SONIFICATION STRATEGIES FOR EXAMINATION OF BIOLOGICAL CELLS

Alistair D N Edwards[1], Andy Hunt[2], Geneviève Hines[3], Vanessa Jackson[4], Alyte Podvoiskis[2], Richard Roseblade[2], Jon Stammers[2]

[1]Department of Computer Science
[2]Department of Electronics
[3]Department of Biology
University of York
Heslington, York, UK YO10 5DD
alistair@cs.york.ac.uk

[4]Cytology Department
Leeds Teaching Hospitals NHS Trust
Britannia House
Morley,
Leeds UK LS27 0DQ

ABSTRACT

Cervical cancer is one of the most preventable forms of the disease thanks to the fact that pre-cancerous changes can be detected in cervical cells. These cells are examined visually under microscopes, but the objective of this project was to ascertain whether their examination could be improved if the visual inspection were accompanied by an auditory representation. A number of different sound mappings were tested. This paper also traces the way the sound experiments evolved in parallel with the underlying research on cell image analysis. The main conclusion is that in this kind of application, the important parameters to sonify are the 'badness' of the cell and the reliability of that rating, and some likely sound mappings to convey this information have been identified.

1. BACKGROUND

Cervical cancer is a slow onset disease whose precursor signs can be detected by inspecting visually, under magnification, samples of cervical cells. The UK National Health Service (NHS) cervical screening program organizes in England the collection and inspection of about 4 million samples each year [1]. It is a highly successful program which saves an estimated 4,500 lives each year in England [2].

The work described in this paper is part of a project which aims to produce an auditory representation of the visual information contained in the sample slides, as a means of increasing the number of clues on which the cytologist (medical person working on cell analysis) bases his/her decision on the normality of the sample. The ultimate aim is to improve the accuracy of screening, thereby to reduce the number of errors (false negatives and false positives) and hence to improve efficiency, reduce stress and in some cases to save lives.

In order to achieve this, a mapping from the existing (visual) data to sounds had to be devised. This paper describes a number of approaches that were tested. It represents work-in-progress. There is not, as yet, an optimum sonification tool, but it is felt that lessons have been learned along the way that will be of use to other researchers. The work illustrates some of the problems of making decisions in the vast space of sounds as well as some of the practicalities of developing sonifications in parallel with research on the phenomena to be sonified.

2. REVIEW

The practice of medicine can be very much a multi-modal skill. Traditionally doctors have relied on touch, smell and hearing as part of the diagnostic process and many are skeptical of the modern trends towards purely visual and numerical approaches.

The stethoscope is an example of the medical use of sound. It is not a sonification, as such, since it directly presents existing sounds (there is no data transformation involved) but nevertheless it demonstrates the power of sound in this context.

Experiments have been carried out on the use of sonification in medical applications. An excellent summary of these was presented in a tutorial by Hermann and Baier at ICAD 2006 [3].

As suggested above, modern medicine relies to a great extent on visual representations of data including the kinds of line graphs generated by machines such as electrocardiographs and electroencephalograms (ECG and EEG) for heart and brain monitoring. Physicians learn to recognize patterns in these traces which are indicative of particular conditions. A number of researchers have investigated the power of sonified alternatives, in which the doctor may *hear* the crucial patterns, including ECGs [4] and a number of different attempts to sonify EEGs [5-9]. Electromyography (EMG) is a similar technique for evaluating and recording the activation signal of muscles, and these have also been sonified [10].

Sonification has been applied to the identification of diseased tissue in magnetic resonance imaging (MRI) images [11]. Another experiment was relevant in that it was concerned with the identification of malignancy [7]. This uses a vocal encoding. Grayscale images are reduced to a vector of three values per pixel, 'the first denoting the probability that the pixel belongs to an abnormal nucleus, the second being the probability that the pixel belongs to a normal nucleus, and the third being the probability that the pixel does not belong to nucleic tissue.' (*ibid.*) These values are used to control parameters of vocal tract models in generating vowel sounds.

