SenseCam: A Retrospective Memory Aid

Steve Hodges, Lyndsay Williams, Emma Berry, Shahram Izadi,
James Srinivasan, Alex Butler, Gavin Smyth, Narinder Kapur*, and Ken Wood

Microsoft Research, 7 JJ Thomson Avenue,
Cambridge, CB3 0FB, UK
{shodges, lyn, v-emmabe, shahrami, i-james, v-alexbu,
gavin.smyth, krw}@microsoft.com
http://research.microsoft.com/sendev/
* Cambridge Memory Clinic, R3 Neurosciences, Box 83,
Addenbrooke's Hospital, Cambridge, CB2 2QQ, UK
narinder.kapur@addenbrookes.nhs.uk

Abstract. This paper presents a novel ubiquitous computing device, the SenseCam, a sensor augmented wearable stills camera. SenseCam is designed to capture a digital record of the wearer's day, by recording a series of images and capturing a log of sensor data. We believe that reviewing this information will help the wearer recollect aspects of earlier experiences that have subsequently been forgotten, and thereby form a powerful retrospective memory aid. In this paper we review existing work on memory aids and conclude that there is scope for an improved device. We then report on the design of SenseCam in some detail for the first time. We explain the details of a first in-depth user study of this device, a 12-month clinical trial with a patient suffering from amnesia. The results of this initial evaluation are extremely promising; periodic review of images of events recorded by SenseCam results in significant recall of those events by the patient, which was previously impossible. We end the paper with a discussion of future work, including the application of SenseCam to a wider audience, such as those with neurodegenerative conditions such as Alzheimer's disease.

1 Introduction

Human memory is all too fallible – most of us frequently forget things that we have to do, and often find it hard to recall the details around what we have previously done. Of course, for those with clinically diagnosed memory disorders – which are by their nature more severe than those found in the average population – these issues are particularly troublesome. One example of such a diagnosis is acquired brain injury, which occurs either through a disease with lasting effect on brain tissue, or a traumatic incident like a car accident. Another example, perhaps of more significance in an aging population, is neurodegenerative disease – essentially an illness which damages the brain such that there is no possibility of recovery. The most prevalent neurodegenerative disease is Alzheimer's disease.

The effects of acquired brain injuries, neurodegenerative diseases and aging in general vary greatly from patient to patient. In a relatively moderate form, there may be

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little noticeable effect – perhaps a patient will be frustrated from time-to-time at their inability to organize themselves as well as they used to. At a more extreme level, a patient may suffer from a near complete inability to remember. Patients with moderate to severe memory problems may fail to remember future intentions, such as buying milk, or making and keeping appointments (*prospective memory*). Prospective memory problems clearly have a big impact on the ability of a patient to look after themselves on a day-to-day basis. A failure of past (*retrospective)* memory, however, and in particular *episodic* or *autobiographical* memory (i.e. the memory of things the patient has done, as opposed to their semantic memory for factual information) is actually critical for a patient to enjoy any real quality of life. This is firstly because nearly all future actions are based on past experiences, so practical day-to-day planning is very difficult when autobiographical memory is impaired. Secondly, and perhaps more importantly, a memory of past experiences is critical to a patient's 'self-concept'. For example, without a memory of shared experiences it is very hard to maintain any kind of relationship, whether it is professional, social or personal. This in turn frequently affects the patient's self-esteem, which can have significant knock-on effects on their well-being [13].

This paper presents a novel ubiquitous computing device, a wearable camera that keeps a digital record of the events that a person experiences. The nature of the device is to take these recordings automatically, without any user intervention and therefore without any conscious effort. We call the device SenseCam [4, 7] because two of the main components of its operation are **sens**ing its environment and using a built-in stills **cam**era to record images.[1] The rationale behind SenseCam is that having captured a digital record of an event, it can subsequently be reviewed by the wearer in order to stimulate their memory.

This paper describes the technology behind SenseCam in detail for the first time, presenting the design of our latest prototype (version 2.3) and discussing some of the issues that have come to light during its development. It also outlines a desktop application that has been developed in tandem with the hardware, to facilitate the viewing of data captured by SenseCam. The prototype hardware and software have been tested in an early clinical trial by a patient suffering from amnesia, and the promising results of this work are presented and discussed.

2 Related Work

The use of external memory aids to help people to compensate for their memory deficits is thought to be one of the most valuable and effective ways to aid rehabilitation (see [13] for a review). Most external memory aids serve to improve prospective memory; that is, they help people to remember to keep appointments, take medication and so forth. Many different types of device are available, including calendars, diaries, alarm watches, whiteboards, timers, post-it notes and more sophisticated tools, such as hand-held electronic schedulers. The combined use of these prospective aids has been effective in increasing independence in brain injured patients [13].

[1] "Cam" is also significant because the camera was conceived and built in Cambridge, UK.

