Evaluation of a wearable computer system for telemonitoring in a critical environment

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Abstract

This paper reports on the evaluation of a wearable computer system designed for use in a critical environment, namely the intensive care unit of a hospital. The nature of the application raised ethical issues for testing in a clinical environment and standard evaluation techniques could not easily be applied. The system was therefore evaluated by clinicians in a multi-tasking environment with a simulated set of patient scenarios. Measures of suitability and wearability were applied. The results were encouraging and the system was deemed suitable for further evaluation in the clinical setting, subject to ethical approval.

Keywords: *Wearable computers, Telemonitoring, Evaluation, Assessment*

1.0 Introduction

Working in a modern Intensive Care Unit (ICU) places increasing demands on staff who are often responsible for the simultaneous care of several seriously ill patients. Intensivists are often not only responsible for patients on their Unit, but also for those deteriorating on the wards or the Accident and Emergency department. These clinical and non-clinical duties (administrative and teaching obligations for example) can mean that they have to leave the physical environment of the ICU [1]. While away from the ICU they still need to be informed of the current state of patients in their care. Traditionally telephone conversations have been used to keep the intensivists informed, but these are time consuming and can only convey indirect, third party information about patients' clinical condition

In an attempt to address this short fall we have developed a portable telemonitoring system that can provide the clinician with direct access to clinical patient information. This system consists of a head mounted display (HMD) powered by a wearable computer connected to a wireless network. Data entry is via a wrist mounted keyboard or hip mounted mouse. In operation contemporaneous clinical patient information, such as heart rate and blood pressure, can be combined with web cam images and transmitted via a wireless network for the clinicians to view.

A schematic diagram of the system is shown below in Figure 1.

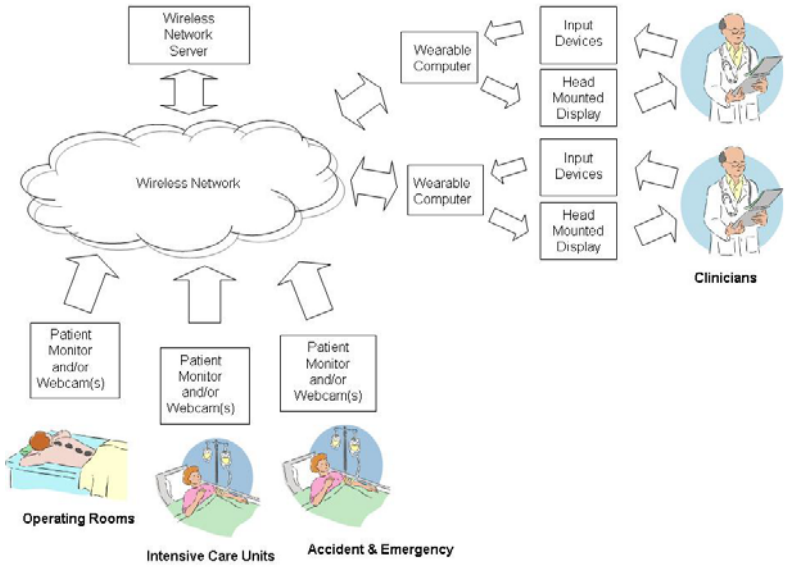


Figure 1: Schematic diagram of wearable clinical telemonitoring system

Due to the nature of the ICU environment the testing this technology directly in the clinical environment could have a negative impact on patients' clinical condition. Therefore the system was first evaluated in an environment that simulated the multi-tasking and interruptive nature of the clinical world yet did not involve patient contact.

Previous reported work on evaluating wearable technology in the medical arena is sparse. Carlsson et al. described a system based on wearable technology for assisting in ward rounds although limited evaluation reported [2]. One of the earliest evaluation studies reported in another domain was Sigel and Bauer's usability study of a wearable system for supporting aircraft maintenance personal in the US Air Forces [3]. Oskerman and colleagues compared a voice activated computer–based performance support system with a book for learning and performing three simple tasks [4]. Thomas and colleagues preformed a comparative study to evaluate three input mechanisms for wearable Computers. The usability of forearm mounted keyboard, virtual keyboard and Kordic keyboard of a wearable computer was examined. Participants performed tasks with all three inputs and gave post-test feedback to achieve the goal of the study [5]. Another comparative study by Ross and Basch aimed to evaluate orientation interfaces for wearable computers (a virtual sound beacon, digitalized speech and a tapping interface). The effectiveness of the prototype orientation system was tested by means of pre- and post-test baseline measurements, recorded street crossing time, with and without the device, and informal interviews [6].

