Analysis and Simulation of User Interfaces

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By taking a mobile phone as a worked example, we show how it and new interfaces can be analysed and simulated. A new interface is shown to reduce the optimal key press costs of accessing the phone's functionality, without losing usability benefits — this is a specific contribution to menu design. However, the approach is not limited to mobile phones, nor just to menus; the techniques are general and can be applied widely. A distinctive feature of the approach is that it is fully inspectable and replicable — this is a contribution to the field of HCI more generally.

Keywords: User interface design, formal methods, menus, new user interfaces.

1 Introduction

The analysis of user interfaces has largely concentrated on issues of human performance, behaviour and cognition. In comparison, device-oriented analyses of user interfaces are rare, which is strange because devices — unlike humans — are precisely known. In the design process, devices themselves are the main areas where usability improvements can be effected. This paper exhibits a range of user interface analyses from a device perspective. An actual device, in commercial production, is used as a case study, and we exhibit a functionally-equivalent user interface that requires under half the key presses to use than the original design on average, and whose worst case cost is just one sixth. The analyses of both the original and alternative user interfaces are described in sufficient detail to be replicated by other usability engineers.

1.1 Contributions to HCI

Often papers in HCI describe ideas that are not replicable; the systems described are incomplete, inaccessible, obsolete or proprietary; the experimental details are not described in sufficient detail; or the methodology used allows vagueness, providing room for mistakes and confusion, which often go unnoticed or may be concealed, accidentally or even deliberately; finally, unspecified craft knowledge is often required to use methods reliably. In contrast the work described in this paper is open, well-defined and fully replicable: all claims and results can easily be reproduced and tested. Indeed, there are several ways to calculate all results claimed, which provides checks and safeguards: if there is anything slightly wrong with our definitions or theories, then the mathematical rigour produces ridiculous conclusions, which we will see and correct. Indeed, automatic and other checks on the mathematics in this paper helped fix typos, most of them of the sort that would easily have been missed in less formal approaches.

A companion paper is available on the World Wide Web, which provides full information behind the results reported here. The method is straight-forwardly mathematical, which means there are many textbooks and other sources of information about it. But, further, the mathematics is 'packaged' as a fully working program, on the web site, and the benefits claimed can be achieved without delving into the technical details. For example, all the diagrams and results shown in this paper were calculated from a single specification of an interactive device (given as an appendix to this paper). The techniques for analysis used here can be used with other device specifications, merely by changing the appendix, or they can be developed for other purposes.

To show that our approach can handle real designs, we analyse an accurate model of the menu user interface of the Nokia 5110 mobile phone. The general approach to design taken here could be used with any push button device, and would be particularly easy to employ when working within a design process that specifies the feature set of a device. (If we had worked with Nokia, of course we could have avoided reverse-engineering the device's user interface, since the user interface specification should have anyway been directly available.)

1.2 Background

Theoretically the motivation behind this paper is expressed in (Thimbleby, 1994), and is also illustrated in approaches such as Furnas (1997). Our approach is in contrast to that actually used by Nokia (Kiljander, 1999; Väänänen-Vainio-Mattila & Ruuska, 2000). Kiljander (1999) mentions that Nokia use state transition diagrams informally as story boards; one wonders why they don't use precise specifications of systems, from which informal story boards are derived reliably.

The present paper is a continuation of research going back to Hyperdoc (Thimbleby, 1993), which was a system for simulating and analysing user interfaces to simple push button devices. Hyperdoc was criticised for only handling small devices (Dix et al., 1998); it was also a platform-dependent tool (it ran in HyperCard on the Apple Macintosh) and its inner workings were never published. The present approach is in *Mathematica* (Wolfram, 1996), which is platform-independent, and

permits the entire approach, including all its details, to be published. (Actually there is no need to use *Mathematica* — Java, for example, could have been used instead; but *Mathematica* happens to be much better documented than Java.)

We use *Mathematica* for the mathematical calculations — using good tools simplifies presenting results rigorously. *Mathematica* allows user interfaces to be analysed, simulated, checked or have conventional usability experiments run on them; *Mathematica* can also generate specifications of the user interface that can be used by, say, Java or C programs, or even converted to hardware — the web site associated with this paper has an automatically generated Javascript simulation for people without access to *Mathematica*. Other advantages of *Mathematica* for HCI work are discussed elsewhere (Thimbleby, 1999), which further suggests how user manuals and other material can also be handled.

Mathematica is a cross between a word processor, graphics program and a symbolic mathematics tool. Like a word processor outliner, sections can be opened or closed to reveal different degrees of detail as needed. What is printed in these proceedings is only part of what the paper actually contains. For example, the *Mathematica* instructions to draw the figures are not needed for most readers of the printed paper, and are therefore concealed; however, the code is still 'inside' the original version of the paper. For example, in the full paper just before each figure there is a piece of *Mathematica* code that generates and either plots or typesets the figure. All versions of the paper were generated automatically from a single master copy (though errors may have crept in during the printing process for the conference proceedings). In short, this paper and its illustrations were not created by a conventional error-prone 'cut and paste' approach.

