Developing a methodology for the design of accessible interfaces

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Abstract. Users with a number of different motion impairment conditions cannot cope with most current computer access systems. Such conditions include athetoid, ataxic and spastic Cerebral Palsy, Muscular Dystrophy, Friedrich's Ataxia, tetraplegia and spinal injuries or disorder. Frequent symptoms include tremor, spasm, poor co-ordination, restricted movement, and reduced muscle strength. Similar symptoms are also seen amongst the elderly able-bodied population from conditions such as Parkinson's Disease, strokes and arthritis.

The primary aim of the programme of research at the University of Cambridge is to enable the design of accessible input systems and interfaces for all motion-impaired users, both elderly and disabled.

Current interface design practices are based on user models and descriptions derived exclusively from studies of able-bodied users. However, such users are only one point on a wide and varied scale of physical capabilities. This paper will show that there are very important differences between those with motion-impairments, whether elderly or disabled, and able-bodied users when they interact with computers. Without a proper understanding of those differences, interface design will remain an exercise in making the interfaces more comfortable for the motion-impaired users, rather than really usable.

This paper describes our experiments to understand how motion-impaired users interact with computers and how we are using this information to develop a methodology for the design of accessible interfaces.

1. INTRODUCTION

Computers can be a source of tremendous benefit to those with motion impairments [Busby 97]. They offer greater freedom to participate in education and leisure activities, as well as increased job potential and satisfaction. They also enable employers to retain the services of experienced employees who might otherwise have to retire through ill health and to recruit those with motion-impairments. For example, the ability to operate a word processor, spreadsheet and database is often sufficient to perform many useful administration tasks.

Computers are also the basis of modern communications systems. The Internet is a prime example that offers a great opportunity for disabled users [Nelson 94]. The advent of e-mail across millions of networked computers and hybrid mail services can enable dialogue that is entirely independent of the ability to speak clearly, often a difficulty for those with motion-impairments, and eliminates prejudices based on appearances. Home life can be improved through access to on-line facilities such as home shopping.

1.1 Developing a design methodology

In order to develop a design methodology it is necessary to adopt a three stage approach [Blessing 95]:

- *Stage 1 - define the problem* - gain an understanding of how motion-impaired users interact with computers and how this differs from able-bodied users;
- *Stage 2 - prescribe a solution* - develop a methodology that takes into account knowledge of the user;
- *Stage 3 - evaluate the solution* - make sure that the methodology is effective.

It is imperative that each step of the design cycle is user-centred. Consequently, user trials need to feature prominently in all stages of the research.

When designing interfaces or interface methodologies, there is a very strong temptation to jump to Stage 2 of the design process, with only a cursory examination of Stage 1. This line of thinking is common and has led to numerous rehabilitation robotics products that are neither usable [Buhler 97] nor commercially successful [Mahoney 97].

The available body of HCI theory is immense. However, it concentrates almost exclusively on able-bodied users. Consequently, operating systems such as Windows 95 offer little support for disabled users, so enhancements to the operating system are required to enable access. Examples of such enhancements include the incorporation of embedded scanning techniques [Savidis97], but these are adaptations to allow access, but with no real comfort or convenience. More fundamental changes to the design philosophy are required to make interfaces more accessible and usable [Karshmer 97].

It is generally accepted that the incorporation of user models into the design of software interfaces is essential for successful interface design. However, most existing user models are based on able-bodied users. To build software that is more accessible to users with motion impairments, it is necessary to have user models that have been calibrated on motion-impaired users as well as able-bodied ones.

Consequently, this paper concentrates on how we have obtained a detailed understanding of motion-impaired users through the application and modification of HCI theory. It will then discuss how we intend to use this information to assess the effects of different symptoms, identify potential remedial measures and to develop a suitable methodology for the design of accessible interfaces.

2. STAGE 1 - A THEORETICAL UNDERSTANDING OF THE USER

Characterisation of human-computer interaction involves the observation of a wide range of parameters with complex interdependencies. To obtain a thorough understanding, a framework is required for the investigation.