Knight and colleagues introduced a methodology for determining the wearability of wearable computers [7]. They used measures for the energy cost, biomechanical considerations and comfort. These measures were determined by the use of existing scales, the Borg Relative Perceived Exertion (RPE) score [8] in the case of energy cost, the Rapid Entire Body Assessment (REBA) [9] and Borg-CR10 scores [8] for biomechanical assessment and finally Comfort rating scale (CRS) [10] and Visual Effects Score (VES) for a measure of comfort [7]. The Borg RPE scale consists of a single observation for perceived exertion between 6 for no exertion to 20 for maximal exertion (This scale is also related to the wearer's heart rate, an estimated heart rate is ten times the RPE score. Hence the

lowest value of 6 (60 bpm) on the scale). Similarly the Borg-CR10 scale divided the wearer's body into nineteen regions and then scored the muscular effort needed to use the wearable in each of these regions. The available scores ranged from 0 for no exertion to 10 for extreme exertion. The REBA test assessed the posture and risk of musculoskeletal disorders for specific areas of the body while wearing the system. The resulting scores range from 1 for through to 15 for extreme. The CRS assessed the comfort and wearability of the system in terms of six aspects; emotion, attachment, harm, perceived change, movement and anxiety. Each was ranked on a twenty point scale according to the wearer's agreement to a series of statements. The VES rated the side-effects of wearing a HMD. These ranged from 0 for no effects to 10 for severe effects such as nausea and dizziness. The scores from these tests are mapped to a measure of effect as shown in the following table.

		Level of Effect				
	Metric	**Low**	**Moderate**	**Large**	**V. Large**	**Extreme**
Energy cost	Borg RPE	6-9	10-11	12-13	14-15	16-20
Biomechanical	REBA	1	2-3	4-7	8-10	11-15
	Borg-CR10	0-1	2-3	4-5	6-7	8-10
Comfort	CRS	0-4	5-8	9-12	13-16	17-20
	VES	0-2	3-4	5-6	7-8	9-10

Table 1: Level of effect (from Knight et al., 2006)

Finally the resulting scores are used to estimate the wearability level of the system on a five point scale as represented in the following table.

no	Wearability level	Level of effects	Outcome
1	Low	WL1	System is **wearable**
2	Moderate	WL2	System is **wearable**, but changes may be necessary, further investigation is needed
3	Large	WL3	System is **wearable**, but changes are advised
4	V. Large	WL4	System is **not wearable**, fatiguing, very uncomfortable
5	Extreme	WL5	System is **not wearable**, potentially harmful

Table 2: Wearability Level (from Knight et al., 2006)

The remainder of the paper firstly develops the methodology of our approach to evaluating the wearable system. We then present the results of the different aspects of the work. Finally we offer some discussion on both our tests and evaluating mobile technology in a critical environment.

2.0 Methodology

The aim of the evaluation was twofold; firstly to determine whether changes in patient condition could be detected fast enough to be of actual use in caring for patients, and secondly to assess the system for wearability and comfort.

To simulate a busy clinical environment five virtual patients' information was displayed using the wearable system while the participants in the study (all clinical staff) were either watching a DVD or playing on a games console (simulating a multi-tasking environment). Although there was no requirement for data entry participants wore a wrist mounted keyboard during the tests to assess its comfort and acceptability. The keyboard was worn on the left wrist although it is possible to wear it on the right wrist. To determine the response time for changes in patient condition a set of scenarios were created. The scenarios would run for defined times, initially five, fifteen and thirty minutes for familiarisation and culminating in the longest run of ninety minutes. This length was determined by the current battery life of the equipment.