1.3 The Nokia 5110 User Interface

As a concrete case study, we will be concerned with the Nokia 5110 mobile handset's menu functions, though there are a number of essential functions that are not in the menu (such as quick alert settings and keypad lock). There are 84 features accessible through the menu. A softkey, [–], called 'Navi' by Nokia, selects menu items; keys [∧] and [∨] move up and down within menus. The correction key [C] takes the user up one level of the menu hierarchy, whose structure is illustrated in Figure 1. With reference to Figure 1, the function ***Service nos*** can be accessed from ***Standby*** by pressing [–] [the phone now shows ***Phone book***], then pressing [–] [shows ***Search***], then pressing [∨] [shows ***Service Nos***] followed by a final press of [–] to access the function itself. All menu items have a numeric code (displayed on the Nokia's LCD panel); for example, ***Service nos*** can also be accessed by pressing [–][1][2] (no final press of [–] is required).

There are some complications, which we ignore in this paper — they are also ignored in Nokia's User's Guide. For example, inconsistently, the [C] key does not work when shortcuts are being used, so [–][2][C][1] is equivalent to [–][2][1], not to [–][1]. The Nokia 'completes' shortcuts, so that [–][1] in fact selects ***Search***, not ***Phone book*** (see Figure 1). There is no fixed relation between shortcuts and the position of functions in the menu, since some functions may not be supported (e.g., by particular phone operators).

There is some ambiguity on what should be taken as a basic function, and what

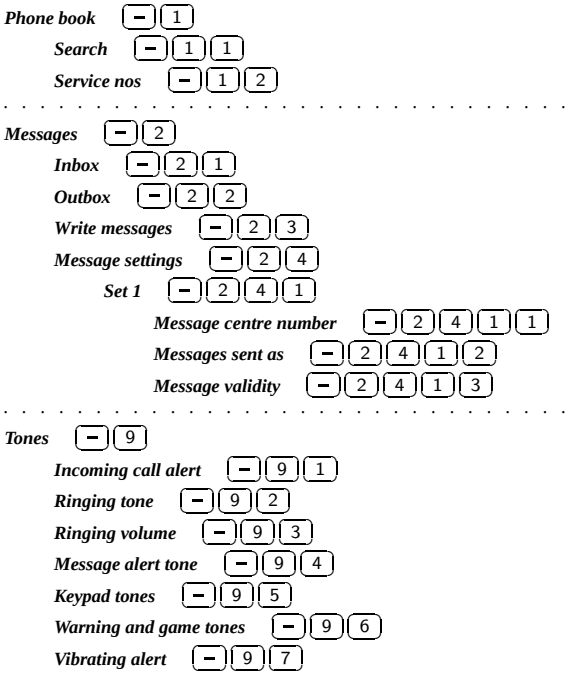

Figure 1: Extracts from the Nokia 5110's menu structure, showing function names and their short cut codes.

as an option within a function. For example, ***Type of view*** is treated by the User's Guide as a function, but it has a submenu (***Name list***, ***Name number***, ***Large font***). For our definitive list, see the specification of the Nokia in Appendix C.1, which was used to generate all the figures and graphs in this paper. It can easily be edited to do analyses based on any variations.

Figure 2 shows the Nokia's ***Standby*** function at the top, and each horizontal row downwards is a group of functions that each take an equal minimum number of key presses to access from ***Standby*** (ignoring the numeric shortcuts). Of the 188 circles, 84 are black: these indicate phone functions of actual use, as opposed to submenus that in themselves have no other purpose than structuring the user interface, such as ***Options***.

Because of the layout of Figure 2, [−] (which selects items from menus, whether submenus or functions) moves downwards, and [C] (which corrects errors) goes upwards; the [∧] and [∨] keys do not move in a systematic direction in this layout. Thus the Figure shows the minimum costs of accessing functions, rather than the menu hierarchy (as in Figure 1).

Each arrow corresponds to a button press: pressing buttons takes the Nokia from one state to another. Since there are 188 states and four buttons, there are 752 arrows,