In contrast, there are few external memory aids designed to improve the ability to remember past experiences. Perhaps the two most obvious examples of retrospective memory aids are cameras and diaries. Reviewing photographs and written diaries may stimulate memory for past events, e.g. photos of a family holiday ten years earlier or notes taken in a meeting two days previously [1, 13]. For example, in one study Bourgeois [1] used photographs to aid conversational skills in people with dementia. Not only did quality of conversation improve, but the memory aid appeared to prompt more general memories related to each item. Of course, in order to stimulate memory in this way, an investment of time and effort must be made *at the time of the original event* (or closely thereafter) in anticipation of a benefit many days or even many decades later. Unfortunately, experience shows that many people find it difficult to remember to take regular photos or keep diaries through their day (especially if they have a diagnosed memory disorder).

It is not surprising that photographs act as a memory stimulant – the importance of visual images in memory functioning is well established. Autobiographical memory is thought to be rich in visual imagery [2, 3]. Brewer [3] found that more than 80% of randomly sampled memories consisted of visual images. This emphasis on visual memory, and the successful role of photographs in memory recall, provides a strong indicator for the use of cameras as aids for autobiographical memory. However, traditional stills cameras have a number of drawbacks when used as a memory aid. Firstly, the patient has to remember to use the camera regularly, which is clearly a stumbling block. In addition, the act of stopping to take a photograph is very disruptive; it can break the patient's train of thought and it may be inappropriate from a social perspective. Finally, the resulting photographs may end up being quite staged rather than forming a simple record of events as they happened. It seems that some kind of 'wearable' camera which automatically captures images through the day might overcome some of these problems.

Wearable cameras have an established role in ubiquitous and wearable computing research and are now also appearing as consumer products [6, 18]. These devices are essentially manually-triggered cameras that can be worn. Mann [17] describes the implementation of WearCam, a wearable head mounted video camera, which can be user-triggered to take video of interesting events. HP's Casual Capture prototype [10] is an always-on wearable video camera. In order to manage the tremendous amount of data such a device captures, HP suggest the use of subsequent image processing to select 'interesting' images and short video clips.

Researchers have also begun to address the issue of automated capture control for wearable cameras. StartleCam [9] comprises of a wearable video camera, a computer (housed in a rucksack), and offboard skin conductance sensors. The system looks for patterns within the skin conductivity signal, which cause the camera to capture video, and optionally, download content to a webserver using onboard wireless communications. Hoisko [11] describes a wearable video camera, heads-up display and DAT recorder for capturing time triggered images and audio, and providing context triggered playback. IR beacons are deployed in the environment to associate a series of captured images and audio with a location. When the user is next in that particular location the appropriate recordings can be played back. Although a rudimentary prototype, the work is significant as it highlights the benefits that such captured data can provide in supporting recall of autobiographical memory.

In order to serve as a useful retrospective memory aid, a wearable camera needs to be very practical. Issues such as ease of use during capture and replay are paramount. The motivation for SenseCam is to extend and unify the body of work reviewed here to create a small, low power, easy to operate and carry, wearable camera, which can automatically capture images of a person's day using purely onboard sensing.

3 SenseCam

SenseCam is a small digital camera that is designed to take photographs automatically, without user intervention, whilst it is being worn (Figure 1). Unlike a regular digital camera or a cameraphone, it does not have a view finder or a display that can be used to frame photos. Instead, it is fitted with a wide-angle (fish-eye) lens that maximizes its field-of-view. This in turn means that nearly everything in view of the wearer is captured by the camera. Examples of the images taken by SenseCam are shown in Figure 2. In addition to the camera functionality, a number of different electronic sensors are built into SenseCam. These sensors are monitored by the camera's microprocessor, and certain changes in sensor readings can be used to automatically trigger a photograph to be taken. For example, a significant change in light level, or the detection of body heat in front of the camera can be used as triggers. Additionally, an internal timer may be used to trigger photograph capture, causing a photo to be taken automatically every 30 seconds, for example. SenseCam also has a manual

Fig. 1. The SenseCam v2.3 prototype shown standalone and as typically worn by a user. The model pictured here has a clear plastic case which reveals some of the internal components.

Fig. 2. Example images captured by SenseCam

trigger button that lets the wearer take pictures in the more traditional fashion and an on-off button which can be used to save the battery and prevent any sensor data logging/photograph capture. LEDs and an internal sounder are used to give the wearer feedback.

3.1 Design Requirements

Experience with early prototypes showed that the form factor of SenseCam is crucial. It must be convenient to put on and take off, and reasonably small and light so that it is comfortable whilst being worn. In trials to date, users have worn the camera on a lanyard around their neck, and this appears to meet these two criteria for most people, most types of clothing, and in most conditions. Our experience shows that ideally the camera should be worn reasonably high-up (towards the eye-line); this tends to generate more compelling images. In addition, the case of the SenseCam has been designed to allow the camera to stand freely on a flat surface. This allows the camera to be temporarily taken off and placed in an interesting vantage point – for example on a table or a shelf – thereby generating images from a third-person point of view. This is not practical for memory-loss patients (who might forget to put the camera back on), but gives flexibility as user trials are extended to a wider population.

In addition to the form factor of the device, other equally important practical issues include battery lifetime, storage capacity and ease of use. Experience with early SenseCam prototypes showed that it was critical for the device to operate for an entire day (i.e. 8-12 hours of continuous operation), and ideally for two to three days in case the patient forgets to recharge it or does not have a charger with them. A related requirement is enough storage for at least one day's worth of data, and ideally in excess of one week. This again means that if the patient forgets to upload data that the device can still be used the following day. With enough on-board storage, it would be possible to travel without needing a computer for data upload every evening. In this case, it is important that image upload time is not excessive.

