What can cytologists learn from 25 years of investigations in visual search?

A. EVERED
Cytopathology Department, Llandough Hospital, Penlan Road, Penarth, South Glamorgan, Wales, UK

Accepted: 3 September 2005

ABSTRACT

This review aims to provide an insight into the nature and mechanisms of the visual screening of cytological preparations and to discuss the implications for current practice. Visual perception in cytology is under-researched and deserves further investigation. Fundamental issues to be addressed include the mechanisms of visual scanning of cytological preparations and the factors affecting search performance. Answers to these questions will have wide reaching impact on issues such as liquid-based technology, automated screening, training, quality assurance, recruitment and selection of staff, and medico-legal problems.

KEY WORDS: Cytology. Visual perception.

Introduction

Whether looking for your car in an overcrowded car park or searching for neoplastic cells in a cytological preparation, visual search is something that all sighted people do every day of their lives. Visual search is a complex phenomenon that has evolved over millions of years and provides humans and other sighted animals with important survival advantages. Thus, unsurprisingly, it is a topic that has challenged and enthralled cognitive psychologists for many years.

A literature search recovered very few peer-reviewed papers directly addressing visual perception in cytology screening. This is perhaps surprising because there are many unanswered questions about the mechanisms, efficiency and accuracy of cytological search, not least of which is what causes screening errors and what can be done to prevent them.

The purpose of this article is to review the psychology literature for what is currently known about visual search and perception. This will be correlated with the limited and dated literature on visual search in cytology. Finally, some inferences about cytological search will be made; however, such inferences must remain speculative until further research is undertaken.

Human visual system

Any description of the mechanisms of visual search must start with an understanding of the anatomy and physiology of the human visual system. A complete account is outside the scope of this review and the reader should consult a text on neuroanatomy for greater detail.[1]

The starting point is the eye, which projects light rays from the environment onto the retina. The retina contains photoreceptor cells that are highly concentrated in a particularly light-sensitive area known as the fovea. Following stimulation, electrical signals are passed along the axons of the receptor cells to the optic disc, where they meet with axons of many other receptor cells to form the optic nerve.

Correspondence to: Andrew Evered
Email: andrew.evered@cardiffandvale.wales.nhs.uk

The optic nerve extends from the eye to a region of the thalamus known as the lateral geniculate nucleus (LGN). This is a crucial location for providing an early account of the motion, colour and detail of visual stimuli. Fibres extend from the LGN to the primary visual cortex, which is located in the occipital lobe at the back of the brain. It is here that further processing of visual stimuli occurs, and attributes other than movement and colour (i.e., orientation, junctions, contrast and textures) are analysed.

Visual search theories

Visual search is the process by which we look for specific objects (targets) in a background of non-target objects (distractors). The tool used most commonly to derive theories of visual search is the 'reaction time versus set size' experiment. Subjects are required to look for a target (usually a simple object such as a number or letter) among a variable number of distractors in a single visual field, and reaction times are measured. Typically, for target-present searches, reaction times increase linearly with the number of distractors. This is known as the set size effect.[2]

The gradient of the reaction time versus set size graph (the search slope) is taken as a measure of the difficulty of the search task. Target-absent searches yield gradients approximately twice that of target-present searches, on the basis that it will take roughly twice as long to confirm the absence of target in a target-absent search than to confirm the presence of a target in a target-present search (Fig. 1).

In 1980, Treisman and Gelade reported the interesting finding that for search targets defined by certain basic features, reaction times do not increase with each added distractor, and the search slope remains close to zero.[3] Targets

defined by special basic features seem to 'pop out' of the visual scene, with little search effort. Targets comprising a combination of basic features (known as conjunction targets) require extra time for processing and recognition. It is as though conjunction targets require effort and concentration to 'bind' features together. It is on this basis that Triesman and Gelade proposed their 'feature integration theory'.

The theory proposes that visual search consists of two phases. First, with little deployment of attention, the visual scene is assessed globally. This is known as pre-attentive or parallel processing because all items are assessed at once. Although rapid, it is fairly coarse because only basic features such as colour, size and motion are processed. This is followed by an attentive phase, whereby features are 'bound' together to form recognisable objects. This phase proceeds in a serial (item by item) manner. The attentive phase requires effort, concentration and the deployment of attention.

Two problems arise from feature integration theory. First, for many searches, search time seems to depend on the nature of the distractors, regardless of the presence of special target features. Second, search slopes vary according to the conditions of the experiment, and do not support the dichotomy of parallel/serial search. In 1989, Duncan and Humphreys put forward a theory in which search efficiency depends on two factors: target–distractor (T-D) similarity and distractor–distractor (D-D) similarity.[4] Experiments showed that, as T-D similarity increases or D-D similarity decreases, search efficiency decreases and search time increases. Duncan and Humphreys' similarity theory proposes that visual processing is a matter of competition between targets and distractors for access to visual short-term memory, based on the degree of similarity between viewed items and visual templates held in the visual system.