User modelling techniques provide such a structure. The origins of user modelling are in neuropsychology and the attempts to understand the brain and its functions through empirical models. User models have since been adapted for use in the field of man-machine interfacing and several models exist, such as the keystroke level and GOMS models, for describing human-computer interaction in particular [Card 83].

2.1 The role of user models

User models are well represented in the field of HCI. They afford designers of interfaces detailed quantitative knowledge of the user for improved design, both in terms of the final end product and the time taken to achieve this. Effectively they serve to discretise the interaction process into distinct types or modes of behaviour. They have been in existence for some time and are well validated for use with able-bodied users.

However, they are almost always calibrated exclusively on able-bodied subjects using traditional input devices such as the keyboard and mouse. User models have not made the transition across to the field of rehabilitation for several reasons. The principal reason is commercial. There are more able-bodied users of computers than there are disabled ones. This means that the financial incentive was to supply interfaces optimised for able-bodied users, because that is where the market is. There simply was not the client-base to make using similarly rigorous techniques for disabled-specific software financially worthwhile. For instance, not only are there fewer end-users available, but user trials are more expensive. The trials usually progress at a slower rate, users are more difficult to locate and the design team have to go to the users, rather than the other way round, as would be general practice for able-bodied design.

One of the other difficulties faced is that not only have the existing user models been calibrated on able-bodied users, they were developed using theories based upon assumptions about the users. As stated above, user models work by segmenting the interaction process into specific categories of behaviour type.

One generic category is the motor response, often subdivided into different types of action. Given the variable nature of impairment across the different disability types, it would seem reasonable to assume that particular motor functions may behave differently for individual users. It is therefore necessary to validate any user model before simply assuming that the theoretical basis is correct for a particular user group.

Given the importance of user models in HCI design, the adaptation and re-calibration of existing user models, and the development of new models, are essential for the successful design of computer-based assistive devices for the motion-impaired user. Therefore, for the purposes of this work the basic principles of the user modelling paradigms are investigated to evaluate how well they described motion-impaired users.

Computer-based assessment tools can be used to provide detailed information on user performance parameters. If designed well, these can provide the basis for a detailed user model. It was then intended to calibrate the models from the data recorded during extensive user trials conducted at the Papworth Trust. The key to good design is the inclusion of user studies and usability testing early in the design process. These are often in the form of regular user trials and facilitate consideration of the loads, both physical and cognitive, on the user.

2.1.1 The Model Human Processor

One of the most straightforward user models is the *Model Human Processor (MHP)*, postulated by Card et al [Card 83]. This model segments the interaction process into three broad function types. These are the time to perceive an event, the time to process the information and decide upon a course of responsive action and, finally, the time to perform the appropriate response. Consequently, total response times to stimuli can be described by the following human interaction cycle equation:

$$\textit{Total time} = x\tau_p + y\tau_c + z\tau_m \qquad [1]$$

where *x, y* and *z* are integers and τ_p, τ_c and τ_m correspond to the times for single occurrences of the perceptual, cognitive and motor functions. Because of the way the brain operates, it is only possible for each constituent of the cycle to occur in multiples of the base time. In other words, it is impossible to have half a cognitive cycle or a third of a motor response. Hence, for simple tasks the coefficients in the above equation are always integers [Card 83].

Using this fact enables the model to be calibrated. For example, taking a relatively simple task, such as an able-bodied user pressing a key in response to a screen flash, the user receives an impulse and perceives that something has happened. There is a single impulse of a particular type, visual in this case and so only a single perceptual cycle, of approximately 100ms, is required [Ganz 75].

The user then recognises that something has happened. It is not necessary to establish what the something is, simply that it has occurred and so again there is only a single occurrence of the cognitive cycle.

Finally, some action needs to be taken in response to the stimulus. In this case, a simple downward action of a finger on a key is sufficient. This is a single motion, requiring no fine-tuning of position and so can be summarised as a single motor response function. Hence for a simple stimulus, the coefficients in the above equation are all one [Card 83].

However, for more complex tasks the coefficients increase. Taking the same basic task as above, but using a key-up action to stop the timing infers that two motor functions are needed to complete the interaction, key down and key up. This combination of actions is automatic and hence a doubling of the *z* coefficient should be sufficient to describe the new interaction process. This will be demonstrated in Section 4.

