not be explicitly shown by the present data, because the search times for peripheral stimuli are not directly comparable to the foveal resolution estimate measured by Näsänen et al. (2006). In summary, saccadic search seems to comprise both focal and distributed information processing: serially made eye movements and at least partially parallel information processing within each eye fixation.

Previously Duncan and Humphreys (1989) proposed that stimulus similarity explains the efficiency of the search. Further, the flat “parallel” search time slopes have been found also for search tasks that require the search for conjunctions of features (e.g. Nakayama & Silverman, 1986; McLeod et al., 1988), which suggests that contrary to the predictions of the traditional Feature Integration Theory (Treisman & Gelade, 1980), search that requires feature integration may also be quite efficient. As will be discussed in detail below, we found that the number of items which can be processed during a single fixation varies for different object types and for different stimulus conditions. Because the slopes of search times are closely related to the number of fixations, it is proposed that the size of the perceptual span is one important factor that may explain the efficiency of saccadic search in different tasks. When perceptual span is small (which may occur due to various reasons, such as increasing complexity or increasing similarity of the stimuli, or low-level

factors resulting in a reduced signal-to-noise ratio), the area within which information can be processed in parallel is reduced, and search becomes less efficient due to the increased number of eye fixations required to identify the target. On the other hand, when the discrimination between targets and distracters is easy (stimuli are clearly visible and target differs sufficiently from distracters), perceptual span covers the whole stimulus area, and only a single fixation is needed, as in classical parallel search. Thus, the size of the span may be helpful in explaining search performance in different saccadic search tasks with different stimuli.

### **5.1.2. Search strategy**

Especially in two-dimensional visual search tasks, the stimulus material may be scattered and there is no obvious order in which to proceed as in reading. Our data show that multiple items can be investigated during a single fixation in visual search, which is in agreement with a previous proposal of Liversedge and Findlay (2000, p. 8) that search proceeds at least partially in a parallel way. However, by definition, information about the target is not available from outside the span. So, how do we decide the direction of scanning and the locations of successive fixations in saccadic search? In our data, the scanning did not proceed in a strictly orderly manner as is previously reported for reading or for one-dimensional search (e.g., Rayner, 1998). Therefore, scanning in two-dimensional visual search did not strictly follow the *visual span control hypothesis* (O'Regan et al., 1983). Instead, the scan paths appeared irregular, saccades were variable in length, and sometimes the same locations were visited more than once during a search trial (examples for characters in Fig. 14 and in Study I, p. 1823, for words in Fig. 2B and Study III, p. 1510, and for faces in Study VI, p. 74). This is qualitatively in agreement with the findings that only few previously visited locations are remembered during saccadic search (Gilchrist & Harvey, 2000; Najemnik & Geisler, 2005; McCarley et al., 2003; Hooge et al., 2005).

The observed irregular scanning patterns are in agreement with Najemnik and Geisler (2005), who showed that, in multiple-fixation visual search, the performance of human subjects was closely similar to an ideal bayesian observer. The model determined the next fixation point as the point having the maximum probability to locate a target. Each location was weighted by the detectability of the target as a function of eccentricity. The scanning behaviour of the model followed a random-looking search pattern. Interestingly, humans acted similarly and performed almost as well as an ideal observer. However, a similar model with genuinely random saccadic locations performed much worse than humans or the ideal model. Therefore, a seemingly irregular scanning strategy may be optimal for two-dimensional stimuli, and eye guidance may be based, at least partially, on some form of parallel utilisation of low-level stimulus information (see also Wolfe, Alvarez, & Horowitz, 2000). Previously, Findlay et al. have also proposed that stimulus area may be processed in parallel

## DISCUSSION

---

prior to the selection of saccade location (see e.g. Findlay, 1995, 1997; Findlay & Walker, 1999; McSorley & Findlay, 2001; for review see Liversedge & Findlay, 2000; Findlay & Gilchrist, 1998; but see e.g. Pollatsek & Rayner, 1999). Further, according to Verstraten, Cavanagh and Labianca (2000), the temporal resolution of covert attention measured in motion tracking is only 4 - 8 Hz, which suggests that only 1 - 2 shifts of covert attention could be made during a typical fixation duration in visual search (200 - 250 ms).

We found that the search strategy was not completely random, either. The number of horizontal and vertical saccades was clearly larger than the number of oblique saccades. Thus, despite irregular scan paths, subjects preferred vertical and horizontal directions over oblique directions (see Fig. 10 for faces, Fig. 4 in Study VII for characters). This may be related to the structure of the stimulus array in the present studies. Another possibility is that the coarse order of the scanning followed vertical and horizontal directions partly because they are pre-learned more strongly (e.g. reading, menu-scanning). This is supported by the fact that the preferred saccadic directions were similar to those in the recent study by Findlay and Brown (2006), in which an irregular stimulus arrangement was used. They showed that in a counting task which required subjects to foveate each stimulus separately, half of the six subjects preferred horizontal or vertical directions of saccadic eye movements, whereas the other three followed mainly the global contours of the clusters of stimuli. Generally, the smaller overall regularity in the scanning paths in our data may be related to the different tasks used in the two studies. When each individual item is not required to be foveated, the systematic order of the scanning becomes less important.

Also in our data the subjects showed some individual differences in their scanning strategies. Some of them utilised the horizontal and vertical directions quite strongly, whereas others had more evenly distributed saccadic directions. Interestingly, the CSE patients (Study VII) as a group had statistically significantly more saccades to horizontal directions than controls. One possibility is that this reflects their stronger reliance on over-learned reading-like patterns, because they may be less flexible in adopting task-specific new strategies. Orderly scanning strategy may also be functional for them because their perceptual span was clearly smaller than that of controls (Fig. 13). When perceptual span is very small, the stimulus area may be easier to cover with a more systematic scanning strategy. This is supported by the fact that relative horizontal dominance was strongest in the patients who also had the largest absolute number of fixations. Further, it has been shown that for CSE patients some pop-out search tasks can be actually serial (Näsänen et al., 2005). Thus, it is possible that there may be qualitative differences in their eye guidance in comparison to healthy controls.

In summary, it seems that the irregular scanning strategy may be optimal for complex two-dimensional stimulus arrays. However, despite apparent irregularity, scanning is not completely random. Further, during each fixation the area within the perceptual span is, at least partially, processed in a parallel manner.

---

## 5.2. Stimulus properties and perceptual span

The irregular scanning strategy makes average saccade amplitudes less useful for estimating the size of the perceptual span than in one-dimensional tasks, where the material is scanned in an orderly manner. Therefore, the span estimates in the present study were based on the number of fixations for different stimulus set sizes, especially on the number of items among which the target was found by using only 1 to 1.5 fixations on average (Fig. 11).

### 5.2.1. Luminance contrast and stimulus size

Within each object type studied (characters in Studies I and II, icons in Study IV), the luminance contrast between stimuli and background had a strong effect on search performance, especially when small characters were used (Figs. 6 A and 7A). This is in agreement with previous studies investigating the effects of luminance contrast and character size on reading performance (Legge et al., 1997, 1987, 1985) and visual search performance for one-dimensional stimuli (Boschmann & Roufs, 1997). Search times for the lowest contrast of 0.037 in Study I were in some cases even ten times in comparison to those for the highest contrast, although our stimulus size in this study was well within the optimal range of 0.25 - 2 deg (Legge et al, 1987). For small characters (0.17 deg in Study II), the reduction of luminance contrast yielded even longer search times. Legge et al. (1987) found that for stimuli within the optimal range, a ten-fold reduction in luminance contrast (0.96 vs. 0.1) resulted in a two-fold reduction in reading speed. Similar to our findings, they found a ten-fold reduction in reading speed for the contrast of 0.03.

We showed that with decreasing luminance contrast also the number of fixations increased. The correlation between the number of fixations and search time is in agreement with several earlier visual search studies using reaction times (Motter & Belky, 1998; Scialfa and Joffe, 1998; Williams et al., 1997; Zelinsky and Sheinberg, 1997). Further, we found that the size of the perceptual span (items/fixation) depended strongly on contrast. It was clearly below 9 items for the lowest contrast, in comparison to over 30 items for high-contrast characters of 0.9 deg (Fig. 6). Thus, the changes in visual search performance seem to be related to changes in the size of the perceptual span. This is in agreement with the *shrinking visual span hypothesis* proposed for reading by Legge et al. (1997). They found that, when the contrast of the text was low, visual span shrank, resulting in a reduction of reading speed. With decreasing contrast, reading speed became increasingly dependent on word length because, with decreasing span, longer words needed to be fixated more than once. This can be explained in the following way. The sampling rate of the retina, particularly ganglion cell density (Curcio & Allen, 1990), as well as contrast sensitivity for stimuli of a given size decrease with increasing eccentricity (Virsu & Rovamo, 1979).

