# The Comfort Assessment of Wearable Computers

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**Abstract**

*This paper presents a tool to measure the comfort of wearable computers. The comfort rating scales (CRS) measure wearable comfort across 6 dimensions. These dimensions are Emotion, Attachment, Harm, Perceived change, Movement and Anxiety. This paper also presents two studies in which the CRS have been used to assess the comfort of two types of wearable technology currently being developed at the University of Birmingham, these are the SensVest and the $\chi 3$. The results of the studies show that the CRS can be used to aid designers and manufactures focus on what modifications are needed to wearable computer design to make them more comfortable. They also show that assessments of wearable computer comfort must be made in situations and environments to which the computer will ultimately be introduced.*

***Key words***
*Comfort, Physical comfort, Cognitive comfort, Comfort rating scales (CRS), SensVest, $\chi 3$*

## 1. Introduction

Gemperle et al., [1] tested their design of wearable forms by asking subjects to carry out activities and rate their level of comfort. By doing so they suggested that an assessment of wearable computers should include an element of comfort analysis.

Comfort has been assessed in ergonomics in numerous areas linked with workplace design including chair comfort [2], thermal comfort [3] and visual comfort [4]. Specific to wearing items, comfort assessment has been carried out for personal protective equipment, such as respirators, shoes, gloves, glasses, coveralls, knee and elbow pads [5]. Indeed, for wearable computer equipment comfort assessment has been carried out for devices incorporated into helmets [6, 7, 8] and for arm worn devices [9].

A major limitation of these studies is that they often score comfort along one scale implying that it is a one-dimensional construct. When wearing something your level of comfort may be affected by a number of factors. These may include the physical dimensions of the wearable (i.e. its size and weight), how it affects movement, and pain either directly (e.g. friction, knocking, heat) or indirectly (e.g. muscle fatigue). In addition when wearing an item levels of comfort may be affected by cognitive responses such as embarrassment.

Therefore just knowing that when wearing a device the wearer has a certain level of discomfort does not help in determining what aspect of the device makes the wearer feel uncomfortable. As such, for wearable technologies comfort should be measured across a number of dimensions. This paper presents a tool developed specifically to measure the comfort of a wearable computer user. It also presents two studies in which this tool has been used to assess the comfort of two different types of wearable computer currently being developed at the University of Birmingham.

## 2. Developing a comfort assessment tool

It is not within the scope of this paper to present a full description of the methods and results used to develop the wearable computer comfort assessment tool. This will be presented in a later paper. Instead, a brief description will be presented here.

To establish the different comfort dimensions the authors first created a list of 92 terms that described how wearing a device may affect the wearer or how the wearer may feel (physically and mentally) about the device. Eight people (mean age 37±16) were then asked to put these terms into groups, associating them based on self-selected criteria. From these groups a term-by-term association matrix was developed whereby the number of times each term was placed in the same group as another was scored.

The matrix was then subjected to multidimensional scaling (MDS) statistical analysis. MDS is a type of exploratory data analysis that enables a picture to be developed that models the structure and dimensions of a set of objects. This is accomplished by assigning observations to specific locations in a conceptual space such that the distances between points in the space match given similarities. The closer the terms in space the greater their similarity. By using MDS on the comfort term matrix a spatial representation of how the synonyms related to each other was developed. MDS was applied to the comfort descriptor matrix using SPSS for Windows V10.0. The results of the MDS are shown in figure 1 where the dots represent each comfort terms location in respect to each other.

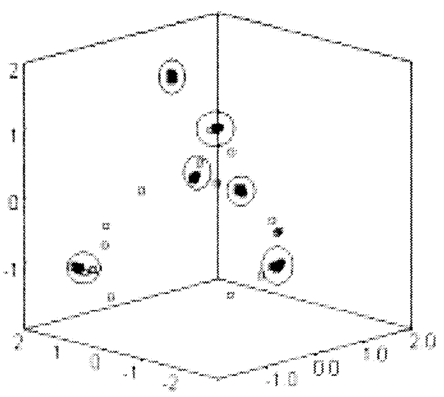

**Figure 1. Multidimensional scaling of comfort terms**

## 2.1. Dimensions of wearer comfort

From figure 1 it can be seen that there are six clusters of terms. Each cluster was inspected to establish what aspect of comfort the terms generally described that disassociated them from the other clusters. From this analysis 6 aspects or dimensions of wearer comfort were derived. These are shown in table 1.