This assumption forms the basis for establishing a direct measurement of the motor response time. Timing the duration of repeated key-presses over a period of time and averaging the time difference will yield the motor response time directly. Each key-press and release will take a time τ_m to perform. Therefore, if the times for each key release are recorded then the value of τ_m is half the difference between the observed times [Card 83].

The perceptual response time can also be measured directly. Although, of all the components of the MHP, this is the one that is most subject to variation. The time to perceive an impulse is directly related to the intensity and nature of the stimulus [Harter 67]. Touch, smell and taste are dealt with by different means within the brain from audio and visual information. However, as the principal forms of feedback from a computer are visual and aural in nature, those are the impulses that are of interest here.

Both are treated in the same way in the brain. An impulse arrives via the optical or auditory nerves and enters the working memory visual and auditory stores. One method of measuring the response time to a visual stimulus is to present the user with a smooth scrolling animation. If a delay is inserted into the animation at a particular point, and the user can successfully identify where that delay is, then the delay time is longer than the perceptual response time of the user. Likewise, if the delay is undetectable, then it is less than τ_p. Hence by a process of iteration, the actual value for τ_p can be obtained [Card 83].

The cognitive processing time cannot be measured directly, but may be inferred from exposure to particular types of stimulus. Card et al provide a methodology for achieving this. Taking a stimulus that is simply a visual event; such as the one proposed above, recognising that something has occurred without having to identify it leads to a coefficient of one for the cognitive processing time.

If the stimulus was designed to impart information, then the associated cognitive processing time would increase in line with the level of abstraction. The lowest level of abstraction is shape and colour recognition. If a choice of, say, a red triangle and a blue circle was presented, then it would take another single cognitive cycle to recognise which of the two was being observed. Hence the total number of cognitive cycles becomes two.

The next level of abstraction is to give the shapes a particular meaning or name. An example of this is letter selection. Asking the user to identify a letter introduces a third cognitive cycle into the loop and consequently increases the corresponding coefficient to three.

Using the different number of cognitive processing steps involved in the recognition of the above three types of stimulus means that by setting up the experimental procedure carefully, the value of τ_c can be obtained by observing the differences in response time to visual stimuli of approximately the same intensity, where the motor task is the same for each stimulus. Hence the model can be calibrated.

Card et al calibrated this model using pen and paper based experiments. Their experimental data from able-bodied subjects showed average times of 100ms (50~200ms), 70ms (25~170ms) and 70ms (30~100) for the perceptual, cognitive and motor cycles.

2.1.2 Other user models

The MHP scheme provides a framework through which very simple tasks can be described and modelled as a series of basic discrete processes. This is a relatively straightforward example of how such a user model can be used in the deeper understanding of the interactions in a man-machine interface. For more complex scenarios, it is helpful to take the model to a higher level of detail or construct a more specific model for that particular task type, such as the Keystroke Level Model (KLM) for keyboard input [Card 83].

$$T_{execute} = \tau_K + \tau_P + \tau_H + \tau_D + \tau_M + \tau_R \qquad [2]$$

where τ_K, τ_P, τ_H, τ_D, τ_M and τ_R are the times for keystroking, pointing, homing, drawing, mental operations and system response respectively.

A common feature of most user models, such as the KLM or MHP, is the segmentation of user actions into discrete, quantifiable chunks that can be combined to describe any action performed by the user in a particular task environment. Models of this type rely upon the assumption of statistical independence between each discrete chunk. However, as seen from the MHP results, the basic assumptions on which these models are based must be carefully validated before applying them.

2.1.3 Understanding cursor control

An integral part of interaction with graphical user interfaces is cursor control. This is reflected in user models such as the KLM, which include pointing and drawing time components.

It has been shown in a number of studies that linear mathematical descriptions of cursor movement for able-bodied users can be derived from assuming a short *ballistic* phase of rapid movement towards a target, followed by a brief *homing* period [Graham 96]. One such example is Fitts' Law, relating the time taken to the size and distance of the target. Preliminary studies undertaken at CUED show that Fitts' Law also applies as a satisfactory mathematical approximation for motion-impaired users. However it is not a very precise description, because there is an observed cyclical combination of the ballistic and homing phases (Figure 1).

