Appendix A

Engagement and Fun: exploring the relationship to enhance user experience

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Abstract

The primarily focus of this study is to explore the relationship of engaging and fun to enhance user experience. The study was preceded with an understanding of the terms engagement and fun, in the context of experience. We then carried out the study by adhering to the four categories of engaging and fun experience which we have identified. The categories are; engaging and fun, not engaging and fun, not engaging and not fun, and fun and not engaging. From our analysis, we discovered that the category of one experience could mutate or transform into other category of experience. We have also unleashed some few issues that related to mutation process. The findings from the examples given then were used in seeking the critical points that indicates the actual point where the mutation occurs. From here, a set of heuristics on how to make experience more engaging and fun is outlined.

1. Introduction

In today's world, technology has become more pervasive, to the extent that we sometimes don't realise we are actually interacting with a piece of technology when dealing with everyday tasks. Therefore, it is true to say that our 'relationship' with technology is not just about interaction, but, it has leaped into somewhere beyond that scope. We are in fact *experiencing* with technology! As Wright and McCarthy put it, we are now living with technology, which it in reality involves us emotionally, intellectually and sensually [10].

When the user is experiencing something, an engagement is presumed to exist in order for it to develop the experience. In addition, the element of fun is essential to hold the engagement in one's experience. Whether these hold any truth, we shall soon find out. We precede the exploration with the definitions of the terms engagement and fun.

Many descriptions of engagement have been brought forward. Brenda Laurel [7] describes engagement as user's feeling of being in control of interaction. Another description of engagement is what Csikszentmihalyi [5] defined as flow. During the flow, "the individual experiences a sense of control, attention focus, curiosity, and intrinsic interest" [6].

In the light of exploring the relationship, we also ought to know the interpretation of fun. The words fun, pleasure, enjoyment, and enchantment, as we often find from our reading, are used interchangeably when it comes to describing fun experience. There is nothing wrong with this, as the definition given in Cambridge Dictionary of fun is pleasure, enjoyment, amusement [3], and throughout this paper, we will adhere to these definitions. In the mean time, there have been some studies that try to give a clear definitions of fun, and pleasure by distinguishing them two [1], and a study of enchantment in its own right [8].

By understanding these terms, we can now embark the exploration of the engagement and fun relationship in respect of user experience. From there, we take a step further to find the critical points by referring to the results found. The final results depict a set of heuristic that can be used to enhance the user experience.

2. Exploring the relationship

This study enables us to find out how fun is related to engagement in the nature of experience. A similar study to this one had been carried out by Brandtzaeg et aln, in which they propose a model to understand the nature of fun [2]. In our discussion, we have given very much attention in the examples of engaging and fun experiences. The examples cover the four important aspects of the relationship: engaging and fun, engaging and not fun, not engaging and fun, and not engaging and not fun. The Venn-diagram below illustrates this.

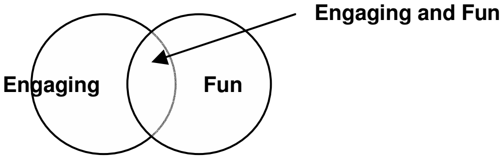

Figure 1: Venn-diagram

2.1 The four states of experience

i. Engaging and fun

Experience of this category consists of both engaging and fun elements. From our discussion, we came up with quite a number of examples for this category. For instance, children playing in the playground, singing karaoke with friends, girls do their shopping spree in the shopping mall, a boy playing video games on Play Station II, a mother baking a birthday cake for her son, spectators watching a spectacular fireworks, teenagers having a slumber party, and school children playing bumper cars.

ii. Engaging and not fun

In this category, the fun element is absent from the experience. Amongst the examples that we found of this category are; an artist painting on a canvas, a student revising his notes, a group of teenager watching a horror movie, an act of praying or performing any similar spiritual prayers, a man driving in his new car in the midst of heavy rain, a contester cycling with all his might to win a race and students answering maths questions in examination hall.

iii. Not fun and not engaging

The type of experience of this category is an experience without the existing of fun and engaging elements. Some of the examples of this category are, waiting for a kettle to boil; queuing to get to the counter desk, trap in a traffic jam, a traveller got stranded in a desert, and a frequent flyer sitting on the plane to get to the destination.

iv. Not engaging and fun

This category refers to the type of experience, which is not engaging, yet fun. From our discussion, we found it difficult to come up with examples of this category, comparing to the three previous categories. One example that we able to come up with is an experience on a thrilled ride at a theme park. There are a few numbers of people whom when they are on this kind of ride, try to deviate their attention to something else to overcome their fear. Hence, the engaging experience of that ride is not happening, but the fun experience of riding that thrilled ride does definitely exist.

Further analysis is carried out onto the identified categories, whereby we tried to move the category of one experience to another. We did this by undergoing the transformation process.

2.2 Transformation

By undergoing transformation, we have made some alterations on the experience, and as a result we could see the experience has moved from its own category to another. Below are some of the examples of experiences that have undergone transformation.

i. Waiting for the kettle to boil

   This is a mundane experience. As we already know, people normally turn their kettle on and leave them to boil, rather than waiting. Here, we are not trying to persuade people to wait for the water to boil, yet, we are attempting to transform this particular experience to something that is more engaging and fun.

   Now, let's us imagine there is a little bird sitting inside the kettle. When the water starts to boil, the pressure of the water slowly raises the bird to the top of the kettle. The bird then appears from a small lid in the middle of the kettle and starts chirping and dancing, until the water finishes boiling. This adds fun to the experience of boiling water in a kettle. Although the moment of engaging (when the bird is singing) is brief, it has indeed successfully transformed the experience to engaging and fun. The engaging experience can be made longer if this transformation is done on transparent kettle.

ii. Queuing in the post office

   Imagine we are stuck in a long queue just to get our parcel posted. This experience somehow or rather does test our patience, and sometimes it could get worse if the pace of the queue is very slow. This is certainly neither engaging nor fun experience. We transformed the experience to engaging by providing them interactive devices that are available along the queue. What we are doing is basically applying the definition of engagement described earlier (see section 1) in order to transform the experience to somewhat engaging.

iii. A 10-year-old kid playing Gameboy

Transformation of experience also includes the transformation from engaging and fun experience to engaging and *not* fun. By looking at the example given, we can see that the 10-year-old boy is enjoying himself playing with Gameboy. But, what if, while he was really engaging and having fun, his mother asking him to stop playing the game so that he can do his homework. This definitely creates a transformation of the previous experience. Although engagement is still exist, the experience of having fun has changed. He is now feeling anxious to finish off the game and a little tense when remembering that the reason of him terminating the game is his school homework.

From the examples above, we have learnt that mutation of experiences, i.e. the transformation of experiences from one category to another, is not an impossible thing to do. This process is possible to take place providing that we understand the experience and able to identify the salient features that can mutate the experience. Nevertheless, there are several issues that are associated with this process of mutation that are worth pointing out. The following section elaborates further.

2.3 Issues

Here, we will discuss the issues related to mutation process, which is applied onto experiences. There are three major points that we would like to bring forward.

i. Fun in an experience

As we can see and understand from the examples given in section 2.1, engaging is a necessity in an experience. This is not the same with fun. In section 2.1(ii), we could see that engaging experience can also exist without the presence of fun. For instance, there are also some other kind of experience like sad experience, horror experience, pleasure, enchanted, wonderful and so on. Therefore, fun in an experience is not an essential entity, whereas, on the contrary, engaging has to be part of the experience.

ii. Internal and external motivations

In the given example of section 2.2(iii), the experience of fun of 10-year-old kid who is playing Gameboy, has mutated to not fun when his mother interferes his concentration on the game. This is an example of an external factor that influences negatively towards the experience, which this we refer to as external motivation.

Now, let's us look at an example of internal motivation. Most of the students dislike sitting for Maths exams. They obviously see this as not fun, yet this is an engaging experience. But this experience is about to change if, he himself could set in his mind that Math is easy, as long as he knows how to apply the concepts in the questions. This particular internal motivation could lead to a change in the experience.

Henceforth, the internal and external, both positive and negative, motivations have such influences in the process of transformation or mutation.

iii. Multi-experiences

Another issue that we would like to highlight is the scenario of when there is more than one experience happening at the same time. In the section of engaging and not fun, there is an example of a person driving his new car in the midst of heavy rain. This example shows that the person is fully engaging in his driving and he is driving carefully (not with fun) to make sure that his new car won't get into an accident. If we look closely, this example consists of two experiences; one is driving a new car, which is supposed to be fun, and second is driving in the midst of heavy rain. The driver could only be in one experience due to what is called as 'selective attention' [9]. During this phenomenon, the ability of conscious attention is limited, which means, one can focuses on one thing and reduce one attention to others.

The same phenomenon occurs when there are two young girls playing swings in the playground, and they both have a chat at the same time. The fun experience of playing the swing is less or absent because the attention is given to the conversation. The experience is then said to be engaging, yet not fun (in reference to playing swing experience).

The three issues discussed above, certainly have given us more insight towards the relationship of engaging and fun. From this point we now know that engaging experience can exist even without the presence of fun, internal and external motivations have the ability to mutate experiences and human can only experiencing one experience at one time due to 'selective attention'.

