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ROLE OF ATTENTION IN VISUAL INFORMATION PROCESSING

Abstract

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INTRODUCTION

VISION AND ATTENTION

Both vision and attention appear very simple. What can be simpler than seeing the world around us, or paying attention to an object that looks interesting? We don't experience the complexity of computations our brain does in order to extract useful description of the world from the distribution of light falling into our eyes.

The essence of attention is selection. There is much more information in the visible world than we ever are able or need to use. At every moment, we pay attention to only one or a few objects. Paying attention to something makes us to see these objects more clearly, more accurately, and remember better. There are different ways to pay attention. You can turn your head, or eyes, or even make a step toward an interesting object. It is well known for more than 100 years that we can also orient attention without any visible accommodation (Von Helmholtz, 1894, cited in Van der Heijden, 1992). Researchers of attention are mainly interested in this type of covert attention. It is considered to be an important mechanism of visual information processing within our brain.

Modern studies of attention started about the middle of the last century, when it became possible to compare human brain or visual system to other real or imaginable information processing machines. In this time, classical questions and conjectures about serial-parallel processing, levels of selection, capacity limitations and other were formulated (e.g. Broadbent, 1958; Deutsch & Deutsch, 1963; Neisser, 1967; Treisman, 1969), and new research methods were invented (e.g. Estes & Taylor, 1964; Eriksen & Collins, 1969).

Many facts of human visual perception are consistent with a simple model of visual system that consists of two subsystems: pre-attentive and attentive (Neisser, 1967; Treisman & Gelade, 1980). Pre-attentive subsystem analyses simple visual features over the entire visual field in parallel. Pre-attentive system is assumed to have unlimited processing capacity. Regardless of the number of objects and features in the visual field, the simple features are registered with the same efficiency. Classical simple visual features are brightness, orientation, size (or spatial frequency), colour, movement, probably curvature, and maybe a few more (e.g. Wolfe, 1998).

The attentive subsystem uses the simple features as input to accomplish more complex tasks like recognition of objects or fine visual discriminations. This system has limited capacity: it can process only a small part of visual field or a single visual object (or maybe a few simple objects) at a time (e.g. Verghese & Pelli, 1992; Treisman & Gelade, 1980). Usually, it is presumed that selection is based on location. The focus of attention can move around in the visual field, and can also accommodate its spread from narrowly concentrated to widely dispersed. Spotlight and zoom lens metaphors are frequently used to characterise the properties of spatial attention (Posner, 1980; Eriksen & St James, 1986).

The opponents of this classical early-selection scheme have shown that even unattended objects can be processed up to the identification (e.g. Allport, Tipper & Chmiel, 1985). Consequently, attentional selection must occur at some later stage when all visual processing is completed. According to this late-selection model, attention may be needed for conscious experience, response selection or remembering.

At present, probably most of the researchers agree that selection can occur at multiple stages. Neurobiological studies show that there are several levels of processing that analyse visual properties from the simplest through intermediate to complex natural objects (e.g.

Riesenhuber & Poggio, 1999; Pasupathy & Connor, 2002). Effects of attention have been observed at nearly all levels of sensory information processing (e.g. Motter, 1993).

In recent years, several studies have demonstrated striking differences of attention requirements between "natural" and "unnatural" stimuli. Oddly oriented images of shaded 3D objects easily pop out among regularly oriented ones (Ramachandran, 1988; Sun & Perona, 1996). Some complex natural objects (e.g. animals) can be detected in near absence of attention (e.g. Li, VanRullen, Koch & Perona, 2002; Rousselet, Thorpe & Fabre-Thorpe, 2004).

On the other hand, the assumption of independent processing of even simple features is violated when stimuli are too close to each other. In such conditions, local interactions like feature contrast, crowding, and grouping can affect the performance (Nothdurft, 1991; Andriessen & Bouma, 1976; Humphreys, Quinlan & Riddoch, 1989). The zones of local interaction are quite large (Bouma, 1970; Toet & Levi, 1992), and it is difficult to discriminate these effects from those of attention.