This sets the ultimate limit to the area within which characters of particular size can be recognised. Decreasing luminance contrast decreases the local signal-to-noise ratio in the periphery so that the area around fovea within which reliable object recognition is possible becomes smaller. When a smaller amount of items can be processed during each fixation (span shrinks), the number of fixations and correspondingly search time increase.

Further, we found that fixation durations increased for the smallest luminance contrast conditions, particularly for the smallest (0.17 deg) characters. This may be related to the increased temporal integration of information, which increases the local signal-to-noise ratio in the periphery. On the other hand, the increase in fixation duration for very small characters and low contrasts may be directly related to decrease in the speed of information processing. Näsänen et al. (2006) have recently shown that the temporal resolution for letter and face identification decreased for low luminance contrasts and small stimulus sizes, whereas temporal resolution for medium and high contrasts and medium and large stimulus sizes was independent of contrast or size. They concluded that at high contrasts and large stimulus sizes the low-level influences were probably negligible, whereas the decrease in the temporal resolution for low contrasts and small stimuli may be related to the low-level factors. These may include e.g. increased latencies of the information transmission at low levels of the visual system, particularly in the retina (Donner & Fagerholm, 2003), as well as contrast attenuation of high spatial frequencies produced by the optical system of the eye (Navarro et al., 1993).

### **5.2.2. Interaction of luminance contrast and colour contrast**

Previously Legge et al. (1990) has found that for 1 or 6 deg characters, high colour contrast could support nearly normal reading rates although simultaneously the luminance contrast was small. Their results are in agreement with our visual search data for large stimuli (1.26 deg) with high colour difference with respect to background (see Figs. 8 - 9 in Study II). However, our results show that for smaller (0.17 deg) characters visual search performance depends on luminance contrast, even when high colour contrast is present, especially for blue-yellow combination. Therefore, it seems that high colour contrast can only maintain efficient visual perception if character size is large, above 1 deg. The large increase in search times for small characters is in good agreement with Mullen (1985), who found that the resolution limit for equiluminous chromatic red-green and blue-yellow gratings is about 10 - 12 c/deg, whereas it is around 40 - 50 c/deg for achromatic stimuli (see, e.g., Virsu & Hari, 1996, Fig. 5). Thus, in completely equiluminous stimuli, the smallest characters in Study II probably would have been impossible to see, since the critical spatial frequencies for letter identification (Solomon & Pelli, 1994) would correspond to a centre spatial frequency of 17.65 c/deg and the spatial frequency band between -8 and 35 c/deg for the smallest letters used.

For a moderate colour difference (green characters on grey background), we found that visual search performance was strongly dependent on luminance contrast for all three character sizes measured (0.17, 0.37, and 1.26 deg). Further, reading rates for texts (0.37 deg) with moderate colour contrast decreased strongly with decreasing luminance contrast (p.177 in Study II). Thus, moderate colour difference alone is not sufficient to maintain efficient visual search. In summary, it seems that for character sizes normally used in user interfaces, the perceptual span and search performance, as well as reading performance, are primarily dependent on sufficient luminance contrast between text and background, not colour difference.

### **5.2.3. Scale invariance of perceptual span**

We found that the perceptual span was constant over a sixteen-fold range of stimulus sizes (Fig. 12A), i.e., the size of the span is not dependent on retinal image size, but an equal number of faces can be processed during a single fixation. This is in agreement with studies showing contrast, lighting, and scale invariance in inferotemporal areas related to object recognition (see e.g. Avidan et al. 2002; Vogels & Biederman, 2002). On the other hand, the search times for faces started to increase (see Figs. 8A, 12B) when stimulus size decreased strongly. A similar increase has been reported by Lindberg and Näsänen (2003) for icon search, when icon width decreased to 0.2 deg. These effects may be related to the previously mentioned decrease in temporal resolution of object recognition for small stimuli (Näsänen et al., 2006), which may decrease the speed of information processing within each fixation. However, fixation durations could not be measured for longer viewing distances in our study to confirm the hypothesis.

The critical spatial frequencies for face search also shifted slightly towards lower object spatial frequencies ( $c/fw$ ) with increasing viewing distance, and the randomisation of the highest spatial frequency information did not affect performance anymore (Fig. 8A). This suggests that the information in the highest spatial frequencies was not (or could not be) used with longer viewing distance. The corresponding shift has previously been reported in studies investigating static letter identification (Alexander, Xie, & Derlacki, 1994; Chung, Legge, & Tjan, 2002; Chung et al., 2002; Majaj et al., 2002) and static recognition of synthetic faces (Näsänen, 1999). In summary, the scale invariance for recognition of complex objects is not complete, but is affected by low-level limitations, when stimulus size is very small.

### **5.2.4. Stimulus layout and perceptual span**

In Study III we investigated the effect of stimulus layout on visual search for words. The span estimated for vertical word lists can be compared to previous horizontal estimates

(Underwood & McConkie, 1985; Legge et al., 1997). When expressed as the diameter of the span (number of characters/span height or width), our vertical estimate of 4 to 5 seems small in comparison to horizontal estimates of 10.6 characters (Legge et al., 1997) or 10 - 12 (Underwood & McConkie, 1985; Rayner, 1998). However, vertical word lists fill the visual field around fovea quite effectively, and actually more characters fit within the perceptual span when a word list is arranged vertically instead of horizontally (28 - 35 vs. 10 - 12 characters).

To estimate the shape of the two-dimensional span, the vertical and horizontal estimates must be converted into comparable units. The characters used in our experiments were larger in vertical than in horizontal direction (1.65:1). We converted Legge's (Legge et al., 1997) horizontal estimate (originally in character widths) to character heights and calculated the ratio of the horizontal to vertical span estimates by dividing the converted horizontal estimate by our mean vertical estimate ( $6.42 / 4.37$ ) and obtained a value of 1.47. Therefore, the two-dimensional area from which words can be identified seems to be elliptical, and elongated in the horizontal direction. The roughly elliptical shape of the two-dimensional perceptual span is qualitatively in agreement with Wertheim's (1894) classical visual acuity results, and with Curcio & Allen (1990), who reported that the retinal ganglion cell density in humans declines with eccentricity so that the diameters of the ellipses of equal density contours are horizontally longer than vertically (the ratio was 1.28 in fovea and 1.59 in periphery). This explains why more eye fixations and longer saccades were needed to gather information from horizontal word lists in comparison to vertical lists (Fig. 9).

### **5.2.5. Stimulus density and perceptual span**

In our data, the search performance did not markedly differ between vertical and horizontal orientations of the word list, because the increased fixation durations (41 ms on average) for densely packed vertical lists compensated for the difference in the number of fixations. However, for the line spacing experiment (Fig. 9), the fixation durations were longer only when there were no spaces between lines at all. Thus, it seems that when items are very densely packed, fixation duration tends to increase. This is in agreement with Vlaskamp, Over and Hooge (2005) who found that when the spacing of simple search stimuli decreased below 1.5 deg, the search times per element increased because of an increased number of fixations, as well as increased fixation duration. The effect may be related to the "crowding effect", in which neighbouring items inhibit each other. Such lateral interactions have recently been suggested to limit visual search performance (Vlaskamp & Hooge, 2006; Wertheim et al., 2006, but see Motter & Belky, 1998; Pöder, 2004, 2006). Vlaskamp and Hooge (2006) found that in one-dimensional visual search for an O among Cs, both the number of fixations as well as fixation duration were affected by irrelevant items added

## DISCUSSION

---

near stimuli to produce crowding. Thus, crowding could, at least partly, explain the increased fixation durations for very densely packed stimuli. In general, our stimuli were not designed to investigate lateral masking, but it can be concluded to be one of the factors limiting the perceptual span also in our results, since mostly our stimuli were closer to each other than  $0.5 \times$  eccentricity, which has been estimated to be the proximity limit within which crowding starts to have an effect (see e.g. Pelli, Palomares, & Majaj, 2004, but see Pöder, 2006).