Having known the four states and understood the process of transformation or mutations, and the highlighted issues, have triggered us to also explore how exactly the experiences mutate to become another type of experience. For instance, at which point exactly does the experience of engaging and not fun becomes engaging and fun. The section below discusses further.

3. Critical Points

As previously stated, we are also interested in exploring the points at where the mutation or transformation of experiences occurs. Comparing to the process of mutation or transformation, this exploration is not discrete in the sense that the boundary is not as distinctive as the former. The points where these changes occur are what we described as the critical points.

The examples of experiences are once again used to assist us in exploring and seeking the critical points.

i. Boiling-water-in-a-kettle experience

As we already know, this particular experience is a mundane experience. It's neither engaging nor fun. Now we are about to see how this experience mutates. Let's add a feature or an element to the kettle. We decided to add a cute little bird to it. So, how exactly can we mutate the experience from not engaging and not fun by adding this new element? This time, we inserted the little bird into the kettle, and designed in such a way that when the water boils, the pressure of the steam pushes the little bird towards the lid. These make the cute little bird pops up and begin to sing and twirl.

Although the engaging experience only occurs at perhaps the moment the bird pops up, the new design of the little bird has successfully added the fun element to the original experience. In this case, the critical point would be the aliveness design of the little bird, which mutated the experiences.

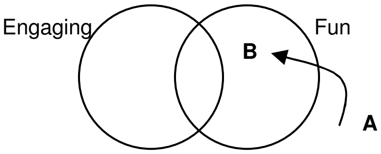

Figure 2: A mutated to B

ii. Interacting with a technological device experience

From the example found in 2.2(ii), we mentioned that the particular experience could be mutated providing there is an interactive device for the customers to interact with while waiting, which this lets them to have engaging experience. Now, we would like to see at which point the experience mutates to fun experience.

We believe that by adding a variety of functionality into the device would make it more fun. This is due to the facts that a selection of functionality that is of different levels would produce challenges, and according to Brandtzaeg [2] and Blythe [1], once said that some people found pleasure and fun from challenges. In addition, users are of different abilities and skills. Therefore, the challenge of many different levels in the device is the critical point in this particular scenario. Some may find fun when encountering higher level of difficulty of challenges, and some may find fun by doing things that are of easy and simple, as long as both eventually reach their satisfaction level.

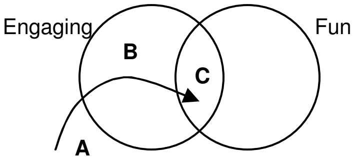

Figure 3: A is first mutated to B then to C

iii. Playing games on Play Station II experience

In this case we have a 10-year-old boy who is really engaging to the games he is playing and having much fun with it. This is the same example taken from 2.2(iii). As we already understand from 2.3(ii), the internal and external motivations could influence one's engaging experience.

Now let's us imagine a situation in which the boy is currently at level 8 and is trying to cheat to get to upper level. Normally, cheating the game would be an easy thing to do. But this time, the game does not allow him to cheat. That boy is now furious, yet is still engaging to the game as he is trying to find a way to get around it. The experience of fun that he initially had has now mutated into annoyance.

So, what exactly has changed his experience of fun to less or no fun at all? The critical point of this mutation would be the interference of factor(s) that does not support or concur to what one interprets fun experience is. If the interference continues, and one cannot overcome the interference, the fun element, or even the experience, is not possible to exist.

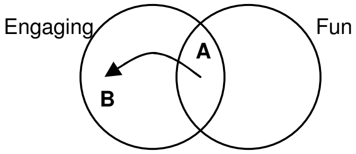

Figure 4: A mutated to B

The critical points that we have discovered have given us some insight towards how to make the both experience more engaging or less, and/or more or less fun. The following section describes how we can actually benefits from the critical points.

4. Heuristics

Having discovered and understood the transformation process, issues and critical points, we would like to outline a heuristics on how to make experience more engaging and fun. We in particular used the results of the critical points for the heuristics as the points are mainly derived from the mutation process and entails issues related to the process.

The heuristics would be beneficial and essential especially in the manufacturing sector. The design department could use the heuristics in the development of everyday things to enhance the users engaging and fun experience. In addition, by following the heuristics, the designers are able to cater the experience of a device according to the user requirements.

Following are the heuristics:

i. Aliveness

Jack-in-a-box, which has the element of surprise and a ballet dancer in a musical box, which has an excellent influence to enchant people, are among of the examples that have the aliveness characteristics presence in them. It is the nature of human being that liked and wanted to see things that are physically moving, which this would leads to engaging. In the case of the musical box, the longer the ballet dancer dances, the longer the person got engaged to it. The element of surprise of an aliveness object leads to fun experience.

ii. Interactions

When interaction takes place, it would exist at least a two-way action, and it also could lead to engaging experience. Feedback plays an important role in interactions. Feedback, as Norman [9] once emphasised in one of his chapter, The Principle of Feedback, is very important factor, which must exist when the user is interacting with something. By providing feedback in an interaction, the user can get to know what is happening, and this gradually develops engagement.

It is worth mentioning here that interaction does not necessarily mean that the user has to interact much with the medium or device. As long as the user perceive and understand what is taking place from the feedback that is all that matters. This is owing to the fact that there is a study on web-entertainment of video streaming, which shows engaging can take place by less clicking and more watching [4].

iii. Challenges

By providing challenges of different levels, the users can experience fun, especially when they able to overcome the challenge. Demands as fun, which include challenges, as what has been described in [9], stated that people take pleasure in contesting intellectuality and variation. As challenges are of different levels, we can provide certain settings to either make it more fun, or less fun. This, of course, are varies on different individuals.

iv. Motivations

There is no doubt that internal and external motivations have such influence on leading where the experience might heads. We have seen the proofs from the examples previously given. By knowing the positive motivations that can be integrated into the medium or device, we are able to make the experience more fun. At the same time, we can make the opposite experience by identifying the negative motivations.

5. Conclusion

This paper focuses on discovering the relationship of engaging and fun experience in order to enhance to user experience. We have answered the question of whether engaging and fun always has to be associated to each other to make engaging experience a success. By now, we already know that engaging experience can exist even without the element of fun. In addition, we have discovered that experience can mutate and transform to become another type of experience, for example, from engaging and fun experience, it can mutates to engaging and not fun experience.

The critical points indicate the factors that enable the process of mutation. Besides that, the critical points have led us to understand that a characteristic can be flexibly changed to something better (engaging and fun), if not worse (not engaging and not fun). The heuristics, which were derived from the critical points, are outlined to assist especially the designer, to enhance the user experience in the respect of engaging and fun.

6. References

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Appendix B

User Engaging Experience: a study of personal and mobile computing environment

User Engaging Experience :
A Study of Personal and Mobile Computing Environments

Introduction:

This preliminary study compares the user engaging experience in two different environments: the personal computer (PC) and mobile computing (PDA). There are four people involved in this study :

- Four people (2 males and 2 females)
  - For PC experiment, all four participants are characterised as **Intermediate.**
  - For PDA experiment, the participants are divided into two groups: **Novice** and **Expert** users.
  - For each group, there is 1 male and 1 female participant.

To help us understand this project even better, we first defined engagement. There are many definitions of engagement from different perspectives such as Human-Computer Interaction (HCI), cognitive psychology, learning theory, etc. What we have come up with is what we already derived from these perspectives. Therefore, we defined engagement as a process that involves any or all of the following :

- holds one's attention
- one is committed with or involved in
- one who is curious about
- one who is interested in

We believe that engagement should be experienced so that learning can happen.

Objectives:

The purposes of this study are to determine:

1. the differences in engaging experience in both systems (PDA and PC)
2. the differences in engagement experienced by novice and expert users
3. the elements that support engagement
4. the differences in behaviours of novices and experts in engagement
5. whether engagement supports learning, hence increasing performance

Methods:

This study employs a combination of methods to gather data on user engaging experience in the two different environments. The methods are:

Methods	**Objective / Purpose**	**How**
Observation	Observe users as they interact with the mobile and PC applications	- by observing the participants closely the way they interact with the devices

		- facial expression / speed / other behaviours
Interview (open and structured questions)	Gather more insight data on user engagement	- by asking questions such as what, why, how, where and when (5 Ws)

The Participants:

This experiment involves four participants : two male and two female participants. Based on the background information, all the four participants have been using the computers (PCs) for at least 10 years, where two of them have actually used for almost 15 years.

Although they have been using the PC quite long enough, they still consider themselves as intermediate users as they still don't fully explore and use many other functions and features of the PC. This is because they have only explored and used functions and features needed by their tasks. All other functions are still left unexplored. Moreover, they perceive the PC as a big machine that houses a lot of complex programs. Therefore, it is impossible for them to master all the skills and knowledge about the PC.

The participants were later asked about PDA knowledge. From here, we divided the participants into two groups: experts and novices. We label novices because they didn't have any experience with the PDA at all. Nevertheless, they knew general information of the PDA. When asked about their perception of PDA, the answers were : PDA is (1) a small version of PC and (2) a personal organising tool.

The other group is expert users. Both of the users have 1½ years of experience with the PDA. One user has been using SONY CLIE PDA and the other one has been using Compaq iPAQ PDA. The choice of the PDA is more towards personal / individual preference such as type of work done on the PDA, choice of programs and the design.