**Table 1. Comfort descriptors**

| Cluster | Description |
|---|---|
| 1 | Emotions, concerns about appearance and relaxation |
| 2 | Physical feel of the device on the body, attachment |
| 3 | Physical effect, damage to the body |
| 4 | Feeling physically different, upset |
| 5 | The device physically affects movement |
| 6 | Worry about the device, safety, and reliability |

Cluster 1 relates to emotional concerns such as worries as how the wearer looks wearing the device and feelings of being relaxed.

Clusters 2 and 3 are related in that they are both concerned with direct physical feelings of the device on the body. However, cluster 2 relates to the non-harmful sensations of the device on the body (e.g. the feel the device either directly as pressing on the body or indirectly as it pulls on clothing or moves in relation to the body). Cluster 3 though, relates directly to harm brought about by the device conveyed through sensations of pain.

Cluster 4 also relates to non-harmful physical affects of the device of the body. However, unlike cluster 2 which represented the feel of the device on the body, cluster 4 suggests that wearing the device leads the wearer to feel different themselves with perceptions of being awkward and uncoordinated forcing the wearer to make conscious compensations or modifications to movements or actions.

Similar to cluster 4 is cluster 5. Both groups contain synonyms that describe changes made to the wearer due to wearing the device. Cluster 5 differs though in that the descriptors suggest that the device itself gets directly in the way of carrying out normal movement patterns, rather than just making the wearer feel that they are moving differently.

Cluster 6 is similar to cluster 1 in that it is concerned with a cognitive dimension of comfort. Cluster 6 expresses worries as to the safety of wearing the device and whether the device is working and acting appropriately.

## 2.2. The comfort rating scales (CRS)

The six clusters of comfort terms were used to produce six scales that score a different element of comfort. The comfort rating scales (CRS) design is based on that of the NASA-TLX, which is a validated tool for measuring mental workload [10].

The CRS are shown in figure 2. They use a 21 point scale which are scored from 0 at the far left to 20 on the far right. This fulfils a criterion of Helander and Makund [11] who recommend the use of eleven or more point scales for subjective evaluations. The scales are anchored at either end with the descriptors 'Low' and 'High'.

Using the scale simply requires that the scorer mark on the line their level of agreement from low to high to the statements made in the description box (figure 3).

## 2.3. Using the CRS

The following sections of the paper present two studies, which have used the CRS to assess the comfort of two different types of wearable computer currently being designed at the University of Birmingham. These are the SensVest and the $\chi3$.