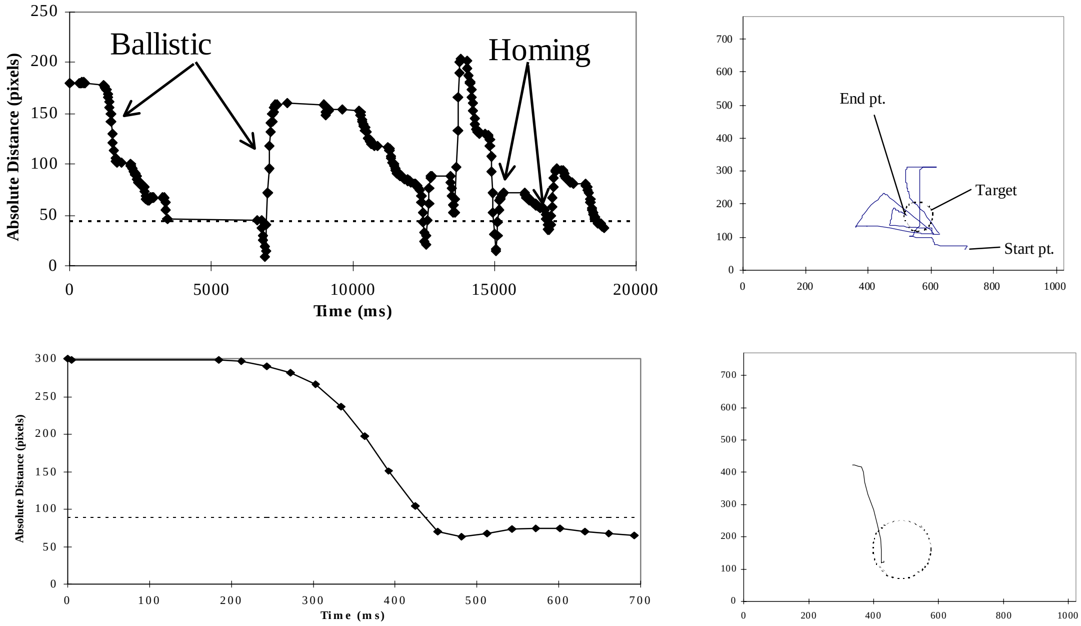

Figure 1. Cursor position plots for a motion-impaired user (top) with Cerebral Palsy and an able-bodied user (bottom), both using a mouse and aiming for a circular target. The left graphs show absolute (Euclidean) distance from the target and the right plots show the actual screen positions.

Other current research on able-bodied subjects has indicated that shape of target and direction of approach also have an influence on cursor control [Whisenand 97]. It is intended to develop these studies further with motion-impaired users.

Once we have complete descriptions of the interaction, we can develop methods of compensating for any difficulties encountered by recognising typical unwanted behaviour. For example, to interact successfully with graphical user interfaces, it is necessary to be able to control the cursor through an input device.

Figure 1, showing a motion-impaired user aiming for an on-screen target, illustrates the noise involved in cursor control by the target users. Analysis of how this behaviour differs from the single ballistic and homing phases would form the basis of methods for compensation. Input processing using low-pass filtering; adapted velocity and acceleration profiles; and self-adaptive interfaces, using intelligent interface agents, will be studied. The attributes of various commercially available input devices will be assessed for physical and cognitive usability. Positioning the cursor is only half of the required input for GUI interaction, the other half is selection. Initial studies have shown that switch-based selection is cognitively easier than either dwelling or gesturing, although it can be more physically demanding. A comprehensive study of appropriate selection techniques will also be undertaken.

3. STAGE 1 - AN EMPIRICAL UNDERSTANDING OF THE USER

User model theory is a very useful starting point for understanding the user. There is, however, a question over the degree to which discretisation of parameters is possible. For example, in the MHP model there is an assumption that the various stages in the interaction cycle are entirely independent. It is thought that motor control is governed by negative feedback control loops [Rosenbaum 91, Mahoney 93] and this throws the assumption of independence into doubt, although the degree of correlation may be statistically insignificant.