3.2 SenseCam Hardware Design and Architecture

The SenseCam is built around a PIC 18F8722 6 MIPS microcontroller with 128KB of flash memory, 4KB RAM, copious general purpose I/O (GPIO) lines and several on-chip peripherals including PWM, UART, I^2C and SPI. Table 1 lists the major components in addition to the PIC along with their basic specifications and method of interface. Note that although a standard SD card is used, thereby supporting up to 2GB of flash memory in the camera, this card is not designed to be removed by the end user – it is hidden within the device. Instead, a high-speed mini-USB connection is used to copy data to and from the camera. This USB connectivity is achieved using a non-standard approach – the SD card is actually multiplexed between the PIC microcontroller (which is selected when the SenseCam is recording data) and an off-the-shelf USB-to-SD card interface chip (which is selected when a USB connection is detected). This allows us to support high speed USB 2.0 operation, which allows data to be transferred at approximately 4MB/s (around 175 images per second, or 10,000 per minute). Early experiments showed that without the speed of USB 2.0 transfer of large amounts of data (e.g. several days' worth) was unacceptably slow. Figure 3 shows the basic architecture of the SenseCam. Figure 4 depicts the front and the back of the SenseCam PCB, highlighting the main hardware components.

The VGA resolution images recorded by SenseCam are stored as compressed JPEG files on the internal SD memory card. The typical image size (around 30k bytes) allows for around 30 thousand images to be stored on a 1GB SD card. This clearly exceeds the design requirements for multi-day storage capacity. In addition to image data, the memory card is used to store a log file, which records the data from the sensors every few seconds in comma-separated variable format. The log file also records the reason for taking each photograph (e.g. manual shutter press, timed capture or significant change in sensor readings). The SenseCam has a built-in real time clock that ensures the timestamps of all files on the storage card are accurate. Timestamp information is also recorded in the log file along with each entry.

Table 1. The main peripherals (including all sensors) in the v2.3 SenseCam, with a summary of their specification and the method of interface to the PIC microcontroller

Component	Part number	Specification	Interface
Flash memory	Standard SD card	To 2GB (1GB standard)	SPI
Camera module	CoMedia C328-7640	VGA (onboard JPEG compression)	UART
Camera lens	Marshall Electronics V-4301.9-2.0FT-IRC	119º (diag) wide-angle lens w/ IR filter	n/a
Accelerometer	Kionix KXP84	Tri-axis	I^2C
Temperature	Nat Semi LM75	Range -55 to +125ºC, ±2ºC	I^2C
Real-time clock	Maxim/Dallas DS1340		I^2C
Light level	TAOS TCS230	RGB intensity	PWM
Passive IR (PIR)	Seiko SKP-MS401	Miniature form factor	GPIO
Push buttons	Omron B3F-3150		GPIO
Sounder	Murata PKLCS1212		PWM
Audio recording[2]	Oki MS87V1021	2Mb DRAM for 60s audio at 8ksps	SPI
GPS[3]	n/a	External GPS unit	BT

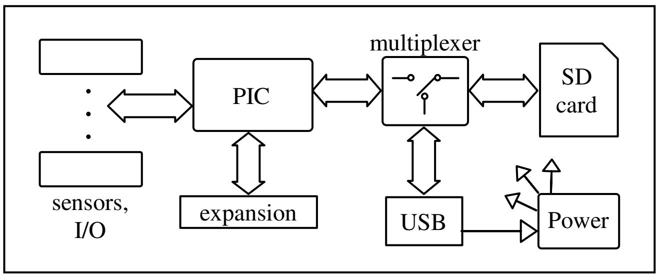

Fig. 3. The basic architecture of the SenseCam. A PIC microcontroller (6 MIPS, 128kB flash and 4kB RAM) interfaces with the major components. A digital multliplexer allows the SD card to be accessed by the PIC.

[2] Audio recording is still under development, and has not yet been tested in a user trial. Audio level (i.e. volume) sensing is present, however.

[3] GPS information from a standalone Bluetooth GPS receiver can be logged by the SenseCam using the Bluetooth plug-in unit (see Section 3.4). This has not yet been tested in a user trial.

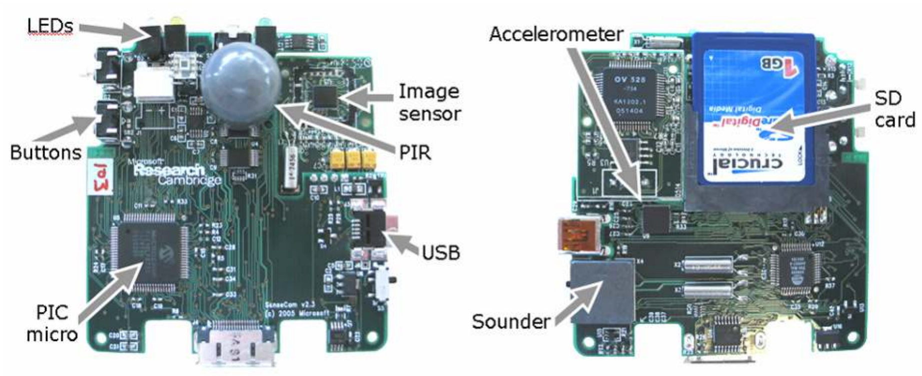

Fig. 4. The front and back of the SenseCam PCB (left and right respectively)