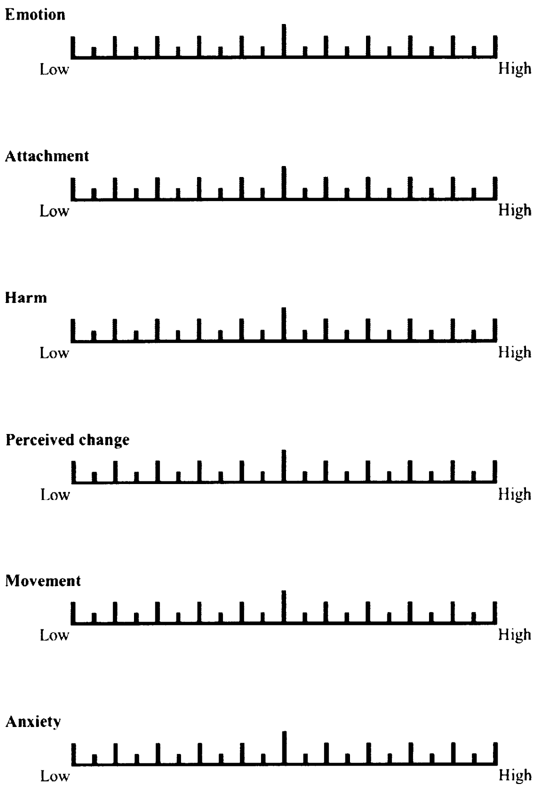


**Figure 2. Comfort rating scales**

| Title | Endpoints | Description |
| --- | --- | --- |
| **Emotion** | Low/High | I am worried about how I look when I wear this device. I feel tense or on edge because I am wearing the device. |
| **Attachment** | Low/High | I can feel the device on my body. I can feel the device moving. |
| **Harm** | Low/High | The device is causing me some harm. The device is painful to wear. |
| **Perceived change** | Low/High | Wearing the device makes me feel physically different. I feel strange wearing the device. |
| **Movement** | Low/High | The device affects the way I move. The device inhibits or restricts my movement. |
| **Anxiety** | Low/High | I do not feel secure wearing the device. |

**Figure 3. Comfort rating scales statements**

## 3. The SensVest

The SensVest is a product currently being developed at the University of Birmingham as part of the Lab of Tomorrow project. It is not within the scope of this paper to discuss this project or the SensVest in depth. Rather this paper considers how using the CRS is aiding the design process.

In brief, the SensVest is a shirt designed to house components that measure and transmit physiological data to a base station. Currently, the SensVest is able to record pulse rate from a microphone positioned over the radial artery or a piezoelectric pressure sensor positioned at the end of the finger. Body temperature is measured from a simple digital thermometer sewn into the armpit of the shirt. Body movement can also be measured from two uniaxial accelerometers, one located at the wrist of the right arm to measure hand movement and one located at the hip to measure whole body movement.

The sensors are connected to a signal conditioning module which then sends the signal to a Mitsubishi M16C processor worn on the back of the shirt. On the front of the shirt is a display. This is used to select the sensors to be used in a recording session and select sampling rates for the accelerometers. The display also presents the pulse rate in beats per minute and temperature in degrees Celsius.

Figure 4 shows SensVest v1.0, which is the first design of the shirt. The shirt is of a sweatshirt design. The signal conditioning module, processor and display are mounted on rubber padding and attached to the shirt with elastic straps and are housed inside large pockets sewn onto the front and back of the shirt. The cabling for the devices is sewn into the lining of the shirt. Elastic cords in the wrist and waistbands of the shirt can be pulled tight to hold the accelerometers firmly in place.

**Figure 4. The SensVest v1.0**

### 3.1. Comfort Assessment of the SensVest v1.0

The overall aim of the SensVest project is to record aspects of everyday activity, which can be used to support or enhance learning. As such the SensVest must be acceptable to the wearer and allow them to perform all the activities that they would normally without modifying their behaviour. To begin to determine if the SensVest fulfils these criteria a comfort assessment of the SensVest v1.0 was carried out.

### 3.2. SensVest v1.0 comfort assessment method

To assess the comfort of SensVest v1.0 wearers were asked to score their level of comfort of the CRS on three occasions under three different conditions.

In the general condition ten postgraduate students at the University of Birmingham (mean age of 25±2 years) were asked to rate the comfort of SensVest v1.0 while carrying out any activity and taking as long as they wished. The participants undertook a range of self selected movements such as walking, sitting-standing, bending, raising and rotating the arms and shoulders and then scored their level of agreement to the comfort statements on the CRS. The participants on the whole took around 2 minutes to carry out the assessment.

In the second and third conditions the comfort was assessed as undergraduate students carried out accelerometer data collection exercises using SensVest v1.0.

In the throwing condition 14 undergraduate students (mean age of 19±1 years) threw three balls at a target 1.5m and 5m away from a chair on which they were sat. The participants threw the balls in a darts style as accelerometer data was recorded from the wrist-mounted accelerometer. After completing the exercise the participants assessed the comfort of the SensVest v1.0 using the CRS.

In the dynamic condition 14 undergraduate students (mean age of 19±1 years) carried out a battery of whole body movements during which accelerometer data from the hip was recorded. The movements involved sitting and standing alternately 3 times, walking and jogging on the spot for 10 seconds each, and jumping vertically 3 times. After carrying out these activities, which took approximately one minute, the participants were asked to rate the comfort of the SensVest v1.0 using the CRS.