A previous attempt to sonify cells was carried out by Nattkemper and colleagues [12]. They investigated multi-channel fluorescence images of cells in a blood sample, whereby the intensity values identify the presence of a molecule

via immunofluorescence. Their sonification was also vocal-related, based on the mapping of data vectors to diphones, thereby generating 'artificial words'. Testing was carried out with non-biologist participants under three conditions: *visual*, *auditory* and *combined*. Participants had to match sample cells to a reference cell and classify them as either *identical* or *different*. These were then scored as either *correct, false positive* or *false negative*.

Results showed no difference between the three conditions. However, this result should not be discouraging. As long as the combined results are no worse than the (conventional) visual method, there is scope for improvement. In particular Nattkemper et al. were working with non-experts. Furthermore, they were being tested under artificial conditions. In a more realistic environment, where technicians are examining samples for hours at a time, the use of multiple channels might prove to make a difference.

3. INTRODUCTION TO THE PROJECT

It is important to clarify the aims of this project. The idea is to support the human cytologist in making decisions about the cells under review; it is not to provide automated classification of the cells. There are viable approaches to automated screening of cervical cells (e.g. [13]). In practice these can be used to screen out clearly normal samples, but when it comes to making more difficult discriminations, human operators are still required.

By the same token, sonification in this context cannot refer to the generation of an alarm when an abnormal cell is encountered. To be able to do that would amount to automated screening.

Rather, the idea is to present the cytologist with additional information which is either not present in the visual image, or is hard to discern within it. Additional information can come from sources such as:

- the direct computation of certain cell statistics (size of cell, size of nucleus, etc.), which the cytologist needs to estimate using his/her experience;
- the microscope magnification power used to produce the audio, which could be higher than that used while screening;
- the use of image enhancement methods, for instance contrast enhancement, on particularly dark regions of the slides.

The auditory field is envisaged as a *complement* to the visual field and matching the cytologist's screening pace.

The project involved a number of different aspects. Much effort was expended on processing the visual images in order to extract the information to be displayed in the auditory form. It was also necessary to find a suitable auditory mapping to display that information and it is this latter aspect which is presented in this paper.

A number of different approaches were investigated. These reflect development of the ideas, but also the fact that the objectives changed as the parallel research on the cell analysis changed. That is to say that ideas developed as to *what* was to be conveyed in the sounds. This paper thus represents a review of the development of the sonification strategies. It is hoped that the reader will learn about some alternative approaches to sonification, the tools that were used to create them and our lessons from coping with the shifting sands of research. Further details of this research can be found in [14].

4. BACKGROUND

Cervical cancer takes time to develop. There is usually a period when some of the cells lining the cervix develop abnormal changes but are not yet cancerous; these can give rise to cervical cancer later on. Doctors can pick up these changes through screening, and a simple treatment can prevent cancer developing.

Women who get cervical cancer have had past infections with a high-risk strain of HPV (Human Papilloma Virus, or wart virus), but the vast majority of women infected with these viruses do not go on to develop cervical cancer.

A vaccine to prevent HPV infection has now been licensed for use within the European Union. This vaccine prevents against the strains of HPV that are most likely to cause cervical cancer. However, it is not complete protection against all strains. Also, as it takes between 10 and 20 years for a cervical cancer to develop after HPV infection, it will still be important for women to carry on with cervical cancer screening.

Nowadays, cervical cancer amounts to 10% of all cancer cases diagnosed in women worldwide, with around 2,880 new cases diagnosed in the UK every year[1].

Thus cervical cancer represents one of the most preventable forms of the disease and regardless of the development of vaccination, screening is going to continue to play a vital part.

Women take part in the test by making a visit to their general practitioner's surgery or to a family planning clinic, where a doctor or a nurse sweeps around the cervix with an implement to collect a sample of surface cells. The sample is then either smeared and fixated onto a glass slide (smear method) or preserved in a fluid (Liquid Based Cytology method) and sent to a laboratory. Women should receive the test result within 6 weeks from the date of the test[2].

At the laboratory, the samples are stained with the Papanicolaou ('Pap') stain. As a result of the staining process, the cells and their major components (cytoplasm, nucleus) are made visible. The sample on the slide is protected by a glass cover strip. All slides are labelled and matched to a patient database. The staining process is described in some detail in [15].