Several researchers are looking for a better model in order to replace the classical attentive-pre-attentive one (e.g. VanRullen, Reddy & Koch, 2004; Hochstein, & Ahissar, 2002; Wolfe, 2004; Joseph, Chun & Nakayama, 1997).

VISUAL SEARCH METHOD

Visual search is one of the few most popular methods for studying visual attention. The method has also a high level of ecological validity, because frequently we have to look for something in our real environment. In a simple search experiment, a set of objects is displayed, and observer has to detect a presence of a predefined target object among them. Usually, set-size (number of displayed objects) is varied and its effect on performance is analysed. Performance is measured either by reaction time or by percentage correct responses. In visual search, load for memory and response system is independent of set-size (Estes & Taylor, 1964). Consequently, set-size effect can be assumed to measure a pure perception.

Most frequently, the results of the studies are interpreted in terms of serial-parallel processing (Bergen & Julesz, 1983; Treisman & Gelade, 1980). A simple serial processing model assumes that stimuli in a display are processed one after another. In this case, increasing the number of to-be-processed stimuli (set-size) should linearly increase the total processing time. Ratio of target present / target absent reaction time slopes near ½ can be considered as an additional evidence for serial search (in target-present trials, observer finds the target, in average, after checking a half of the stimuli; in target-absent trials it is necessary to check all the stimuli in order to decide that the target is not present). A simple (unlimited capacity) parallel model assumes that all stimuli are processed independently, and the number of stimuli has no effect on the processing efficiency. Unfortunately, we can almost never be sure that our model is the correct one, because there are parallel models that behave like serial ones, and vice versa (Townsend, 1971). Early results of RT studies of visual search were consistent with the idea that simple features (e.g. a red spot among blue spots) can be detected in parallel, but finding the conjunctions of simple features (e.g. a red vertical line among blue vertical and red horizontal lines) needs serial scanning (Treisman & Gelade, 1980). However, several counterexamples have been also found (e.g. Nakayama & Silverman, 1986; Theeuwes & Kooi, 1994), and this simple scheme has been modified by including some type of pre-attentive guidance of attention towards target conjunctions (Wolfe, Cave & Franzel, 1989; Treisman & Sato, 1990).

SIGNAL DETECTION THEORY (SDT) OF VISUAL SEARCH

In recent years, several people (e.g. Palmer, Ames & Lindsey, 1993; Eckstein, 1998; Morgan, Ward & Castet, 1998; Baldassi & Verghese, 2002) have attempted to explain the regularities of visual search with Signal Detection Theory. The main assumption of SDT (Green & Swets, 1966) is that representations of stimuli in observer's brain are noisy, and that noise limits perceptual performance. This idea leads to a simple explanation of set-size effects in visual search. Assume that there is a certain probability of perceiving a single distractor as the target. With a large number of distractors, the probability that at least one of them looks like the target is much larger. Thus, even if perceptual processing of the stimuli is independent in different locations and unlimited in capacity, some decrease of performance with increasing set-size is expected (e.g. Eriksen & Spencer, 1969). With certain assumptions, and given performance level (e.g. accuracy) for set-size one, we can calculate the same performance measure for all other set-sizes. Shaw (1980, 1984) derived the equations for these calculations and tested several versions of SDT based search models against experimental data. She found that set-size effect in a simple luminance increment detection task was well in accordance with the unlimited capacity SDT model. For letter discrimination, however, the set-size effect was much larger, and was accounted for by strict limited capacity (sample size) model.

Palmer and his associates (Palmer et al, 1993; Palmer, 1994; Palmer, Verghese & Pavel, 2000) developed these models for another performance measure – target-distractor difference threshold, and demonstrated that set-size effects in visual search for many simple features (line length, orientation, brightness, aspect ratio of rectangle, colour) are in accordance with the predictions of unlimited capacity SDT model (at least for set-sizes 1-8).