Each scenario consisted of a number of pre-defined events. These ranged from a single patient becoming slightly unstable to two patients deteriorating simultaneously. Each change in state was displayed for one minute. Tables 3 to 5 show the strategy for the different times with the scenarios and times of the occurrence of incidents for the all four tests. For example in Table 3, the 15 minute test shows that an incident occurs ten minutes into the test when patient 5 becomes unstable. This state would be displayed of one minute and then the display would return to normal. At all other times, not mentioned in the tables, all the five "patients" were shown as stable. The participants were observed while undertaking the scenarios and the times taken to observe the change were recorded. In addition the participants were taken for a walk round the hospital and to a coffee shop while wearing the equipment to further gauge comfort and self-consciousness while wearing the system.

	5 minute test scenario		15 minute test scenario		
Incident	1	finish	1	2	finish
Patient/ Status	5/unstable		3/slight	5/unstable	
Time (mins)	3	5	3	10	15

Table 3: Five/ fifteen minute session scenarios

30 minute test scenario							
Incident	1	2	3	4	5	6	finish
Patient/Status	2/slight	3/unstable	4/slight	4/unstable	1/unstable 4/slight	5/unstable	
Time (mins)	2	10	15	16	20	28	30

Table 4: Thirty minutes session scenario

90 minute test scenario										
Incident	1	2	3	4	5	6	7	8	9	Finish
Patient/status	1/slight	3/unstable 4/slight	1/slight	4/unstable	1/slight, 3/slight	3/unstable 4/unstable	2/unstable 5/slight	1/slight 2/slight	5/unstable	
Time minutes	2	15	30	51	55	63	80	85	88	90

Table 5: 90 minutes session scenario

These scenarios were designed to test if participants were able to notice changes on the screen at the very beginning of the session while a participant gets used to the system, approximately half way through the tests when concentration could deteriorate, and finally in the second half of the session, when participant may become tired and less focused. The session also aimed to test if participants were able to notice more than one change of patient condition, particularly when they occurred in adjunct patients on the display, for example emergencies with patient 3 and patient 4 at 63 minutes in the ninety minute test (Table 5).

In addition to recording the observations of events the participants answered two questionnaires, one before undertaking the tests and a larger one on the completion of the tests. The pre-test questionnaire gathered only qualitative data about participants' backgrounds and their general feelings and knowledge about IT and wearable computers.

The post- test questionnaire gathered both qualitative and quantitative data. It was intended to gather information about the participants' impressions of the system after the tests and to use these to estimate the wearability of the wearable computer. The questionnaire consisted of three components. The first aimed at examining the energy cost, comfort level and visual fatigue; the second part was based on the REBA test.. A measure of the wearability of the system was then calculated using the methodology described by Knight et al. [7]. The third part of the questionnaire contained qualitative data that represented general information about participants' feelings after the test. The data gathered allowed consideration of usability and acceptability aspects of the equipment in the ICU. The Questions asked during the interviews were:

- What is your general impression of the wearable computer?
- Do you find it useful for clinical work?
- What do you like about the equipment?
- What do you dislike about the equipment?
- Do you have any suggestions for improving the efficiency, usability and wearability of the equipment?
- Did you feel ill during the tests?

- Do you find the level of concentration during the tests adequate to the level of attention during work in the Unit or in an operation theatre?

3.0 Results

A total of seventeen tests were performed in this study [11]. Nine tests were with the participant watching a DVD, the remaining eight tests involved the participant playing a console based computer game. The nine DVD tests included three with post-graduate students (average age 27 years) to pilot the evaluation procedure and scenarios.

Six of the participants, four male and two female (lowest age 27, highest 31, mean 29.33, SD 1.63) performed the tests watching a DVD. Eight participants, four males and four female (lowest age 25, highest 33, mean 29.25, SD 2.54) performed the tests while playing on the game console. These numbers included two participants (one male, one female) who undertook both DVD and games console tests.

No participants reported taking any medication at the time of the evaluations. Nine participants wore glasses or contact lens (– 0.5 to – 7 dipotres) during the tests and one participant with short-sightedness took the tests without any optical support. All participants were familiar with a personal computer (PC), eight having received formal training and nine participants regularly used a personal digital assistant (PDA) or Global Positioning System (GPS). All participants reported regularly surfing the Internet with the number of hours on-line ranging three to forty hours per week.