On the other hand, we found that when the same amount of information was distributed over a large area, such as with the largest line spacing (3 and 4 lines between words), more fixations and longer saccades were needed, and also search times increased. This means that the perceptual span for words did not fully scale with stimulus density, but slightly fewer words could be processed during a single fixation, when line spacing was very sparse. In contrast, Motter and Belky (1998) have found that the probability of detecting the target on the next saccade as a function of eccentricity in simple visual search tasks performed by monkey subjects was equivalent across stimulus densities. They concluded that the area within which target can be detected is approximately 1.5 - 2 times the distance of the average nearest neighbouring item, that is, the span consists of a fixed number of items irrespective of stimulus density. Similarly, for simple O's and C's (Vlaskamp et al., 2005) and for computer icons (Lindberg and Näsänen, 2003), search performance and span also seem to remain nearly constant (items/fixation) with increasing stimulus spacing. It remains unclear, whether the effect we found is related to the complexity of our stimuli. Legge et al. (2001, see also Crossland & Rubin, 2006) have shown that the perceptual span for words is smaller in peripheral vision than near the fovea. This could explain why identification performance of the outermost words in very sparse lists was reduced. Therefore, the scaling of the span for spatially elongated complex objects may not be fully equivalent to that for simple stimuli, for which the perceptual span (items/fixation) is largely constant across spatial densities.

### **5.2.6. Stimulus type and span size**

The increase in search times with increasing set size was clearly steeper for faces and words than for characters. Thus, visual search for simple objects (characters) seems to be more effective when compared to complex objects (faces) or words (6A). Eye movement data shows that the number of fixations increased strongly with increasing set size, whereas the changes in fixation duration and saccade amplitude were relatively small (6B - D). Thus, the extent of the perceptual span seems to be related to the differences in set size effects. Indeed, the estimated two-dimensional perceptual span was found to be around 35 - 40 items per fixation for high-contrast characters, and 30 - 35 items for icons (calculated for high contrast icons from set size of  $13 \times 13$ ), whereas for faces, as well as for words, the

two-dimensional span was about 4 – 5 items. Thus, the two-dimensional perceptual span was noticeably smaller for more complex stimuli. Perceptual span for icons estimated from our data is in agreement with Lindberg and Näsänen (2003), who found that at least 5 x 5, in some cases even 7 x 7 icons, could be processed within a single fixation.

Is it possible that the resolution requirements of identification of certain stimulus types determine the span? Perhaps the relevant features for identification of more complex objects simply contain higher spatial frequencies, which can not be processed as far in the periphery as the critical features of simpler objects, and thus, low-level effects would explain the decrease in performance with increasing stimulus complexity? To compare different object types, we can compare critical spatial-frequency information used for letter and face recognition in one dimension. Previous estimates for faces are around 8 – 11 c/face width (e.g. Näsänen et al., 1999; Study V) and for characters 2 - 3 c/letter height (Solomon & Pelli, 1994). If we multiply these by the span estimates obtained in our studies I, III, and VI and take blank spaces between stimuli into account (i.e., the width of the stimulus array of 2 x 2 faces, height of 5 x 5 character array, and height of five-word vertical list), we obtain values of 17.6 - 24.2 c/span for faces (8.8 – 12.1 c/facial image), 15.6 – 23.3 c/span for characters (3.4 - 5.1 c/character space), and 15 – 22.5 c/span for words (3 - 4.5 c/vertical character space in a word list).

Unfortunately, the critical spatial-frequency information for the recognition of icons is unknown, and exact estimates cannot be calculated. However, our data in Study IV show that search times for icons start to increase when arrays are low-pass filtered using cut-off frequencies below 2 c/icon width (Fig. 5 in Study IV). Thus, critical information may lie somewhere above 2 c/icon width. This would give estimates starting from 12 - 17 c/span for span estimates of 5 x 5 or 7 x 7 icons (Lindberg & Näsänen, 2003), respectively. In summary, different span estimates converted to cycles of critical spatial frequencies are relatively similar, which suggests that low-level information used in the recognition of complex objects may explain the differences in the effectiveness of visual search between different object types.

### **5.3. When do high-level factors affect perceptual span?**

Results discussed so far suggest that low-level factors have a strong effect on the perceptual span and thus, on search performance. This is in agreement with previous studies, that have utilised signal detection models into visual search for simple stimuli (e.g. Geisler and Chou, 1995; Najemnik and Geisler, 2005; Palmer et al., 2000) and into reading (Legge et al., 2002), and shown that low-level physiological mechanisms of the visual system, e.g., the declining visual resolution with eccentricity, explain human performance quite well

even without assuming any high-level cognitive control. Thus, low-level visual factors may explain a considerable proportion of the variance also in complex visual information processing tasks. However, there is some evidence that also information processing at higher levels of visual system affects the size of the perceptual span in certain situations.

### **5.3.1. Effects of task complexity, learning, and allocation of attention**

Although the resolution requirements (critical spatial frequencies for each object type) seem to be related to the size of the perceptual span as discussed in previous section, high-level factors may also play a role in complex search tasks. Pöder (2005) found that, in a simple detection task of Gabor patch orientations, the set size effect was well predicted by an unlimited-capacity signal detection model, whereas in the more demanding orientation identification task for similar stimuli, the decrease in performance with increasing set size was larger than predicted by the low-level model. Similarly, the set size effect for a simple feature search was qualitatively different from the set size effect for the more complex task, although the stimuli were identical, and thus, the two tasks were comparable in low-level target-distractor similarity (Pöder, 1999). This is in disagreement with Duncan & Humphreys (1989), who suggested that the stimulus discriminability is sufficient to explain the search efficiency. The results suggest that although low-level stimulus information seems to be sufficient to explain set size effects for simple tasks (e.g. Palmer et al., 2000), for more complex search tasks, high-level processes may have an additional role.

High-level factors possibly affecting the perceptual span in visual search include allocation of attention and perceptual learning. Qualitatively, our subjects showed interesting individual differences in their eye movement patterns (see individual data for each subject in Study I). Some normal subjects have fewer but longer fixations, whereas others utilise shorter but more numerous fixations and achieve similar performance. Since it is unlikely that anatomically their visual resolution, or other visual low-level factors would be so clearly different, it is suggested that these inter-individual differences could rather reflect their different strategies or abilities to utilise the peripheral regions of the perceptual span. My personal experience during several years of extensive practice is that the utilisation of peripheral information is gradually enhanced, i.e., learned, and the span can be slightly expanded. Indeed, recently Chung et al. (2004) showed that the perceptual span for recognition of letter-trigrams in peripheral vision of normal subjects increased by means of perceptual learning. Moreover, the effect generalised to untrained retinal locations, to another task (reading performance), as well as was retained over a period of three months. Previously similar generalisation of learning has been found for simple stimuli in visual search (Sireteanu & Rettenbach, 2000) and has been considered as evidence for cortical (high-level) information processing (Ahissar & Hochstein, 1997; Hochstein & Ahissar,

2002; Sireteanu & Rettenbach, 2000). Also Green and Bavelier (2003) have shown that extensive training in action video games requiring peripheral allocation of attention can extend perceptual span, as well as shorten the attentional blink in RSVP task, i.e., improve temporal allocation of attention. Further, Leonards et al. (2002) have shown that, some originally inefficient visual search tasks can become efficient with extensive practice, if there is a unique visual feature associated to target that can be learned. However, they found that even after prolonged practice, the parallelisation did not take place for conjunction search tasks, in which target items changed from trial to trial. They concluded that parallelisation via improvement in the allocation of attention can take place, but only to certain subtypes of originally inefficient search tasks. These studies are in agreement with our observations that visual search for complex objects with several simultaneous targets remains inefficient with practice, although slight changes in the perceptual span can take place, possibly via learning to allocate attention to the periphery more effectively.

One well-documented effect often attributed to spatial allocation of attention is the asymmetry of the perceptual span to the direction of reading in comparison to the symmetrical visual span in terms of letter recognition accuracy (Rayner, 1998). This probably reflects the parafoveal allocation of attention into the word that will be fixated next (Hoffman, 1998). Attentional modification of perceptual span in peripheral vision is in agreement with studies indicating that allocation of covert attention to periphery affects performance in that location in simple feature and conjunction search (Carrasco, Giordano, & McElree, 2006; Carrasco & Yeshurun, 1998) as well as in texture segregation and spatial resolution tasks (Yeshurun & Carrasco, 1998, 1999, 2000; but see Westheimer, 2001). Further, it is in agreement with physiological studies indicating that allocation of attention within a certain region of a receptive field enhances the neural processing in that region (e.g. Desimone & Duncan, 1995). Interestingly, the asymmetry of the perceptual span was among the features *not* accounted for by the low-level ideal-observer model for reading, which explained many eye movement phenomena during reading (Legge et al., 2002; see also Legge et al., 2001).