The SenseCam is powered from a built-in 980mAh 3.7V lithium ion rechargeable battery, from which 3.3V and 5V supplies are generated using a linear regulator and DC-DC converter respectively. The battery is recharged from a PC or from a mains power adapter over a USB connection. It takes around three hours to recharge using mains power, and ten hours to recharge whilst connected to a PC. In order to maintain the real-time clock and to detect the connection of a USB host when the SenseCam is not being used, there is no hard on-off switch. Instead, pressing the ‘power’ button causes the SenseCam to enter a very low power standby mode. The hardware is designed so that all peripherals which consume more than ~10uA in their lowest power state are subject to explicit power control by the microcontroller. This results in a total power consumption of 152uA in standby mode, which in turn means that the SenseCam will maintain its real-time clock for up to nine months without use.

The table shown in Figure 5 presents the power consumption of the SenseCam in its various operating modes. The most power is consumed when capturing images and saving them to flash memory. This means that battery lifetime depends on how frequently images are taken on average; the graph in Figure 5 shows this. Here we see

Mode	Description	Power consumption
Standby	Waiting for USB connection or power on, RTC running	152uA
Running	Microcontroller active but no sensing or logging	20.5mA
Sensor capture	Sensors being read and logged	35.0mA
Image capture	Image (or audio) being transferred to SD card	104mA

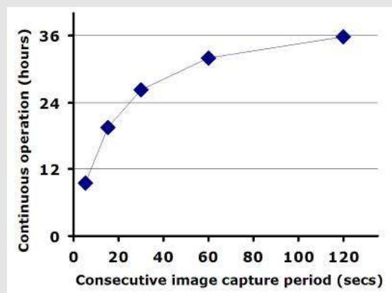

Fig. 5. The main operating modes of the SenseCam, and the associated current consumption for each of these (table left). Graph showing how battery life is affected by frequency of image capture (graph right).

that capturing images at the maximum rate of once approximately every 5 seconds yields a battery life just below 12 hours. Typically the SenseCam captures images every 30 seconds or so, yielding a battery life close to 24 hours of continuous operation. This meets the design requirement outlined in Section 3.1.

3.3 SenseCam Firmware

We employ a simple algorithm to trigger the camera based on data from the onboard sensors. The aim is to capture images of significant events, but without capturing excessive numbers of images. In theory, it would be possible for SenseCam to simply capture images as quickly as possible and then to select an optimal subset of these at a later time. However, there are a number of disadvantages to this approach from a practical point of view. In particular this would use significantly more power and memory which would likely violate our design requirements. Also, we felt that a wearable device that continuously captures images is more likely to arouse concern about privacy than something that takes a snapshot every thirty seconds or so.

The sensor-based algorithm used in the camera automatically triggers image capture if there is a significant change in light level, temperature or audio level. In addition, if the device is stationary (detected from accelerometer readings) and the PIR detects movement then image capture is also triggered. Finally, if no picture has been taken within a set timeframe (e.g. 30 seconds) then a picture is automatically taken. Sensors can be individually enabled or disabled at run time, through the use of a configuration file on the SD memory card. This file can be created or edited using a standard text editor while the SenseCam is connected to a PC over USB. When the SenseCam is then disconnected, the firmware updates the real-time clock if appropriate and reads in any new configuration settings.[4] Not only does this aid testing and development, but it makes it possible for patients themselves (or their carers) to tailor behaviour to suit particular requirements.

3.4 Developing and Extending SenseCam

From the outset it was clear that whatever selection of sensors was included in the SenseCam design, there would always be scenarios which warranted experimentation with additional types of sensors and hardware components. For this reason, the camera has an expansion port which exposes various electrical signals to facilitate the retro-fitting of additional functionality. The specific signals exposed (PIC in-circuit programming and debugging, power supply, general purpose I/O and communication buses) were chosen to provide the maximum flexibility for development, debugging and future expansion.

So far, we have built two different plug-in units. The first is a miniature ‘external camera’ that connects to the SenseCam via a flying lead. This can be used in place of the built-in camera – so that the SenseCam unit itself can be worn inside a pocket for example, to protect it from the rain. Alternatively, the external camera may be used as a second image capture device – to generate a larger field of view, or to take images in two different directions (e.g. facing forwards and backwards simultaneously). The

[4] To achieve the necessary PC compatibility, the SenseCam uses the FAT filesystem format. The associated firmware was developed from scratch in order to meet the PIC RAM limitations.

second plug-in device we have built for SenseCam is a Bluetooth adaptor, shown in Figure 6. This secures to the bottom of the main unit, making the camera body a little longer. A serial port profile connection may be established between the SenseCam and an external Bluetooth device to allow images to be sent wirelessly from the SenseCam to that device. For example, images sent to a Smartphone can be displayed on the phone or uploaded to a remote server over GPRS. It is also possible to use the Bluetooth plug-in to connect additional sensing devices. Examples which we are currently experimenting with include GPS and a heart-rate monitor.