Before starting the tests every participant went through a procedure to identify their dominant eye. All participants then chose whether to wear the display on the dominant eye. Eleven out of the fourteen participants preferred to wear the display in front of the dominant eye as this felt more comfortable.

Although the main emphasis of the results is on the clinical participants the following graph shows the average response times for the students and the clinicians watching the DVD during the ninety minute test. While the overall

trends are approximately similar the response times of the clinicians is significantly faster than the students.

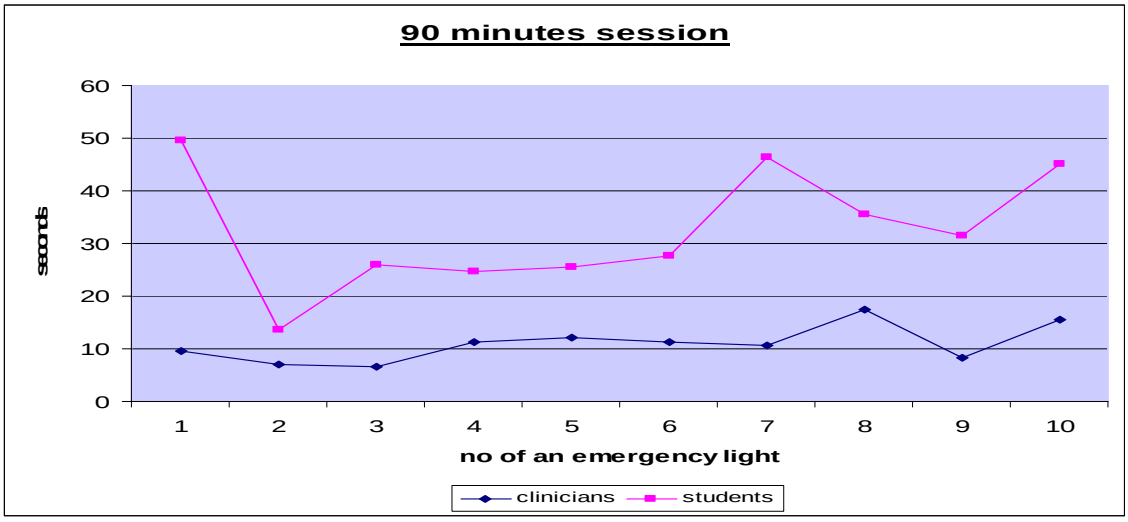
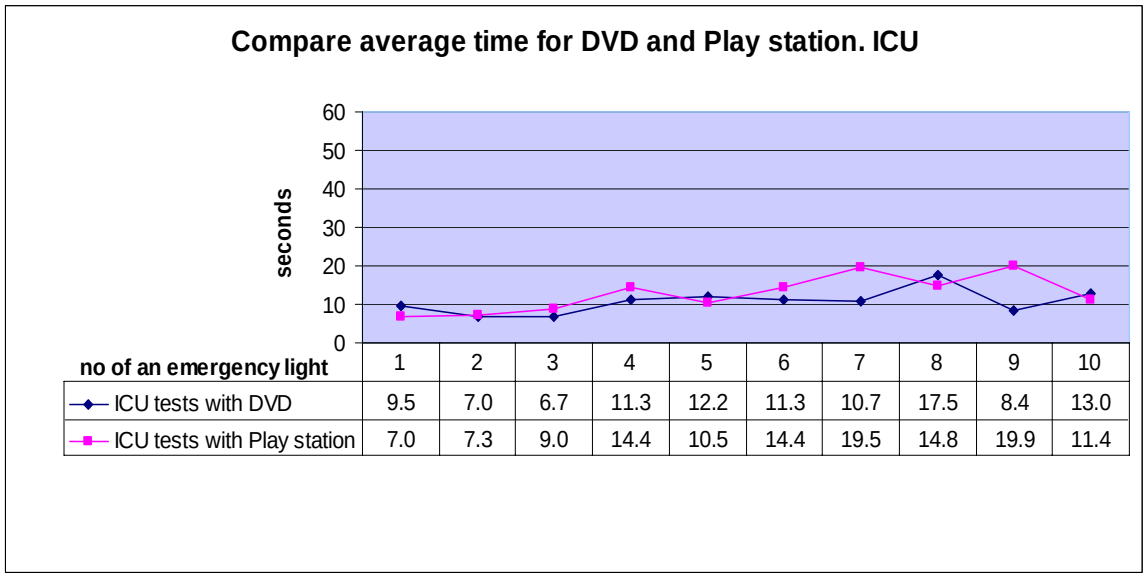