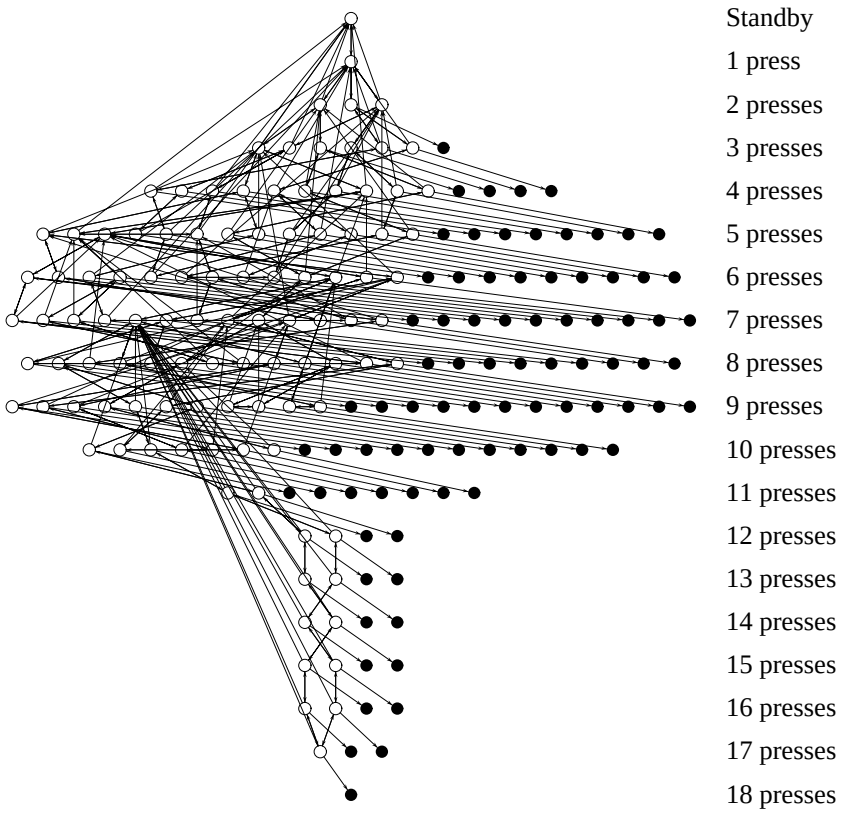

Figure 2: Visualising the error-free cost of accessing Nokia menu functions. For clarity arrows *from* functions (black dots) are not shown.

but for clarity Figure 2 does not show arrows going out of each of the 84 black circles, whether for error-correction (pressing C) or back to ***Standby*** (pressing −), which not all functions support — otherwise the Figure gives an accurate idea of the complexity of the user interface that is the subject of this paper.

2 User Interface Simulation

The specification of the Nokia handset can be used to animate a complete working simulation of the user interface. Interactively, a user can press buttons and the simulated display will show what the Nokia would have shown. Additionally, the simulation can be instrumented so that it collects statistics on user behaviour.

The *Mathematica* code required to run the user interface simulation is simple

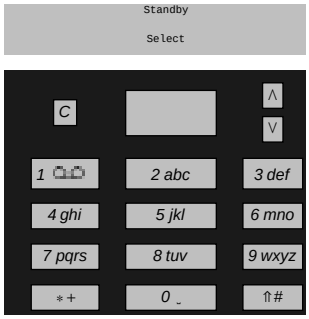

Figure 3: Simulation of the Nokia handset. The picture (which is full size in the *Mathematica* version of this paper) is active code and works when it is clicked.

and brief. After a few lines of support code (see Appendix D), Figure 3 provides the interactive functionality of the user interface: clicking on the buttons makes it work in the full *Mathematica* version of this paper. The complete keypad is about 20 lines of code, including specifying the keytop fonts and sizes, plus the data structure — also *Mathematica* code — for the graphics symbol on the 1 key.

3 User Interface Analysis

A single specification, for the Nokia 5110 menu functions, can be used to support a variety of analyses, as well as provide the basis for generating novel user interfaces that provide the same functionality.

Usability depends on many factors. The analyses, below, while not exhaustive of the sorts of mathematical questions that can be raised, are based on key press costs. A keystroke model could be used to estimate time, but this would take us beyond the space available for this paper; see Silfverberg et al. (2000), whose formula gives 240ms per keystroke, assuming skilled, continuous use of the index finger to press the menu keys. Another measure of usability is the probability that a particular key is used: the Nokia 5110 design appears to have attempted to increase the frequency − is used — it is a soft key, and reduces the number of other keys required. This creates the visual impression of a simple user interface as well as reducing finger movement. Yet it also means that menu functions (such as the phone's calculator) are inaccessible during phone calls, because in this mode − ends the phone call. Whether users need, say, a calculator during a phone call and whether this need should override the keypad aesthetics is an empirical question beyond the scope of mathematical analysis. Whatever we choose to analyse mathematically, design trade-offs can be formulated, which then raise interesting insights and questions that suggest further empirical work . . .