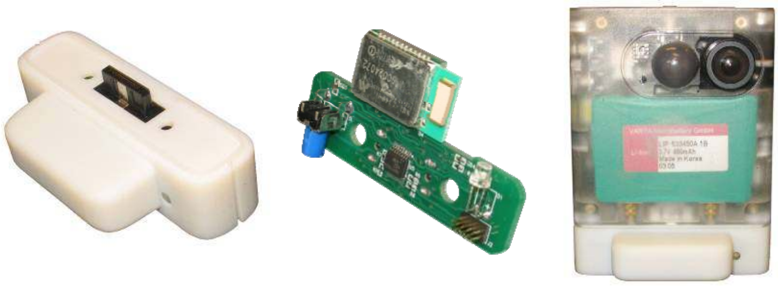

Fig. 6. The Bluetooth expansion adapter and the PCB shown on the left, and the assembled unit shown attached to a SenseCam on the right. It plugs directly into the SenseCam expansion connector and is secured from below with two M3 screws.

3.5 Replaying Captured Data

In addition to the SenseCam itself, we have also developed a PC-based viewer application (shown in Figure 7) that can be used to manage and replay image sequences and sensor data captured by the device at a later date.

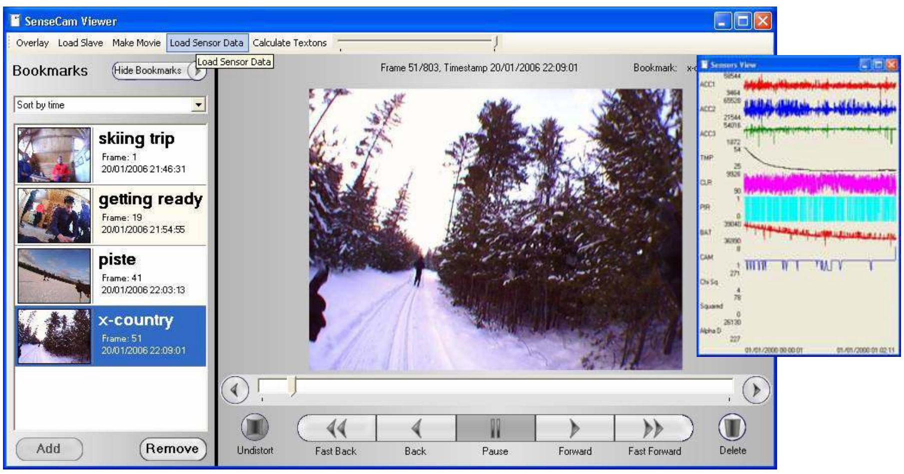

Fig. 7. The SenseCam viewer application, allowing playback and review of SenseCam images and associated sensor readings

When the user attaches the SenseCam to a PC, the SenseCam Image Viewer software will automatically download the images and sensor data. The basis of the viewer, which is designed to be very straightforward to use, is a window in which images are displayed, and a simple VCR-type control which allows an image sequence to be played slowly (around 2 images/second), quickly (around 10 images/second), re-wound and paused. The fast-play option creates a kind of ‘flip-book’ movie effect – the entire event represented by he images is replayed as a time-compressed movie. It is possible to delete individual images from the sequence if they are badly framed or of poor quality. An additional option is provided to correct for the ‘fish-eye’ lens effect using an algorithm which applies an inverse model of the distortion. With long sequences of images, it can be useful to associate ‘bookmarks’ with certain images. A bookmark is created by pausing playback on the image in question, and then clicking on the ‘Add’ button at the bottom left of the screen. The bookmark will appear as a thumbnail on the left of the window, and a user can assign a name to it. Once created, bookmarks can be used to help navigate a long image sequence – clicking on the thumbnail of a bookmark automatically advances or rewinds playback to that particular image in the sequence.

There are several options for playback. It is possible to display an analogue clock face to the right of the image sequence during playback to indicate at what time of day the image currently displayed was originally taken. It is also possible to load and display the raw sensor data associated with an image sequence, although this feature was not used in our user study. An example is shown inset in Figure 7. One final option in the viewer software is to process the entire sequence of images to determine which images are most like each other, using an image similarity algorithm based on textons [12]. This effectively splits the image sequence into segments of related images, which may aid navigation of long sequences in particular.

4 Assessing SenseCam as a Retrospective Memory Aid

In order to test the hypothesis that SenseCam can be used as a retrospective memory aid, a preliminary study was conducted to evaluate its ability to improve recent autobiographical memory in a patient with amnesia. By capturing an event using SenseCam, and subsequently reviewing the captured data regularly, we hoped that the patient could use the SenseCam images as a pictorial diary to both cue and to consolidate autobiographical memories.