Initially, we planned to have both groups: novices and experts, for both environments: PC and PDA. Unfortunately, we couldn't get any PC novice users because it is more difficult to find someone who is totally inexperienced or new with the computers (PC) nowadays than someone who is inexperienced with the PDA. PDA is still quite relatively new to a lot of people. Because of these reasons, we could not gather data on novices and experts in the PC environment.

The Experiment :

For the experiment, we setup a task dealing with a word processor on both systems: PC and PDA.

For the PC experiment, tools involved were:

- hardware
    - notebook computer – Fujitsu C2010, attached with:
        - input devices – built-in QWERTY keyboard and touchpad; and external optical mouse
        - output devices – a built-in 14" display monitor and two external speakers
- software
    - operating system – Windows XP Home Edition
    - word processor – MS Word 2002 Office XP version

Reasons for choosing the above tools are:

1. all the participants are very familiar with the Microsoft programs (Windows operating system and MS Office products)
2. notebook computer is very much similar to desktop computers such as QWERTY keyboard and external mouse, therefore, it won't affect participants' performance.

For the PDA experiment, tools involved were:

- hardware
    - PDA – Compaq IPAQ H3850

- software
    - Operating system – Pocket PC 2002
    - Word processor – Pocket Word

Reasons for choosing the above tools are:

1. Compaq IPAQ is using Microsoft operating system and has all the Microsoft Office programs which all the participants are familiar with.
2. The PDA interface design is very much similar to that of the PC such as Start button and desktop shortcuts, thus, making learning is easier for the novices.

Because of these reasons, the novices didn't really need any training session before the experiment. Even so, they were still briefly instructed about the PDA and given about 5-10 minutes with the PDA so that they had some ideas about the PDA.

The tasks were the same for both environments (PC and PDA):

Participants:

1. typing a short paragraph on a blank document using the word processor
2. editing and formatting the paragraph
3. saving the document
4. rename the document

Experimenters:

1. observe participants' behaviours
2. record interaction activities and behaviours
3. ask questions and do follow-ups for further clarification

Results (Discussion):

The experiment was carried out to investigate the following project objectives:

1. **The difference in engaging experience in PC and PDA systems**

Personal Computer (PC)	Personal Digital Assistant (PDA)
It is quite difficult to record/notice the 'engagement' because: • Participants are very familiar with the PC and have been using it for at least 10 years. Therefore, PC is not something new to them. • The tasks assigned are the common, routine tasks for the participants. They managed to perform them quickly and easily. Their actions were seen to be more general. They used a lot of 'short-cuts' available and known to them such as icons and tool bars on the screen, and also short-cuts on mouse and keyboard. • Therefore, they were seen *less* engaged in the tasks.	As mentioned earlier, the participants were divided into novices and experts. For the expert users, the results are almost the same as those of the PC experiment. • They did the tasks quite more easily and quickly than the novices. • They used quite a lot of the 'short-cuts' available and known to them such as icons and toolbars. For the novice users, we could see noticeable engagement in the interaction. • They spent more time performing tasks. o PDA is new to them. They need more time to explore and learn its capability. o They relied a lot on their experience with the PC.

	o They were very careful in almost everything they did as to avoid or minimise errors (based on previous experience) • They were also noticed using some ‘short-cuts’ which were known and available to them.

2. **The differences in engagement experienced by novice and expert users in PDA environment**

Since we couldn’t find any novice users for the PC, we could only carryout this experiment for the PDA environment. From our experiment, we are still not very sure whether the different computing environment plays a role in engagement.

Expert users	Novice users
They were seen *less* engaged in the tasks. Reasons for this : • They can easily carryout the tasks because they are familiar with both functions and features of the PDA. Their actions were seen as ‘swift and general’. • They can quickly complete the tasks because (1) they know location of functions, for example, to save a document, they look under **NEW** menu, (2) they use shortcuts known and available to them such as icons and buttons on the screen. One of the expert users put some icons on the screen that might be used repeatedly or frequently as the shortcuts. • They felt indifferent. They could be seen *more* engaged when they were : (1) trying to explore other features that they didn’t know (ie. Advanced features) or (2) trying to do things that they couldn’t do before (3) trying something challenging	They were noticeable seen as ‘engaged’ in the tasks because : • They were trying to find out the functions available to carryout and complete the tasks. o They relied a lot on their PC experience. • They were curious and interested to find out more about the PDA features and capabilities. o The PDA GUI design also helped them a lot in exploration when they could no longer use their PC experience to locate functions and features on the PDA. • Their feelings changed from (1) anxious to more in control and (2) eager to excitement.

3. **The elements that support engagement**

Good Feelings	In the experiment, we recorded feelings that the participants had before, during and after the experiment. We found out that the good change in feelings did help the participants engage in their tasks. One novice user reported that she was very nervous as she didn’t know whether she would do something stupid and what to expect from the PDA. But once she tried using it, she felt much better and more in control. Good feelings like excited, eager and I feel better, certainly play important role in engagement.

	Contrary to what the novices experience, both expert users reported to have indifferent feelings towards the use of the PDA as they have been using it for most of the time. Therefore, it is quite difficult to identify whether they were engaged in the tasks.
Good Interface design	Beside good feelings, the interface design also plays an important role. If the program is badly designed, the users won't be able to explore much. The users will only use basic and common features. Hence, there will be no or less engagement in the tasks. PDA is purposely designed similar to that in the PC so that the users can apply their PC experience to the PDA environment. If they can't apply their experiences, the PDA design helps them a lot in searching for certain functions and exploring other features. One novice user reported to have accidentally closed a document. He was afraid that he would lose his file because he didn't save it at all. Then, he went through a list of Pocket Word document files and found out that the document was there. Only then he knew that the document was automatically saved once the document was closed. Later, he was seen more eager to discover and learn other new features on the PDA.
Tasks and computing device	The participants were only assigned with the common, routine tasks for both environments. As a result, the tasks were very easy to be completed by the expert and intermittent users in both PDA and PC environments, respectively. Again, it is quite difficult to identify whether these participants engaged in the tasks. Whereas for the novices, although the tasks were routine, the computing device (that is PDA) was new to them, therefore, they were seen engaged as they spent some time exploring and learning the features and functions of the PDA.

4. **The differences in behaviours of novices and experts in the engagement in the PDA environment**

Expert users	Novice users
During typing: They were seen using both the handwriting program and onscreen keyboard to type data on the PDA. From our observation, we can conclude that they already mastered the handwriting rules and skills as to avoid or minimise the errors. Actually the primary reason for using the handwriting program is the speed of performance. They usually use this program whenever they are in the meeting and record any spontaneous thoughts or ideas. They are not worried about making mistakes in writing since these mistakes can be corrected later. In fact, PDA has a function where the users can retain or save their handwriting without being translated into block letters, which may produce wrong results.	They were seen using a lot of the onscreen keyboard to type data on the PDA. The reasons for this option are : • They are already familiar with the PC keyboard – the PDA onscreen layout design is very similar to the PC's keyboard, except the fact that the onscreen keyboard keys are very closely placed next to each other. Therefore, they have to be very careful during typing / data entry. • They are afraid of making any errors or mistakes. So, they didn't want to risk losing data or get errors on the PDA. One novice user said that since she was very new to the PDA, she didn't want to take a risk by trying another method that she was not

Interacting with the program: They were seen to know and use shortcuts more than the novices. For example, to rename a filename, they just pointed to that file with the stylus pen and pressed and held it gently until PDA opened up a small tasks window. They just selected **RENAME** option from the list in that window. In fact, they were seen to have identified some common functions which might be used repeatedly or frequently and have them saved on the screen for easy access to the functions.	confident with. Their primary reason for choosing the onscreen keyboard is the data accuracy. Because of this option, it slowed them during the typing process. When they carried out the tasks, they looked for familiar functions and features by recalling their experience with the PC, which helped them a lot. For example, to underline a word, they first looked for an Underline icon on the screen. If they couldn't find it, they would look under **FORMAT** menu.

5. **Whether engagement supports learning, hence increasing performance.**

For this objective, we produced a separate evaluation for different type of user:

- Novices – carryout the same tasks again
- Experts – try out new PDA features and functions, so that they become *more* engaged (refer to results on Table 2 on page 5)

What we observed were:

- Novices could simplify their actions by using some short-cut methods and encountered no or few errors compared to first trial
- Experts were focused while trying out new features of PDA

Later they were asked to explain the steps to carryout the above tasks. As predicted, all of them were able to carryout the tasks successfully and with understanding.

Findings (Analysis) :

There are some notable results gathered from this experiment:

1. Novices are more engaged than experts in the same computing environment.
    a. High engagement occurs when:
        1. users are dealing with a new computing device
        2. tasks assigned are new and/or challenging
        3. users are exploring other than common features
        4. users have good feelings towards the tasks

2. The elements or components that support engagement:
    a. good feelings – bad feelings or indifferent can prevent engagement from happening
    b. good interface designs – help users use their previous experience and explore safely
    c. new, challenging tasks – this is true for expert users
    d. new computing device – true for novices although the tasks assigned are basic and routine

3. If engagement occurs, the users will be in control and learning will take place. Thus, it can increase/improve the performance.