Across the UK, the preparation method used for smears is the Liquid Based Cytology (LBC) method – which gives better quality slides. The term 'smear' is frequently given a general meaning that includes both smears and LBC slides.

The slides go through a strict screening process, whose aims are 1) to detect any abnormal cell changes, 2) to assess the type and severity of abnormal cell change when it is observed, and 3) to report the presence of a number of infectious agents, when detected.

[1] http://info.cancerresearchuk.org/cancerstats/types/cervix/index.htm
[2] http://cancerscreening.org.uk/cervical/index.html

The number of cells per slide varies, depending on a number of factors, but it is usually of the order of 40,000 to 10,000. See Figure 1.

Two screening modes are used: the *full screen* where every cell in the slide must be inspected, and the *rapid screen*, used in quality control reviews, where only a reduced number of fields of views are inspected. Full screenings should be processed at a rate of 8-12 slides per hour and a recommended rapid screen takes about 60 seconds [16].

In a full screen, the slide is scanned methodically, in a vertical or horizontal fashion and using overlapping fields of view. The screening of a slide is usually done at a lower magnification (x10 or x20), switching to x40 if anything of interest is present on the field of view. Also, although with the LBC technique the cells are mostly arranged on the slide in a monolayer, the cells themselves have a thickness that can be explored by adjusting the lens's focus. The outline of a normal cell's nucleus should be regular and unchanging on the whole thickness of the cell. Cell clumps are also often inspected at various focus depths.

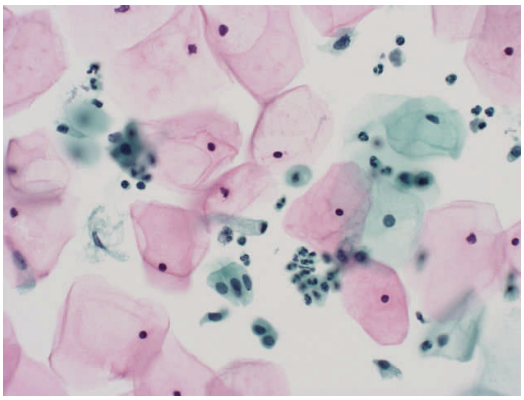

Figure 1. *An LBC slide at x40 magnification. This slide contains no abnormal cells.*

Cytologists work under a strictly controlled regime with regard to the number of hours they can work and the breaks that they must take. Despite all the care taken, errors do occur. False negatives and false positives are both to be avoided as much as possible. A false negative is clearly dangerous as it implies a woman who is likely to develop cancer believing that she is healthy. False positives cause patients unnecessary stress and over-treatment.

The objective of this project is to provide the cytologists with additional support in their task. The hope is that information encoded in sounds will help them to analyze features of cells that are hard to detect visually or even not present in the visual rendering.

5. APPROACHES TO SONIFICATION

Data represent the lowest level of information. In digital technology, data is represented (and can be measured) in *bits* and can be easily manipulated and transformed. At a higher level, data can be transformed and combined to represent *information*. This can be achieved through technology, but it is also something that people are good at. In other words, coherent data, represented appropriately can reveal *patterns*. Many branches of information technology are concerned with this kind of processing: either automatically identifying the patterns in the data, or transforming the data so that the patterns become more apparent to the human observer – or combinations of both of these. This is the objective of sonification: to transform data into an (auditory) form to facilitate pattern recognition and hence extraction of information by human users.

In the case of this project, data are available from the scanning (in visible light) of microscopic cells. Those data are conventionally presented as visual pictures (visualizations), and skilled operators learn to extract the relevant information from that representation (i.e. to recognize abnormal cells). Yet, there is no reason why the same data should not be represented in an auditory form. There are a number of potential benefits:

- information which is contained in the data but which is not apparent in the visual representation may be detected in the auditory one;
- presenting the same data on different channels simultaneously may help the user's interpretation;
- multimodal presentation may also (positively) affect other, higher-level human factors, such as concentration, attention and (alleviation of) boredom.