3.1 Goal Weights

From the Nokia specification we can work out the optimal key press sequences to activate any function. The expected optimal number of presses is 8.83 ± 3.29, meaning that if the Nokia is used optimally without error then users will take 8.83

Function name	Rank	Presses	Probability
Search	1	3	0.0613
Incoming call alert	2	4	0.0306
Inbox	2	4	0.0306
Speed dials	2	4	0.0306
Service nos	2	4	0.0306
...	...	...	...
Português	14	16	0.00438
Svenska	14	16	0.00438
Español	15	17	0.00408
Norsk	15	17	0.00408
Suomi	16	18	0.00383

Figure 4: Summary of functions, ranked by presses and Zipf probabilities.

presses on average to activate menu functions with a standard deviation of 3.29. But of course, as well as not always being as efficient, a real user will access some commands infrequently — especially the ones that Nokia have made less accessible. For example, it takes 11 presses to change the phone's security settings, as against the ***Search*** function, which only requires 3 presses to access. We would get a more realistic expectation of the number of presses if they were weighted by how likely each function is required by a user.

We could use the simulated handset to obtain weights by getting users to run simulated tasks, but this would take a long time (and many users), as well as begging the question where we could get appropriate distributions of tasks. No doubt Nokia has, over time, collected enough statistics of use to do this accurately. If we had such figures, we could use them. Instead, for the purposes of this paper, it is sufficient to obtain a plausible probability distribution.

We will assume Nokia has arranged things so that more likely, more frequently used, functions take fewer key presses to activate. The Zipf distribution (Zipf, 1949) meets the requirements and is easy to calculate; moreover, the Zipf distribution occurs naturally in many contexts (e.g., it relates the length and frequency of English words) — the frequency of an item is inversely proportional to its cost. Weighting presses by the Zipf probabilities, we obtain an expected number of presses of 7.15 ± 2.95. This number is of course less than the unweighted expectation because we have chosen a probability distribution that makes large numbers less likely.

Figure 4 shows an extract from the phone's functions, ranks, costs and Zipf probabilities, ordered by rank. (With all functions shown the probabilities would sum to 1.)

Given the state probabilities, and other assumptions such as the probability of making errors and of pressing [C], we could work out button probabilities. Without known error rates, for this paper we take the probabilities of pressing buttons to be equiprobable (i.e., 0.25) but other values can easily be written into the code in Appendix C.1 if required.

The Nokia allows users to exit some functions returning to the previous position

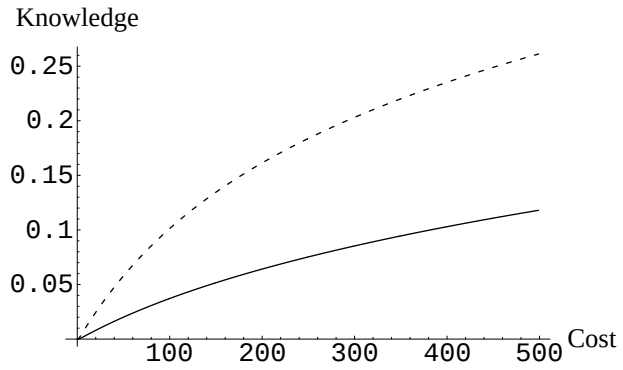

Figure 5: Cost of knowledge graph for the Nokia 5110 function menu. Dashed line is Zipf weights; solid line is uniform weights.

in the menu hierarchy, whereas others enter different modes or return to ***Standby***. For example, the search function can be used to look up a phone number, which is then dialled. At the end of the phone call, the phone is back in ***Standby***, rather than returning to the phone book part of the menu hierarchy. We will assume, for uniformity, that when the user has accessed a function, with probability 1 on the next button press the device is returned to ***Standby***.

3.2 Cost of Knowledge Graphs

There are many ways to analyse a user interface from its specification. The *cost of knowledge graph* was introduced and justified for usability analysis by Card et al. (1994) to visualise how easily a user can access the state space of a system. The graph shows the number of goal states a user can access against the number of user actions, that is, the cost of acquiring the knowledge available in each state. The cost of knowledge graph can be constructed from empirical data, from cognitive analysis, or analytically, as we now do. Our approach is probabilistic and does not assume error-free behaviour; the more realistic the probabilities used, the more realistic the evaluations that can be drawn from them. Details of the mathematics are given in Appendix A — for practical purposes (e.g., use by designers, rather than HCI researchers), what is important is the visualisation, rather than the way it is calculated; indeed, for anyone using this paper in its full *Mathematica* form, all that is necessary is to invoke a function that has already been defined, and the graph is drawn automatically.

A cost of knowledge graph for the Nokia menu system is shown in Figure 5. The solid line shows an unweighted cost of knowledge graph, but weighting (by the Zipf probabilities) gives a more realistic measure of knowledge — since the user is less interested in some functions than others, and the Zipf probabilities reflect this well. The dashed line shows the weighted cost of knowledge graph.