In both the throwing and dynamic conditions the SensVest was linked directly to a desk mounted PC and accelerometer data was collected through HyperTerminal and analysed off line. The lead connecting the SensVest to the PC was long enough not to affect movement.

### 3.3. SensVest v1.0 comfort results

The CRS scores recorded after wearing SensVest v1.0 and carrying out general movements, performing a throwing activity and performing a number of dynamic whole body activities are shown in figure 5. Statistical analysis for differences between comfort dimension CRS scores, within each condition, is shown in table 2. The statistical analysis involved running paired t-tests on SPSS for Windows V10.0.

**3.3.1. Overall Pattern of SensVest CRS score.** For the SensVest the CRS scores ranged from 2.2±2.4 to 13.5±4.1 dependent on comfort dimension and activity. Between the comfort dimensions the highest CRS score was for the Attachment dimension with an overall average CRS score of 12±4.4. The next highest was for the Perceived change dimension at 11.3±5.7, followed by Movement at 10±5.4, Emotion at 8.5±5.4 and Anxiety at 5.2±4.6. The lowest overall CRS score was for the Harm dimension at 3.2±3.2.

**3.3.2. Within condition results for SensVest comfort.** In the General activities condition the pattern of CRS score on the whole followed that of the overall pattern. The highest CRS scores were for Attachment (12±4.8) and Perceived change (10±6.1), which were significantly higher than the other dimensions (except between Perceived change and Movement). The lowest scores were for the Harm (3.4±4.7) and Anxiety (4.3±5.1) dimensions, which were significantly lower than all the other dimensions. The only departure from the overall pattern was that Emotion (7.3±5.5) scored higher than Movement (7±5.3), though not significantly.

The throwing condition differed from the overall pattern of CRS score with Movement (11.9±5.1) scoring the highest and the Attachment (10.6±4.1) scoring the third highest after Perceived change (11±6.2). Between these dimensions there were no significant differences in CRS score. The lowest score was again for Harm (2.2±4.9), which scored significantly lower than all the other dimensions. Anxiety (4.9±4.4) also scored significantly lower than the other dimensions except Emotion against which there was no significant difference and Harm against which it scored significantly higher.

The Dynamic condition followed the overall pattern with Attachment (13.5±4.1) scoring highest followed by Perceived change (12.4±4.9), Movement (10.1±5.0) and

Emotion (9.1±5.0). Again there was no significant difference between these dimensions CRS scores, but they were significantly higher than Harm and Anxiety, which again scored lowest (3.9±2.4, and 6.1±4.5 respectively). Emotion scored between these groups, being significantly lower than Attachment and Perceived change but higher than Harm.

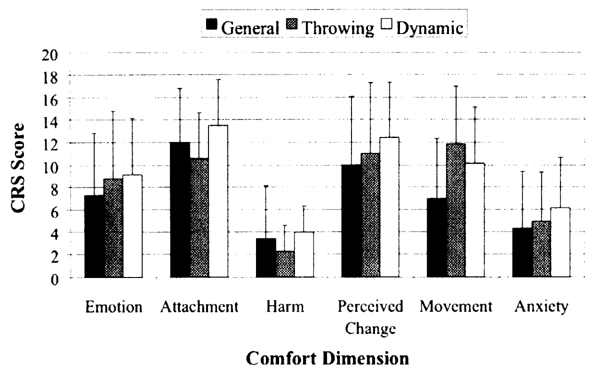


**Figure 5. CRS scores for the SensVest v1.0**

**3.3.3. Between condition results for SensVest comfort.** Overall the Dynamic condition generated the highest CRS scores across the comfort dimensions. The only case when this wasn't so was for the Movement dimension, where the Throwing condition generated the highest score. Between the General and Throwing conditions, the Throwing condition scored highest for the Emotion, Perceived change, Movement, and Anxiety dimensions, whereas the General condition scored highest for the Attachment and Harm dimensions.

Between the conditions the greatest change in CRS score was for the Movement dimension, which increased by 4.9 from the average General CRS score of 7 to the average Throwing condition CRS score of 11.9. The next greatest change of average CRS score was for the Attachment dimension with 2.9 followed by the Perceived change dimension with 2.4. The Emotion, Anxiety and Harm dimensions each had similar ranges of average CRS score across the conditions of 1.8, 1.8 and 1.7 respectively. Although there were apparent changes in CRS score between conditions within the dimensions the only significant difference was between the General and the throwing conditions' Movement score [$t(22)=2.25$, $p<0.05$].