With these objectives in mind and given the data that were available from cell samples, appropriate and effective sound mappings had to be found. A number of different approaches were tried and they are described in the following sections.

5.1. Color mapping

Since smear slides are colored with chemical stains, an overview of the status of cells is aided by the fact that cell nuclei are colored purple, and that other colors tend to attach to certain cell attributes. Typical signs of abnormal cells include:

- enlarged cell nuclei
- irregular nuclear outlines
- uneven distribution of chromatin (nuclear material)
- generally dark staining of the nuclei.

Thus an algorithm was created which deduced the average HSV (Hue, Saturation and Value, a measure of Brightness) of a section of the slide containing several cells [17]. Using the software toolkit *Pure Data*[1] the user was allowed to move the mouse freely around the image, and sound was continually synthesized, mapping luminance and hue onto a frequency scale, and saturation onto the sound's amplitude.

The synthesis method was very simple, so that the focus could be on the effectiveness of the interaction. Frequency modulation of two sine waves was used, and a series of experiments was carried out to ensure that the more intensely dark-stained a cell was, the higher the carrier frequency, the more extreme the modulation, and the louder the overall amplitude. This has the effect of making darker areas give rise to loud, high frequency sounds which were (on purpose) rather unpleasant. This allowed the user to freely move around the

[1] http://puredata.info/

image and easily hone in on areas which were more densely and darkly stained.

In experiments, test participants were asked to identify a cell field as 'normal', 'slightly abnormal' or 'abnormal', simply by listening to the sounds produced as they moved around an image (invisible to them) of a field of cells. Our researcher Podvoiskis concluded:

> *Results from both experiments showed subjects were able to identify and classify images based on a sound representation only. These results were proven to be statistically significant.* [17]

It is interesting to note that the test participants at this stage were not trained cytologists, but music technology students, yet they were able to identify correctly the more grossly abnormal cells by sound alone.

However, these very positive effects were only apparent when grossly abnormal cells were present in suitably large clusters, and could be picked up by a user moving a mouse to 'focus in' on such denser areas. Subsequent study showed that the majority of cells which need to be identified by cytologists are usually much more borderline, and this method was not able to distinguish these. In addition, the synthesis method was very simple and would not stand up to long-term listening.

The technique of mapping colors of a cell-field to sound is still worthy of further investigation, particularly if the spatial position of each contributing cell could be portrayed in sound.

5.2. Scanning images for texture

Next, we undertook a series of experiments [18] working with *CSound*[1], to generate sounds which represented the internal structure of individual cells. One of the major indicators of abnormal cells is an irregular distribution of chromatin inside the cell nucleus.

This work explored the use of granular synthesis to create sounds whose perceived 'grittiness' portrayed the severity of the distribution of the chromatin, and was thus an indicator of abnormality. The mapping used looked at the gradient of pixel darkness to show where the dark spots were placed within the cell's nucleus. The horizontal spacing of these spots was portrayed using stereo panning; the vertical was represented by a frequency scale. The user is not allowed to freely scan the image with a mouse, but instead the computer performs an auto- scan left to right across the cell and then repeated down the cell.

The segmentation and modification of the image prior to sonification (using custom-defined image processing algorithms in MATLAB) became an important part of the work (Figure 2), but one which was time-consuming.

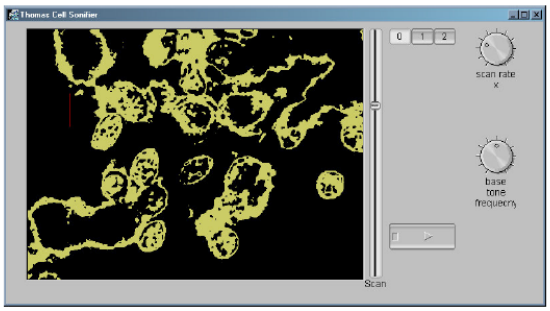

Figure 2. *Interface to the MATLAB/CSound sonification tool, allowing basic control of the audio scan carried out on visually processed cell images.*

Test participants reported that the granular sounds were highly irritating and would not be put up with for long periods.