Significance of the findings

1. To confirm that :
    a. Engagement leads to learning
    b. Engagement is able to put user in control

2. Understanding the users is essential in the design process:
    a. Their background – level of expertise, knowledge, skills
    b. Experience – how long they have been using the computers, how they deal with the computers, their tasks
    c. Perception – how they perceive computers, expectation, tasks they are able to do with the computers, tasks the computers are able to do

3. Results help in designing mobile learning interface:
    a. Kind of learning material
    b. Presentation of learning material
    c. Interaction design

Appendix C

Exploiting Mundane Device Success for Novel Device Design

Exploiting Mundane Device Success for Novel Device Design

First author's name

Affiliation
Address
e-mail address
Optional phone number

Second author's name

Affiliation
Address
e-mail address
Optional phone number

ABSTRACT

The vision of ubiquitous and tangible computing is a world filled with a plethora of objects beneath which lie vast amounts of computational power. This poses new design challenges in the attempt to bridge the physical and digital worlds. This paper describes a study of day-to-day electronic devices in order to understand what makes physical interactions and physical–logical mappings natural and comprehensible. In particular we articulate the design issues, which enable physical devices to exploit their physical form to assist user interaction with the logical functions they support. Our aim is to exploit the design knowledge embodied in these existing devices in order to reapply it to novel device design. We demonstrate this by using the derived concepts in the analysis of "Cubicles" – novel cube-shaped devices developed for wearable and tangible interfaces.

Author Keywords

Tangible UI, ubiquitous computing, consumer appliances, physical interaction, fluidity

ACM Classification Keywords

H.5.2.User Interfaces – Input devices and strategies, Interaction styles.

INTRODUCTION

Every day we interact with physical artifacts. Devices and consumer appliances are used in order for us to get our jobs done in our daily activities. Sometimes, we have trouble understanding how to manipulate these devices and appliances. We need to read the manual before we can actually use them. But other devices and appliances have been designed in a way that enables the user to interact naturally. It is this naturalness is what we are after both from these mundane devices and from novel devices.

In this paper, we study real physical controls on really-used artifacts in order to understand the features of physical interaction and of the physical-logical mapping that make them comprehensible and natural.

Our aim is to use the rich knowledge implicit in the design of day-to-day artifacts to uncover principles that can be used in the design of novel tangible interfaces.

This naturalness of physical interaction is related to both Gibson's notion of natural affordance, as well as the more culturally informed aspects of affordance brought into HCI by Norman and Gaver [11]. Dix et al. [5] describes this naturalness of interaction as fluidity, which is "the extent to which the physical structure and manipulation of the device, naturally, relate to the logical functions it supports". Our own work builds particularly on this notion of fluidity.

Some studies of day-to-day artifacts. notably much of Norman's work [13], focus primarily on the failings of design and the way appropriate use of cognitive or other design principles might have avoided these design mistakes. The lesson from these is mostly about what to avoid! In contrast, we are looking particularly for the positive lessons from day-to-day devices, in particular how the tangible nature of these can harness innate human abilities.

The next section of this paper describes the rationale behind this study. The following section analyses mundane devices looking at the factors that determine their success. This analysis is then applied to a novel device, the Cubicle [17]. We will conclude by looking at related work and future directions.

Rationale

Consider the ubiquitous vision, introduced by Weiser [20], adopted by the ubicomp community and recently popularised in *Minority Report*. At first it seems as though the future envisaged by this is far from the devices we see today, but perhaps they are not so different after all …

The Vision …

Ubiquitous computing paints a world where the day-to-day activities of our lives are suffused with computation. Each item from briefcase to breakfast cereal packet becomes a locus for interaction. Some of this is incidental to the activities we are doing [5]: the briefcase keeps track of its contents and talks to the wall calendar so that it can warn if an important document for today's meeting is missing. But other actions require more intentional although still implicit interactions [15]: tipping the breakfast place-mat from side to side to turn the pages of the morning paper displayed on it. Others are more explicit still, the magic wand that acts as universal control [8].

We are focusing in this paper on the latter two categories: the intentional but implicit and the more explicit interactions. Both involve physical objects or controls. However, as the world fills with physical objects that have meaning in the electronic world, then how do we understand those meanings? How do we turn the device that is a wonderful demonstration when you know how it works into an object that is "pick up and use"? And even when you know how it works, what are the affordances of the object and the properties of the physical–logical relationship that allow the use to become natural?

… And The Mundane

In the current world our lives are suffused with computation. Many items from Walkman to washing machine are a locus for interaction. Some of this is incidental to the activities we are doing: the set-top box that monitors your watching habits and consults the electronic TV guide so that it can pre-record the programmes you may want to see later. But other actions require more intentional although still implicit interactions: the volume control on the phone that naturally sits under your thumb. Others are more explicit still: the dial and switches on the washing machine control panel.

Focusing again on the latter two categories, designers of day-to-day products are constantly faced with the issue of how to make these devices comprehensible to ordinary people. A mini-disk controller that makes a wonderful demo to a group of fellow designers ... or even computer scientists ... could win you a design award, but will be a market flop if people cannot pick it up and use it. A 27 page manual is not acceptable whilst jogging.

Designing Physical Interaction

So, we can see that the novel interactions envisaged in ubiquitous computing, although different in detail, do share much with more mundane day-to-day appliances! By studying these appliances we can learn much that would be hard or impossible to learn by extensive experimentation with novel devices.

First we all have an extensive first and second hand knowledge of these devices and their use. Of course we have to be careful as researchers and designers when generalizing from our own anecdotal experiences, however, neither should we ignore this rich resource.

Second these devices are only popular if they ‘work’ for people. Although little-used controls may not be optimal it will generally be the case that the more heavily-used aspects will have designs that have been found to be usable otherwise the products would not sell. Obviously this second argument does not hold where there is an effective monopoly, as is the case with certain software goods, but for most consumer appliances there is considerable competition and also consumers will have seen them in friends’ houses, or for personal products perhaps borrowed them and tried them out.

Finally these products embody the knowledge of their designers. Some are successful because they happen to be, but many are successful because they are designed to be. Because of the different styles of the disciplines, much of this design knowledge is communicated through exemplars rather than abstracted principles. However, this community knowledge as well as individual skills are evidenced in the products we find.

Of course not all appliances are well designed, in particular, aesthetics may dominate usability. Indeed, the failings of such devices are the constant topic of after-dinner conversation in HCI conferences and are often lampooned in books and publications (e.g. Norman [13]). However, this should not detract from the overall ease with which we conduct most of our technological use of artefacts.

Natural Interaction

It is also hard to distinguish those aspects of devices that work because of cultural norms developed due to exposure to technology, which can thus be expected to change (albeit slowly) over time, as opposed to more innate understandings of the physical world. Whilst it is not essential for many purposes to separate these we do try to make this distinction based on the properties of natural physical objects such as stones. These properties (often violated by electronic, and even mechanical devices) include:

- *directness of effect* – A small push makes a small movement, a large push makes a large movement; a push in one direction followed by an equal push in the opposite direction gets something approximately back where it started.
- *locality of effect* – When you do something it has an effect here and now. If you push a stone you do not expect it to move 5 seconds later.
- *visibility of state* – The fixed appearance, shape and other properties may be very rich, but the changeable ones are relatively simple (location, orientation, velocity) and immediately visible.

If a physical object is constructed to violate these properties, for example, a beach ball part-filled with water, the behaviour appears ‘magic’ or ‘alive’ as the ball appears to move of its own volition. Part of the complexity of computer systems is that they violate these simple principles of physicality.

mundane device success

In this study, we have chosen a selection of day-to-day devices and consumer appliances including washing machine and speaker control to represent some of the rich physical interactions available on these mundane appliances.

In most of these, the explicit design of the physical object enables the user to understand how to manipulate the device as they exhibit strong affordances. However, we see that there are additional aspects of these devices that exploit the physical form of the device to inform the users' interaction with the logical function they control. In some cases we will see that this is not the case and then the devices employ various 'recovery' strategies to make the non-physical aspects more obvious.

Exposed State

Some controls, such as simple on-off switches for lights, expose the underlying logical state of the system by their physical state. The interaction potential and feedback for the user is thus immediate as there is a direct mapping between the physical appearance and logical state. Thus, the interaction appears to be natural, and the user can immediately apprehend how to control the device.

The directness of this mapping is obvious if we draw the state diagrams corresponding to the controlling device and the underlying system. Figure 1 shows the state of a kettle switch and also of the kettle itself. There is a one-to-one mapping between the states of the switch and kettle.

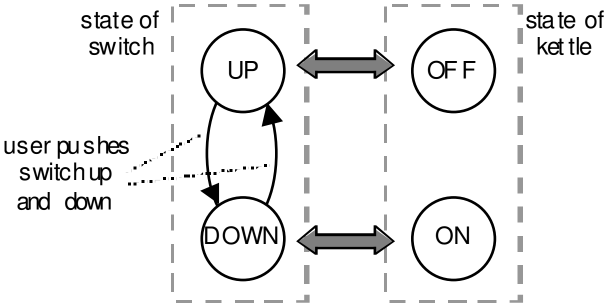

Figure 1. States for simple switch (UK conventions)

Of course, the ability to apprehend the state of the system from that of the device only holds so long as the user knows what aspect of the state is connected with the physical device and also the mapping.