However, similarity theory does have its own problems. In many search tasks, targets tend to pop out of the visual field at a rate that is independent of the number and nature of distractors. Additionally, many conjunction searches are quite efficient. In fact, some triple-conjunction searches are more efficient than the search for targets defined by double conjunctions. To deal with these problems, Wolfe has proposed the guided search theory.[5,6]

Before describing this theory, however, a distinction must be made between bottom-up (stimulus-driven) and top-down (observer-driven) visual processing. Bottom-up processing measures how different an object is from its neighbours. This, in itself, is not sufficient to recognise complex targets in our environment. However, the visual system contains millions of templates that have been stored from previous similar visual encounters. Top-down (observer-driven) processing describes the way in which such templates are selected and compared with incoming stimuli (Fig 2).[7–9]

In guided search theory, information from an image is first fed into the visual pathway by a bottom-up mechanism and then compared with templates drawn from the visual cortex by top-down visual processes. An activation map is then built up by combining the bottom-up and top-down mechanisms. Peaks in the activation map represent areas of high probability of the presence of a target. Attention is drawn (or guided) to peaks in the activation map in order of decreasing activation. This theory appears to explain many of the experimental observations that others cannot.

Targets with special features yield strong bottom-up influences and activation peaks, regardless of the number of distractors that are present and pop out of the visual scene. In some cases, targets defined by a conjunction of features may also be detected efficiently. In terms of guided search theory, the explanation for these effects is that the conjunction targets are detected by dominant top-down influences.

Role of eye movements

Eye movements are uncontrolled for many experiments in visual search. This is not to say that they are unimportant, only that they are not the determining factor in experiments that involve relatively large objects in sparse displays. In such experiments, covert attention facilitates efficient discrimination and selection of visual information.[10] In the more complex visual scenes experienced in real life, rapid involuntary ballistic eye movements known as saccades move the fovea to enable fixation on peripheral objects. A saccade is therefore an overt orientating mechanism that supplements the covert attentional mechanisms provided by the visual system.[11,12]

Eye movements preceded by and coupled with visual attention are mandatory for efficient and accurate search. It is important to note, however, that the eye is essentially blind during a saccade. This is known as saccadic suppression. Information is only acquired during the relatively long periods of fixation that intervene between saccades. The role of eye movements in vision has been researched in such diverse scenarios as tumour detection on X-rays, driving and sporting activities.[13–17]

One particular phenomenon relating to visual attention and eye movements is worthy of note. Known as attentional weighting, this is the tendency for subjects to divide attention unevenly across the visual field when searching for targets among distractors.[18] The bias favours the inferior, as compared to the superior, visual field. In evolutionary terms, this bias may have arisen from the fact that there is more ecologically relevant information in this region of space. No bias has been observed between the left and right visual field. This may have relevance for defining an optimum search strategy for cytology screening.

What attributes guide visual attention?

Attention may be defined as the process that allows visual selection.[19] Wolfe and Horowitz recently addressed the notion of attentional guidance.[20] Undoubted guiding attributes include object colour, size, motion and orientation. Contrast boundaries, shape, curvature and stereoscopic depth are probable guiding features, whereas, perhaps surprisingly, object novelty and faces are unlikely candidates. This list is based on evidence accumulated in the psychology literature over several decades. It is not an exhaustive list and the interested reader should consult the paper by Wolfe and Horowitz for a more complete discussion.[20]

Questions relating to cytological search

Despite clinical importance, little research has been carried out into the mechanisms, efficiency and accuracy of the

microscopic search for neoplastic cells in cytological preparations. A list of relevant questions, although not exhaustive, might include:

- What are the mechanisms involved?
- Is there an optimum search strategy?
- Is the method of cell preparation important?
- What factors might enhance search efficiency?
- What factors might impede cell search?
- Are there differences between individuals?
- Are there learning effects?

Can the answers to these questions be applied to issues such as liquid-based cytology (LBC) preparation technology, automated screening, cytology training programmes, recruitment and selection of staff, quality assurance and medico-legal problems?

What are the mechanisms involved, and can we define an optimum search strategy?

It is helpful to start with some of the known facts about the nature of cytological preparations, the instruments used to examine them and the staff employed to undertake cell search. For descriptive ease only LBC preparations will be discussed, and no attempt is made to distinguish between different LBC technologies.

A typical LBC preparation is a circular deposit of 50,000–70,000 cells distributed randomly and uniformly on a glass slide. The density of cell populations is equally variable, but for an adequate sample it will be in the order of 700–1700 cells per field of view at x10 magnification.

Cervical epithelial cells range in size from 20 μm (parabasal cells) to 40 μm (superficial cells) in diameter and are made visible by Papanicolaou (Pap) staining. This comprises haematoxylin, which stains nuclei blue/black, and a combination of counterstains that render the cytoplasm of the cells pink, green or orange, depending mainly on the maturation of the cell.

In any one preparation the proportion of cells that are neoplastic (the target:distractor ratio) can range from zero to almost 100%. The numerical ratio of target cells to distractors is often very low. The morphological variability of both neoplastic and normal cells is extreme, and no single special feature adequately defines a neoplastic cell.

The field of view of a modern light microscope with a 25 mm focal length eyepiece subtends an angle of 25 degrees. Simple trigonometry allows the calculation of the angle subtended by epithelial cells, which, when examined using x10 objective magnification, ranges from about 0.23 degrees for parabasal cells to 0.5 degrees for superficial cells.

A cytology screener may spend five minutes scanning a preparation for abnormal cells. If all cells are examined, which they should be, this equates to approximately 200 cells per second. A screener will examine cervical samples for up to five hours per day, and by the end of a typical working week will have examined 18 million cells.