Later phases of the work explored the use of filtered noise sounds as a 'softer and smoother' portrayal of the chromatin, and later still some more-musical notes based on piano synthesis. Some promising results were obtained by using the scanning technique to directly sonify the pixels as binary values once they had passed through the thresholding algorithm.

One of the main limitations of this method is the long time (not available to pressured cytologists) taken to:

- visually identify a cluster of cells
- zoom in to the correct resolution
- modify the image's coloration to achieve best contrast
- listen to the scanning of the nuclear data from left to right and then downwards.

However, the main problem with this approach is that, whatever the sound quality, it would inevitably be perceived as in some sense an 'average' of the cells in view, whereas what the cytologist is generally looking for is the one cell (or small number of them) which is abnormal, that is *not* average.

The following studies were then carried out to discover if it were possible to clearly portray the state of multiple cells surrounding the current position by using sound spatialization.

5.3. Sound Spatialization

We undertook an investigation into whether all the cells surrounding the user's current position could be rendered in a sonic space around the listener [17].

The software used was *Scilab*[2], an open-source computation package similar to MATLAB. Data was spatialized using Head-Related Transfer Functions (HRTFs). The image being 'viewed' was split into 9 segments surrounding the current 'centre-point'. The software produces a radar-type sweep around the image, and generates sound in the corresponding positions for a listener wearing headphones.

At this point in the research it was decided to produce a 'badness' rating for each cell undergoing examination, by pre-processing the cell data, mapping to a number from 1 to 10, where 1 is 'normal' and 10 is 'highly abnormal'.

[1] http://www.csounds.com/

[2] http://www.scilab.org/

We experimented with a variety of sonification methods to portray the 'badness' of each cell surrounding the listener. These included:

a) Additive synthesis, where increasingly discordant overtones are added as the badness number increases. This was found to produce mostly unpleasant sounds.
b) Sampled audio files, where sounds are used to represent a natural landscape (based on [7]). Cows gently mooing were mapped onto 'not bad', dogs barking were in the middle and a person screaming represented the severely abnormal cells. (Table 2).

User tests found that the sampled audio portrayal was much easier to listen to and locate. However, the apparently arbitrary choice of animal sounds came across as quite bizarre to some, and not an obvious linear mapping of 'badness'. Future work in this area should attempt to dispense with the disorientating 'sweep' and to play all of the sounds together in one surround-sound field, which is much more analogous to how multiple sounds reach our ears from the real world. Based on these sounds, a questionnaire was devised where the participants were the screening cytologists of the Leeds NHS Trust. It covered questions about:

- The individual's music preferences and listening mode (headphone, iPod, speakers, live music etc.);
- their attitude to the research (bearing in mind these are visual analysts being asked to consider audio input);

Sample Name	Original Length (ms)	Max Level (dB)	'Badness' range	Notes on Design Method
1.wav	14	-18.32	0-99	Created from a slice of human speech. Very short and quiet.
2.wav	80	-23.54	100-199	Unedited recording of a 'popping' sound made with lips.
3.wav	57	-11.24	200-299	Edited recording of a bubble popping in boiling water.
4.wav	53	-25.79	300-399	Synthesized 'pop' sound – high in treble content. Short reverb used.
5.wav	379	-3.69	400-499	Edited recording of noises made with the mouth. EQ applied.
6.wav	154	-0.15	500-599	Synthesized 'pop' combined with recording of mouth noises. EQ
7.wav	354	-5.93	600-699	Recording of another type of mouth 'pop', with effects.
8.wav	315	-0.01	700-799	Synthesized 'pop' combined with recording of mouth noises. EQ
9.wav	424	-0.19	800-899	Synthesized 'pop' combined with recording of mouth noises. Reverb.
10.wav	649	-0.01	900-999	Boiling water recording with heavy editing. Huge amounts of EQ and reverb used.