**Table 2. Paired samples T-tests for significant differences between comfort dimensions CRS scores for the SensVest**

| | | Comfort Dimension | | | | |
|---|---|---|---|---|---|---|
| **Comfort Dimension** | **Condition** | ***Attachment*** | ***Harm*** | ***Perceived change*** | ***Movement*** | ***Anxiety*** |
| ***Emotion*** | *General* | t(9)=8.1 | t(9)=3.2 | t(9)=2.7 | ns | t(9)=2.8 |
| | *Throwing* | ns | t(13)=3.7 | ns | ns | ns |
| | *Dynamic* | t(13)=2.4 | t(13)=3.3 | t(13)=2.6 | ns | ns |
| ***Attachment*** | *General* | | t(9)=6.4 | ns | t(9)=4.8 | t(9)=7.1 |
| | *Throwing* | | t(13)=6.8 | ns | ns | t(13)=3.3 |
| | *Dynamic* | | t(13)=11.4 | ns | ns | t(13)=4.7 |
| ***Harm*** | *General* | | | t(9)=3.5 | t(9)=2.9 | ns |
| | *Throwing* | | | t(13)=4.7 | t(13)=7.4 | t(13)=3.3 |
| | *Dynamic* | | | t(13)=6.3 | t(13)=5.5 | ns |
| ***Perceived change*** | *General* | | | | ns | t(9)=3.3 |
| | *Throwing* | | | | ns | t(13)=2.5 |
| | *Dynamic* | | | | t(13)=2.3 | t(13)=3.1 |
| ***Movement*** | *General* | | | | | t(9)=3.7 |
| | *Throwing* | | | | | t(13)=3.8 |
| | *Dynamic* | | | | | ns |

Note: All values significant at $p<0.05$, ns – not significant

## 3.4. Discussion of SensVest comfort

As a prototype the SensVest v1.0 is useful as it demonstrates that the devices for the Lab of Tomorrow project can be worn on the body and data can be collected from it. However, the CRS scores show that improvements to its design need to be made to make it more comfortable. Using the six dimensions of the CRS scores shows that numerous elements of comfort are affected when wearing the SensVest v1.0. Many of these may simply be due to the size and bulk of the shirt.

The components fitted into the shirt can be felt and pull the shirt out of shape. This may be the reason for the high Attachment and Perceived change values. The devices are not held firmly against the body, which may also explain the high values for these comfort dimensions and why they increased in the dynamic condition. The increase in Movement CRS score in the throwing condition indicates that the shirt impedes arm movement. This may be due to the wire connecting the wrist accelerometer to the signal-conditioning module or due to the sensation of the components on the shoulder blade.

The Emotion and Anxiety CRS scores indicate that the shirt affected cognitive elements of comfort as well as physical. The Emotional score indicates that the wearers were concerned about their appearance when wearing the shirt and did not feel relaxed. Again this may be due to the size and bulk of the shirt making the wearer feel conspicuous, but probably includes elements of the aesthetics of the shirt. The Anxiety score began relatively low in the general condition but increased in the throwing and dynamic condition. In the general condition no data was being recorded, whereas in the other conditions data was being recorded. This may indicate that the wearer became worried due to the device being active. It may also be that there was some concern for damaging the device when carrying out the more dynamic activities. This may have links to perceptions of the device on the body and it moving.

The Harm score was low in all the conditions indicating that the shirt was not painful to wear. However, the value was higher in the more dynamic activities. This may be due to the devices in the shirt moving and colliding with the body.

### 3.5. SensVest v2.0

The next design of the SensVest, version 2.0 will be smaller, lighter and have adjustable straps so that the devices can be held firmly against the body. These modifications will hopefully reduce the CRS scores. SensVest 2.0 will also be of a vest design, which will make it possible to wear it under a normal shirt, making it less conspicuous. This will hopefully reduce the emotion score.