It is therefore necessary to validate user models and verify their theoretical predictions through contact with potential users in trials. To this end, user trials were established at the Papworth Trust with the users detailed in Table 1.

User	Condition
PJ1	Athetoid Cerebral Palsy
PJ3	Tetraplegia (from head injury)
PJ4	Muscular Dystrophy
PJ5	Spastic Quadriplegia Cerebral Palsy
PJ6	Athetoid Cerebral Palsy
PJ7	Friedrich's Ataxia
PJ8	Athetoid Cerebral Palsy

Table 1. The users from the Papworth trials.

User trials also offer a valuable source of observational data of the users. Such observations can provide quantitative reinforcement of theoretical predictions and also indications of other behaviour should the theory prove to be inappropriate or in need of modification.

Three computer programs were written to evaluate each of the three cycle times involved in the MHP. The first, Figure 2, was designed to evaluate the perceptual response time, the second the motor response time and the third was for the cognitive processing time.

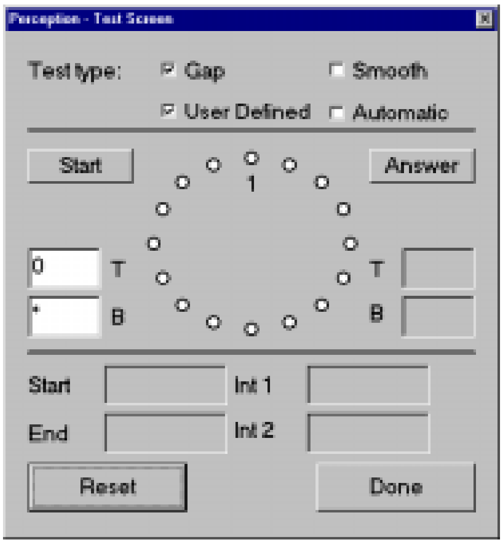

Figure 2. Screen shot of the perception program. The central arrangement of white circles shows where the black dot appears. The other screen features are for defining the program parameters.

3.1 Evaluating the perceptual response time, τ_p

Measuring the perceptual response time was done by cross-referencing the results from two tasks, both involving a black dot moving in a circle on the screen. The first task, Delay, involved the user observing the motion of the dot whilst time delays were inserted into the motion at random points. Initially, a time delay of 500ms was used to illustrate the break in motion that was to be identified, and then the time delay was incrementally decreased until the user could not determine the location of the delay. The smallest delay successfully observed was recorded.

A second task, Smooth, was also presented to the users, in which the dot was sent round the screen in discrete segments of motion. The duration of each movement segment was varied between 10ms and 150ms. The user was asked to state whether the motion was smooth (continuous), jerky (discrete) or borderline. An analogy to an aeroplane propeller was used to describe the kind of effect that was being studied. As a propeller begins moving slowly, it is possible to make out each of the blades. However, as it gains in speed, the propellers begin to merge until they become indistinct and all that can be seen is the impression of a circle. It was the borderline between these cases that was being investigated and was the time recorded, corresponding to τ_p [Card 83]. This task was performed with both able-bodied and motion-impaired users. Tables 2(a) and 2(b) summarise the results observed.

User	τ_p Delay (ms)	τ_p Smooth (ms)
A	75	70 - 80
B	95	70 - 90
C	75	70 - 80
Average	82	77

Table 2(a). Perceptual response times for able-bodied users.

User	τ_p Delay (ms)	τ_p Smooth (ms)
PI3	115	110 - 120
PI5	105	90 - 110
PI6	95	90 - 100
PI8	75	70 - 80
Average	97	96

Table 2(b). Perceptual response times for motion-impaired users.

3.2 Evaluating the cognitive response time τ_c

A software application was developed to evaluate the cognitive cycle time. The program consisted of three tasks. The first involved activating a large OK button as soon as it flashed up on the screen. The button was placed on a brightly coloured background to maximise the visual stimulus and made sufficiently large that no cursor movement was necessary for activation. The users selected the space bar, Enter key or a mouse button as the selection method. This task corresponded to the simple reaction time $\tau_p + \tau_c + 2\tau_m$.