Figure 2: Comparison of students vs clinicians average response times while watching DVDs

The average time taken for the clinicians to observe the incidents during the ninety minute test is shown below in Figure 3



no of an emergency light	1	2	3	4	5	6	7	8	9	10
ICU tests with DVD	9.5	7.0	6.7	11.3	12.2	11.3	10.7	17.5	8.4	13.0
ICU tests with Play station	7.0	7.3	9.0	14.4	10.5	14.4	19.5	14.8	19.9	11.4

Figure 3: Comparison of the average time of incident identification by clinicians with DVD and games console during 90 minutes session

More detailed information for the average response times for each option are given in the following two tables. In each case the minimum, maximum and mean times (plus standard deviation) are given for the identification of the scenarios described in Table 5. Firstly DVD results in Table 6.

Scenario	1	2	3	4	5	6	7	8	9	10
Min	3	4	4	5	7	6	5	9	5	6
Max	20	11	9	24	21	22	20	45	60*	33
Mean	9.5	7	6.67	11.33	12.17	11.33	10.67	21	22.41*	19.5
SD	6.29	2.90	1.75	7.79	5.74	5.61	5.20	15.41	20.4*	13.48

Table 6: Results for clinicians in 90 minute test while watching DVD film

* One participant did not notice the change on the screen in 60 seconds

Secondly results from using the games console are shown in Table 7.

Scenario	1	2	3	4	5	6	7	8	9	10
Min	3	4	6	8	7	10	10	11	10	9
Max	22	16	15	32	15	27	52	26	42	60*
Mean	7	7.25	9	14.38	10.5	14.38	19.5	14.75	19.88	18.88*
SD	6.16	3.88	3.66	8.55	2.67	5.95	17.19	5.2	10.58	16.77*

Table 7: Results for clinicians in 90 minute test with computer console game

* One participant did not notice the change on the screen in 60 seconds (this was a different person to the one noted in Table 6)

The wearability scores were calculated after the ninety minute tests. The following table (Table 8) shows the participants responses for the individual tests that contribute to the final wearability rating. The entries in the table refer to the total scores from each tests, for example the Borg RPE test only has a single value for the energy cost but the Borg CR-10 has values for each region of the body so has more values in Table 8.

Participant no	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Sum
BORG RPE															0
Low	1														1
Moderate			1	1			1		1				1		5
Large		1			1	1		1		1	1	1			7
V. Large														1	1
Extreme															0
REBA															
Low			2				2						2		6
Moderate	2	2		2	2	2		2	2	2	2	2		2	22
Large															0
V. Large															0
Extreme															0