Sometimes the corresponding state is obvious because of locality – the switch is on the kettle and there is only one thing to control. Where this is not the case naturalness breaks down, for example British people visiting the US often become confused when electrical outlets are not working – this is because the switches that control them may be wall mounted a long way off.

The mapping is often more difficult. Conventions can help … but of course often differ between cultures (e.g. US vs. UK light switches – is up on or off?). However, for devices such as kettles both up=on and down=on may be found at which point additional decoration is often applied – for example a red colour that is only visible when the switch is on.

The washing machine dial is a more complex example of visible state (see Figure 4). The dial shows the chosen program (indicated by written legends) and when a wash is in progress it also shows the current state of the wash cycle. This device displays the internal washer state as well allowing the user to set it (we will discuss this dual role later under Compliant Interaction).

Obviously, the visible state of a control can only be used when there is a corresponding number of internal states. This is a simple but very powerful design heuristic. This sounds almost too simple to be worth stating, but some years ago a friend of one of the authors was tasked with producing the software for a car audio system where the number of volume levels in the tuner and the number of LCD cells in the display were both fixed … and different!

Hidden State

In contrast to exposed state, there are controls where the physical appearance does not expose the logical state. An example is the twist control of the speaker in figure 2, which has no intrinsic on/off position given by its physical shape. The naturalness hardly exists for the user to know how exactly to manipulate the device. Therefore, this type of device requires additional features to provide further information. Sometimes this can be supplied by physical markings, for example a dot on the dial. In this case there is no such marking and the marks behind the control serve only to clarify which direction to increase or reduce the volume.

Figure 2. Speaker control.

Hidden state can expose in two conditions, pre-use and while-using. The pre- level is when the additional features like text, signs, pictures, and lights that can be found around or close to physical controls give suggestions or instructions to the user of how to manipulate the device control. The marks are pre-use in the sense that before actually manipulating the device the user can begin to builds a mental model [13] of the hidden physical–logical mapping

Some physical controls provide the naturalness of interaction by embedding a sense of feltness when manipulating the controls. This is the while- condition. In the earlier example of speaker control, the physical control has a palpable bump so that the user can feel it go past the on/off position. This does not give the user a knowledge of the current state, but whilst manipulating the device, the user is made aware of critical transitions.

The latter effect has been emulated in the iDrive haptic controller for the BMW series 7 [9]. The controller itself is a small knob with no specific markings and is used to control a variety of functions though a menu interface. Electronic haptic feedback means that as the user twists the knob to move through menu options a small bump is felt for each menu transition. This can allow the user to perform frequent selections without needing to look continuously at the screen – very important whilst driving!

In older devices the physical control was often connected directly to the internal mechanism. As controls have become electronic this connection is often lost and this becomes apparent in hidden state. Particularly problematic are 'touch' buttons. For example, old tape recorders have buttons that stay depressed while the corresponding activity is occurring (play, record etc.) – strong exposed state. In contrast, touch controls initiate the change of state but have no apparent state themselves. In the case of mechanical push buttons there is at least some intrinsic haptic feedback that the press has occurred whereas capacitative or low travel buttons may have no physical feedback whatsoever. In such cases one sees the sure sign of poor exposed state – an additional on/off light or other soft visual display!

Inverse Actions

As with any dial, turning the rotary knob clockwise increases volume, turning it anti-clockwise decreases volume (see Figure 2). In many of these controls, these inverse effects, like the dial, exploit natural physical inverse actions – if you push a cup across the table, unless it falls off the edge, you can push it back in the opposite direction.

Figure 3. Volume control – linked buttons.

Just as in graphical user interfaces, the existence of an undo reduces the risk of exploration. However with physical devices it is not just that an inverse exists but that the inverse exploits a natural physical inverse such as push/pull, twist clockwise/anti-clockwise, or push up/down. In the best cases this is intrinsic to the device (as in the speaker's rotary knob), but may also be made apparent using visual or tactile decoration. Figure 3 gives an example of the latter where two buttons are clearly linked by being 'yoked' together.

Inverse action is especially important if the user does not have a perfect knowledge of the physical-logical mapping. This allows the user to experiment with the physical control and find out the logical functions the control supports, by reducing the chances of getting the actions wrong.

A particular case of this is when a physical control may manipulate more than one logical function. The user can discover the different logical functions that lie under the physical appearance by inversing the actions. For example, some mobile phones have a small 'scroll' button which can be pressed up or downwards. This may control volume whilst in the middle of a call or scroll through lists when searching the address book. Although this sounds very confusing it does not prove to be in practice. There is an immediate visual or audible feedback of the effect of the control and if the effect is not as desired the natural inverse makes it easy to correct.

In some cases, inverse actions adopt the hidden state's additional features in order to provide additional information of the logical function that the physical form supports. The speaker control, which has been described earlier, has around it painted dots of different sizes that increase from one end to another, indicating to the user that the volume increases as he/she turns the knob clockwise and reduce the volume in opposite direction. This additional feature with the volume of sound coming from the speaker, provide some sense of coherence between the physical state and the logical function.

Inverse actions, in some other cases, work together with exposed state to deliver natural interaction, the tuning frequency of an old radio for example. Besides the manipulation of tuning the frequency by rotating the knob clockwise and anti-clockwise, it also exposed the position of the frequency that is pointed by a vertical line from a display as the user rotates the knob.

The naturalness of inverse actions' interaction may only be achieved when the user gets immediate feedback – for example, the sound of the speaker increasing and decreasing. Under certain circumstances, feedback may be delayed, for example in an electric cooker there is a lag due to the time it takes to heat the metal in the cooker's rings. As we discussed, temporal locality is one of the features of physical interaction, and not surprisingly these delays are not dealt with naturally. For example, many people will adjust central heating beyond the desired temperature to 'heat the room more quickly'. So strong is this effect it even applies to those who understand the system well and know it will not have the desired effect!

Compliant Interaction

The rotary knob on the washing machine (see Figure 4) is not just a good example of exposed state, but also exhibits a symmetry of interaction. The user sets the program by turning the dial, but the system also turns the dial itself as the program advances.

Figure 4. Washing machine and its control.

The simpler exposed state and compliant interaction differ in that the compliant interaction shows some kind of mechanical movement that advances as the same way as the system when the program advances. A simpler example is the on/off switch on some electric kettles, which can be moved up and down by hand, but when the kettle boils flicks to the off position. Old tape recorders also did this and the 'play' button would bounce back up when the tape reached the end.

Note how the kettle's on/off switch differs from a simple on/off switch such as a light switch. In the latter there is no control involved from the system, it solely depends on the user's interaction.

The state diagram in Figure 5 illustrates a simplified version of the washing machine control. Because it has an exposed state the internal and visible states coincide, so these are not distinguished as they are in Figure 1. The plain and dashed arrows show the user and system control of the device respectively. It is clear how these coincide except in that the system cannot turn the washing machine on from the stop state!

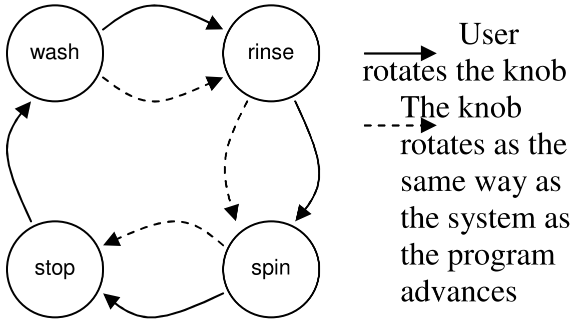

Figure 5. State diagram of washing machine.

Compliant interaction means that the user can easily learn the relationship between the state of the control and the state of the device. The naturalness of compliant interaction enables expert users to use the device to exert fine control over the system's action. This is evident in expert washing machine users who can intervene in the washing program, such as skipping parts of the program, and start in unconventional places, as they learn how to fine tune the device.

In principle this control could give rise to confusion as turning the dial does not complete the wash cycle that the system has been programmed to do. In practice this does not seem to occur with washing machine use or the electric kettle (switching it off is not assumed to have magically boiled the kettle). However, this does appear to be a potential danger for less well understood applications.

Note that compliant interaction is named from compliant motion as used in robotics. This refers to things like a tapered screw where the action of putting it into the hole is guided by the physical resistance of the screw. If the screw is placed slightly to one side there is a natural force pushing it into the right place. In contrast without the taper a slight miss means it just doesn't go in. The physical properties of the screw makes automatic assembly easy.

fluidity of novel interactions

We will now consider how these concepts of physical–digital interaction can be applied to novel input devices. Note that whereas the previous discussion has been about analysing an existing device with a given physical–logical mapping, here we are considering a novel device and using the conceptual categories to suggest appropriate mappings.

Cubicles

Cubicles are cubes of various sizes that are instrumented with different kinds of sensors so that properties such as orientation, location etc. can be detected. These sensed attributes can then be used to control various devices. Cubicles are being developed as part of the EQUATOR project investigating the integration of digital and physical life and use Smart-It technology to allow rapid prototyping of sensor-based systems [18].

One example of a Cubicle is of a small cube with sides approximately 3 in (7.5 cm) that is used to control the feed into a large situated display in the seating area of the Lancaster Innovative Interactions Laboratory. Each of the sides is labelled with one of the possible feeds into the display: TV tuner, laptop cable, fixed computer, etc. The cube sits on the coffee table and is simply turned over to select a particular feed. Inside the cube is a standard Smart-Its main board with micro controller and wireless communications. A small Smart-Its plug-in module has accelerometers to detect orientation.