Table 1. *Sounds used in the sound preferences experiment.*

'Badness' range	Sound
0-99	cow mooing
100-199	frog croaking
200-299	horse whinnying
300-399	bird tweeting
400-499	cat meowing
500-599	seagull crying
600-699	man shouting
700-799	dog barking
800-899	monkey howling
900-999	woman screaming

Table 2. Mappings from 'badness' values to sounds.

- how they would prefer to interact with a sound-generating system;
- their thoughts about what different types of cell should 'sound like'.

The questionnaire concluded with a practical session:

- The playback of several of the sounds, and the request to rate them as 'good' to 'bad', and 'like' to 'hate'.
- Several cell images, with the subject being asked to select from a choice of 3 sounds which best represented that cell. (Figure 3).

Results showed that cytologists, on the whole, would like to hear an ear-catching, alarm-type sound when an abnormal cell is present, but that a quiet sound should be present the whole time, to 'show that the system is still working'. They did not want to hear sounds which were directly related to real-world sounds (such as some of the examples water-type sounds) and many were not convinced how 'musical' sounds might be perceived.

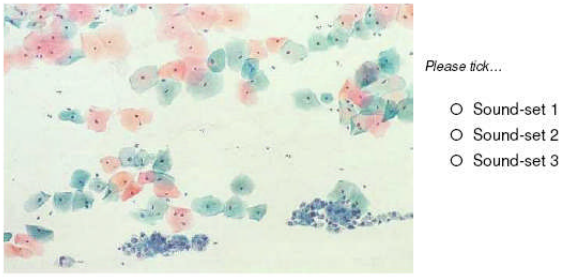

Figure 3. *Sample selection screen. Participants indicated which sound they felt best represented the cells in view.*

5.4. Subjective sound selection

It had become evident in the image analysis research that it would be possible to calculate two quantities for cells: 1) the apparent degree of abnormality and 2) the confidence of that rating. It also became evident that the distinction was not between 'good' and 'bad' cells, but rather between *normal* and *bad*. That is to say that most of the cells a cytologist will see are normal. The message to be communicated (aurally) to the cytologist for the majority of cells should be calm and neutral.

For cells which might be abnormal there should be an alerting sound (but not an alarm – see the earlier discussion) and the sound should be more insistent if the probability of abnormality is greater.

None of the previous experiments specifically provided guidance on the choice of such sounds. It was therefore decided to embark on a different kind of experiment to help with identifying suitable kinds of sounds. Some of the sounds generated in the earlier experiments were to be included, though, for comparison.

It was important to test the perception of sounds by as wide a population as possible in order to identify ones which would be likely to have the highest acceptability to any users. We would want to include specialists (cytologists) in the testing, but not to be exclusive to them. It was therefore necessary to ask people to map sounds to qualities that would be meaningful to them – and not cell images which would convey meaning only to cytologists. It was therefore decided that the mapping should be to 'Smiley faces', as in Figure 4.

In order to capture data from as wide a population as possible, the test was mounted on the Web[1]. Visitors started on a briefing page and gave their assent to taking part. They would then hear a set of 42 sounds, one at a time (and only once each). They would then select which of the Smileys they thought best matched the sound. They also had the option of selecting *Don't use this sound*, in which case they were invited to explain their opinion. This was in order to ensure that sounds which are (generally) aesthetically unacceptable could be identified. At the end of the sounds the participants filled in a short background questionnaire.

Figure 4. *The three Smileys used in the experiment.* Normal *represents most cells, which are not cause for concern;* bad *would be a cell which is almost certainly abnormal and* undecided represents *the (common) case in which the cell may be abnormal, but the probability that it is so is not high.*

The sounds used varied greatly. Some came from the previous experiments, others were everyday sampled sounds and still others were based on everyday sounds but processed in some way. We started with no preconceptions. That is to say that we had no intent as to which sounds would be mapped to which image. The aim was to find out about the *kinds* of sounds which mapped well to the categories. Later we would investigate how to create a set of sounds which would then convey the required categories – and the spaces between them. That is to say that it is not anticipated that all cells will be classified into one of the three classes; there will be a large space between (for instance) *Normal* and *Undecided*.