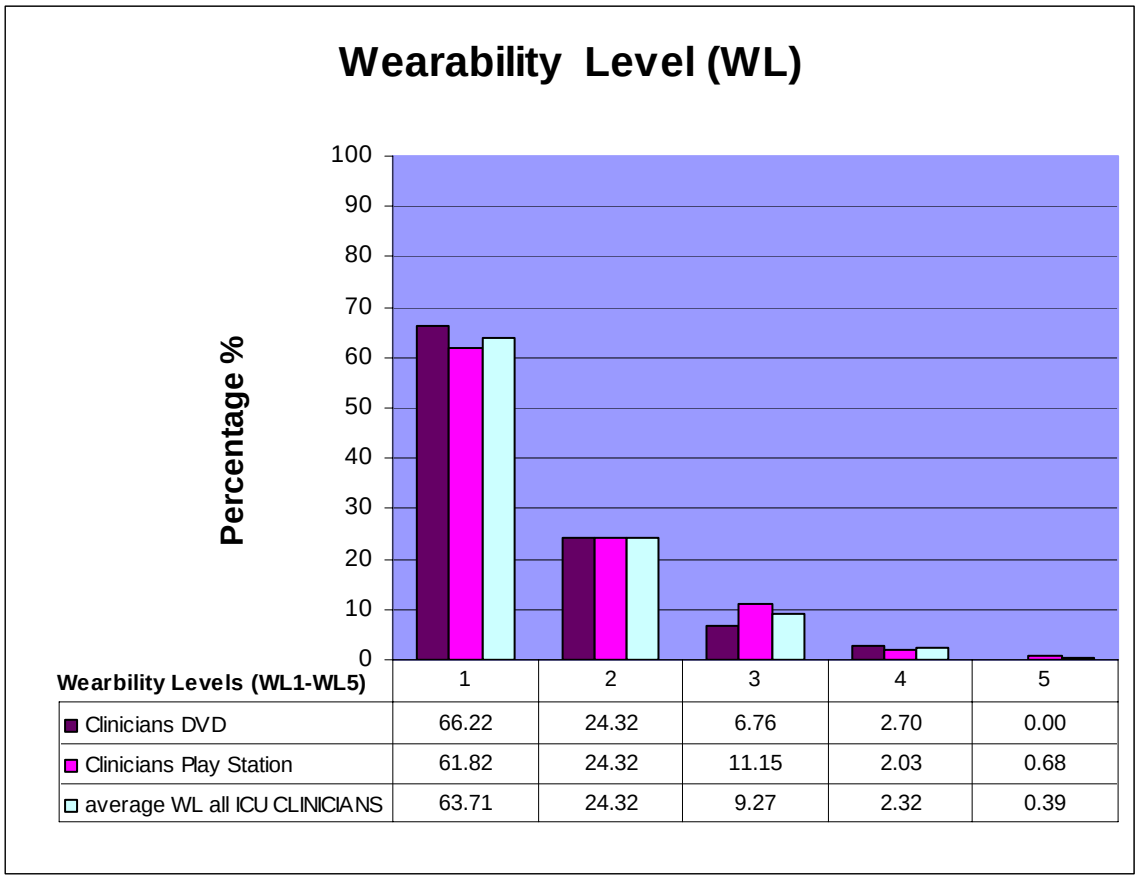
BORG CR10															
Low	17	15	18	12	15	14	18	7	14	14	18	13	16	14	205
Moderate	1	4	1	6	3	5	1	7	5	3	1	4	2	5	48
Large	1			1	1			5		2		2	1		13
V. Large															0
Extreme															0
CRS															
Low	2	2	3		3	4	3		1	3	1	2	3	5	32
Moderate	3	2	2	2	3	2	3	4	2	2	4	2	1	1	33
Large	1	2		3				1	1	1	1	2	1		13
V. Large			1	1				1	2	1					6
Extreme													1		1
VES															
Low	8	5	9	6	4	7	9	7	7	6	7	4	2	5	86
Moderate	1			3	2	2					2	1	3	4	18
Large		1			2				2	2		4	3		14
V. Large		3			1								1		5
Extreme								2							2
Average															
Low (WL1)	28	22	32	18	22	25	32	14	22	23	26	19	23	24	330
Moderate (WL2)	7	8	4	14	10	11	5	13	10	7	9	9	7	12	126
Large (WL3)	2	4	0	4	4	1	0	7	3	6	2	9	6	0	48
Very large (WL4)	0	3	1	1	1	0	0	1	2	1	0	0	1	1	12
Extreme (WL5)	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2

Table 8: The wearability tests results for clinicians.

Note1: Participants 1-6 undertook the tests while watching a DVD and participants 7-14 used a games console during the tests.

Note 2: Participants 3 (DVD) and 7 (Games console) were the same clinician (male), similarly participants 5 (DVD) and 12 (Games console) were the same person (female).

The following figure shows the final total scores presented as a bar graph. The totals for both the two forms of multitasking and the combined average are shown



Wearability Levels (WL1-WL5)	1	2	3	4	5
Clinicians DVD	66.22	24.32	6.76	2.70	0.00
Clinicians Play Station	61.82	24.32	11.15	2.03	0.68
average WL all ICU CLINICIANS	63.71	24.32	9.27	2.32	0.39

Figure 4: Wearability scores for clinical participants

4.0 Discussion & Future work

The wearability level results seem to indicate that the wearable computer system concept would be suitable for providing clinicians with real time information on patient condition while they are remote from the patient. 88% of the wearability scores for the combined DVD and computer games trials are wearable level 1 (system is wearable) or wearable level 2 (system is wearable but changes may be necessary).