Using the CRS has shown that comfort is affected across numerous dimensions when wearing the SensVest v1.0. However, by scoring comfort across the dimensions modification to the SensVest design can be assessed. The CRS will therefore be used on SensVest v2.0 to determine if the changes made have improved wearer comfort. This will be determined by a significant reduction of CRS score.

## 4. The $\chi 3$

The $\chi 3$ is a wearable computer currently being developed at the University of Birmingham. It is not within the scope of this paper to describe the $\chi 3$ in any depth. A full description of the $\chi 3$ is presented in Bristow et al., [12]. Briefly though the $\chi 3$ comprises of a PC104 embedded PC board running a 166Mhz Pentium processor. It measures 170mm x 40mm x 100mm and weighs approximately 600g. The $\chi 3$ is worn in an over the shoulder bag by the side of the body (figure 6). A hand held mouse provides input. Visual output is provided by a MicroOptical head mounted display.

### 4.1. The $\chi 3$ and comfort

The $\chi 3$ has been designed to be wearable as such it must be comfortable and acceptable to the wearer. To assess the comfort of the $\chi 3$ it was scored on the CRS.

**Figure 6. The $\chi 3$**

### 4.2. Method

The comfort of the $\chi 3$ was assessed under two conditions. The first condition was similar to the general condition used in the assessment of the SensVest v1.0. In the first condition ten postgraduate students at the University of Birmingham (mean age of 25±2 years) were asked to rate the comfort of the $\chi 3$ while carrying out any activity and taking as long as they wished in a laboratory. The participants undertook a range of self selected movements such as walking, sitting-standing, bending, raising and rotating the arms and shoulders and then scored their level of agreement to the comfort statements on the CRS. The participants on the whole took around 2 minutes to carry out the assessment.

In the second condition the comfort was assessed after user trials of the $\chi 3$. By using a GPS receiver mounted on the shoulder of the belt, the $\chi 3$ is able to determine the location of the wearer and present information relevant to that location. In the second condition 8 undergraduate students (mean age 19±1) used the $\chi 3$ as a context aware wearable computer while walking around the University of Birmingham campus. This study is presented in full in Bristow et al. [12]. After carrying out the user trials the participants scored the comfort of the $\chi 3$ on the CRS.

### 4.3. The χ3 comfort results

The CRS results for the χ3 when wearing it in the laboratory and in the field are shown in figure 7. Statistical analysis for between comfort dimension CRS scores, within each condition is shown in table 3. As with the SensVest study, the statistical analysis involved running paired t-tests on SPSS for Windows V10.0.

**4.3.1. Within condition results for the χ3 comfort.** In the laboratory condition the highest CRS score was for Attachment (11.6±5.4), which scored significantly higher than all the other dimensions. The lowest scores were for Harm and Anxiety (2.6±3.0 and 1.4±1.8), which scored significantly less than the other dimensions but not between each other. Perceived change and Movement scored similarly at 7.3± and 7.0±5.9. Emotion scored less than these two dimensions (5.4±4.0), though not significantly.

In the field condition emotion was the highest scoring comfort dimension at 12±2.5. The next highest were Attachment (10.8±2.1), Perceived change (10.4±4.2) and Movement (9.0±5.5). The only significant differences between the comfort dimensions in the field condition was for Harm which was significantly lower than all the other dimensions at 2.6±2.7.

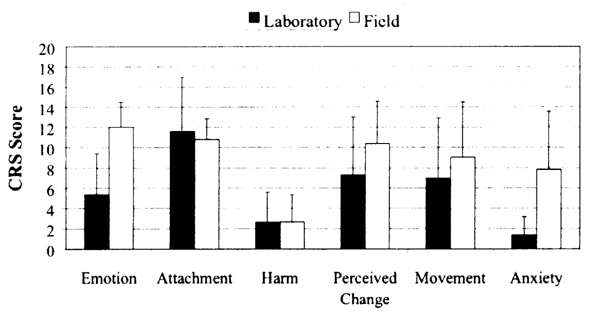


**Figure 7. CRS scores for the χ3**

**4.3.2. Between condition results for the χ3 comfort.** For all comfort dimensions except Attachment and Harm (which scored similarly) the CRS score was higher in the field condition than in the laboratory condition. The most noticeable difference was for the Anxiety and Emotion dimensions. Anxiety was significantly [$t(16)=3.4$, $p<0.05$] higher in the field condition with an average value more than 5 times greater than the laboratory condition. The Emotion dimension was also significantly [$t(16)=4.1$, $p<0.05$] higher in the field condition with an average value more than twice that of the laboratory condition. The Perceived change and Movement dimensions were also noticeably higher in the field condition, but not significantly.