[1] http://www-users.cs.york.ac.uk/~alistair/sonify

This experiment is continuing and it is too soon to draw any conclusions. It is perhaps not surprising that initial results suggest high levels of subjectivity in responses. This reinforces the observation that sound aesthetics are vital and subjective. It might imply that different sound sets should be provided from which individuals can select.

6. DISCUSSION

Pattern matching is a fundamental skill, not the least in medical investigations. Many researchers have remarked on the power of human hearing to detect patterns in sounds and hence have tried to apply sonification as an alternative or an addition to visual pattern recognition in medical data. That is the approach applied in this project.

The richness of the sound space gives much scope for the use of sounds – but it also poses a dilemma for the designer in making choices as to what kinds of sounds to use and how to map the relevant parameters onto them. This is a common problem, articulated in most publications on sonification. Within this project was also apparent another problem (which is probably common in other similar projects) – that the underlying application represents a moving target as the research on it develops.

The work on extracting data from the cell images and classifying it was proceeding in parallel with the development of sounds, and the ideas as to what was important about the cells changed.

The initial assumption was that all cells in the visual field should be sonified in parallel. That was dropped because it became apparent that any such sonification would effectively present an 'average' of the cells, whereas it is the one or two non-average (abnormal) cells which are important. Thus, it was decided to concentrate on the one 'most interesting' cell in the current field of view.[2]

It was realized early in the project that cytologists and others expected that sonification would amount to the playing of an alarm sound on the detection of an abnormal cell but this was technically infeasible. However, it was less apparent as to what the sounds should represent. We gained greater insight into what information could be extracted from the images and as to the nature of the cytologists' task. Thus, it became apparent that the vast majority of cells encountered are normal and no cause for concern. Then there are others which might be abnormal (or 'bad') and so we looked at the assignment of scales of 'badness' and their representation in sound. It was realized that the scale was not (as might be conventionally expected) from 'bad' to 'good', but from 'bad' to 'normal'; there are no cells which are 'better' than normal ones.

Subsequently we came to a further realization, which was that cells cannot be mapped onto a one-dimensional 'badness'

[2] The idea of sonifying a field of cells has not been abandoned all together, though, and may be revived in future work. If it is possible to separate out different dimensions, then the 'averaging' effect may not occur. For instance, drawing on this work, it might be that the stain colours are 'heard', along with chromatin textures, but these are displayed spatially for all cells but only emphasizing the worst cases by filtering what we play according to badness.

scale. This is because the information available is not unambiguous. In other words a cell may be classified as 'bad' with different degrees of confidence. A cell which has a high probability of being bad is more significant than a) one which is classed as bad, but only with a low probability and b) one which is classed as quite bad but with a high probability. These subtleties must be captured in sound.

Cells are arranged on the two dimensions of a microscope slide. It can be assumed that the one in the center of the field of view already has the cytologist's attention, but if one off center is of interest, how should the cytologist's attention be directed to that one? Sound spatialization is the obvious mechanism. Experiments with this were positive, although it was found that the 'radar sweep' was inappropriate.

Anyone working in the use of sounds is aware of the importance of aesthetics, of subjective reactions to sounds and we have managed to find some of the preferences of cytologists in this application.

This paper has set out to frankly present this story in the hope that it will be of benefit to future researchers who find themselves working in a similarly shifting environment.

7. CONCLUSIONS

Sonification potentially has a number of applications in medicine. Whereas natural sounds have long been a part of doctors' diagnostic tools, derived sounds have still to make a significant mark in medical applications. This paper has presented one more investigation of the possibility of doing this in one particular application. The work has demonstrated a number of the real-world constraints on this kind of research.

A number of lessons have been learned including:

- Sonification must support the operator in the classification of cells; and is not a form of automatic recognition, generating alarm sounds.
- Selection of the right kinds of sounds is imperative.
- The means by which the user or cytologist interacts with the sonification interface is also very important.
- Spatialization of sounds can be helpful in locating the cells of interest.
- In this kind of application, the important parameters to sonify are the 'badness' of the cell and the reliability of that rating.