Cytologists are highly trained individuals, but nevertheless vary in their degree of experience, training and expertise. Cytology screening is not completely accurate. False-negative rates of 5–10% are expected, but this figure can be higher.[21] Specificity is also limited, and over-reactions to benign inflammatory and degenerative conditions are not unusual. There are no set rules for scanning strategy and little is known about the mechanisms involved.[22,23]

The limited research undertaken in the field of radiology, airport security and cytology allows an initial attempt at defining an optimum search strategy for cytology screening.[13, 22–26] The factors under direct control of the cytologist are the speed of search, degree of overlap of microscope fields, voluntary eye movements, stage movements and the technical aspects of cell preparation.

The following model and suggested strategy for cytological search is proposed, based on contemporary visual search theory and what is known about the nature of cytology screening. It is not intended to be prescriptive, as research indicates that search strategies vary according to individual preferences and search task complexity.[27]

Phase 1 – parallel search

Initially, the field of view is assessed globally. Visual information is assimilated in parallel fashion. This early phase identifies a set of basic cell features, which may include cell size, luminance (i.e., staining intensity), contrast boundaries and possibly other features. Although this phase may not strictly be 'pre-attentive', recognition of these coarse features is nevertheless efficient and fast. Part of the aim of cytology training programmes is to teach and learn the basic features that are most likely to be present in neoplastic cells.

Phase 2 – saccadic eye movements

If a suspected neoplastic cell is present (i.e., an object possessing one or more of the basic features), covert attentional mechanisms trigger a saccade. The eye is essentially blind during these movements. The purpose of a saccade is to move the image of a potential target from a peripheral retinal location to the fovea.

With the image of a potential target cell now occupying high-resolution foveal vision, a slower but more detailed visual assessment ensues. This may include examination at higher magnification. The information supplied by the stimulus-driven, bottom-up visual pathway is combined with a concept-driven, top-down process to enable the observer to recognise and define the object. A decision about whether to accept or reject it as a neoplastic cell is then made.

Very little research into the role of eye movements during cytological search has been undertaken.[23] The extent to which the efficiency of saccadic eye movements are observer dependent is largely unknown.[28,29]

Phase 3 – voluntary eye movements and serial search

Over 90% of routine cervical cytology samples contain only normal cells, and in the remaining 10% the neoplastic cells may be present in only the occasional field of view. Most of the time, therefore, initial parallel assessment of the visual field fails to trigger attentional mechanisms. This is not to say that eye movements do not take place. In the absence of attentional triggers, voluntary eye movements attempt to foveate as many objects as possible. In stark contrast to the first phase of visual assessment, this proceeds more slowly. It takes place in a serial manner, and involves the deployment of attention to each cell in turn, in an effort to identify any neoplastic cells that were 'missed' during the pre-attentive

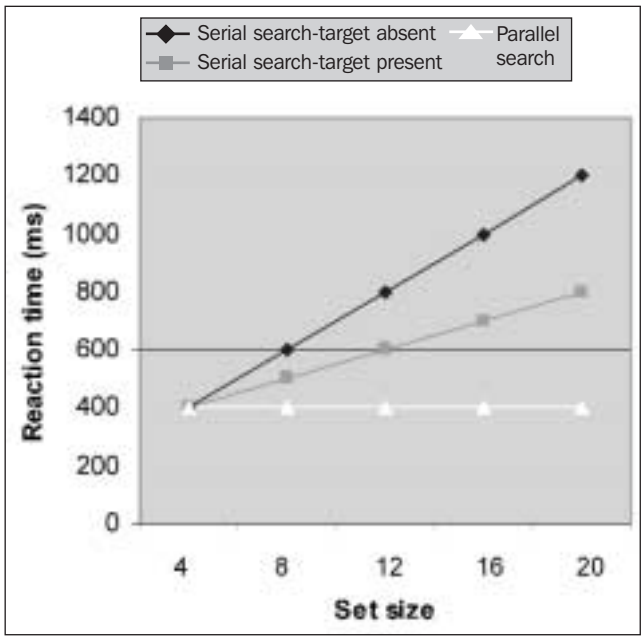

Fig. 1. The set size effect (hypothetical graph).

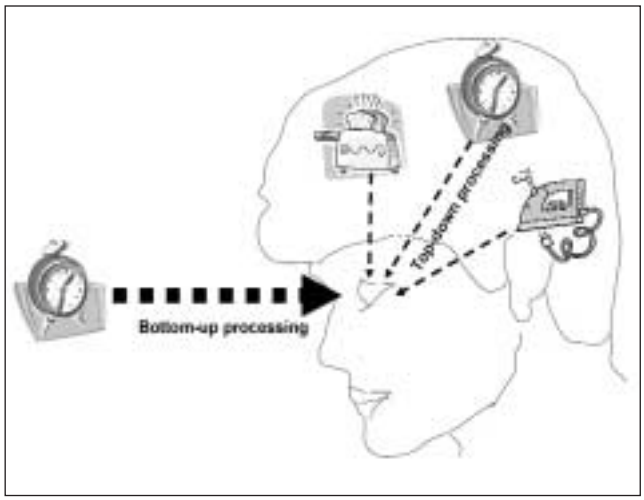

Fig. 2. Bottom-up and top-down processing.

phase. This phase of cytological search might be termed the 'attentive phase'.