**Table 3. Paired samples T-tests for significant differences between comfort dimensions CRS scores for the χ3**

| | | Comfort Dimension | | | | |
|---|---|---|---|---|---|---|
| **Comfort Dimension** | **Condition** | ***Attachment*** | ***Harm*** | ***Perceived change*** | ***Movement*** | ***Anxiety*** |
| ***Emotion*** | *Laboratory*<br>*Field* | t(9)=3.2<br>ns | t(9)=2.5<br>t(7)=6.5 | ns<br>ns | ns<br>ns | t(9)=4.0<br>ns |
| ***Attachment*** | *Laboratory*<br>*Field* | | t(9)=5.4<br>t(7)=6.6 | t(9)=3.0<br>ns | t(9)=3.1<br>ns | t(9)=6.3<br>ns |
| ***Harm*** | *Laboratory*<br>*Field* | | | t(9)=2.3<br>t(7)=5.7 | t(9)=3.1<br>t(7)=3.9 | ns<br>t(7)=2.9 |
| ***Perceived change*** | *Laboratory*<br>*Field* | | | | ns<br>ns | t(9)=4.0<br>ns |
| ***Movement*** | *Laboratory*<br>*Field* | | | | | t(9)=3.0<br>ns |

Note: All values significant at $p<0.05$, ns – not significant

### 4.4. Discussion of the χ3 comfort

Wearing the χ3 involves wearing something relatively large and bulky over the shoulder as such it is highly physically noticeable. This explains the relatively high Attachment, and Perceived change CRS scores. By reducing the size of the device these scores may be reduced. The device is loose fitting over the shoulder and down the side of the body, as such it moves with respect to the body when in motion. This may also contribute to the Attachment and Perceived change score. Attaching a strap across the body would hold the χ3 more firmly to the body and may alleviate this score. As the device is worn by the side of the body it inhibits the arm from swinging when walking this may be the reason for the Movement CRS score. Shifting the device around the back of the body would allow the arm to swing normally when walking.

The most dramatic result of the comfort assessment of the χ3 was the increase in cognitive dimensions of comfort CRS score when in the field condition. This suggests that when wearing the χ3 in public the wearer was concerned about their appearance and felt conspicuous. Making the devices smaller would make them less conspicuous as would hiding the wiring by sewing it into the lining of the bag element. When interacting with the χ3 the wearer was also highly concerned about the device making them feel less secure. Making the modifications mentioned previously (i.e. reducing size, making less conspicuous) may reduce the Anxiety score as the wearer is less conscious of wearing an item of electrical technology.

## 5. Implications of the CRS

In the two studies presented in this paper the highest CRS scores were on the whole scored for the Attachment, Perceived change and Movement dimensions. This suggests that focus should be placed on physical factors such as size, weight, weight distribution, location of device on the body and its method of attachment in the design of wearable computers. These findings are not new. However, the scales also showed that cognitive components, such as emotion and anxiety, should be examined. The results of the studies therefore show that wearer comfort should not be measured by one single scale, but should be assessed over a range of dimensions.

The CRS provide a tool, which enables comfort to be assessed over a range of dimensions. As such it can be used to aid designers and researchers of wearable computers in measuring total wearer comfort. Using the CRS may assist designers in determining what aspects of the wearable device to focus on to improve wearer comfort. The CRS scales can be used to measure the level of comfort specific for comfort dimension and device, determine which comfort dimensions score highest for a specific device or compare the comfort between different devices.

By comparing CRS score pre and post alteration the CRS can also be used to determine the effectiveness of modifications of computer design to wearer comfort.

The results of the studies also show that comfort should also be assessed while carrying out a range of activities, and in the locations and conditions in which the device will finally be introduced.

## 6. Acknowledgements

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