The patient for this study, referred to here as Mrs B, is a 63 year-old well educated woman, married to a retired businessman (Mr B). In March 2002, Mrs B was admitted to hospital with fever and confusion and was diagnosed with limbic encephalitis (inflammation of deep structures of the brain). Subsequent MRI scans revealed bilateral cell loss in the hippocampus, an important memory structure (see Figure 8). After her recovery from the physical illness, an assessment of Mrs B’s cognitive functioning revealed that she had significant memory problems. Typically, Mrs B now only has partial recall of a significant event a couple of days after the event. After a week, she

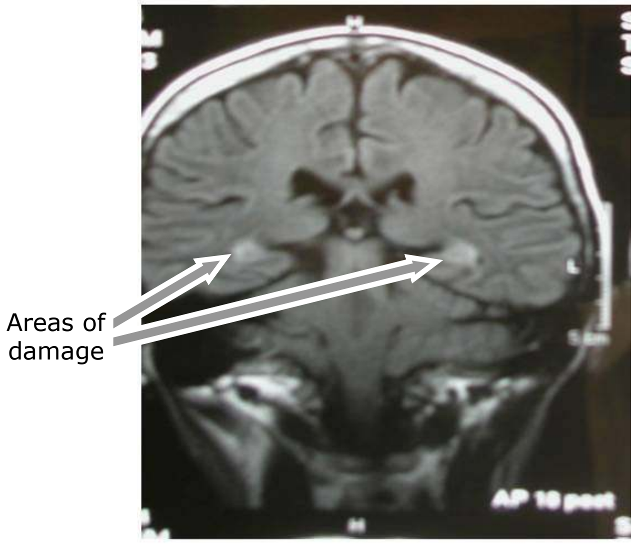

Fig. 8. Magnetic resonance (MRI) brain scan of Mrs B showing bilateral hippocampal lesions (the two brighter areas either side of the midline)

has no recall at all of the event.[5] Mrs B has tried to maintain and regularly review a written diary in order to improve this situation, but as is typical for people in her condition, she finds this a burden and it has little beneficial effect.

4.1 Evaluating the Effect of SenseCam on Short-Term Recall

Mrs B was given a SenseCam and asked, with the help of her husband, to wear it whenever she anticipated a 'significant event' – the sort of event that she would like to remember (i.e. not just something routine or mundane). After wearing SenseCam for the duration of such an event, Mr and Mrs B uploaded the SenseCam data to a laptop computer, but they *would not* review the data at all at this stage. The next day, Mr B asked his wife if she recalled the previous day's events. Mr B noted what Mrs B said about the events, and these responses were later graded. After noting her responses, Mr B immediately showed Mrs B the images from the SenseCam using the SenseCam image viewer software described in Section 3.5. Typically, they would run through the images one-at-a-time at first, and then review the entire sequence as a flip-book movie.[6] This was done up to three times, and Mr and Mrs B would talk about the images and the event as they did this. Two days later, Mr B again asked his wife what she remembered of the event that had occurred a few days previously. As before, he graded her responses and then showed her the SenseCam images. Two days later, the procedure was again repeated, and so on for a period of two weeks or more.

[5] Mrs B also has difficulty recollecting events from a 30 year period prior to her illness, but apart from these memory issues, her cognitive functioning is otherwise intact.

[6] Mr B usually reviewed the images himself before showing any to Mrs B, and he deleted any that he thought were not useful, for example if they were blurred or very badly framed.

Mr B kept a log of how many times Mrs B had viewed the images of an event, and her corresponding recall of that event each time.

At the time of each event Mr B documented a number of key points which he felt were important or memorable. The following is an example of the key points noted on a trip to Southampton General Hospital.

> *'Drive to East Cowes, walk to ferry, ferry to Southampton, taxi to hospital, taxi back to shopping centre, shopping, light lunch, walk to ferry, walk to car, drive home'.*

Other examples of important points to remember might be that they met up with friends (and if so which friends), if anything memorable happened whilst they were out and so on. The assessment of Mrs B's memory of an event was based on her ability to remember the associated key points. If Mr B recorded 10 key events and Mrs B subsequently remembered 7 of them when she was tested, she scored 70% recall.

Over the course of three months, Mrs B used the SenseCam to record nine different significant events. Some of these events were quite close in time to each other (i.e. the tests were not done in complete isolation from each other). The results were very encouraging; over the course of a two week period of testing and review of a given event, Mrs B's recall of that event nearly tripled on average, to a point where she could typically remember nearly everything about that event. This is compared to the situation with no SenseCam where Mrs. B would usually have forgotten the little that she could initially remember within just a few days.

4.2 Testing SenseCam as a Longer-Term Autobiographical Memory Aid

Given the success of the short-term memory testing with Mrs B, it was decided to carry out a longer-term assessment of her recall. Due to the limited availability of SenseCam prototypes, this longitudinal test with Mrs B was at the expense of additional short-term trials with new patients. However, we felt that it was equally important to see if the positive effects were longer-lived. Also, Mr and Mrs B found the SenseCam so beneficial that they did not want to give it back!

At the end of the three month period during which Mr and Mrs B regularly reviewed SenseCam images as part of the short-term recall experiment outlined above, there was a one month period during which they did not view or explicitly talk about the associated events at all. At the end of this one month period, Mr B tested his wife on her recall of all nine events. He once again graded her responses in the manner described previously.