Other Cubicle designs have included much smaller or larger cubes and also cubes with different physical properties: soft ones that can be squeezed, furry ones that can be stroked. Separate work has investigated how these factors affect the way people choose to interact with Cubicles [17].

Visible State

In the screen-control Cubicle there is a very clear one-to-one mapping between the visible state of the Cubicle (the uppermost face) and the logical state of the situated display. However, like an on-off switch, this only allows the control of six-state applications. Also the unique labelling of the sides mean that it is largely a single purpose device. It is interesting to note however how subtle changes in the decoration of the Cubicle change the number of visible states and the way they can be used in interaction.

If a labelled Cubicle is placed on a flat surface and there is no preferred direction on the surface, then there are only 6 states corresponding to the uppermost face. In a situation like the communal coffee table this is exactly what we have.

If, however, there is a preferred direction, perhaps the direction of the display, then we can also distinguish the orientation of the cube. In principle, there are 360 degrees of orientation that could be detected, and if the Cubicle were a flat plate with an arrow inscribed on top, then these would all be potentially usable.

In fact, the strong rectilinear visual affordance of the cube suggests that states with a face or possibly corner facing towards the screen are preferred., so, for illustrative purposes we'll consider the cube as 'normally' in aligned face positions which means that strictly there are 24 states: 6 possibilities for the uppermost face and 4 further orientations.

In the case of the screen controller the fact that the faces are labelled with text (which suggests a single 'right' orientation) and the lack of relation between the sides meant that this was effectively reduced to 6. An alternative decoration of the sides, for example, a squared-off globe would suggest treating the orientation as significant and hence allow all 24 states to be used.

Both the text labels and globe decoration are very much single purpose. One of the goals of Cubicles is also to use them as generic controllers, so we also consider more open decorations.

One extreme is a fully labelled cube, for example with each side a different colour, or as in the case of a normal die, a number. Here all 24 states are in principle available, although in the case of the die there are strong cultural suggestions that one should consider it a 6 state device.

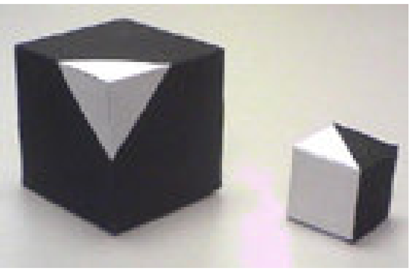

Figure 6. Coloured Cubicles

More minimal labellings include colouring one half of the cube so that one side becomes significant or painting one corner only (see Figure 6). In the former case there are 6 states (painted side down or up and 4 'sideways' states) although there are strong visual suggestions to regard these as 3 major states: face up, face down and sideways, with 4 orientation 'sub-states' when sideways. When the corner is painted there are 8 possible states although there is some suggestion that the corner could be used as a pointer, so possibly this may be used as 360-degree controller.

Notice that some of the visible states of the Cubicle are given by its physical properties, but others depend on cultural or contextual factors.

Inverse Action

The simplest decoration of all is an entirely unlabelled cube, which has no distinguishable states whatsoever. Although this sounds not very useful it means that it can be used in the same way as a mouse or joystick can, where the absolute location is not important: it is the relative movements (rotating, twisting) that are significant. For example, given a menu structure, tipping the cube from side-to-side can be used to cycle through options and tipping it forward can be used to select an option. Depending on the sensors in the Cubicle, slowly tipping in a direction can be distinguished from a quick 'flick' in a direction or actually turning in the same direction. The desire to return to the 'natural' orientation of the cube with flat face up, suggests that the tipping action, rather like a sprung joystick, affords more continuous velocity effects, whereas a flick or turning of the face is a discrete action, more like cursor keys.

Whilst movements like this can be used to make a Cubicle into a universal controller, there are problems of registration. Which way is 'forwards'? For the users this would probably be tipping the cube away from them, but if the Cubicle does not have any absolute location or orientation sensors (which are more difficult than tilt sensors) then this may not agree with the Cubicle's 'own' idea of 'forward'. Also a new user coming to the Cubicle, perhaps finding it on a coffee table, would need to learn the interactions.

Just as in the appliances we have studied, these are exactly the situations where natural inverse actions can help. The use of opposing directions for moving in different directions through a menu list means that tipping the cube in one direction can be undone by the opposite movement. Similarly if tipping forward is selection of an alternative, tipping backward should be the 'go back' action. So long as this is the case a user picking up the Cubicle in the 'wrong' direction can learn up the effects and if desired then re-orientate the Cubicle. Where the inverse action breaks down, for example when selecting an option has an irreversible effect, then some sort of orientation independent action, such as a sharp tap of the Cubicle, will be necessary.

Compliant Action and Haptic Feedback

As we have seen compliant action is comparatively rare, but very powerful when used appropriately as in the washing machine dial, or on-off buttons on electric kettles.

Cubicles are predominantly passive and untethered input devices, so do not naturally suggest control back from the application. However, some potential designs have a small display on each side. This would allow interactions where the user could rotate a particular face upwards, but this could then change over time under the applications control. For example, if the Cubicle is used to control a menu system, then the system could gradually 'fall back' into a standard state after a period of inaction.

Haptic feedback is even more problematic although a heavy gyroscope could be used to give controllable resistance to rotation or even used to autonomously flip the cube!

More practically a ball-bearing moving within a face-centred octahedral void within the Cubicle would enhance the 'joystick' effect – as one tipped the cube, even in mid air, it would be trying to get back to a face down state. Alternatively having a ball bearing roll within the cube itself would tend to suggest holding to with a corner pointing down and hence radically change its interaction affordances.

Related Work

Interfaces to consumer products, like those we have considered here, are also studied closely in an industrial design setting. Overbeeke et all [14], discuss 10 rules (guidelines) focused particularly on making engaging products, for example “don’t think beauty in appearance think beauty in interaction”. Whilst our aim has been more to understand the visceral qualities of mundane interaction, their more aesthetic and our more articulatory approaches have common features. For example, the quoted rule, which they relate to Dunne’s “aesthetics of use” [7], concerns the naturalness of physical interaction. In addition, they take as a starting point the observation that modern devices often hide their functionality behind buttons and icons and propose designs that expose functionality, echoing the issues of exposed state and compliant interaction we have discussed.

Our study and incipient set of physical–logical design principles complements other work in tangible interfaces and augmented reality. For example, Ullmer and Ishii's MCRpd interaction model exposes various aspects of the physical–digital mapping [19] and Koleva et al. discuss a variety of attributes of tangible interfaces that contribute to a sense of 'coherence' between the physical and digital representations [10]. Benford et al’s sensible/sensable/desirable framework focuses more on the affordances of a ubiquitous device and how this can suggest opportunities for extending the physical–digital mapping [1].

Looking at the conventional interface literature, it is interesting to consider Shneiderman's direct manipulation principles: continuous representation, physical actions instead of syntax and rapid incremental and reversible operations [16], and also other early work on understanding direct manipulation [12]. These, and indeed the whole GUI endeavour, are effectively about trying to harness the naturalness of physical interactions in the digital domain.

We can see the connections between these related areas if we consider a simple 2x2 matrix looking at the controlling devices and the functionality controlled; both of which may be physical or virtual. Of course no device is completely virtual, some physical interaction with the user is always necessary, with the possible exception of direct brain sensing! By virtual, we mean devices such as on-screen buttons which have no direct tangible properties.

In the real world we have physical devices with an immediate physical effect (the thing itself!), in direct manipulation we have logical devices and logical effects, and in our studies, tangible and some ubiquitous computing we have physical devices with logical effects. All exploit our innate abilities to live and act in the physical world.

	functionality	
devices	physical	virtual
physical	the real world, exposed mechanisms	tangibles, consumer devices
virtual	industrial control, heads-up displays	GUI and direct manipulation

The reason these different techniques work so well is that we have deep-seated mental and physical abilities attuned to the physical world. We are not far from Neanderthals! There is strong evidence that we reason differently with different kinds of experience, for example, physical vs. social situations [6]; [2]; [3]. Whilst we can reason explicitly about most types of situation this is both slower than more innately driven responses and requires conscious attention. This is why the ‘M’ (mental processing) operator in Card, Moran and Newell’s keystroke-level model was always so problematic [4]. Interfaces that break the natural properties of physical interaction may be difficult to learn, difficult to use or lead to various kinds of superstitious interpretative models [5].

conclusion

In this paper we have presented a study to understand what makes physical interaction and physical–logical mappings natural and comprehensible. Analysing mundane devices and consumer appliances, such as speaker controls and washing machines, has enabled us to identify four aspects of design success that influence naturalness in interaction: exposed state, hidden state, inverse actions and compliant interaction.

We suggest that these four conceptual categories can be used to suggest appropriate mappings of physical–digital interaction and we have applied these in exploring aspects of a novel input device: the Cubicle.

We do not believe we have an exhaustive set of critical aspects and intend to elaborate these further, including working with industrial designers. Also we plan to work with colleagues developing novel tangible devices applying the existing and any further principles in order to validate these in novel settings.

In short, this study offers new ways to understand natural interaction with tangible controls. We believe that this will allow the experience embodied in existing mundane appliances to be applied to the design of novel ubiquitous devices.