In cytology, where productivity is almost as important as accuracy, the attentive phase must entail an element of speed–accuracy trade-off. It is physically impossible to serially attend to all 70,000 cells in a preparation without a dramatic increase in the time allocated for each preparation. Thus, we are left with two important conclusions. First, cytologists must rely heavily on pre-attentive global mechanisms to trigger saccades for the detection of abnormal cells. Second, when target cells are not found by pre-attentive mechanisms, search is terminated before all cells are serially attended to.

Chun and Wolfe have offered an explanation for efficient search, despite the apparent flaw of early termination.[30] The solution is based on guided search theory. The observer first computes the probability that each item is a target, based on its difference from other items and its similarity to the target. This takes place in parallel fashion and results in a 'probability map'. Peaks in the map are examined in

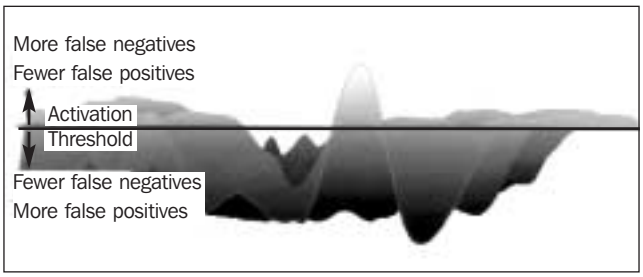

Fig. 3. Probability map for target presence. Lowering the threshold increases the sensitivity for target detection, but lowers the specificity. Raising the threshold has the opposite effect.

decreasing order. The observer adaptively sets a threshold for accepting a peak as a target (the activation threshold). The threshold is reduced if the number of 'misses' increases, and is raised if the number of false alarms increases.

Thus, the decision about whether or not a target is present in a visual scene is one of probabilities and variable thresholds. This concept has important implications for cytology because the decision about the presence or absence of abnormal cells in a preparation is one of probability rather than certainty (Fig. 3).

To further improve the efficiency of cell search, cytologists should maximise the use of voluntary eye movements and attend to as much of the visual field as possible. The advantage here is that although target cells may not be present, foveal stimulation is constantly changing. This ensures repeated firing of receptor cells and helps prevent desensitisation of the fovea.

It is important to point out that the three phases discussed above are separated for ease of description. In reality, it is likely that all three phases proceed concurrently.

Phase 4 – stage movement with overlap

The final phase is a mechanical movement of the microscope stage to bring into view a new field of cells. Early work on the analysis of stage movements during visual screening appears not to have been followed up.[23] Guidelines in the UK indicate the need for overlapping fields, but this has not been quantified.[31]

Conventional wisdom states a minimum of one-third overlap of a field of view, but there is no evidence on which to base this assumption. The rationale is presumably one of increasing the number of viewings received by cells, and to assist in bringing as many cells as possible into foveal vision.

A review of the psychology literature allows a more rational approach to field overlap. Posner has proposed the spotlight model of visual attention, in which the area of maximum visual attention is limited to an area roughly the size of foveal vision.[32] The size of this 'spotlight' has been estimated to be one degree of visual angle.[33] This is approximately the size of two superficial cells viewed at x10 magnification.

There is, however, some evidence that the total area attended to is somewhat larger than this. Known as the 'useful field of view' (UFOV), its size is generally thought to be about five degrees.[24,34] The logical conclusion is that, during a cytology search at x10 magnification, only one-fifth of the 25-degree microscope field of view, equating to the width of about 10 superficial cells, receives attention at any one time. This offers some evidence that a cytological search

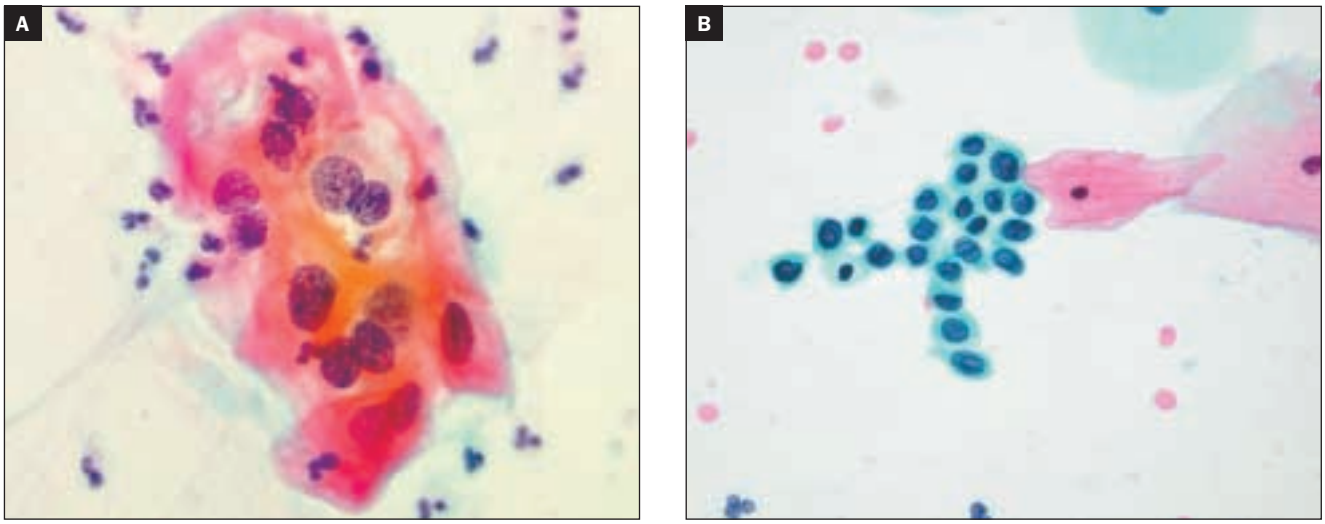

Fig. 4. (a) Easy search (mild dyskaryosis) and (b) difficult search (small-cell dyskaryosis). Papanicolaou stain (original magnification x600).