The objective of the project is to produce sample sonifications which will be tested. It is hoped that these will demonstrate that screening with sounds is at least as accurate as conventional, purely-visual screening. Work is continuing to that end.

8. REFERENCES

[1] *Cervical Screening Programme England 2005-6*. 2006, The Information Centre (http://www.ic.nhs.uk/webfiles/publications/cervicscrneng2006/Cervical%20bulletin%202005-06.pdf).

[2] *Cervical screening: The facts*. 2007, NHS Cancer Screening Programmes.

[3] Hermann, T., et al., *Vocal sonification of pathologic EEG features*, in *Proceedings of the 12th International Conference on Auditory Display (ICAD2006)*. 2006: London.

[4] Ballora, M., et al., Heart rate sonification: A new approach to medical diagnosis. *Leonardo*, 2004. **37**(1): p. 41-46

[5] Jovanov, E., et al., EEG analysis in a telemedical virtual world. *Future Generation Computer Systems*, 1999. **15**: p. 255-263.

[6] Hermann, T., et al. Sonifications for EEG data analysis. in *Proceedings of the 8th International Conference on Auditory Display (ICAD2002)*. 2002. Kyoto, Japan.

[7] Mauney, B.S. and B.N. Walker. Creating functional and livable soundscapes for peripheral monitoring of dynamic data. in *Proceedings of the 10th International Conference on Auditory Display (ICAD04)*. 2004. Sydney.

[8] Hermann, T. and G. Baier. *The Sonification of Human EEG and other Biomedical Data*. 2006 [cited 2010 12 January]; Available from: http://www.sonification.de/projects/eegson-icad2006/index.shtml.

[9] Baier, G. and T. Hermann, *Event-based Sonification for EEG monitoring and analysis*, in *Proceedings of the 12th International Conference on Auditory Display (ICAD2006)*. 2006: London.

[10] Pauletto, S. and A. Hunt, *The sonification of EMG data*, in *Proceedings of the 12th International Conference on Auditory Display (ICAD2006)*. 2006: London.

[11] Martins, A., et al. Auditory display and sonification of textured image. in *Proceedings of the 3rd International Conference on Auditory Display (ICAD 96)*. 1996.

[12] Nattkemper, T.W., et al., *Look & listen: Sonification and visualization of multiparameter micrographs*, in *Proceedings of the 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC2003)*. 2003: Cancun, Mexico.

[13] Parker, E.M., J.A. Foti, and D.C. Wilbur, FocalPoint slide classification algorithms show robust performance in classification of high-grade lesions on SurePath liquid-based cervical cytology slides. *Diagnostic Cytopathology*, 2004. **30**(2): p. 107-110.

[14] Edwards, A.D.N., G. Hines, and A. Hunt. Segmentation of biological cell images for sonification. in *International Congress on Image and Signal Processing (CISP 2008)*. 2008. Sanya, China: IEEE Computer Society.

[15] Roseblade, R., *Sound and interface design for improving detection of cervical cancer*, in *Department of Electronics*. 2006, University of York.

[16] *Laboratory Organisation: A Guide for Laboratories Participating in the NHS Cervical Screening Programme*. 2003. NHSCSP Publication No 14 (http://www.cancerscreening.nhs.uk/cervical/publications/nhscsp14.pdf).

[17] Stammers, J., *Developing synthesis techniques for the sonification of precancerous cells*, in *Department of Electronics*. 2006, University of York.

[18] Butterfield, T., *Improving the detection of cancer by using sonification to supplement visual displays*, in *Department of Electronics*. 2005, University of York.

Acknowledgements

Some of the work reported herein has been carried out by students at the University of York. In addition to those listed as co-authors, we acknowledge the invaluable contribution of Thomas Butterfield. The Leeds Teaching Hospitals NHS Trust has provided the medical input. In addition to the co-author, we acknowledge the assistance of David Brooke in setting up the project and of the team of cytologists who graded a large set of cell images.

The work was funded by the UK Engineering and Physical Sciences Research Council, grant number EP/C512413/1. We thank the Council for its positive attitude in extending the project's duration and acknowledge the help of John Grogan MP in obtaining this.