ACKNOWLEDGMENTS

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Appendix D

Fluid Interaction with Physical Devices: mining the ordinary to design the extraordinary

Fluid Interaction with Physical Devices: mining the ordinary to design the extraordinary

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ABSTRACT

Whilst seamless integration of physical and digital worlds seems like a vision of the future, in fact it is day-to-day experience: knobs, dials, switches are everywhere. This paper examines mundane devices to uncover design principles for physical interaction. We are looking particularly at how these exploit our innate human understanding of the physical world to allow fluid, natural interaction. An initial collection of principles is presented and used to explore in detail the interaction potential of a particular tangible device, the Cubicle. A wider range of tangible interfaces are then examined in the context of a tangible user interface framework.

Author Keywords

Tangible user interface, ubiquitous computing, consumer appliances, physical interaction, fluidity, affordances

INTRODUCTION

Every day we interact with physical artifacts. Devices and consumer appliances are used in order for us to get our hob done in our daily activities. Sometimes, we have trouble understanding how to manipulate these devices and appliances. We need to read the manual before we can actually use them. But other devices and appliances have been designed in a way that enables the user to interact naturally. This naturalness is what we would like both from these mundane devices and also from novel devices.

In this paper, we study real physical controls on really-used artifacts in order to understand the features of physical interaction and of the physical-logical mapping that make them comprehensible and natural.

Our aim is to use rich knowledge implicit in the design of day-to-day artifacts to uncover principles that can be used in the design of novel tangible interfaces.

This naturalness of physical interaction is related to both Gibson's notion of natural affordance, as well as the more culturally informed aspects of affordance brought into HCI by Norman and Gaver (McGrenere and Ho, 2000), Dix et al. (2004a) describes this naturalness of interaction as fluidity, which is "the extent to which the physical structure and manipulation of the device, naturally, relate to the logical functions it supports". This paper expands on this notion of fluidity and relates it to Koleva et al.'s conceptual mapping of the tangible interaction space (Koleva et al., 2003).

Many of the studies of day-to-day artifacts in HCI, notably much of Norman's work (e.g. Norman, 1988), focus primarily on the failings of design and the way appropriate use of cognitive or other design principles might have avoided these design mistakes. The lesson from these is mostly about what to avoid! In contrast, we are looking particularly for the positive lessons from day-to-day devices, in particular how the tangible nature of these can harness innate human abilities.

We begin this paper with a rationale as to why we believe it is productive to study mundane devices and appliances when our eventual aim is to understand the design of novel tangible and ubiquitous devices. We will then look at related work set within a model of physical-logical interaction. Day-to-day devices, traditional GUI interfaces, augmented reality and tangible interfaces all draw on innate human understanding of physical interaction, and so we will look at some of the properties of 'real world' interaction with physical objects.

The paper will then move on the results of studying a range of consumer appliances and the ways in which they exploit natural physical interactions. This is used to produce a set of principles and issues of physical interaction. Finally, these principles are applied to a novel tangible interface device, the Cubicle and also examined against a broader range of tangible interfaces within the context of Koleva et al.'s TUI framework.

Motivation

Why are we considering day-to-day devices at all? These are typically independent devices with low computational power and very traditional technologies. In contrast research in tangible and ubiquitous technologies seems to be technologically far removed. This radical view of the future has captured the media's imagination, for example ubicomp researchers contributed strongly to the film *Minority Report* which has popularized the ubiquitous vision of the future first articulated by Weiser (1993). This science fiction world seems far removed from the devices we see today, but perhaps they are not so different after all …

The Vision …

Ubiquitous computing paints a world where the day-to-day activities of our lives are suffused with computation. Each item from briefcase to breakfast-cereal packet becomes a locus for interaction. Some of this is incidental to the activities we are doing (Dix et al. 2004b): the briefcase keeps track of its contents and talks to the wall calendar so that it can warn if an important document for today's meeting is missing. But other actions require more intentional although still implicit interactions (Schmidt, 2000): tipping the breakfast place-mat from side to side to turn the pages of the morning paper displayed on it. Others are more explicit still, the magic wand that acts as universal control (Fails and Olsen, 2003).

We are focusing in this paper on the latter two categories: the intentional but implicit and the more explicit interactions. Both involve physical objects or controls. However, as the world fills with physical objects that have meaning in the electronic world, then how do we understand those meanings? How do we turn the device that is a wonderful demonstration when you know how it works into an object that is "pick up and use"? And even when you know how it works, what are the affordances of the object and the properties of the physical–logical relationship that allow the use to become natural?

… And The Mundane

In the *current* world our lives are suffused with computation. Many items from Walkman to washing machine are a locus for interaction. Some of this is incidental to the activities we are doing: the set-top box that monitors your watching habits and consults the electronic TV guide so that it can pre-record the programmes you may want to see later. But other actions require more intentional although still implicit interactions: the volume control on the phone that naturally sits under your thumb. Others are more explicit still: the dial and switches on the washing machine control panel.

Focusing again on the latter two categories, designers of day-to-day products are constantly faced with the issue of how to make these devices comprehensible to ordinary people. A MiniDisc controller that makes a wonderful demo to a group of fellow designers ... or even computer scientists ... could win you a design award, but will be a market flop if people cannot pick it up and use it. A 27 page manual is not acceptable whilst jogging.

Harvesting the Experience in the Ordinary

So, we can see that the novel interactions envisaged in ubiquitous computing, although different in detail, do share much with more mundane day-to-day appliances! By studying these appliances we can learn much that would be hard or impossible to learn by extensive experimentation with novel devices.

First we all have an extensive first and second hand knowledge of these devices and their use. Of course we have to be careful as researchers and designers when generalizing from our own anecdotal experiences; however, neither should we ignore this rich resource.

Second these devices are only popular if they 'work' for people. Although little-used controls may not be optimal it will generally be the case that the more heavily-used aspects will have designs that have been found to be usable otherwise the products would not sell. Obviously this second argument does not hold where there is an effective monopoly, as is the case with certain software goods, but for most consumer appliances there is considerable competition and also consumers will have seen them in friends' houses, or for personal products perhaps borrowed them and tried them out.

Finally these products embody the knowledge of their designers. Some are successful because they happen to be, but many are successful because they are designed to be. Because of the different styles of the disciplines, much of this design knowledge is communicated through exemplars rather than abstracted principles. However, this community knowledge as well as individual skills are evidenced in the products we find.

Of course not all appliances are well designed; in particular, aesthetics may dominate usability. Indeed, the failings of such devices are the constant topic of after-dinner conversation in HCI conferences and are often lampooned in books and publications (e.g. Norman, 1988). However, this should not detract from the overall ease with which we conduct most of our technological use of artefacts.

Related Work

Interfaces to consumer products are also studied closely in an industrial design setting. Overbeeke et al. (2003), discuss 10 rules (guidelines) focused particularly on making engaging products, for example “don’t think beauty in appearance think beauty in interaction”. Whilst our aim has been more to understand the visceral qualities of mundane interaction, their more aesthetic and our more articulatory approaches have common features. For example, the quoted rule, which they relate to Dunne’s “aesthetics of use” (Dunne, 1999), concerns the naturalness of physical interaction. In addition, they take as a starting point the observation that modern devices often hide their functionality behind buttons and icons, and propose designs that expose functionality, echoing the issues of exposed state and compliant interaction we will discuss.

This paper and its set of physical–logical design principles complements other work in tangible interfaces and augmented reality. For example, Ullmer and Ishii's MCRpd interaction model exposes various aspects of the physical–digital mapping (Ullmer and Ishii, 2000). and Benford et al’s sensible/ sensable/ desirable (SSD) framework focuses more on the affordances of a ubiquitous device and how this can suggest opportunities for extending the physical–digital mapping (Benford et al., 2003). In order to help see how our principles fit into the current state of tangible interfaces we use Koleva et al.’s framework which analyses the attributes of tangible interfaces that contribute to a sense of 'coherence' between the physical and digital representations (Koleva et al., 2003).

Looking at the conventional interface literature, it is interesting to consider Shneiderman's direct manipulation principles: continuous representation, physical actions instead of syntax and rapid incremental and reversible operations (Shneiderman, 1988), and also other early work on understanding direct manipulation (Norman and Draper, 1986). These, and indeed the whole GUI endeavour, are effectively about trying to harness the naturalness of physical interactions in the digital domain.

We can see the connections between these related areas if we consider a simple 2x2 matrix looking at the controlling devices and the functionality controlled; both of which may be physical or virtual. Of course no device is completely virtual, some physical interaction with the user is always necessary, with the possible exception of direct brain sensing! By virtual, we mean devices such as on-screen buttons, which have no direct tangible properties.

		functionality (logical state)	
		physical	virtual
devices	physical	the real world, exposed mechanisms	tangibles, consumer devices, augmented reality
	virtual	industrial control, heads-up displays	GUI and direct manipulation

Table 1. styles of physical–virtual interaction

In the real world we have physical devices with an immediate physical effect (the thing itself!), in direct manipulation and graphical user interfaces we have logical devices and logical effects, and in our studies, tangible and some ubiquitous computing we have physical devices with logical effects. All exploit our innate abilities to live and act in the physical world.