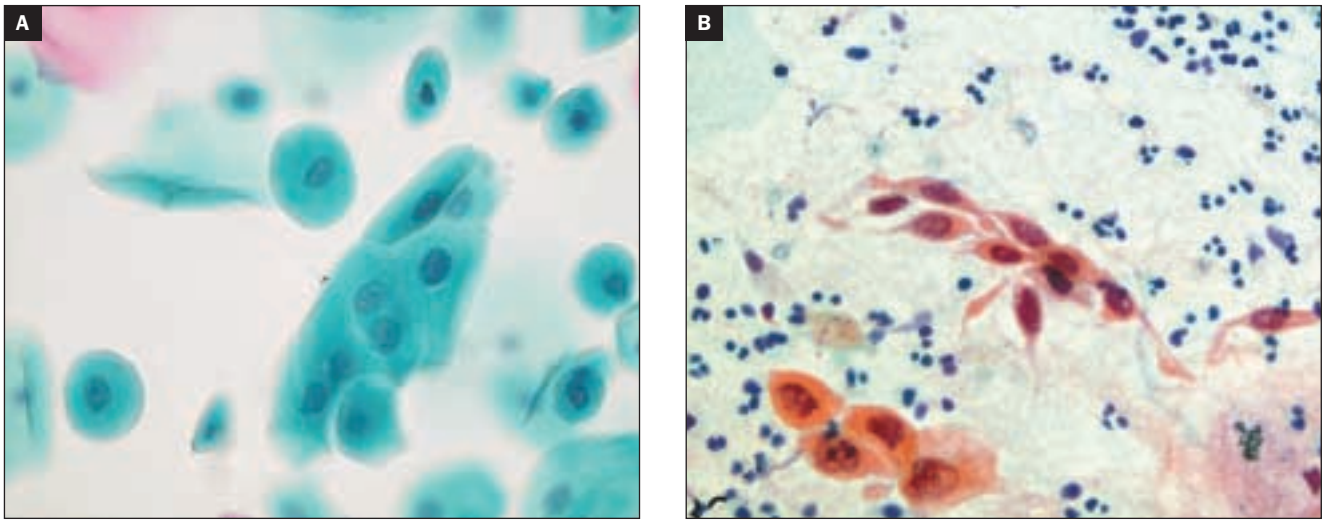

Fig. 5. (a) Cyanophilic and (b) eosinophilic/orangeophilic staining with the Papanicolaou method (original magnification x600).

strategy involving field overlaps of four-fifths would maximise the likelihood of all cells falling within the useful field of view. The problem, as always, is that this strategy is slower than a one-third field overlap and is therefore detrimental to screener productivity.

A confounding factor here is that the size of the UFOV is variable and depends to a large extent on stimulus density and familiarity.[24,35–37] Observer-related factors such as age, fatigue and experience may also influence the size of the UFOV.[38–41] Therefore, advice to cytology screeners should be to reduce screening speed and increase field overlap if they suspect or anticipate a reduction in the size of their UFOV.

An important consideration is whether a smooth stage movement accompanied by pursuit eye movements is more or less efficient than a stop-and-look strategy. Pursuit eye movements serve to track moving objects in the visual field. They are not usually under voluntary control and their purpose is to stabilise retinal images of moving objects, thereby enabling their perception in detail.

Vision research shows that motion can be used to guide search if some items are moving and others are not, but there is no benefit when all items are moving uniformly (as during a microscope stage movement).[42–44] Indeed, there is a risk of retinal image smear if pursuit eye movements do not match stage velocity perfectly. Pursuit eye movements during stage movement do not occur to any great extent during visual screening in cytology.[23]

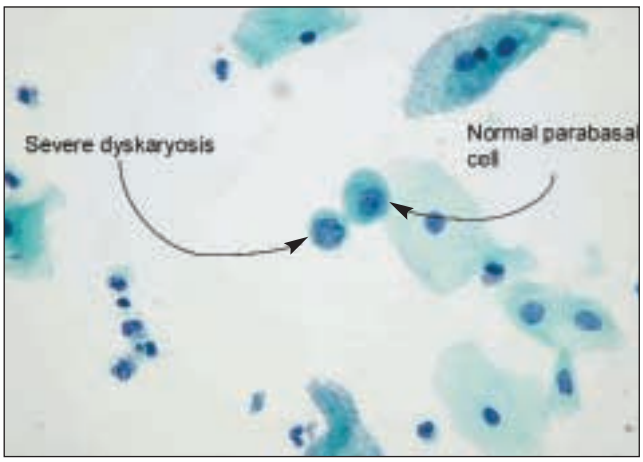

Fig. 6. High target–distractor similarity. Papanicolaou stain (original magnification x600).