Eckstein (1998) applied similar SDT models to the task of search for conjunctions of simple features and found, contrary to the widely held view, that even with these stimuli, set-size effects were consistent with unlimited capacity.

Palmer (1994) tested some more complex stimuli (rotated Ts and Ls, objects consisting of pairs of black and white dots) and obtained results intermediate between unlimited and limited capacity models. Moreover, he found that non-attentional "sensory" interactions were larger with these complex stimuli that complicated the measurement of "pure" set-size effect related to central capacity limitations. Thus, the capacity limitations were not convincingly demonstrated within SDT paradigm of visual search, and the roles of central (attentional) and peripheral (sensory) factors were far from being determined.

EXPERIMENTAL STUDIES

The present work includes 4 experimental studies on different aspects of visual attention. All of them use some variants of visual search method. Studies I and II apply SDT model to search for simple feature and relative position stimuli. The third study analyses the special role of location and size in attentional selection. The fourth study explores the role of masking in determining the requirement of attention for perception of orientation of simple spatial patterns.

STUDY I: RELATIVE POSITION STIMULI

This study follows the ideas of John Palmer and his colleagues (Palmer et al, 1993; Palmer, 1994) in applying SDT models to visual search. I attempted to find theoretically simple “complex” stimuli that would require attentional processing. Good candidates are stimuli that consist of the same elements but differ in their arrangement. Stimuli of this type are generally hard to discriminate without focused attention (e.g. Beck & Ambler, 1973; Cheal, Lyon & Hubbard, 1991). In order to use the Palmer’s difference threshold method, it must be possible to vary quantitatively the difference between target and distractor stimuli. I found simple stimuli that satisfied these requirements. These were squares bisected asymmetrically by a vertical line segment, with target being the mirror image of the distractors. These “complex” stimuli also have their simple feature counterparts: asymmetrically bisected target and symmetrically bisected distractors.

I measured the set-size effects for these new stimuli using the difference threshold method from Palmer et al (1993). The results show that set-size effect for relative- position stimuli is much larger than the prediction of unlimited capacity model and can be well accounted for by a strict limited capacity (sample-size) model. The set-size effect for the otherwise very similar feature stimuli was consistent with the unlimited capacity model. Thus, this study supports the view that limited capacity attentional processing is needed for discrimination between the stimuli that differ only in the relative position of the same elements. The results are consistent with some earlier studies where either RT or percentage correct had been used as the dependent variable (Logan, 1994; Saarinen, 1996; Bergen & Julesz, 1983), and reject the hypothesis of Duncan and Humphreys (1989) that target-distractor (and distractor-distractor) similarity should determine the efficiency of visual search.

STUDY II: CENTRAL (GLOBAL) VS. PERIPHERAL (LOCAL) LIMITATIONS

The visual field has a finite size, and it is hard to vary the number of simultaneously presented objects without varying distances between them. Thus, in most of the visual search studies there is some confound between set-size and density of the displayed stimuli.

In my study I, elementary means to control the local interactions between adjacent stimuli were used. However, these were far from perfect. Also, a complete model of visual search should include both central (global) and peripheral (local) limitations.

In the second study, I used the same stimuli, but systematically varied both the set-size and distance between stimuli in the display. The results show that the effect of distance between adjacent stimuli is similar for feature and relative position stimuli, and is accounted for by the same lateral masking model (Levi, Klein & Hariharan, 2002). The set-size effect, even after the elimination of the effect of lateral masking, was remarkably different. The results support the view that the capacity of central processing limits detection of the target, which has no simple features different from the distractors.