Remarkably, despite the fact that Mrs B's memory had not been stimulated with images from the events for an entire month, she still showed significant recall when tested. This prompted two further similar tests, but for periods of two and three months. In each case, Mrs B initially reviewed images from all nine events, and at the end of the period (during which she did not see or discuss images from any of the events) she was tested. Mrs B showed a 76% average recall across all the events at the final test. Once again, this appears to be exceptional, bearing in mind that the original occurrence of some of the events and had been as much as 11 months earlier. Recall at this level of detail and after such a long period has not previously been reported in the literature.

4.3 Comparison with a Meticulous Written Diary

The results of the short- and longer-term studies described above are incredibly promising. They indicate that if Mrs B is exposed to a period of review of SenseCam images, this acts to consolidate her own memories of the event and this in turn aids their subsequent recall. However, it is possible that any kind of rigorous review of an event would have a similar effect – in which case there is nothing particularly special about the use of SenseCam as a memory aid. For this reason, Mr and Mrs B took part in one final experiment.

The method for this experiment was analogous to those described above, but instead of Mrs B recording an event using SenseCam, her husband instead kept a detailed written diary of it. Mrs B was tested in the same way as before, but after each test Mr and Mrs B reviewed the written diary (rather than SenseCam images). This was done for three different events across a one-month period. The results indicate that periodic review of such detailed diaries acts to maintain Mrs B's memory of an event, but that as soon as there is a significant gap those memories are completely lost. This differs to the results when SenseCam is used, where Mrs B's memory actually improved during the periodic reviews, and was maintained across very significant gaps.

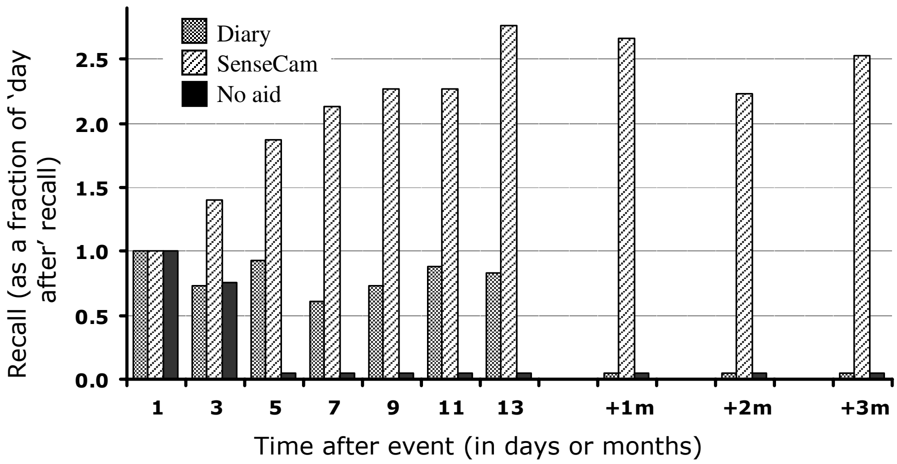

Fig. 9. Mrs B's recall of autobiographical events. Three conditions are plotted, namely recall when no memory aid is used, the effect of reviewing a meticulous written diary, and what happens when SenseCam is used.

4.4 Summary of Recall Testing

The results from all three experiments are brought together in Figure 9. Two events were tested with no memory aid to demonstrate the baseline condition; in this case Mrs B recalls nothing about an event that occurred just five days earlier, even if her husband reminds her every couple of days. Three events were recorded with a meticulous written diary, and in this case Mrs B's memory can be maintained (more-or-less) by way of periodic review. However, after a one month period of no review, this memory is permanently lost. For the SenseCam study nine events were tested, and these clearly show two trends. Firstly, Mrs B's recall improves consistently ($X^2(1) = 62.59$, $p<0.001$) during the period of regular review, to the point where she can remember nearly three times as many details as she could before the first review. Secondly, in the SenseCam condition, Mrs B's ability to recall an event hardly reduces at all, even after a significant period during which that event has not even been mentioned. Such effects in an amnesic patient have never previously been reported.

5 Discussion

The study presented in the previous section demonstrates that through the use of SenseCam, a markedly amnesic patient was consistently able to remember aspects of several events. Recall was maintained almost a year after some of the events took place, and without any review of those events for up to three months. Since recall of a number of different events which occurred over a three month period was successfully demonstrated, it appears that there was little 'contamination' between the different events, which is clearly important. Equally significant is the anecdotal evidence reported by Mr and Mrs B during the period of the trial. Mrs B said that seeing the beginning of a clip brought memories *'flooding back'*. Her descriptions of events demonstrated that she remembered the events themselves, rather than the SenseCam pictures alone. For example, she would remark that someone had been rude to her on a particular day, or that the food hadn't tasted nice – clearly this information is being recalled from her own memory. Additionally, we observed that Mr. B. was always quick to point out when his wife was retelling facts or a narrative that she had learned rather than having a true recollective experience, suggesting that these would not be mistaken as false positives. These observations reflect very positively on the ability of SenseCam to act as a valuable, practical retrospective memory aid.