The analysis could be refined. For example, we took the probability of pressing C as 0.25, which is possibly too high. Nevertheless, the point demonstrated is that

Function name	Rank	Presses	Probability
Search	1	3	0.0243
Inbox	1	3	0.0243
Incoming call alert	1	3	0.0243
Speed dials	1	3	0.0243
Service nos	1	3	0.0243
...	...	...	...
Norsk	3	5	0.0081
Español	3	5	0.0081
Suomi	3	5	0.0081

Figure 6: Summary of Huffman costs and probabilities.

with data (whether empirical or estimated) useful insights can be derived. Here we see, for instance, that in "average" use (i.e., as might occur in field studies) to achieve a coverage of 25% takes 455 button presses. (This figure does not translate nicely into a time, since the cost of knowledge assumes the user acquires knowledge, and thus pauses in each new state.)

Furnas (1997) suggests the pair (maximal outdegree, diameter) is a good indicator of the usability of a device; the original Nokia is (4, 19), compared to the Huffman tree alternative using the same keys discussed below, which is (4, 8). The digit key Huffman tree, also discussed below, is (11, 5) — showing that when more keys are used (here 10 digit keys and one correction key, [C]) the worst distance between states (the diameter, 5) can be considerably reduced. Many other measures can be obtained from the specification. For example, to test whether every button works correctly in every state takes a *minimum* of 3914 presses, assuming error-free performance. Such a high number suggests that human testing would be inadequate.

4 Alternative User Interfaces

A mobile phone can be controlled with many sorts of user interface. In this paper, following Nokia, we restrict ourselves to tree-structured interfaces. There are other alternatives, which can be much more effective: see Marsden et al. (2000) and Thimbleby (1997) for examples.

The Nokia uses four keys to select from 84 functions. If reducing the number of keystrokes was a design goal, then a Huffman tree (Huffman, 1952) is the most efficient way, in terms of keystrokes, to do this. From the original list of functions, we can construct a Huffman tree using three keys for navigation and one key (retaining [C]) for correcting errors. Under these assumptions, we achieve an expected optimal number of presses of 4.04 ± 0.53 (or 4.18 ± 0.52 unweighted). See Figure 6 for comparison with the ranking of Nokia functions (Figure 4).

The entries in the Huffman table are in the same overall order as the original Nokia table; this is a consequence of building the Huffman interface on the Zipf probabilities, which were in turn inversely proportional to the ranks of the functions in the original design.

Figure 7 (note the different vertical scales compared to Figure 5) shows that

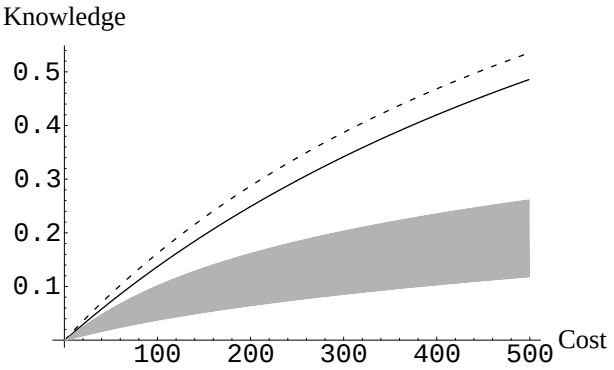

Figure 7: Cost of knowledge graph for the Huffman tree interface (the dashed line is Zipf weights; the solid line is uniform weights). For comparison, the lower grey region represents the range of data from the original Nokia as shown in Figure 5.

the cost of knowledge graph for the Huffman tree interface is *considerably* better (in terms of speed of access to the device's functions) than the original design; for example it achieves 25% coverage after 168 presses (compared to 455 presses for the original Nokia). Even so, the model over-estimates the costs because of the assumption of pressing [C] with probability 0.25.

A Huffman tree organises functions according to their probability, which would be convenient for a highly skilled user, but might seem arbitrary to a conventional user. There are two obvious improvements: first, the probabilities could be determined from the actual user's operation of the handset — the user interface would then adapt to be optimal for the user's own patterns of behaviour (see Knuth (1985) for an algorithm); secondly, the navigation keys could be left as they are (i.e., with a more-or-less topic-organised structure) and the numeric keys could be used for rapid access, providing shortcut codes.

In fact, the Nokia already uses numeric keys for faster access; some numeric codes are shown in Figure 1. Although the Nokia allocation of numeric codes corresponds to the menu structure, since the menu structure and in particular the order of functions is of little interest to users, the codes are effectively arbitrary — for example, even if a user knows [−] [2] [4] [1], they are not likely to be able to work out what [−] [2] [4] [2] is! If we use ten numeric keys and [C] instead of just three navigation keys (i.e., creating a Huffman tree with fan-out of 10), we can access functions with 2.98 ± 0.26 (3.01 ± 0.24 unweighted) key presses. Note that using the digit keys means that a menu key is required (otherwise the digits pressed would just dial a phone number), compared to using the dedicated keys where any of them can be pressed immediately without ambiguity. This adds 1 to the costs, which is included in the figures. In comparison the original Nokia shortcuts have higher expected optimum presses of 3.39 ± 0.92 (3.64 ± 0.92 unweighted).