### **5.3.2. Perceptual span in CSE**

In Study VII, the visual search and eye movement measurement were used to characterize visual perception of patients with chronic solvent encephalopathy (CSE). The effects of low-level factors were controlled as well as possible by using large (1 deg) characters with maximum luminance contrast, and investigating the visual function of all subjects carefully. Perceptual span estimated from fixation data was smaller for patients than controls, whereas other eye movement measures were not affected. Since subjects were comparable in their visual acuity (investigated for viewing distance used), contrast sensitivity, oculomotor eye movement parameters, age, and education level, and because the psychophysical method

## DISCUSSION

---

used excluded the effects of possible manual slowness, it is concluded that the differences in the perceptual span between groups were not related to low-level visual information processing. Instead, the difference was attributed to a reduced capacity of spatial allocation of attention in CSE patients. The size of the perceptual span estimated in visual search was shown to be related to the performance in Trail Making Test (TMT), a neuropsychological test considered to measure visual search, psychomotor speed, shifting of attention and cognitive flexibility (Lezak et al., 2004). In summary, it is suggested that perceptual span size may in some cases reflect the changes in higher-level information processing.

## 6. CONCLUSIONS

We found that 4 – 5 faces, 4 – 5 words, 30 - 40 characters, and 30 - 35 icons could be processed for identification during a single eye fixation. The estimates of perceptual span may appear surprisingly large when compared to everyday experience. The values reported in this study may be somewhat exaggerated, because the search tasks in real life are far more complex than in simplified laboratory conditions. In real life, the objects are viewed from variable viewing angles and directions, lighting conditions vary, and stimuli are rarely arranged so that the full extent of the span can be utilised. In addition, the span estimates reported here represent performance near the threshold at the accuracy level of 0.79. Nevertheless, it is interesting that several complex objects could be processed within a single fixation. Thus, it is clear that we do not need more than one fixation for the recognition of a complex object.

The present study shows that even for demanding search tasks with complex objects, low-level factors limit perceptual span and, thus, strongly affect the saccadic search performance. The results are consistent with the *shrinking visual span hypothesis* proposed by Legge et al. (1997). The contribution of low-level factors was found to be especially strong when luminance contrast was low or stimulus size small. Under these conditions, the information available to high-level processing may be limited by low-level factors.

The size of the perceptual span also depended on object type (face, word, character, or icon). The smaller size of the perceptual span for more complex objects is suggested to be related to the different resolution requirements for the recognition of different object types, i.e., the critical spatial frequencies used in object recognition may limit the size of the perceptual span.

High-level information processing, such as attentional capacity or perceptual learning, is proposed to exert its effect by modifying the perceptual span within the limits set by the low-level physiological factors. Top-down control is always related to visual search because of the adaptive nature of the task. For example, the goals of a search task determine the targets that are currently essential, and when to terminate the search. Also the control of eye movements requires some form of high-level information processing, as reviewed in the Introduction. However, when high-level factors are investigated, it should be ensured that low-level factors are taken into account in interpreting the results, and stimuli should be chosen so that low-level factors restrict performance as little as possible (or can be assumed to be consistent across conditions).

The present study, together with the recent data by Näsänen et al. (2006), suggest that information processing within the perceptual span is parallel. Therefore, the “serial” saccadic search may actually consist of both serial (eye movements) and parallel (processing within fixation) components. However, further studies are needed, because the temporal characteristics of object identification in the peripheral regions of perceptual span are not known.

---

## 7. APPENDIX: Application of the results to visual ergonomics

The knowledge of the limits that normal humans have in visual information processing can help design the user interfaces so that the salience and clarity of relevant information is supported, and the effectiveness of visual search is enhanced. This could save substantial amount of time by increasing the rate by which information is searched, by decreasing error rate, and increasing satisfaction of users, as the visual search in user interfaces would become more comfortable. Particularly important is the clarity of the user interfaces used in safety-critical areas, such as aviation, traffic, process control, and health care. It should be noted, that the list below regarding the aspects to be considered - most directly concerning information on computer displays - is not exhaustive, as many other factors, such as illumination and reflections, are also important. This list consists of applied aspects of the present and related results.

### Size and luminance contrast

- Maximum reading rate and visual search speed are achieved at character heights between 0.25 - 2 deg (corresponds to about 0.25 - 2 cm from 57 cm viewing distance), and performance decreases for both increasing and decreasing character sizes (Legge et al., 1985; Legge, et al., 1987; Knoblauch, et al., 1991).

- Character size and luminance contrast have an interaction. For optimal character sizes around 1 degree of visual angle, the speed of perception is markedly reduced only for relatively low luminance contrast levels (below 0.1). However, for character sizes smaller than 0.2 deg, luminance contrast must be high to maintain high performance. Thus, luminance contrast should be higher for small characters than for larger characters. Generally character size used in user interfaces is too small (notice that character height of 5 mm corresponds to 0.5 deg from 57 cm viewing distance).

- In a user interface, the legibility remains quite good for a wide variety of character sizes if luminance contrast between text and background is high. Highest luminance contrast is between black and white or black and bright yellow. However, differences in performance between medium and high luminance contrasts are relatively small if character size is sufficient (e.g. larger than 0.3 deg). On the other hand, for small luminance contrasts (< 0.05) visual search becomes very slow, and the number of fixations increases strongly, when only small amount of information can be processed within single fixation (Figs. 6A and 7A; Legge et al., 1987, 1997).

- One way to check the luminance contrast is to evaluate the user interface from a three-fold viewing distance in comparison to the expected distance and see, whether the information is still visible. This is based on the fact that increasing viewing distance corresponds to a reduction of the angular character size, and at small character sizes the human visual system is more sensitive to decreasing luminance contrast. If luminance contrast cannot be further increased, the situation can be compensated for to some extent by increasing the character size.

### **Sharpness (blur)**

- When one target icon was searched among distracter icons, blurring the coloured computer icons only had a small effect on visual search times and the number of fixations. Effects were slightly larger for the less conspicuous target icons.

- Search times for very small characters and for low contrast ( $< 0.2$ ) are faster in LCD than in CRT displays, because the stimuli in CRT have reduced sharpness for very small characters (Näsänen, Karlsson, & Ojanpää, 2001).

### **Colours**

- Visual acuity is much lower for pure colour difference than for luminance difference. Therefore, moderate colour difference is not sufficient to maintain efficient visual perception, but there should always be clear brightness difference between characters and background. Search performance is better for larger characters than for very small characters with moderate colour difference.

- Maximum colour difference (blue-yellow, or green-red) can support efficient visual search, but only if character size is larger than that usually used in user interfaces (above 1 deg). For small characters ( $< 0.2$  deg), high colour contrast does not guarantee good legibility, and sufficient luminance contrast is crucial. In addition, maximum colour differences can cause other visual problems, such as chromatic aberration, and these colour combinations should therefore be avoided (e.g. Charman, 1991).

### **Layout**

- In visual search, 4 - 5 words (28 – 35 characters) can be processed during a single fixation in vertically arranged word lists, whereas a single horizontal line of words allows only 10 - 11 letters (1 - 2 words) to be processed during a single fixation.

## APPENDIX

---

- Vertical lists fit the retinal area of high resolution more effectively than horizontal lists of similar length. It follows that more fixations are needed for horizontal lists than for vertical lists of similar length. Also longer saccade amplitudes are used in horizontal than in vertical direction. Lists should not be extremely densely packed, because the lateral interactions between neighbouring items affect the speed of search. On the other hand, when the spacing between items becomes very large (>3 empty lines between items), the search performance declines, because more fixations are needed for them than for optimally spaced lists.

- For computer icons the spacing of one is preferred over smaller and larger densities, and very dense arrangement without spaces is least preferred (Lindberg & Näsänen, 2003).

## 8. ACKNOWLEDGEMENTS

This work has been done during years 2002 – 2006 at the Brain and Work Research Centre at the Finnish Institute of Occupational Health (FIOH), and at the Neuropsychology Research Group at the University of Helsinki, Department of Psychology (HU). The work has been supported by the 4-year Ph.D. position at the Finnish Graduate School of Neuroscience (FGSN) funded by the Ministry of Education. I wish to express my deep gratitude to all these institutes, especially to the Research Professor Kiti Müller from the FIOH, Professor Veijo Virsu from the HU, and Professor Kai Kaila from the FGSN, who made this work possible by starting this kind of research co-operation for the first time. Professor Virsu is also warmly acknowledged for his active initiative in the matter; without it I would have never started this work.