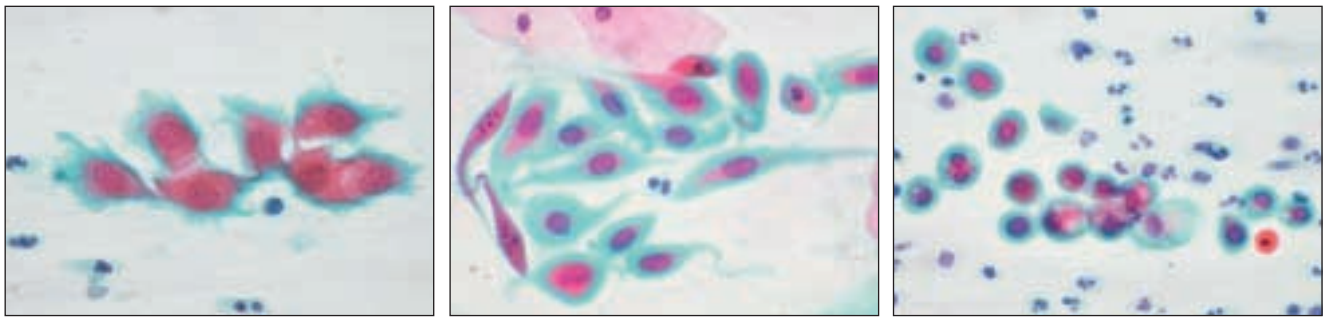

Fig. 7. Range of morphological appearances in squamous metaplasia: low distractor–distractor similarity. Papanicolaou stain (original magnification x600).

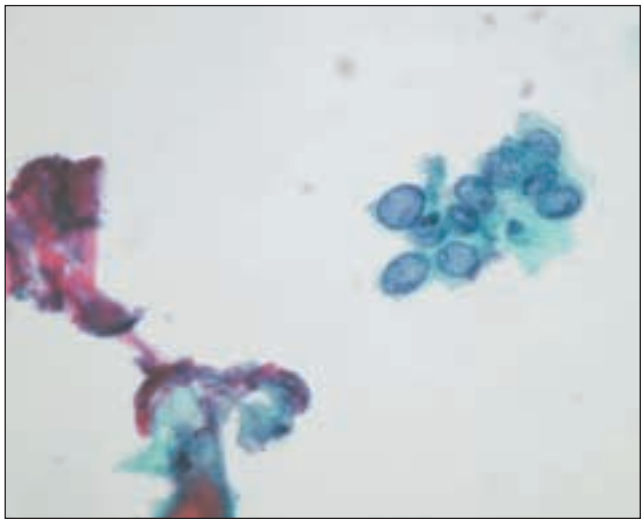

Fig. 8. Difficult search: pale dyskaryosis. Papanicolaou stain (original magnification x600).

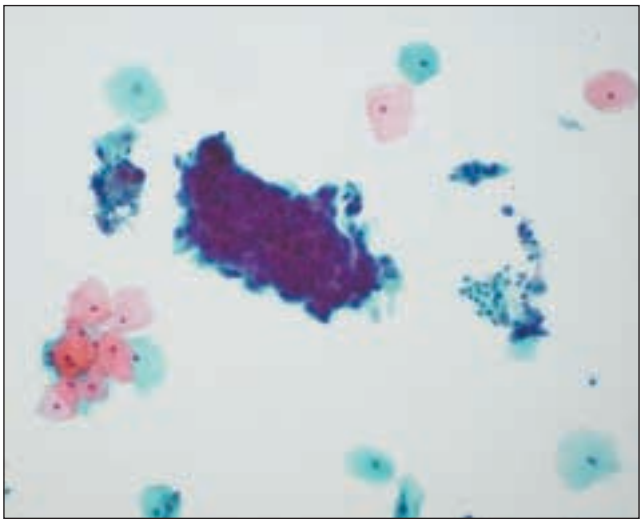

Fig. 9. 'Satisfaction of search' can result in abnormal tissue fragments being interpreted as normal. Papanicolaou stain (original magnification x600).

In radiology the optimum scanning strategy appears to be a stepwise search of 'fixation clusters' spaced five degrees apart.[24] A chest image subtends 25 degrees when viewed from a distance of 70 cm – coincidentally, about the same as a field of view in a modern microscope used in cytology. Until there is evidence to the contrary, it seems reasonable to advise a similar stepwise observation of five-degree fixation clusters during cytological search.

Regarding screening speed, it is generally accepted that there is a speed–accuracy trade-off with cytology screening. Screeners are advised constantly that accuracy is more important than speed, but they are also reminded of the need to maintain productivity. Thus, what is the maximum rate (in fields per second, say) a preparation can be screened without compromising accuracy? Clearly, it depends on several factors and it is impossible to be prescriptive.

Is the method of cell preparation important?

Characteristics of the cell preparation itself will undoubtedly modulate search strategy. High-density, low-contrast displays are likely to impede search and reduce the size of the UFOV, as will background clutter and small object size. Until more is known about the effect of these variables on the efficiency of cytological search tasks, it would appear sensible to adopt a slower search strategy with greater overlap of fields, and possibly the use of higher magnification scanning in such scenarios. With the widespread adoption of LBC preparation techniques in the UK and elsewhere, cytologists now have the opportunity to vary the appearance of cell preparations, in terms of density, background clutter and staining quality. This opportunity must be grasped, for it may yield advantages for screening accuracy and productivity.