Instead of the brightly coloured background, the second task had the OK button accompanied by either a green triangle or blue square. To overcome the problems of learning and the impact of extra motor movement, the same single input method was used by each of the users. The criterion used before activating the button was simply to recognise the shape seen. The time to complete this task was $\tau_p + 2\tau_c + 2\tau_m$.

Finally, the users were presented with a letter accompanying the OK button and the same procedure followed as for the symbols. Recognising the letter before pressing the button gave a time corresponding to $\tau_p + 3\tau_c + 2\tau_m$.

Tables 3(a) and 3(b) show the cognitive cycle times obtained from the computer-based able-bodied and motion-impaired user trials. The calculated time for τ_c from Card is 70ms.

User	τ_c (ms)
A	100
B	95
C	90
D	89
Average	93

Table 3(a). The cognitive cycle times for able-bodied users.

User	τ_c (ms)
PI3	105
PI4	116
PI5	101
PI6	121
PI7	107
PI8	128
Average	113

Table 3(b). The cognitive cycle times for motion-impaired users.

3.3 Evaluating the motor response time, τ_m

The next step was to calculate the motor function time. This was achieved by an application that consisted of a large OK button that was cleared on every key-up or button-up action and re-appeared for a total of ten clearances. The time was recorded each time the button was cleared. Consequently, each time observed was equivalent to $2\tau_m$. Again, this was performed with both able-bodied and motion-impaired users. The task was repeated for a number of times until the times observed had settled down to a consistent value, to allow for the effects of learning. The times obtained for the motor function are shown in Tables 4(a) and 4(b).

These tables of results show that the able-bodied users are all consistent and compare well with the 70ms time from Card. However, the motion-impaired results show a different story. There appear to be three distinct bands of times. The lowest value band is sufficiently close to the able-bodied values to be explained away as the effect of the motion-impairment producing slower motion. However, the other bands require more careful analysis.

User	τ_m (ms)
A	78
B	81
C	70
D	67
E	61
Average	72

Table 4(a). The motor function times for able-bodied users.

User	τ_m (ms)
PI4	120
PI6	96
Average	108
PI3	223
PI7	198
Average	211
PI5	306
PI8	297
Average	302

Table 4(b). The motor function times recorded for motion-impaired users.

3.4 Interpretation of the results

The differences between the τ_m time bands are 103ms and 91ms respectively. These time differences are approximately the same as half the sum of one perceptual and cognitive cycle. This is important because the values obtained for τ_m are based on the assumption that the time recorded is $2\tau_m$ and hence divided by a factor of 2. The discrepancy of half the sum of τc and τ_p implies that a full perceptual and cognitive step must have been present in the original value.

Hence, for these users the key-presses are not automatic, as assumed by the theory, and there are extra τ_p and τ_c terms present in the describing equations. Consequently, for the intermediate range of values, the interaction process is:

Release key (stops previous cycle, starts new one)
See that button is cleared (perceptual cycle)
Decide that button is cleared (cognitive cycle)
Press key (motor function)
Release key (motor function)

Taking the values for τ_p and τ_c derived above, this process gives a total time of $\tau_p+\tau_c+2\tau_m \approx$ (96+113+108*2) = 425ms. When divided by a factor of two, as for Table 5.4, a time of 213ms results (cf. 211ms observed).

The third variation involves extra cognitive and perceptual steps in recognising that the key has been pressed.

Release key (stops previous cycle, starts new one)
See that button is cleared (perceptual cycle)
Decide that button is cleared (cognitive cycle)
Press key (motor function)
Check that button is fully depressed (perceptual cycle)
Decide to release button (cognitive cycle)
Release key (motor function)

This gives a total interaction time of 2*(96+113+108) = 634 giving a time of 317ms (cf. 302ms observed).

This observation of extra cognitive and perceptual cycles is supported by two different sources. The first is empirical observations. By watching the users, particularly their direction of gaze, whilst they interacted with the computer, it was possible to see when cognitive processing was occurring rather than physical motion. It was this observation that initially indicated the presence of the extra cycles.

Secondly, the times taken to respond to a simple stimulus for two of the users showed an apparent discrepancy between the times recorded for τ_p, τ_c and τ_m for the motion impaired users and the reaction time to a simple stimulus. The values obtained are shown in Table 5.