On investigation the WL5 score (0.68 % of games console, average 0.39%) resulted from a single participant who indicated extreme general tiredness and visual fatigue. This participant was short-sighted (-0.5 dioptres) in both eyes with the display worn on a dominant right eye. She was the only participant with less than perfect vision that did not wear glasses during the test (she reported that glasses were only needed when driving). It could therefore be supposed that the extreme visual effects experienced could have reduced by wearing glasses.

The WL 4 (2.7 % DVD and 2.03% games console, average 2.32%) was the result of comments in three aspects. One participant (male) reported a very large energy cost. Two participants returned poor scores for the comfort effects (CRS), these consisted of feeling self-conscious while wearing the device (male) and feeling awkward with the device affecting movement (female). Finally three participants reported poor scores in the visual effects with irritation in eyes (male, short-sighted), visual fatigue (female, normal vision) and headache (female, short-sighted).

The system used for the tests was based on commercially available equipment and so was not optimal for the clinical environment in terms of size, construction and battery life. It was therefore expected that more participants would report poor comfort scores although there was some difference in feedback with several participants reporting “It was comfortable, especially the weight” although another reported “It is a bit uncomfortable because of the size”.

Feeling self-conscious while wearing the system is a potential problem about which we are quite concerned and feel that consideration of this is important for ultimate user acceptance. The poor reported scores for the visual effects are also a cause for concern. An aspect that was highlighted during the tests was clinicians reporting for the evaluation after an on-call shift. These usually involve little sleep. As one participant reported, “I felt slight headache which may be related to other reasons such as general tiredness of a long week and the lack of sleep.”

We did not consider the effect caused by using the wearable system during the evaluation on the primary task. For example, there was no comparison of the accuracy of the comprehension of the DVD or score from playing the computer game with and without the wearable system. This aspect would need to be considered prior to any implementation.

With the exceptions of the two missed incidents every change of condition was on average observed in less than 25 seconds. This is the maximum time for contacting the ward prior to assimilating information and organising remedial treatment [12]. However, perhaps more notice should be taken of the longest

times for recognising a change. In two cases a participant totally missed a scenario and in others recognition times of 32, 33, 42, 45 and 52 seconds were recorded. A purely visual alarm may not be optimal in these cases and a supplementary audio alarm may need to be considered if there is no response from the clinician after a defined period with one participant suggesting "….. the visual alarm alone won't be noticed unless there is a sound alarm added".

Obviously in the high dependency environment seriously ill patients are not left in isolation and are still under observation when the lead clinician is not in the immediate locality. However, providing continuous additional information in a consistent format enables them to be better informed about the simultaneous status of a number of patients quicker than via a telephone conversation.

The applicability of the tests as a simulated multi-tasking environment needs to be considered. A simulation of the stresses, atmosphere and seriousness of the high dependency environment is hard to create. The reported tests asked the participants to firstly observe two different systems in the case of watching a DVD and in the scenario with the computer game to undertake a basic interaction with a computer generated surroundings. In both cases there was little seriousness in the task, the DVD or computer games were not "life or death" situations. We were assuming that the participants were trying their best to understand the film or win the game but this may not have been the case. However, the approach presented in this paper did provide the participants with a multi-tasking environment, as one participant reported "The play station was quite a good distraction."

The informal interviews after tests were not efficient in terms of judging the suitability and wearability of the system however they gave an idea of the clinicians' general impression of the system, their suggestions for the utilization of the system and subjective feelings about wearability of the system. In general all participants had a positive impression of the device; most of them were surprised by the HMD which had a clear image despite the relatively small size. Most of the participants were disappointed with physical size of the system which seemed bulky, cumbersome or uncomfortable, particularly the wrist mounted

keyboard which proved to be unpopular. Most clinicians agreed that the system could be useful in a high dependency unit, especially for a short period while they are outside the ward. The computer games used in the second part of the study appeared to be less effective if a participant did not like playing games so was not concentrated on a game well enough. The male participants were found to be more familiar with playing computer games. The full list of comments for the informal questions are given in Appendix A

An interesting aside was that a competition developed between participants. They became very involved in the study and were keen to know who had the fastest recognition times.