STUDY III: A SPECIAL ROLE OF LOCATION AND SIZE

In the third study, the role of different visual attributes in attentional selection was analysed. It is well known that we are able to direct attention voluntarily to a given location in the visual field, but also to an object of a given colour, size or any other feature (Sperling, 1960; von Wright, 1968). However, all these attributes are not equal in terms of how good cues for selection they are. Many studies have revealed a special role of location in attentional selection (e.g. Nissen, 1985; Van der Heijden, 1992). Usually, location seems to mediate the attending to other visual features. For example, in order to attend to a red object we attend to the part of visual field where this object is located. Size is another simple feature and supposedly similar to colour in many aspects. The size-based selection also appears to be mediated by location (e.g. Moore & Egeth, 1998; Shih & Sperling, 1996).

However, location to be attended must itself have a size (we cannot select a part of visual field without explicitly or implicitly determining the size of that part). This simple truth implies that size, similar to location, should have a special role in attentional selection.

I ran several experiments in order to study attentional selection by size. The stimuli were letters and numerals displayed as a stream of Rapid Serial Visual Presentation (RSVP). The small and large characters alternated in the stream. Observer's task was, for example, to identify a target numeral presented among letters. Earlier studies (Shih & Sperling, 1996; Farell & Pelli, 1993) have reported that prior knowledge of the target size does not facilitate its identification in similar conditions. In these studies, six or more characters have been presented in each frame. I varied frame size from 1 to 6, and found effective size-based selection for frame sizes of 1-2 characters. A control experiment with alternating green and red characters demonstrated the impossibility of colour-based selection in similar conditions. This study shows that size together with location has a special role in visual attention, because both location and size are the compulsory parameters of spotlight (or window) of spatial attention.

STUDY IV: EFFECT OF MASKING AND VISUAL TASK

The purpose of the fourth study was to explore the interaction of attention, visual masking, and observer's task (detection vs. identification).

Several studies have reported different effects of attention for detection and identification (or fine discrimination) tasks (Sagi & Julesz, 1985; Bonnel, Stein & Pertucci, 1992) while others argue that the same models are applicable for the both tasks (e.g. Braun & Julesz, 1998; Yager, Kramer, Shaw & Graham, 1984; Solomon, Lavie & Morgan, 1997).

The relationship between attention and masking is another controversial issue. Many traditional masking models are based on quite low-level processes that are presumably not affected by attention (e.g. Foley; 1994; Wilkinson, Wilson & Ellemberg, 1997). However, some types of interactions of masking and attention have been reported. Effect of attention can be modified at least by backward masking (Enns & Di Lollo, 1997; Smith, 2000), and effect of crowding (lateral masking) is found to be dependent on attention (Zenger, Braun & Koch, 2000). Actually, different forms of masking (simultaneous masking, backward masking, lateral masking) may have different relations with attention. Also, there may be different varieties of attention (e.g VanRullen et al, 2004) that may be not similarly affected by masking.

The study reported here begins with using classical simultaneous masking stimuli (e.g Foley, 1994). Vertical and horizontal Gabor patterns were used as targets and distractors in a visual search task. These were superimposed with maskers – diagonal Gabors of larger spatial extent.

The first experiment demonstrated an interesting effect of interaction between attention, masking and observer's task. In the detection task, the set-size had little effect on the performance (as predicted by the unlimited capacity SDT model). In the orientation identification task, increasing the set-size from 1 to 8 resulted in a much larger decline in performance. A control experiment confirmed that this effect of attention was present only with simultaneously masked stimuli.

The additional experiments attempted to reveal attentional mechanisms behind the effect found in the first experiment. In these experiments the relative size and extent of spatial overlapping of relevant and masking stimuli were varied. The results suggest that attention may reduce the crowding effect of maskers. Several authors have reached similar conclusions (Zenger et al, 2000; Morgan et al, 1998); others, however, have found quite opposite results (Nazir, 1992; Wilkinson et al, 1997; Parkes, Lund, Angelucci, Solomon & Morgan, 2001). Future studies should help to understand the causes of these differences.