I am greatly indebted to my excellent supervisors, Docent Risto Näsänen, Ph.D. and Professor Virsu. It has been a real once-in-a-lifetime opportunity to learn from the very best experts. Warm thanks for many long conversations, and for all your time spent in commenting various manuscripts! I know it really is priceless, and I truly appreciate your thorough work. However, the most I admire the sincerely positive attitude that both of you have had towards my dream to do research work without forgetting my family life. During these five hectic years, me and my husband have also had two wonderful children, Juha (b. 9. 3. 2004) and Saana (b. 2. 8. 2006), and I have been able to leave the dissertation project temporarily completely aside with good conscience, and without anyone (else than me) questioning my ability to eventually complete it. I thank my husband Sami for keeping my feet on the ground, and for staying by my side for ten years now.

All co-authors deserve my warmest thanks. Ilpo Kojo is also warmly acknowledged for introducing me and FIOH in 1999. Special thanks go to my current “home team” in FIOH, namely the vision science group consisting of Docent Risto Näsänen, Ph.D., Juha Päällysaho, Ph.D., O.D., and Docent Markku Sainio, M.D., Ph.D. I thank M.Sc. Kristian Lukander, M.Sc. Kati Hirvonen, and M.Sc. Jussi Virkkala for their technical (as well as mental) help with the research equipment. Many other co-workers in the Brain and Work Research Centre have helped me in numerous ways that are impossible to list here in detail. You all create our truly multidisciplinary work team and its special atmosphere. I will miss that sound of laughter coming from our coffee room (although, to be honest, sometimes it also disturbed the actual writing...). I also wish to thank all other FIOH co-workers that have contributed to the publications, especially Kaarina Rantala, M.Sc. for assessing the patients’ solvent exposures, and Ms. Outi Fischer, Ms. Hannele Kataja, Ms. Seija Karas, and Ms. Riitta Velin for their help in handling the patients’ medical records.

Neuropsychologists Ritva Akila, Lic.Psych., Jutta Gröhn, Lic.Psych., and Taina Nybo, Ph.D., deserve my special thanks for their kind and thorough guidance to the world of clinical neuropsychology. I also thank Marja-Leena Haavisto, Lic.Psych. for interesting

## ACKNOWLEDGEMENTS

---

conversations about cognitive psychology, and Docent Mikael Sallinen, Ph.D., for morning walks. I owe you all much for helping to preserve my occupational identity as a psychologist during these years.

I thank the reviewers of the work, Professor John M. Findlay and Professor Gordon E. Legge for their thorough and constructive comments on the manuscript. All the reviewers of the original publications are acknowledged. All fellow Ph.D. students that have commented my manuscripts in Prof. Virsu's seminar are thanked for helping me to further clarify my text. I also want to express my sincere gratitude to all participants in the studies. I also thank Ph.D. Katri Wegelius, the coordinator of the FGSN, for answering many of my impossible questions so patiently.

My warmest thanks to each and every one of my friends for support and understanding.

Finally, I wish to thank few special people in Finnish: Lämmin kiitos vanhemmilleni Heikki ja Maija-Liisa Erkkilälle, isoveljelleni Hannulle perheineen, sekä isoäidilleni Eila Ylä-Kojolalle kaikesta tuestanne. Eilan lapsena oppima elämänohje ("älä sano että en minä osaa, sano että kyllä minä opettelen") on ollut toimiva ohjenuora tässäkin työssä.

Järvenpää, September 2006

Helena Ojanpää

## 9. REFERENCES

- Ahissar, M. & Hochstein, S. (1997). Task difficulty and the specificity of perceptual learning. *Nature*, *387*, 401-6
- Alexander, K. R., Xie, W., & Derlacki, D. J. (1994). Spatial-frequency characteristics of letter identification. *Journal of the Optical Society of America A*, *11*, 2375-82.
- Allison, T., Puce, A., Spencer, D. D., & McCarthy, G. (1999). Electrophysiological studies of human face perception. I: Potentials generated in occipitotemporal cortex by face and non-face stimuli. *Cerebral Cortex*, *9*, 415-30.
- Army Individual Test Battery. *Manual of directions and scoring*. Washington, DC: War Department, Adjutant General's Office 1944.
- Avidan, G., Harel, M., Hendler, T., Ben-Bashat, D., Zohary, E., & Malach, R. (2002). Contrast sensitivity in human visual areas and its relationship to object recognition. *Journal of Neurophysiology*, *87*, 3102-16.
- Bertera, J. H., & Rayner, K. (2000). Eye movements and the span of the effective stimulus in visual search. *Perception & Psychophysics*, *62*, 576-85.
- Boschman, M. C., & Roufs, J. A. J. (1997). Text quality metrics for visual display units: II. An experimental survey. *Displays*, *18*, 45-64.
- Broadbent, D.E. (1958). *Perception and communication*. London, UK: Pergamon Press Ltd.
- Campbell, F. W. & Robson, J. G. (1968). Application of Fourier analysis to the visibility of gratings. *Journal of Physiology*, *197*, 551-66.
- Carrasco, M. & Frieder, K. S. (1997). Cortical magnification neutralizes the eccentricity effect in visual search. *Vision Research*, *37*, 63-82.
- Carrasco, M., Giordano, A. M., & McElree, B. (2006). Attention speeds processing across eccentricity: feature and conjunction searches. *Vision Research*, *46*, 2028-40.
- Carrasco, M., McLean, T. L., Katz, S. M., & Frieder, K. S. (1998). Feature asymmetries in visual search: Effects of display duration, target eccentricity, orientation and spatial frequency. *Vision Research*, *38*, 347-74.
- Carrasco, M. & Yeshurun, Y. (1998). The contribution of covert attention to the set-size and eccentricity effects in visual search. *Journal of Experimental Psychology*, *24*, 673-92.
- Charman, W. N. (1991). Limits on visual performance set by the eye's optics and the retinal cone mosaic. In J. J. Kulikowski, V. Walsh, & I. J. Murray (Eds.), *Vision and Visual Dysfunction, Vol 5. Limits of Vision* (pp. 81-96). UK: The Macmillan Press Ltd.
- Chelazzi, L., Duncan, J., Miller, E. K., & Desimone, R. (1998). Responses of neurons in inferior temporal cortex during memory-guided visual search. *Journal of Neurophysiology*, *80*, 2918-40.
- Chelazzi, L., Miller, E. K., Duncan, J., & Desimone, R. (1993). A neural basis for visual search in inferior temporal cortex. *Nature*, *363*, 345-7.
- Cherry, E. (1953). Some experiments on the recognition of speech, with one and with two ears. *The Journal of the Acoustical Society of America*, *25*, 975-9.