What factors might enhance search efficiency?

The technical aspects of sample preparation and visual, psychological and physiological factors all must be considered. Technically, the ideal cell preparation allows maximum probability of detecting abnormal cells in the minimum amount of time. The factors under direct technical control that are probably important in determining search efficiency are the spatial distribution of cells (degree of cell crowding), the size of the cell preparation, and the nuclear/cytoplasmic contrast.

The first two can be controlled by the choice of LBC preparation system. Of the two currently available systems, one produces a relatively dense display of cells in a small (13 mm diameter) circular deposit, while the other yields a less dense but larger (19 mm diameter) deposit. Both result in

roughly equivalent search times, presumably because the smaller, denser preparation requires a slower search strategy. Currently, there is insufficient evidence to suggest any difference in the accuracy of these two systems in terms of sensitivity and positive predictive value.[45]

Nuclear/cytoplasmic contrast is controlled by the appropriate selection of dyes and staining protocols. The effect of contrast on cell search has not been studied, but visual search literature indicates that a high contrast between nucleus and cytoplasm is likely to be crucial to efficient cell search.[25,46–52]

One aspect of visual processing that requires special mention in terms of how it facilitates search efficiency is 'inhibition of return'. This refers to the ability to completely exclude old items from search once they have been examined and rejected as distractors.[53,54] It is as though attention 'knows' where it has been. This would certainly help to explain the efficiency with which cytologists are able to visually scan cytological specimens.

The psychological and physiological variables affecting cell search must not be underestimated. Training, experience, expertise, stress, fatigue, confidence and the 'fear factor' all play a role. Cytologists must be well trained, with less-experienced staff supported by the more experienced, and working practices must be managed in a manner that minimises stress and fatigue and maximises confidence.

The fear of 'missing' an abnormality impacts on sensitivity, specificity and search time. In the context of cervical screening there is a tendency to err on the side of caution, resulting in relatively high detection rates but lower specificity and extended search times.

What factors might impede cell search?

The observation that some search tasks are easy and efficient while others are not leads us to question what factors might operate to impair efficient search. This is not just of academic interest. The answer is crucial to the understanding of real-world search tasks such as airport security scanning, medical imaging and cytology screening. Referring to the theories of visual search and other literature, it seems reasonable to conclude that the following search scenarios are difficult, inefficient and prone to error:

- crowded visual scenes[2,24,26,35,55–60]
- small object size[20,21,51,61]
- low colour contrast between targets, distractors and background[46–52]
- visual scenes with high target–distractor similarity or low distractor–distractor similarity[4]
- targets that are not defined by the presence of a guiding feature[20]
- targets made up of multiple conjunctions of basic features[3]
- observer-related factors such as fatigue, inexperience, training or age[39,40,49,62–67]
- phenomena such as search asymmetry,[68,69] attentional blink[70–73] and satisfaction of search.[13,74,75]

Effect of crowding

In real-world search tasks there may be significant background clutter. For example, Bravo and Farid examined the effect of clutter and ill-defined targets in the scanning of luggage by airport security workers.[26] Search was extremely slow and inefficient for 'compound' targets (i.e., objects made up of multiple parts) in cluttered displays.

Kundel *et al*. investigated the factors affecting the performance of search for lung nodules in chest X-rays.[24] They concluded that the optimum field size for the scanning of images by a human is a circle with a visual angle of five degrees, and that the peripheral vision beyond five degrees is of little value in discovering new nodules (as an approximation, the outstretched thumb nail of an adult subtends about one degree). On this basis they suggest that an optimum scanning strategy for lung radiographs consists of sequential viewing of five-degree circular fields, and that the role of peripheral vision is to trigger an eye movement in order to foveate potential new nodules.

Mackworth speculates that the size of the scanning field is inversely related to the amount of clutter in the image.[35] Kundel *et al.* propose a model whereby the probability of detecting a nodule decreases rapidly as a function of distance from the axis of gaze.[24] This has been termed the 'eccentricity effect'.[76–79]

Although not suggested by Kundel *et al.*, it is conceivable that the eccentricity effect is variable, depending on such factors as object crowding, clutter, fatigue, training, experience, etc. This is worthy of further applied research, not just in the field of radiology but in cytology also.

Effect of cell size

Observations such as those by Treisman and Gormican make it clear that large objects make easier targets than small ones.[20,51,61,68,69] This has clear implications for cytology screening. Low-grade abnormalities tend to present as relatively large cells that are generally easier to find than the smaller cells that are characteristic of high-grade lesions (Fig. 4). Cytological review of missed high-grade dyskaryosis has identified small cell size as an important characteristic of false-negative cervical smears.[21,80,81]

Effect of contrast

High-contrast displays are central to efficient visual performance. Given the choice, humans prefer images of higher contrast.[49,82–84] This concept is exploited in such diverse fields as cinema, video, photography, computer graphics, medical imaging and in the design of computer displays, printers, photocopiers and microscopes. Contrast is determined by luminance differences and also colour combinations. In terms of colour, the primary rule for obtaining maximum contrast is to avoid juxtaposing adjacent parts of the hue spectrum (red, orange, yellow, green, blue, violet, purple).