Based on the results from this initial study the HMD and wearable computer system does potentially provide some benefit to the clinician while away from seriously ill patients but that further testing is need. The next stage is to obtain ethical approval and undertake evaluations in the full clinical environment while still be aware of maintaining patient care. This could be achieved by a wearable equipped clinician shadowing a "traditional" colleague. Both participants would then experience the same conditions and stresses so realistic comparisons could be made between the reaction times, tiredness and accuracy of response of the two clinicians. Finally, the use of an additional audio alarm will be investigated.

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Appendix A: Participants' comments from final interview. We have included the interesting responses and excluded "Yes", "No" and "Don't know" comments. These comments were transcribed from taped recordings with minimum grammatical editing.

Q1: What is your general impression about the computer?

- It is comfortable, especially the weight. The software is main problem. The screen is blurring.
- It was very comfortable.
- It is wearable.
- It was enjoyable. The computer itself and the keyboard are bulky. Monitor: very good picture. The computer is slightly heavy to wear. The white background of the interface makes it is difficult to look at, black background would be better.
- It is exciting.
- It was good in general. I think that it is quite large.
- Interesting, The screen in the corner of the eye, so can see all around, Not heavy, Novel
- It is a bit uncomfortable because of the size. The smaller is the better.
- I felt it strange wearing the device, sometimes felt tired and in general I found that the location to wear is inconvenient.
- It was quite light weight.
- It was very comfortable.

Q2: Do you find it useful in clinical environment?

- Yes. It is very useful.
- I am not sure. It has potential.
- Yes but I am afraid that in real work atmosphere (involved in some procedures or talk with patients or colleagues) the visual alarm alone won't be noticed unless there is a sound alarm added (combined alarm).
- Yes, it can be used when you are not in the ward and to communicate with colleagues.
- Useful for short term: if you have to leave the unit and you have few patients you are worried about, then it would be a solution
- Yes, after explaining the idea of the project.

- If I were a car driver I would need it, but in the hospital I do not have to stare at one point. In the unit I may not need a video monitoring system in front of my eyes continuously. Monitor on my forearm with vibrator. It may be useful in surgery theatre.
- Yes. It can be useful for general medical and surgery team monitoring high –dependency patients or HDU – high –dependency patients unit.

Q3: What you did not like about the computer?

- It is cumbersome.
- You have to be always aware about the monitoring system. The device is bulky, glasses are heavy.
- The device is bulky but can be better once you get used to it.
- The system may interrupt and take from the main task
- I suppose that a smaller font size will not be seen clearly.
- I can not wear it for long. If you have a lot on the screen you would not be able to pay attention much/ reading. Feel embarrassed while wearing it because people stare
- It will be difficult to work with it.
- The device is not useful in the ICU.
- It was a bit odd and irritating. It is extra weight you have to carry.
- At some point you can get too used to the screen, may not pay as much attention as you should.

Q4: What did you like about the computer?

- Even though the screen is small but still a user is able to see what is written on it.
- The idea is very good.
- It is possible to get used to it.
- Good way of imparting small amount of information and it would not affect the way you walk etc. Minimal stimulates from it
- Glasses are comfortable
- I liked the screen. The device itself is great provided it implemented where it needed.
- It has small size, light weight and the idea of the project.

- You do not have to concentrate on it too hard. At some point you can get too used to the screen. More you use it, more convenient it seems.

Q5: What is your suggestion for the efficient of the computer?

- Make it lighter, less wires.
- Make the device smaller
- It would be useful to provide the access to the patients' data from the computer.
- Monitor patients in HDU.

Q6: Did you feel ill during the test?

- Not really.
- I felt pressures in the eye area, not really ill.
- I felt slight headache which may be related to other reasons such as general tiredness of a long week and the lack of sleep.
- No, but tired in the end of the session.
- I had a headache; my active eye was pulling during the test.

Q7: Was the level of attention of the test was adequate to the level of attention demanded in the ICU?

- It depends on a person. The level of attention depends on a person. Day dreaming would be more appropriate here. I was bored with game and I did the night shift before I came here.
- Not sure, because it is be absolutely different environment from the one we have in the ward.
- Play station was quite good distraction.