## REFERENCES

---

- Chouanière, D., Cassitto, M. G., Spurgeon, A., Verdier, A., & Gilioli, R. (1997). An international questionnaire to explore neurotoxic symptoms. *Environmental Research* 73, 70-2.
- Chung, S. T. L., Legge, G. E., & Cheung, S. (2004). Letter-recognition and reading speed in peripheral vision benefit from perceptual learning. *Vision Research*, 44, 695-709.
- Chung, S. T. L., Legge, G. E., & Tjan, B. S. (2002). Spatial-frequency characteristics of letter identification in central and peripheral vision. *Vision Research*, 42, 2137-52.
- Chung, S. T. L., Levi, D. M., Legge, G. E., & Tjan, B. S. (2002). Spatial-frequency properties of letter identification in amblyopia. *Vision Research*, 42, 1571-81.
- Chung, S. T. L., Mansfield, J. S., & Legge, G. E. (1998). Psychophysics of reading XVIII. The effect of print size on reading speed in normal peripheral vision. *Vision Research*, 38, 2949-62.
- Ciuffreda, K.J., & Tannen, B. (1995). *Eye movement basics for the clinician*. St. Louis: Mosby-year Book, Inc.
- Corbetta, M., Kincade, J. M., Ollinger, J. M., McAvo, M. P., & Shulman, G. L. (2000). Voluntary orienting is dissociated from target detection in human posterior parietal cortex. *Nature Neuroscience*, 3, 292-7.
- Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature reviews. Neuroscience*, 3, 201-15.
- Costen, N. P., Parker, D. M., & Craw, I. (1996). Effects of high-pass and low-pass spatial filtering on face identification. *Perception & Psychophysics*, 58, 602-12.
- Crossland, M.D., & Rubin, G. S. (2006). Eye movements and reading in macular disease: Further support for the shrinking perceptual span hypotheses. *Vision Research*, 46, 590-7.
- Curcio, C. A. & Allen, K. A. (1990). Topography of ganglion cells in human retina. *Journal of Comparative Neurology*, 300, 5-25.
- Curcio, C.A., Sloan, K.R., Kalina, R.E., & Hendrickson, A.E. (1990). Human photoreceptor topography. *Journal of Comparative Neurology* 292, 497-523.
- Cutrell, E. B., & Marrocco, R. T. (2002). Electrical microstimulation of primate posterior parietal cortex initiates orienting and alerting components of covert attention. *Experimental Brain Research*, 144, 103-13.
- Déruaz, A., Goldschmidt, M., Mermoud, C., Whatham, A. R., & Safran, A. B. (2005). The relationship between word length and threshold character size in patients with central scotoma and eccentric fixation. *Graefé's Archive for Clinical and Experimental Ophthalmology* [Electronic version ahead of print: DOI 10.1007/s00417-005-0111-7].
- Desimone, R. (1996). Neural mechanisms for visual memory and their role in attention. *Proceedings of the National Academy of Sciences of the United States of America*, 93, 13494-9.
- Desimone, R. (1998). Visual attention mediated by biased competition in extrastriate visual cortex. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 353, 1245-55.
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, 18, 193-222.
- Deubel, H. & Schneider, W. X. (1996). Saccade target selection and object recognition: evidence for a common attentional mechanism. *Vision Research*, 36, 1827-37.

## REFERENCES

---

- Deutsch, J. A., & Deutsch, D. (1963). Attention. Some theoretical considerations. *Psychological Review*, *70*, 80-90.
- Donner, K., & Fagerholm, P. (2003) Visual reaction time: Neural conditions for the equivalence of stimulus area and contrast. *Vision Research*, *43*, 2937-40.
- Driver, J. (2001). A selective review of selective attention research from the past century. *British Journal of Psychology*, *92*, 53-78.
- Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological Review*, *87*, 272-300.
- Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, *96*, 433-58.
- Eckstein, M. P. (1998). The lower visual search efficiency for conjunctions is due to noise and not serial attentional processing. *Psychological Science*, *9*, 111-8.
- Farah, M. J. (1990). *Visual agnosia: Disorders of object recognition and what they tell us about normal vision*. Cambridge, Massachusetts: The MIT Press.
- Findlay, J. M. (1995). Visual search: Eye movements and peripheral vision. *Optometry and Vision Science*, *72*, 461-6.
- Findlay, J. M. (1997). Saccade target selection during visual search. *Vision Research*, *37*, 617-31.
- Findlay, J. M. & Brown, V. (2006). Eye scanning of multi-element displays: I. Scanpath planning. *Vision Research*, *46*, 179-195.
- Findlay, J. M. & Gilchrist, I. D. (1998). Eye guidance and visual search. In: Underwood, G. (Ed.), *Eye guidance in reading and scene perception* (pp. 295-312). Elsevier Science Ltd.
- Findlay, J. M., & Walker R. (1999). A model of saccade generation based on parallel processing and competitive inhibition. *Behavioral and Brain Sciences*, *22*, 661-721.
- Fink, G. R., Dolan, R. J., Halligan, P. W., Marshall, J. C., & Frith, C. D. (1997). Space-based and object-based visual attention: shared and specific neural domains. *Brain*, *120*, 2013-28.
- Fiorentini, A., Maffei, L., & Sandini, G. (1983). The role of high spatial frequencies in face perception. *Perception*, *12*, 195-201.
- Geisler, W. S. & Chou, K.-L. (1995). Separation of low-level and high-level factors in complex tasks: Visual search. *Psychological Review*, *102*, 356-78.
- Giesbrecht, B., Woldorff, M. G., Song, A. W., & Mangun, G. R. (2003). Neural mechanisms of top-down control during spatial and feature attention. *NeuroImage*, *19*, 496-512.
- Gilchrist, I., & Harvey, M. (2000). Refixation frequency and memory mechanisms in visual search. *Current Biology*, *10*, 1209-12.
- Gold, J., Bennett, P. J., & Sekuler, A. B. (1999). Identification of band-pass filtered letters and faces by human and ideal observers. *Vision Research*, *39*, 3537-60.
- Green, C. S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature*, *423*, 534-7.

## REFERENCES

---

- Hamker, F. H. (2005). The Reentry Hypothesis: the putative interaction of the frontal eye field, ventrolateral prefrontal cortex, and areas V4, IT for attention and eye movement. *Cerebral Cortex*, *15*, 431-47.
- Harmon, L. D., & Julesz, B. (1973). Masking in visual recognition: Effects of two-dimensional filtered noise. *Science*, *180*, 1194-7.
- Haxby, J. V., Hoffman, E. A., & Gobbini, I. M. (2000). The distributed human neural system for face processing. *Trends in Cognitive Sciences*, *4*, 223-33.
- Hochstein, S., & Ahissar, M. (2002). View from the top: hierarchies and reverse hierarchies in the visual system. *Neuron*, *36*, 791-804.
- Hoffman, J. E. (1998). Visual attention and eye movements. In: H. Pashler (Ed.), *Attention* (pp. 119-153). East Sussex, UK: Psychology Press.
- Hoffman, J. E. & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception & Psychophysics*, *57*, 787-95.
- Hooge, I. Th. C., Over, E. A. B., van Wezel, R. J. A., & Frens, M. A. (2005). Inhibition of return is not a foraging facilitator in saccadic search and free viewing. *Vision Research*, *45*, 1901-8.
- Hopfinger, J. B., Woldorff, M. G., Fletcher, E. M., & Mangun, G. R. (2001). Dissociating top-down attentional control from selective perception and action. *Neuropsychologia*, *39*, 1277-91.
- Howell, D. C. (2002). *Statistical Methods in Psychology* (5th ed.). Pacific Grove, CA: Duxbury.
- Jacobs, A. M. (1986). Eye-movement control in visual search: how direct is visual span control? *Perception & Psychophysics*, *39*, 47-58.
- Kandel, E. R., Schwartz, J. H., & Jessell, T.M. (2000). *Principles of neural science* (4th ed.). New York: McGraw-Hill.
- Kaukiainen, A., Riala, R., Martikainen, R., Akila, R., Reijula, K., & Sainio, M. (2004). Solvent-related health effects among construction painters with decreasing exposure. *American Journal of Industrial Medicine*, *46*, 627-36.
- Kennard, C., Mannan, S. K., Nachev, P., Parton, A., Mort, D. J., Rees, G., Hodgson, T. L., & Husain, M. (2005). Cognitive processes in saccade generation. *Annals of the New York Academy of Sciences*, *1039*, 176-83.
- Knoblauch, K., Arditi, A., & Szlyk, J. (1991). Effects of chromatic and luminance contrast on reading. *Journal of the Optical Society of America*, *8*, 428-39.
- Kowler, E., Anderson, E., Doshier, B., & Blaser, E. (1995). The role of attention in the programming of saccades. *Vision Research*, *35*, 1897-1916.
- Krauzlis, R. J., Liston, D., & Carello, C. D. (2004). Target selection and the superior colliculus: goals, choices and hypotheses. *Vision Research*, *44*, 1445-51.
- Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in Cognitive Sciences*, *9*, 75-82.
- Legge, G. E., Ahn, S. J., Klitz, T. S., & Luebker, A. (1997). Psychophysics of reading – XVI. The visual span in normal and low vision. *Vision Research*, *37*, 1999-2010.