Noteworthy is the curious fact that the most commonly used stain (Papanicolaou) in cytology utilises a blue nuclear stain to contrast against green cytoplasmic staining (Fig. 5a). Eosin and Orange G 6 are also incorporated (Fig. 5b), but staining reactions are generally unpredictable. The use of the Papanicolaou stain is historical and is based on the protocol devised by George Papanicolaou in 1942.[85] This staining protocol subsequently failed to evolve with the changing purpose of female genital tract cytology, namely the search for cervical cancer precursors. Research into an alternative staining technique that maximises nuclear–cytoplasmic contrast and optimises cell search would be worthwhile.

High target–distractor similarity
This is an intrinsic factor relating to the cell sample and is not possible to control. A close similarity between 'target' cells and 'distractors' occurs in such instances as high-grade dyskaryosis with coincidental metaplasia or atrophy (Fig. 6).

Low distractor–distractor similarity
A cytological example of distractor heterogeneity is squamous metaplasia, where there is a broad spectrum of normal morphological appearances (Fig. 7).

Observer-related factors
The same variables that may enhance search efficiency can be responsible for search errors. These will include poor training, poor working conditions or high levels of stress and fatigue.[62]

Search asymmetries
Another possible impeding factor is the presence of search asymmetries. Described by Treisman and Gormican in 1988, and discussed more recently by Wolfe, search asymmetry refers to the situation where the search for item 'A' among 'B' distractors is easier than the search for 'B' among 'A'.[68,69] For instance, in an array of small and big items, it is easier to detect big among small than small among big.

In 1996, Poller *et al.* referred to search asymmetries as a possible source of error during cytological screening.[86] Search asymmetries can either increase or decrease search efficiency and may help to explain the difficulty that cytologists have in the detection of small-cell dyskaryosis, pale dyskaryosis and other cytological entities (Fig. 8).[21,80,81,86]

The literature on visual search identifies other sources of error that may be relevant to cytological search. 'Attentional blink' refers to a period of several hundred milliseconds following visual fixation, during which it is impossible to deploy attention to another stimulus.[70–73] Scanning speed may therefore be a crucial factor leading to attentional failures and errors in cytology screening.

'Satisfaction of search' is the term used in radiology, in which the detection of one abnormality interferes with the detection of other abnormalities on the same radiograph.[13,74,75,87] It is unclear whether this phenomenon is due to premature termination of search or to inappropriate allocation of visual attention. Whatever the explanation, it is likely that the same phenomenon operates in some instances during cytological search.

Missed abnormal cells in cervical cytology tend to be few in number, may be obscured by inflammatory exudate or may have unusual presentations such as small pale cells or as tissue fragments (Fig. 9).[21,80,81,86] Each of these scenarios might give rise to early termination of search or may fail to trigger attentional mechanisms.

Are there differences between individuals, and are there learning effects?

Nodine *et al.* investigated how training and experience affect the performance of observers searching mammograms for breast lesions.[25] Perhaps unsurprisingly they found that observers with the most extensive training and experience conducted the fastest and most accurate searches. They conclude that the purpose of training and experience is not to develop better search strategies, but to provide exposure to exemplars and to develop distinctive diagnostic criteria.

In pure research, numerous studies have shown that visual performance varies between individuals and that practice can improve the discrimination of visual attributes such as location, orientation, spatial frequency, contrast and Vernier offset.[29,88–109] Endogenous factors such as age and visual system pathology are also known to affect visual performance.[66,110–121]

It is a common assumption that training and experience improve the efficiency of cytological search, but there is little evidence on which to base this assumption. A better understanding of the role that training and experience play in the development of effective search strategies could lead to improvements in the design, delivery and outcome of cytology training programmes.

Conclusions

Visual search is a complex process that has evolved over millions of years and impacts on our everyday lives. It has been studied extensively in academic departments of psychology but applied research is lacking. Some literature exists in the areas of radiology and airport security, but very little research has been undertaken in cytology. This is perhaps surprising considering that over four million cervical samples and tens of thousands of non-cervical specimens are scanned visually by cytologists each year in the UK.

Currently, cervical screening is undergoing a renaissance, with conventional cytology being replaced by LBC preparations. Reductions in inadequate rates are undoubted, as are visually clearer preparations, and it is hoped that this technology will deliver improvements in sensitivity and specificity for detecting cervical neoplasia. Automated scanning devices are on the horizon, and the designers of such devices may benefit greatly from a better knowledge and understanding of the nature of visual processes.[122–125]

Another issue in cervical cytology relates to negligence claims for missed abnormalities. This is a major concern in cervical screening programmes and has huge psychological and financial implications for women, cytology staff, hospitals and insurance companies. A more thorough understanding of the extent to which screening errors are related to the biological limitations of human vision and perception could go some way towards resolving the medico-legal problem in cervical cytology.

Decisions about staff recruitment in cytology continue to be based on quite arbitrary criteria. The development of aptitude testing using sound research in visual perception in cytology would be welcomed by those responsible for staff selection.

Visual cell scanning is likely to remain in the cytology laboratory for many years to come and perhaps now is the time to restart the research that began almost 20 years ago.□

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