CONCLUSIONS

The four studies reported here explored different aspects of visual attention. All the results are consistent with the general concept of relatively low-level location based selection (and pre-attentive parallel processing of simple features). Location must be defined by both position in the visual field and size of the attended area. While visual search for simple features can be well modelled by SDT without limitations on processing capacity, there are visual stimuli and visual tasks that require limited resources of attentional processing. Concentrated attention is necessary for the perception of relative position of components within a stimulus, and it may also reduce crowding effects for some combinations of stimuli and tasks.

There seems to be some controversy between studies II and IV. Study II modelled the central capacity limits and crowding as independent mechanisms residing supposedly at separate levels of processing. Study IV suggests that central capacity limits may be dependent on crowding in some conditions. Thus, the exact relationship between central and peripheral limitations of vision is a problem for future studies.

Another goal for further studies may be development of models that are more consistent with recent psychophysical and neurobiological data. In particular, several levels of attentional selection, differences between natural and unnatural images, and effects of perceptual learning need much better understanding.

TÄHELEPANU ROLL NÄGEMISINFORMATSIOONI TÖÖTLEMISEL

Kokkuvõte

Töös uuritakse tähelepanu funktsioone nägemisinformatsiooni töötlemisel inimese ajus. Lähtepunktiks on klassikaline mudel, mille järgi koosneb nägemissüsteem piiramatu töötlusmahuga tähelepanueelsest ja piiratud töötlusmahuga tähelepanu allsüsteemist. Oluliseks küsimuseks on: milliste visuaalsete tunnuste ja milliste nägemisülesannete puhul on piiratud võimsusega tähelepanusüsteemi kasutamine vajalik? Töös kasutatakse erinevaid visuaalse otsingu katse variante, kus katsealune peab otsima mingit etteantud objekti teiste (segavate) objektide hulgast. Katsete tulemusi võrreldakse signaalide detekteerimise teoorial põhinevate mudelite ennustustega. Töö koosneb neljast artiklist.

Uurimuses I võrreldakse lihtsa tunnuse alusel ja samade komponentide suhtelise asukoha alusel eristatava eesmärkobjekti otsingu efektiivsust. Lihtsa tunnuse järgi eristamisel mahulised piirangud puuduvad, kuid komponentide suhtelise asukoha eristamine vajab piiratud mahuga tähelepanulist töötlust.

Artiklis II uuritakse tsentraalse tähelepanumehhanismi ja lokaalsete piirangute (lateraalse maskeerimise) vahekorda. Leiti, et lokaalsete interaktsioonide mõju on sarnane erinevat tüüpi stiimulite puhul, kuid tsentraalse tähelepanumehhanismi piirangud ilmnesid ainult komponentide suhtelise asukohaga määratud objektide otsingul.

Publikatsioon III käsitleb objekti suuruse iseäralikku rolli tähelepanulisel valikul. Uurimuses tehti kindlaks, millistel tingimustel on tähelepanuline valik objekti suuruse alusel võimalik ja millistel mitte. Tulemused on seletatavad tähelepanu "valguslaigu" ruumilise olemusega.

Uurimuses IV selgitatakse visuaalse (samaaegse) maskeerimise, ülesande tüübi (detekteerimine või orientatsiooni eristamine) ja tähelepanu kombineeritud mõju. Leiti, et piiratud mahuga tähelepanuline töötlus on vajalik ainult maskeeritud stiimuli orientatsiooni eristamise ülesande puhul; sama ülesanne ilma maskeerimiseta ning avastamisüleanne (nii maskeeritud kui ka maskeerimata stiimulitega) on täidetavad mahupiiranguteta.

Töö tulemused aitavad paremini mõista tähelepanu rolli nägemisinformatsiooni töötlusel ning tähelepanu suhteid teiste tajumehhanismidega. Loodetavasti aitavad tulemused kaasa senisest adekvaatsemate nägemistaju mudelite loomisel.

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