## REFERENCES

---

- Legge, G. E., Hooven, T. A., Klitz, T. S., Mansfield, J. S., & Tjan, B. S. (2002). Mr. Chips 2002: new insights from an ideal-observer model of reading. *Vision Research*, *42*, 2219-34.
- Legge, G. E., Mansfield, J. S., & Chung, S. T. L. (2001). Psychophysics of reading XX. Linking letter recognition to reading speed in central and peripheral vision. *Vision Research*, *41*, 725-43.
- Legge, G. E., Parish, D. H., Luebker, A., & Wurm, L. H. (1990). Psychophysics of reading. XI. Comparing color contrast and luminance contrast. *Journal of the Optical Society of America A*, *7*, 2002-10.
- Legge, G. E., Pelli, D. G., Rubin, G. S., & Schleske, M. M. (1985). Psychophysics of reading – I. Normal vision. *Vision Research*, *25*, 239-52.
- Legge, G. E., Rubin, G. S., & Luebker, A. (1987). Psychophysics of reading – V. The role of contrast in normal vision. *Vision Research*, *27*, 1165-77.
- Leigh, R. J., & Kennard C. (2004). Using saccades as a research tool in the clinical neurosciences. *Brain*, *127*, 460-77.
- Leonards, U., Rettenbach, R., Nase, G., & Sireteanu, R. (2002). Perceptual learning of highly demanding visual search tasks. *Vision Research*, *42*, 2193-204.
- Leonards, U., Sunaert, S., Van Hecke, P., & Orban, G. A. (2000). Attention mechanisms in visual search -- An fMRI study. *Journal of Cognitive Neuroscience*, *12*(Suppl. 2), 61-75.
- Lezak, M. D., Howieson, D. B., & Loring, D.W. (2004). *Neuropsychological Assessment* (4th ed.). New York: Oxford University Press.
- Lindberg, T., & Näsänen, R. (2003). The effect of icon spacing and size on the speed of icon processing in the human visual system. *Displays*, *24*, 111–20.
- Liversedge, S. P., & Findlay, J. M. (2000). Saccadic eye movements and cognition. *Trends in Cognitive Sciences*, *4*, 6-14.
- Majaj, N. J., Pelli, D. G., Kurshan, P., & Palomares, M. (2002). The role of spatial frequency channels in letter identification. *Vision Research*, *42*, 1165-84.
- Mazer, J. A., & Gallant, J. L. (2003). Goal-related activity in V4 during free viewing visual search: evidence for a ventral stream visual salience map. *Neuron*, *40*, 1241-50.
- McCarley, J., Wang, R. F., Kramer, A. F., Irwin, D. E., & Peterson, M. S. (2003). How much memory does oculomotor scanning have? *Psychological Science*, *14*, 422-6.
- McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics*, *17*, 578-86.
- McLeod, P., Driver, J., & Crisp, J. (1988). Visual search for a conjunction of movement and form is parallel. *Nature*, *332*, 154-5.
- McPeck, R. M. & Keller, E. L. (2004). Deficits in saccade target selection after inactivation of superior colliculus. *Nature Neuroscience*, *7*, 757-63.
- McPeck, R. M., Maljkovic, V., & Nakayama, K. (1999). Saccades require focal attention and are facilitated by a short-term memory system. *Vision Research*, *39*, 1555-66.

## REFERENCES

---

- McSorley, E. & Findlay, J. M. (2001). Visual search in depth. *Vision Research*, *41*, 3487-96.
- Mort, D. J., & Kennard, C. (2003). Visual search and its disorders. *Current Opinion in Neurology*, *16*, 51-7.
- Motter, B. C., & Belky, E. J. (1998). The zone of focal attention during active visual search. *Vision Research*, *38*, 1007-22.
- Muggleton, N. G., Juan, C.-H., Cowey, A., & Walsh, V. (2003). Human frontal eye fields and visual search. *Journal of Neurophysiology*, *89*, 3340-3.
- Mullen, K. T. (1985). The contrast sensitivity of human colour vision to red-green and blue-yellow chromatic gratings. *Journal of Physiology*, *359*, 381-400.
- Najemnik, J., & Geisler, W. S. (2005). Optimal eye movement strategies in visual search. *Nature*, *434*, 387-91.
- Nakayama, K., & Silverman, G. H. (1986). Serial and parallel processing of visual feature conjunctions. *Nature*, *320*, 264-5.
- Navarro, R., Artal, P. & Williams, D. R. (1993). Modulation transfer of the human eye as a function of retinal eccentricity. *Journal of the Optical Society of America A*, *10*, 201-12.
- Nobre, A. C., Gitelman, D. R., Dias, E. C., & Mesulam, M. M. (2000). Covert visual spatial orienting and saccades: overlapping neural systems. *NeuroImage*, *11*, 210-6.
- Näsänen, R. (1999). Spatial frequency bandwidth used in the recognition of facial images. *Vision Research*, *39*, 3824-33.
- Näsänen, R., Karlsson, J., & Ojanpää, H. (2001). Display quality and the speed of visual letter search. *Displays*, *22*, 107-13.
- Näsänen, R., Kaukiainen, A., Hero, V., Päällysaho, J., Müller, K., Hari, R., Akila, R., & Sainio, M. (2005). Effects of long-term occupational solvent exposure on contrast sensitivity and performance in visual search. *Environmental Toxicology and Pharmacology*, *19*, 497-504.
- Näsänen, R., Ojanpää, H., Tanskanen, T., & Päällysaho, J. (2006). Estimation of temporal resolution of object identification in human vision. *Experimental Brain Research* [Electronic version ahead of print: DOI 10.1007/s00221-006-0354-5].
- O'Connor, D. H., Fukui, M. M., Pinsk, M. A., & Kastner, S. (2002). Attention modulates responses in the human lateral geniculate nucleus. *Nature Neuroscience*, *5*, 1203-9.
- Oppenheim, A. V., & Lim, J. S. (1981). The importance of phase in signals. *Proceedings of the IEEE*, *69*, 529-41.
- O'Regan, J. K. (1990). Eye movements and reading. In Kowler, E. (Ed.), *Eye movements and their role in visual and cognitive processes* (pp. 395-453). Elsevier Science Publishers.
- O'Regan, J. K., Lévy-Schoen, A., & Jacobs, A. M. (1983). The effect of visibility on eye-movement parameters in reading. *Perception & Psychophysics*, *34*, 457-64.
- Osaka, N. (1992). Size of saccade and fixation duration of eye movements during reading: psychophysics of Japanese text processing. *Journal of the Optical Society of America A*, *9*, 5-13.

## REFERENCES

---

- Osaka, N., & Oda, K. (1991). Effective visual field size necessary for vertical reading during Japanese text processing. *Bulletin of the Psychonomic Society*, *29*, 345-7.
- Palmer, J., Verghese, P., & Pavel, M. (2000). The psychophysics of visual search. *Vision Research*, *40*, 1227-68.
- Pashler, H. E. (1998). *The psychology of attention*. Cambridge, Massachusetts: The MIT Press.
- Paus, T. (1996). Location and function of the human frontal eye-field: a selective review. *Neuropsychologia*, *34*, 475-83.
- Peers, P. V., Ludwig, C. J. H., Rorden, C., Cusack, R., Bonfiglioli C., Bundesen, C., Driver, J., Antoun, N., & Duncan J. (2005). Attentional functions of parietal and frontal cortex. *Cerebral Cortex*, *15*, 1469-84.
- Peli, E., Lee, E., Trempe, C. L., & Buzney, S. (1994). Image enhancement for the visually impaired: The effects of enhancement on face recognition. *Journal of the Optical Society of America A*, *11*, 1929-39.
- Pelli, D. G., Palomares, M., & Majaj, N. (2004). Crowding is unlike ordinary masking: Distinguishing feature integration from detection. *Journal of Vision*, *4*, 1136-69.
- Pierrot-Deseilligny, C., Milea, D., & Müri, R. M. (2004). Eye movement control by the cerebral cortex. *Current Opinion in Neurology*, *17*, 17-25.
- Piotrowski, L. N., & Campbell, F. W. (1982). A demonstration of the visual importance and flexibility of spatial-frequency amplitude and phase. *Perception*, *11*, 337-46.
- Pollatsek, A., Raney, G. E., LaGasse, L., & Rayner, K. (1993). The use of information below fixation in reading and in visual search. *Canadian Journal of Experimental Psychology*, *47*, 179-200.
- Pollatsek, A. & Rayner, K. (1999). Is covert attention really unnecessary? In: Open peer commentary. *Behavioral and Brain Sciences*, *22*, 695-6.
- Póder, E. (1999). Search for feature and for relative position: measurement of capacity limitations. *Vision Research*, *39*, 1321-7.
- Póder, E. (2004). Effects of set-size and lateral masking in visual search. *Spatial Vision*, *17*, 257-68.
- Póder, E. (2005). Effect of attention on the detection and identification of masked spatial patterns. *Perception*, *34*, 305-18.
- Póder, E. (2006). Crowding, feature integration, and two kinds of "attention". *Journal of Vision*, *6*, 163-9.
- Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology*, *7*, 65-81.
- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*, 372-422.
- Rayner, K., & Fisher, D. L. (1987). Letter processing during eye fixations in visual search. *Perception & Psychophysics*, *42*, 87-100.
- Rivaud, S., Müri, R. M., Gaymard, B., Vermersch, A. I., & Pierrot-Deseilligny, C. (1994). Eye movement disorders after frontal eye field lesions in humans. *Experimental Brain Research*, *102*, 110-20.
- Rizzolatti, G., Riggio, L., Dascola, I., & Umiltá C. (1987). Reorienting attention across the horizontal and vertical meridians: evidence in favor of a premotor theory of attention. *Neuropsychologia*, *25*, 31-40.