Reaction times to simple stimulus(ms)	Card: able-bodied	CUED: able-bodied	CUED: motion impaired
Predicted	310	318	420
Observed	-	320	622

Table 5. Response times to a simple stimulus.

The 202ms discrepancy for the motion-impaired users is not explained by the standard MHP paradigm, but could be explained as being approximately equal to an extra cognitive and perceptual step under the above regime (209ms). This corresponds with the second of the two interaction processes postulated above, where the user checks that the key has been depressed before releasing it. The interaction process is: τ_p (see event), τ_c (decide event seen), τ_m (press key), τ_p (perceive key down), τ_c (decide key down), τ_m (release key).

It is interesting that all of the users exhibit this behaviour during this task, but not all do so for the repeated key pressing activity. The most likely explanation for this is because of the added complexity of the task, the users are more unsure of themselves and so require greater feedback during the interaction process.

Hence, overloading or even just heavy loading, both cognitive and physical, will not only result in users disliking a system, even if it offers them greater functionality or ease of use in the long-term, but also affects the performance of the MHP. Under these circumstances the MHP equation probably begins to break down as the cognitive stage becomes decreasingly linear and the assumption of independence becomes increasingly strained. The MHP model can therefore be thought of as being bound-limited.

In summary, Table 6 shows the times recorded by Card and those obtained from the computer-based able-bodied and motion-impaired user trials.

Times (ms)	Card: able-bodied	CUED: able-bodied	CUED: motion impaired
τ_p	100	81*	90*
τ_c	70	93	114
τ_m	70	72	108
Reaction to simple stimulus	310	320	646

* averaged across the τ_p values obtained by direct measurement from the Delay and Smooth experiments and those from the measurement of the reaction times

Table 6. The times for the MHP obtained by various user trials.

3.5 Conclusions from the Model Human Processor

The results from the user trials show that the individual components of the Model Human Processor are comparable for able-bodied and motion-impaired users, with the largest observed difference being in the motor function time. For this the motion-impaired users were approximately 50% slower than their able-bodied counterparts, but this is to be expected given the differences between the two users groups.

A slight variation of 20ms was also noted between the times for the cognitive cycles, with the motion-impaired group being slower. The precise cause of this cannot be identified by the results obtained. It could be experimental noise, or a systematic error, such as difference in familiarity with using computers between the two groups. Another possibility is that there is an in-built delay due to the extra effort required to plan and control physical movements by the motion-impaired users.

These results show that the basic theory behind the individual component times is sound for both user groups.

When combining these times into a known interaction process, such as pressing a key in response to a simple stimulus, all of the able-bodied users produced response times in accordance with the predicted results. The motion-impaired users did not. This at first appeared to show that the user model was not working and was not applicable. However, a careful study of the users during the interaction process and of the times obtained showed that extra perceptual and cognitive cycles were being inserted.

This result shows the value of user models. Given a recorded time and observations of the users, it was possible to construct an accurate representation of the interaction process.

4. DEVELOPING AND EVALUATING A DESIGN METHODOLOGY

Recent discussions about the concept of *user interfaces for all* have shown that traditional HCI approaches are not the best way to achieve *universal* accessibility and that more specific studies are required to reach this goal [Stephanidis 97]. Two core themes from this work are *proactivity* - addressing the issue of accessibility at design time, and *adaptation* - the ability for the interface to be tailored to the user [Stary 97].

A number of guidelines for designing interfaces for physically-impaired users do exist, the most notable of which are the Trace Center guidelines [Vanderheiden 94]. However, these guidelines have generally been produced as a collection of desiderata and considerations for software designers to contemplate when constructing an interface, rather than a complete design methodology per se. There is a wide breadth of coverage of the problems rather than depth of solution.

We have experience of developing a methodology for the proactive design of assistive technology, based on the application of usability heuristic [Clarkson 97]. The methodology has been validated through the successful re-design of an interactive robot and its associated interface for remote visual inspection tasks.

Therefore, the intention of our current and future research is to build on and extend existing guidelines for motion-impaired users to provide a more comprehensive methodology for the design of interfaces from first principles.