We can use *unallocated* shortcut codes from the Nokia design (for example, [−] [8] [3] is not allocated) and achieve an expected number of presses of 3.09 ± 0.45

Design	Min	Max	Weighted	Unweighted
Nokia navigable menu	3	18	7.15 ± 2.95	8.83 ± 3.29
Huffman, 3 keys	3	5	4.04 ± 0.53	4.18 ± 0.52
Nokia digit shortcuts	2	5	3.39 ± 0.92	3.64 ± 0.92
Unallocated codes	2	4	3.09 ± 0.45	3.29 ± 0.48
Huffman, 10 digit keys	2	4	2.98 ± 0.26	3.01 ± 0.24
Shortest codes	2	3	2.69 ± 0.46	2.87 ± 0.34

Figure 8: Summary of expected optimal costs of accessing all goals.

(3.29 ± 0.48 unweighted) — which is marginally faster than Nokia's shortcuts. Since these codes are all different from Nokia's, we could have both schemes available at the same time (if we wanted to), so each function would have two codes, Nokia's original and the faster, unallocated codes. Since the codes are different, there is no confusion: either could be used. Since the user presumably doesn't care what the shortcut codes are, they could use Nokia's shortcuts if these are better, or the unallocated codes if these are better. This is having the best of both worlds, and unsurprisingly it works out even faster — at 2.69 ± 0.46 (or 2.87 ± 0.34 unweighted).

All results are summarised in Figure 8. With reference to Figure 8, there appear to be two errors. The Shortest codes have a maximum length shorter than either the Nokia shortcuts or the Unallocated codes, yet it is based on both of them. The explanation is that the Unallocated codes do not take advantage of any of the Nokia's short codes, so some are quite long; the Shortest codes approach makes use of the short Nokia codes, and then has spare short codes of length 3 to replace the longer Nokia codes of length 4 and 5. The second apparent error is that the maximum length of the Shortest codes is 3, but the maximum length of the Huffman codes is 4. Yet Huffman codes are theoretically shortest — so hasn't something gone wrong? The explanation is that Huffman codes are unambiguous (they are prefix-free), but the Nokia as so far described is not.

For example, if a user presses [-] [1] [7] [2] they get ***Memory status***. If they press [-] [1] [7], which is a prefix of that, they first get ***Options***, but it autocompletes to ***Type of view***, which (also) has shortcut [-] [1] [7] [1]. To avoid the apparent ambiguities, the Nokia effectively has an extra user action, [Pause], "pressed" when the user delays. Thus ***Type of view*** has a shortcut [-] [1] [7] [Pause] — which is not a prefix of [-] [1] [7] [2]. Thus the Shortest codes cost is based on having effectively 12 keys (10 digits and [Pause] for navigating, plus [C] for corrections) as compared to the Huffman tree that makes do with 11 keys (10 digits plus [C]). Since the Shortest codes are making use of more "keys," the maximum length of a shortcut can legitimately be less than the maximum length of the Huffman code. It is interesting that by entering the definition of the Nokia straight from the User's Guide, and spotting a potential error in our analysis, we discovered a design feature that was not documented.[†]

The Shortest codes scheme has advantages — it preserves Nokia's original structure for the menu shortcut codes *and* permits faster access where possible —

[†]The 5110 has numerous other timing issues that are not discussed in this paper.

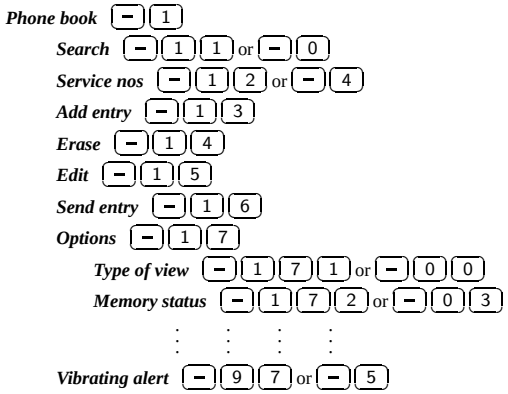

Figure 9: Extract from "shortest codes" menu. Both shortcuts can be used.

and it is better than the Huffman code approach, which has no advantages other than reducing key press counts. It is a design worth considering further and evaluating empirically. Figure 9 shows what the new codes look like, compared with the original Nokia codes (compare with Figure 1). For example, to access ***Memory status***, the user can press either − 1 7 2, as specified by Nokia, or they can press − 0 3, saving a press. (The alternative menu codes in Figure 9 have been allocated so that shorter codes are preferentially allocated to higher Zipf probability functions.)