## REFERENCES

---

- Roelfsema, P. R., Lamme V. A. F., & Spekreijse, H. (1998). Object-based attention in the primary visual cortex of the macaque monkey. *Nature*, *395*, 376-81.
- Ross, J., Morrone, M.C., Goldberg, M. E., & Burr, D.C. (2001). Changes in visual perception at the time of saccades. *Trends in Neurosciences*, *24*, 113-21.
- Rovamo, J. & Virsu, V. (1979). An estimation and application of the human cortical magnification factor. *Experimental Brain Research*, *37*, 495-510.
- Rovamo, J., Virsu, V., & Näsänen, R. (1978). Cortical magnification factor predicts the photopic contrast sensitivity of peripheral vision. *Nature*, *271*, 54-6.
- Saukkonen, P., Haipus, M., Niemikorpi, A., & Suikala, H. (1979). *Suomen kielen taajuusanasto*. Porvoo: Söderström.
- Schall, J. D. (2004a). On the role of frontal eye field in guiding attention and saccades. *Vision Research*, *44*, 1453-67.
- Schall, J. D. (2004b). The neural selection and control of saccades by the frontal eye field. *Philosophical transactions of the Royal Society of London. Series B*, *357*, 1073-82.
- Scialfa, C. T., & Joffe, K. M. (1998). Response times and eye movements in feature and conjunction search as a function of target eccentricity. *Perception & Psychophysics*, *60*, 1067-82.
- Sireteanu, R. & Rettenbach, R. (2000). Perceptual learning in visual search generalizes over tasks, locations, and eyes. *Vision Research*, *40*, 2925-49.
- Solomon, J. A., & Pelli, D. G. (1994). The visual filter mediating letter identification. *Nature*, *369*, 395-7.
- Somers, D. C., Dale, A. M., Seiffert, A. E., & Tootell, R. B. H. (1999). Functional MRI reveals spatially specific attentional modulation in human primary visual cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *96*, 1663-8.
- Theeuwes, J., & Kooi, F. L. (1994). Parallel search for a conjunction of contrast polarity and shape. *Vision Research*, *34*, 3013-6.
- Thompson, K. G., & Bichot, P. (1999). Frontal eye field: A cortical salience map. In: Open peer commentary. *Behavioral and Brain Sciences*, *22*, 699-700.
- Thompson, K. G., Biscoe, K. L., & Sato, T. R. (2005). Neuronal basis of covert spatial attention in the frontal eye field. *Journal of Neuroscience*, *12*, 9479-84.
- Tieger, T., & Ganz, L. (1979). Recognition of faces in the presence of two-dimensional sinusoidal masks. *Perception & Psychophysics*, *26*, 163-7.
- Treisman, A. M. (1960). Contextual cues in selective listening. *Quarterly Journal of Experimental Psychology*, *12*, 242-8.
- Treisman, A. M. (1986). Features and objects in visual processing. *Scientific American*, *254*, 106-15.
- Treisman, A. M. (1998). Feature binding, attention and object perception. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *353*, 1295-1306.
- Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*, 97-136.

## REFERENCES

---

- Underwood, N. R., & McConkie, G. W. (1985). Perceptual span for letter distinctions during reading. *Reading Research Quarterly, 20*, 153-62.
- Ungerleider, L. G., Courtney, S. M., & Haxby, J. V. (1998). A neural system for human visual working memory. *Proceedings of the National Academy of Sciences, 95*, 883-90.
- Verstraten, F. A. J., Cavanagh, P., & Labianca, A. T. (2000). Limits of attentive tracking reveal temporal properties of attention. *Vision Research, 40*, 3651-64.
- Virsu, V. & Hari, R. (1996). Cortical magnification, scale invariance and visual ecology. *Vision Research, 36*, 2971-7.
- Virsu, V., & Rovamo, J. (1979). Visual resolution, contrast sensitivity, and the cortical magnification factor. *Experimental Brain Research, 37*, 475-94.
- Flaskamp, B. N. S., & Hooge, I. Th. C (2006). Crowding degrades saccadic search performance. *Vision Research, 46*, 417-25.
- Flaskamp, B. N. S., Over, E. A., & Hooge I. Th. C (2005). Saccadic search performance: the effect of element spacing. *Experimental Brain Research, 167*, 246-59.
- Vogels, R. & Biederman, I. (2002). Effects of illumination intensity and direction on object coding in macaque inferior temporal cortex. *Cerebral Cortex, 12*, 756-66.
- Vuilleumier, P. (2005). How brains beware: neural mechanisms of emotional attention. *Trends in Cognitive Sciences, 9*, 585-94.
- Vuilleumier, P., Armony, J. L., Driver, J., & Dolan, R. J. (2001). Effects of attention and emotion on face processing in the human brain: an event-related fMRI study. *Neuron, 30*, 829-41.
- Vuilleumier, P., Armony, J. L., Driver, J., & Dolan, R. J. (2003). Distinct spatial frequency sensitivities for processing faces and emotional expressions. *Nature Neuroscience, 6*, 624-30.
- Vuilleumier, P., Richardson, M. P., Armony, J. L., Driver, J., & Dolan, R. J. (2004). Distant influences of amygdala lesion on visual cortical activation during emotional face processing. *Nature Neuroscience, 7*, 1271-8.
- Vuilleumier, P., & Schwartz, S. (2001). Beware and be aware: Capture of spatial attention by fear-related stimuli in neglect. *NeuroReport, 12*, 1119-22.
- Wertheim, A. H., Hooge, I. T. C., Krikke, K., & Johnson, A. (2006). How important is lateral masking in visual search? *Experimental Brain Research, 170*, 387-402.
- Wertheim, T. H. (1894). Über die indirekte Sehschärfe. *Zeitschrift für Psychologie und Physiologie der Sinnesorganen, 7*, 172-87. (Translated in English by Dunskey, I.L. (1980). Peripheral visual acuity. *American Journal of Optometry and Physiological Optics, 57*, 915-24.)
- Westheimer, G. (2001). Is peripheral visual acuity susceptible to perceptual learning in the adult? *Vision Research, 41*, 47-52.
- Wetherill, G. B., & Levitt, H. (1965). Sequential estimation of points on a psychometric function. *British Journal of Mathematical and Statistical Psychology, 18*, 1-10.

## REFERENCES

---

- Williams, D. E., Reingold, E. M., Moscovitch, M., & Behrmann, M. (1997). Patterns of eye movements during parallel and serial visual search tasks. *Canadian Journal of Experimental Psychology*, *51*, 151-64.
- Wilshire, B. W. (Ed.) (1984). *William James. The essential writings*. Albany: State University of New York Press.
- Wolfe, J. M. (1992). "Effortless" texture segmentation and "parallel" visual search are not the same thing. *Vision Research*, *32*, 757-63.
- Wolfe, J. M. (1994). Guided search 2.0. A revised model of visual search. *Psychonomic Bulletin & Review*, *1*, 202-38.
- Wolfe, J. M. (1998). What can 1 million trials tell us about visual search? *Psychological Science*, *9*, 33-9.
- Wolfe, J. M., Alvarez, G. A., & Horowitz, T. S. (2000). Attention is fast but volition is slow. *Nature*, *406*, 691.
- Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search: an alternative to the Feature Integration Model for visual search. *Journal of Experimental Psychology: Human Perception & Performance*, *15*, 419-33.
- Yeshurun, Y., & Carrasco, M. (1998). Attention improves or impairs visual performance by enhancing spatial resolution. *Nature*, *396*, 72-4.
- Yeshurun, Y., & Carrasco, M. (1999). Spatial attention improves performance in spatial resolution tasks. *Vision Research*, *39*, 293-306.
- Yeshurun, Y., & Carrasco, M. (2000). The locus of attentional effects in texture segmentation. *Nature Neuroscience*, *3*, 622-7.
- Zelinsky, G. J., & Sheinberg, D. L. (1997). Eye movements during parallel-serial visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *23*, 244-62.