The methodology for achieving this goal is to extend even further our understanding of how motion-impaired users interact with computers. This encompasses both user models and cursor control studies. Once this is achieved, it is necessary to understand and quantify how the input devices used affect the interaction. This will yield mathematical descriptions of user performance that can be optimised. We have already started this process in the research involving user models and in studies of cursor control described in previous sections.

Once we fully understand how the user behaves, we can look at how to design the interface to maximise the information transfer rates between user and computer. For example, knowing the optimal size, shape and positioning of buttons on the screen, or the relative breadth and depth of menus should improve interaction rates. Further applications of the knowledge about the user include improved filtering techniques and prediction strategies.

It is essential to incorporate the user into all stages of the development of the methodology. The research programme that we are pursuing has been structured to include extensive user trials throughout.

4.1 Stage 2 - Developing the design methodology

The objective of the user modelling trials was to investigate whether models developed for use in the human-computer interaction community could be transferred directly to motion-impaired users. The results obtained imply that the basic principles of able-bodied user models do apply to motion-impaired users, but that they do need to be validated through careful user trials and possibly modified before being applied. Consequently, we have developed a research programme to build on this and our studies of cursor control and multimodal input for motion-impaired users.

We will continue to adapt and develop work in user modelling and usability engineering from mainstream HCI theory for application to motion-impaired users, paying particular attention to identifying how different motion impairment *symptoms* demand specific modifications to the models. Studying the effects of symptoms, rather than conditions, on interaction offers a powerful approach for deriving generic methods of compensation. Such generic compensations would enable automatic self-tuning of interfaces without having to rely on time-consuming training.

We will also consider entirely new paradigms both for input and output. Any computer input system intended for use by people with varying physical disabilities and designed around one method of input is unlikely to be flexible enough to cope with the diverse needs and demands of all users satisfactorily. This is not to say that it might not suffice, but for extended computer usage more flexibility may be required.

A growing area of research interest is multi-modal input [Glinert 97]. There is evidence to suggest that increasing the degrees-of-freedom of input devices, such as incorporating finger flexion, can improve interaction rates [Zhai 96]. Extending this principle to input systems with multiple input channels implies the possibility of improved information transfer rates through an increase in the available communication bandwidth. This research will build on our findings that multi-modal input design must follow a user-centred design approach, otherwise cognitive and physical loads on the user will become excessive [Keates 98].

Psychological aspects of the interaction process will also be addressed. These will include assessing the level of attentional demand required by the interaction and the impact of that on interaction rates. The effect of incorporating specific knowledge about the intentions of the user into the interfaces, using plan recognition, will also be studied.

Using the insight gained from the poor performance of existing interfaces and input systems and correlating that with best practice interface design, we will develop a methodology for designing truly accessible systems. This will complement and go significantly further than existing guidelines for universal access, such as those issued by the Trace Center.

4.2 Stage 3 - Evaluating the methodology

The methodology developed will be evaluated and validated through a number of case studies in conjunction with our industrial collaborators: The Post Office, Don Johnston Special Needs (UK) Ltd and the Olivetti and Oracle Research Laboratory.

The case studies will consist of three assessments based on impairment symptom types:

1. *interface adaptation* - a suitable existing application, such as a web browser, will be selected and a self-tailoring veneer designed that will sit between the user and the program;
2. *input system re-design* - the second case study will take a similar approach to that above, but will be used with differing input systems;
3. *control study* - benchmark comparisons with the unmodified use of the target applications will be used to evaluate the effectiveness of the new approaches.

Through the use of case studies, the methodology will be iteratively refined and developed.

5. CONCLUSION

As discussed in the introduction, there are three stages of a design cycle: problem definition, prescription of solution and evaluation of solution. Through our continuing research into the application of user models and the study of cursor control, we have made significant progress towards understanding the motion-impaired user and achieving a problem definition.

In so doing, potential solutions are becoming apparent for incorporation into a final comprehensive methodology for the design of accessible interfaces, which we are currently developing.

The ultimate long-term aim of the programme of research at the University of Cambridge is to construct a computer system that is aware of the user's abilities and automatically tailors itself, both in terms of input paradigms and interface structure, for optimal ease of access. The research and results presented here represent a significant step towards achieving that goal.

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