It is also worth noting that Mrs B's subjective levels of anxiety reduced when wearing SenseCam. Before she started using the device, she lacked confidence in company and was generally anxious in everyday life, which is common in patients with memory loss. However, when using SenseCam she felt more confident about her memory and she was more able to relax at social events instead of feeling anxious. When asked about the effectiveness of SenseCam as an aid to improve autobiographical memory Mrs B said *'I think it is a terrific help, I really and truly do'*. This was confirmed by Mr B, who said that SenseCam *'significantly helps her recall'* and expressed his *'sheer pleasure'* at being able to share experiences with his wife again.

The diary was not nearly so effective a memory aid as SenseCam. It is also important to note that maintaining such a written diary takes a lot of work, and reviewing it is much harder work and therefore less pleasant. In fact, the written diary study was limited to just three events because Mr and Mrs B found it very onerous. Although external memory aids are well recognized as an effective form of rehabilitation, the people who most need them – people with memory disorders – almost always have the most difficulty using them. This is not just because the patient has to remember to use them, but also because memory aids often require executive skills (the ability to plan, organize, problem-solve and think flexibly), which are often affected after brain injury. Moreover the use of memory aids may entail a great deal of motivation and effort. Health professionals have to weigh up the potential benefit of the memory aid with the motivation and the skills of the patient to use them.

SenseCam has the potential to form a more suitable tool for patients in this regard. Because it autonomously captures images, it has particular benefits for acquired and degenerative brain injured patients, enabling them to record their experiences without the need to keep operating equipment and without conscious thought. Because it allows a person to truly participate in an event without having to pause to capture the moment, the patient does not feel burdened. In our trial, no particular concerns over privacy were raised. Of course, many of the people who may have been captured by SenseCam were probably not aware of it, but we believe that the low resolution of the images coupled with the infrequency of capture (around one frame every 30 seconds) are important factors in alleviating privacy concerns. Nonetheless, part of our agenda of future work with respect to SenseCam is a more thorough investigation of the privacy issues raised.

It is not clear what neurological processes enhanced Mrs B's recall of events recorded by SenseCam (and to a lesser extent, those recorded in the written diary). However, it seems that regular review coupled with the process of talking through the events, facilitated consolidation and recall of autobiographical memories that had already been encoded. Similarly, intermittent review could be characterized as a form of spaced repetition, in which learning trials are distributed over a period of time, allowing for gradual consolidation and reconsolidation of memories. This form of spaced presentation is thought to be an effective way of improving learning [16]. As discussed earlier, there is strong evidence that visual imagery is important to the consolidation and retention of autobiographical memories [3, 8]. It is therefore likely that the SenseCam images provided a particularly powerful set of stimuli or triggers that cued recall of previously stored memories. Although these explanations may account in part for Mrs B's successful recall of events, they do not explain in full the significant retention of these memories many months after the event with no further SenseCam presentations.

6 Conclusions and Future Work

The results of this preliminary study using SenseCam as a retrospective memory aid for patients with memory loss are very promising. Mrs B, the patient who took part in the work reported here, showed a significantly improved recall of autobiographical memories which was maintained in the long-term. Reviewing SenseCam image sequences is clearly a powerful aid to recall, although it is not completely obvious why this effect is so marked. We are planning a series of further clinical studies using advanced brain activity imaging techniques such as functional magnetic resonance imaging (fMRI), with the aim of determining what effect viewing a SenseCam image sequence has on activity in different parts of the brain. It is hoped that this will further our understanding of the neurological processes associated with recall.

Although we are taking steps towards capturing additional data to draw more significant conclusions, one theory on the promising results from initial trials of SenseCam is that because the images are from the wearer's point of view, the sequences more closely mimic human autobiographical memories. Furthermore, human memory is thought to be split into short time slices, delimited by changes in intent. That is, episodic memories are formed at goal junctions of action sequences when there is major change in the predominating goal [5]. It is possible therefore that the detection of changes in the wearer's activity and in their environment through onboard sensors caused the SenseCam to trigger at junctions of goal processing. Therefore, for these reasons it could well be possible that SenseCam produces images that are close in nature to visual autobiographical memories, providing a strong stimulus for recall.

We are also planning another programme of clinical trials with a wider variety of memory-loss patients, including those with different types of acquired brain injuries (such as epilepsy, accident and stroke), and also those with degenerative brain pathology (e.g. Alzheimer's disease and Semantic dementia). It is hoped that SenseCam will prove useful in these more general cases, in which case it could be a powerful tool for combatting the early effects of such conditions.[7] We are building more SenseCams and working with a number of leading clinicians and academics to carry out these studies. Finally, we are starting a series of further trials with Mrs B, in order to answer questions such as: 'What is the optimum time between experiencing a significant event and viewing images, in terms of a patient retaining memories of that event?', 'How often and at what interval are patients required to view the images in order for the memories to become consolidated?' and 'For how long are memories retained?'.

In addition to these clinical trials we are also carrying out experiments with the onboard sensors to investigate and improve the triggering algorithm. Currently we make extensive use of PIR, light, audio level and accelerometer data, but we will be experimenting with audio capture, temperature and location information from GPS, and comparing these more sophisticated approaches with the simpler approach of purely timer-triggered capture. We seek to enhance the therapeutic effect of SenseCam by optimising the capture and replay of images.

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