5 Conclusions

Despite having being around for many years, and having had many opportunities for improvement, consumer electronics, such as mobile phones, video recorders and fax machines, are notorious for having poor user interfaces (Thimbleby, 1992). Certainly it takes skill to perform usability evaluations well, and unfortunately the time pressures of manufacturing often mean usability considerations come too late to have any significant impact. Even if usability studies are done, in the time available, they are unable to cover entire designs — instead, practical evaluation concentrates on usability disasters or marketing features. As ubiquitous bad design proves, conventional usability engineering is relatively ineffective, whether because it is not used, or because it is used but has little impact. The sorts of analyses and simulations presented in this paper can be done automatically, by tools that are in any case required to specify, document and build working products. Ideally, this would help ease technical designers into usability issues. The paper showed that analysis done in this way can raise and help explore interesting design issues.

More generally, this paper showed that a user interface can be specified, simulated and analysed "on paper." The work reported here is fully replicable, and can be checked and developed easily. As it happened, the paper exploited *Mathematica*; worthwhile further work would be to embed and cosmetise the appropriate features inside design tools.

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Ann Blandford and Matt Jones both made very valuable comments. Nokia is a registered trademark of Nokia Corporation, Finland; Navi is a trademark of Nokia Mobile Phones.

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A The Cost of Knowledge Graph

We are concerned with probability distributions of state occupancy. A vector v represents the probability of the device being in each state; we discussed one such vector above, using Zipf probabilities. With a stochastic transition matrix P, if the distribution is v, one button press later it is vP; two button presses later it is vP^2; three button presses later it is vP^3; ... and so on. (A stochastic transition matrix is a transition matrix, where each transition is a probability. Each row sums to 1; the leading diagonal represents the probability of the device doing nothing in each state.)

If v_0 is the distribution at press zero (typically 1 in standby and zero in all other states) then $v_n = v_0 P^n$ is the distribution at press n. The probability of being in a given state, i, on press n is then $v_n(i)$, which may be written more clearly as $\Pr(\text{in state } i \text{ at press } n)$. The probability the device is not in state i at press n is then $1 - \Pr(\text{in state } i \text{ at press } n)$. Thus the probability it was never in state i over presses 0 to t is the product of these probabilities, with n ranging over 0 to t. The probability it was sometime in state i is therefore 1 minus that:

$$1 - \prod_{n=0}^{t} \Big(1 - \Pr(\text{in state } i \text{ at press } n)\Big)$$

where $\prod$ is the symbol for a product, just as $\sum$ is the symbol for a sum.

The expected number of states visited to press t is the sum of these probabilities considered over all states. Since we are, more specifically, interested in the proportion of states visited to press t, the following formula is used for plotting the cost of knowledge function:

$$\text{knowledge}(t) = \sum_{i \in \text{States}} w(i) \left(1 - \prod_{n=0}^{t} \Big(1 - \Pr(\text{in state } i \text{ at press } n)\Big)\right)$$

In this paper we take the state weights $w(i)$ to be the Zipf probabilities, or for 'unweighted' analyses from $\{0, 1/|\text{Goals}|\}$ depending on whether the state is a goal state. Since the weights sum to 1, the measure of knowledge ranges over 0 to 1.

Throughout the paper, costs are given in the form $n \pm \sigma$, meaning n is the expected value and σ the standard deviation. If $c(i)$ is the minimum cost of reaching state i from ***Standby*** (calculated by a *Mathematica* shortest path function) then the expected cost is $n = w.c$ and the standard deviation is $\sigma = \sqrt{w.(c^2) - (w.c)^2}$.

B Utility Functions

This Appendix forms the common *Mathematica* code that creates all the data structures (e.g., the transition matrices) from the basic definitions, which are given in Appendix C. (It has to be placed before the definitions of the various devices.) To save space for the printed paper, this code has been hidden.

C Device Specifications

C.1 Nokia 5110

It is easiest to specify the Nokia 5110 by writing out a definition that is as close a match to the Nokia's User's Guide as possible. We then use a *Mathematica* function

to convert this “human readable” specification into a complete device specification.

```
readable[nokia] ^= menu["standby",
    {menu["phone book", {"search", "service nos", "add entry", "erase", "edit",
          "send entry", menu["options", {"type of view", "memory status"}],
          "speed dials"}],
     menu["messages", {"inbox", "outbox", "write messages",
          menu["message settings", {menu["set 1",
               {"message centre number", "messages sent as",
                "message validity"}],
          menu["common", {"delivery reports", "reply via same centre"}]}],
          "info service", "voice mailbox number"}],
     menu["call register", {"missed calls", "received calls",
          "dialled numbers", "erase recent calls",
          menu["show call duration", {"last call duration",
          "all calls' duration", "received calls' duration",
          "dialled calls' duration", "clear timers"}],
          menu["show call costs", {"last call cost",
          "all calls' cost", "clear counters"}],
          menu["call costs settings", {"call costs' limit", "show costs in"}]}],
     menu["settings", {menu["call settings",
          {"automatic redial", "speed dialling", "call waiting options",
           "own number sending", "automatic answer"}],
     menu["phone settings", {menu["language",
          {"Automatic", "Engish", "Deutsch", "Français", "Nederlands",
           "Italiano", "Dansk", "Svenska", "Norsk", "Suomi", "Español",
           "Português", "<Russian>",‡ "Eesti", "Latviesu", "Lietuviu",
           "<Arabic>",‡ "<Hebrew>"‡}],
          "cell info display", "welcome note",
          "network selection", "lights"}],
          menu["security settings", {"PIN code request",
               "fixed dialling", "closed user group",
               "phone security", "change access codes"}],
          "restore factory settings"}],
     menu["call divert", {"divert all calls without ringing",
          "divert when busy", "divert when not answered",
          "divert when phone off or no coverage", "cancel all diverts"}],
     menu["games", {"memory", "snake", "logic"}], "calculator",
     menu["clock", {"alarm clock", "clock settings"}],
     menu["tones", {"incoming call alert", "ringing tone",
          "ringing volume", "message alert tone", "keypad tones",
          "warning and game tones", "vibrating alert"}]}];
```

This readable tree structure is converted into a list of transitions using the following code. In this example, the button probabilities are set equal at 0.25, but other values can easily be used. The code also gives a name to the specification, as was used, for instance, in Figure 8. (It may seem tedious to provide this code, but it shows *exactly* how the Nokia’s keys are assumed to work.)

```
convert[nokia] := Module[{auxconvert, p = {}, goals = {}, transition},
   transition[from_, button_, prob_, to_] :=
      AppendTo[p, {menuname[from], button, prob, menuname[to]}];
   auxconvert[menu[name_, items_]] :=
      Module[{i}, transition[name, "Navi", 0.25, items[[1]]];
         For[i = 1, i ≤ Length@items, i++,
             transition[items[[i]], "Down", 0.25,
                        items[[If[i == Length@items, 1, i+1]]]];
             transition[items[[i]], "Up", 0.25,
                        items[[If[i == 1, Length@items, i-1]]]];
             transition[items[[i]], "C", 0.25, name];
             If[Head@items[[i]] === menu,
                auxconvert[items[[i]]],
                AppendTo[goals, accessed@menuname[items[[i]]]];
```

‡The Nokia handset displays these items in Arabic, Cyrillic and Hebrew fonts.

```
                transition[items[[i]], "Navi", 0.25, Last@goals];
                Map[transition[Last@goals, #, 0.25, "standby"]&,
                    {"C", "Navi", "Up", "Down"}]
            ]
        ]
    ];
    auxconvert[readable[nokia]];
    symbolicGoals[nokia] ^= goals;
    startState[nokia] ^= "standby";
    Map[transition["standby", #, 0.25, "standby"]&, {"C", "Up", "Down"}];
    symbolicTransitions[nokia] ^= p;
    initialise[nokia, "Nokia navigable menu"];
];
convert[nokia];
```

The final line of code (`initialise`) converts the symbolic specification into all the forms required by the body of the paper. It also performs various internal checks (e.g., that probabilities add to 1).

C.2 Other Device Specifications

The Huffman tree, the Nokia shortcuts and the other device specifications are built automatically from the Nokia specification (as defined in the previous section). The definitions are omitted in the printed version of this paper.

D User Interface Code

The user interface code is simple enough to be given in its entirety, even in the printed version of the paper. A function is defined to operate the LCD display panel, which itself is just a *Mathematica* paragraph defined with a grey background and black text, to simulate the Nokia's LCD appearance.

```
lcd[stateno_] := Module[{nb = InputNotebook[]},
   NotebookFind[nb, "LCD", All, CellTags]; SelectionMove[nb, All, CellContents];
   NotebookWrite[nb, GridBox[{{StyleBox[capitalise[FromStateNo[nokia, stateno] /.
         accessed[s_] :> "Do " <> s]]}, {StyleBox["                    "]},
         {StyleBox[If[stateno == startState[nokia], "Menu", "Select"]]}}]]];
```

There is some special-case code to say when the user activates a function, to capitalise the first letter of state names, and to display the Navi button's prompt as "Menu" or "Select" depending on whether the handset is in the start state, ***Standby***.

The `press` function, executed when the user presses any button, relies on a function `nextState` that takes the device (whatever it is) from one state to the next, depending on which button is pressed. It would be trivial to modify `press` so that button presses (and timings if required) were recorded for analysis.

```
press[key_] := nextState[stateNumber, key];
```

The rules for the `nextState` function are generated automatically from the device specification:

```
numericTransitions[nokia] /. {from_, button_, prob_, to_}
       :> (nextState[from, button] := lcd[stateNumber = to]);
```

Finally it is necessary to initialise the state to the start state, and display the appropriate text for that state in the LCD panel:

```
lcd[stateNumber = ToStateNo[nokia, startState[nokia]]];
```

After this initialisation, Figure 3 (in the *Mathematica* version of this paper) works and behaves as specified.