In the bottom left corner of table 1 we have placed industrial ‘glass’ controllers and similar kinds of controls such as heads-up controls in an aircraft cockpit. These are effectively some form of virtual control of a physical process (the operation of the factory, or movement of the plane).

In fact, industrial controllers remind us that the world is a little more complex than a simple diagram can show! The focus of the control is a remote physical process, but the control panel itself may include very physical knobs and dials. However, this is equally true of some of the devices we will analyse where the ‘logical’ system controlled is in fact an important physical process: cooking food in a microwave, washing clothes. As we noted, even a GUI is controlled by a physical device, the mouse, and often produces physical outputs on paper. In fact virtually all computer related interactions are at some level of the physical–virtual–physical kind, but do differ in terms of the focus, the directness of the relationship between control device and controlled process and the extent to which we receive feedback directly through the device or indirectly through the controlled process.

Figure 1 shows some of the manipulation and feedback paths between the user and logical system (physical or virtual). The control device is central to this both for its effects on the underlying logical system and also the nature of its physical manipulation and visual and haptic effects. The user–device interactions are labeled with lower case letters (a)–(d), the system–device interactions with roman numerals (i)–(iii) and the feedback loops using uppercase (A)–(C).

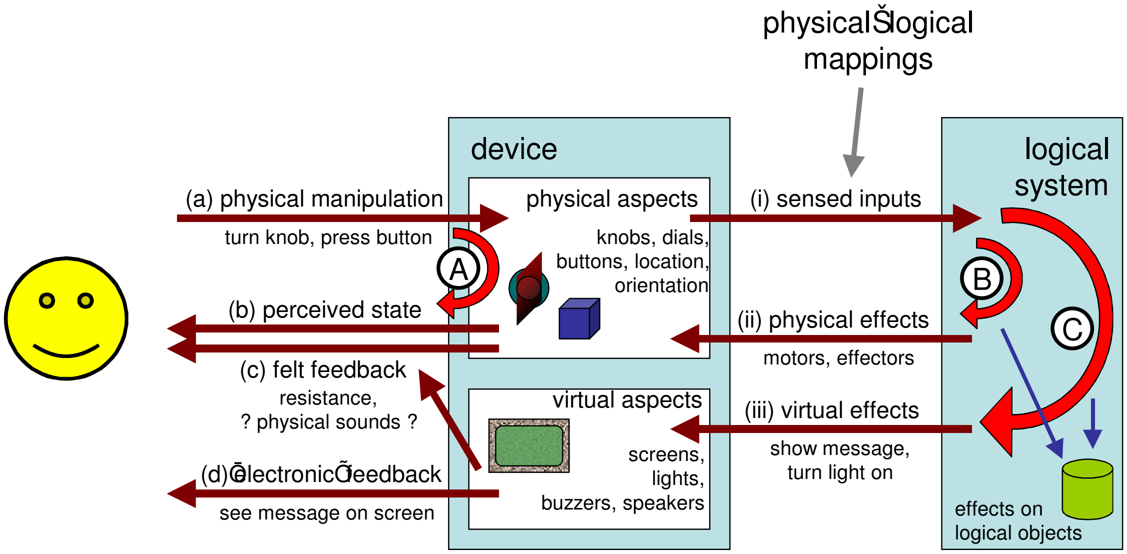

Figure 1. Physical–logical feedback loops

Loop (A) represents the immediate physical effects of the user on the object. This includes, the springiness or resistance of a button or knob, the fact that an on–off switch is visibly in the on position, the (physical) click of a button being pressed. In an augmented reality application such as the Augurscope (Koleva et al., 2002), this would include the interactions with the tangible aspects of the system, for example the orientation of the Augurscope screen.

Loop (B) is for haptic interfaces where the system creates some physical effect that can be felt by the user. There are two sub-cases. The first (B.1) is when the physical aspects controlled by the system and perceived by the user are independent of those controlled by the user; for example, the turning of the tub in a washing machine. In this case the user can see that the tub is turning through the glass door. The second (B.2) is where the same physical devices are being affected by both user and system; for example, the dial of the washing machine, which both acts as control device and is also a visible indication to the user of the system's state.

Finally, loop (C) represents deep semantic feedback from the underlying logical state of the system. This is often via some soft display (LCD panel, screen). As this depends on computation or physical processes there may be longer delays compared with loops (A) or (B). Direct manipulation attempts to elide the difference between device actions and virtual effect and so often relies on the semantic feedback (e.g. dragging an icon). However, where there are delays, this can then lead to problems. Where this may occur, it is important to recognize that this is in fact an indirect manipulation and supply immediate feedback (Dix, 1994). However, we shall see that even where there is some instant semantic feedback, the directness of actual physical feedback from the device can be very powerful.

Often several of the feedback paths are significant in a single interaction. In the case of the washing machine the noise and appearance of the tub as well as the location of the dial. Also in traditional interaction with a desktop PC there are multiple feedback paths: the sound and feel of the key being pressed (loop A) and the result on screen of the key press (loop C). In a membrane keyboard the first of these feedback loops is not naturally present; instead such systems typically generate simulated key clicks that for the user are very like the physical sound of a real key (loop B).

When looking at a simple physical object, such as a cup, there is no separate logical state and simple affordances are about the physical manipulations that are possible (a) in figure 1) and the level to which these are understood by the user: Norman's 'real' and perceived affordances (Norman, 1999). For a more complex, mediated interface the effect on the logical state becomes critical: the speaker dial affords turning but at another level affords changing the volume. Hartson (2003) introduces a rich vocabulary of different kinds of affordances to deal with some of these mediated interactions.

Benford et al.'s SSD framework (2003) deals with this relationship between the physical device and logical state. It considers three aspects of the relationship: sensable – the aspects of the physical device can be sensed or monitored by the system, sensible – the actions that the user might reasonably do to the device, and desirable – the attributes and functionality of the logical system that the user might need to control. These can be used to explore the design space and in particular mismatches between the sensible, sensable and desirable can be used to suggest directions for re-design. In terms of figure 1, the sensable aspects correspond to (i), whilst the sensible ones refer to those possible actions ('real' affordances) of the device (a) that the user might reasonably perform. The desirable part of the framework refers to the internal possibilities of the logical state.

Note that what is sensible to do with a device depends partly on its perceived affordances and partly on the user's mental model of the relationship between the device and the logical state.

The concept of fluidity introduced in Dix et al. (2004a) and expanded in this paper is focused on the way in which this mapping is naturally related to the physical properties of the device. Whereas the SSD framework is primarily concerned with what it is *possible* to achieve, fluidity is focused on what is *natural* to achieve.

Understanding physical interaction

As we have noted direct manipulation, augmented reality and tangible interfaces all emulate or use interaction with real physical objects. The reason these different techniques work so well is that we have deep-seated mental and physical abilities attuned to the physical world. We are not far from Neanderthals! There is strong evidence that we reason differently with different kinds of experience, for example, physical vs. social situations (Barkow et al., 1993; Bownds, 1999; Donald, 1991). Whilst we can reason explicitly about most types of situation this is both slower than more innately driven responses and requires conscious attention. This is why the 'M' (mental processing) operator in Card, Moran and Newell's keystroke-level model was always so problematic (Card et al., 1980). Interfaces that break the natural properties of physical interaction may be difficult to learn, difficult to use or lead to various kinds of superstitious interpretative models (Dix et al. 2004b).

Furthermore, at the lowest level, motor activities involve neurological feedback loops within our bodies that do not involve conscious thought at all. These loops operate in time scales far faster than can be controlled using more cognitive processes and are hard to train. For example, learning new fingering patterns for a musical instrument or physical actions during sports. Low-level hand-eye coordination, such as those used in Fitts' law tasks, are also largely unconscious. Where systems emulate aspects of the physical world they can take advantage of existing low-level responses rather than requiring new ones.

Natural Interaction

It is often hard to distinguish those aspects of devices that work because of cultural norms developed due to exposure to technology, which can thus be expected to change (albeit slowly) over time, as opposed to more innate understandings of the physical world. Whilst it is not essential for many purposes to separate these we can try to make this distinction based on the properties of natural physical objects such as stones. These properties (often violated by electronic, and even mechanical devices) include:

- *directness of effect* – A small push makes a small movement, a large push makes a large movement; a push in one direction followed by an equal push in the opposite direction gets something approximately back where it started.
- *locality of effect* – When you do something it has an effect here and now. If you push a stone you do not expect it to move 5 seconds later.
- *visibility of state* – The fixed appearance, shape and other properties may be very rich, but the changeable ones are relatively simple (location, orientation, velocity) and immediately visible.

If a physical object is constructed to violate these properties, for example, a beach ball part-filled with water, the behaviour appears 'magic' or 'alive' as the ball appears to move of its own volition. Part of the complexity of computer systems is that they violate these simple principles of physicality.

mundane device success

In order to understand how these natural interactions can be used effectively in design, we have studied a selection of day-to-day devices and consumer appliances including a washing machine and speaker volume control. We have sought to analyse and represent some of the rich physical interactions available on these mundane appliances.

In most of these, the explicit design of the physical object enables the user to understand how to manipulate the device as they exhibit strong affordances. However, we see that there are additional aspects of these devices that exploit the physical form of the device to inform the users' interaction with the logical function they control. In some cases we will see that this is not the case and then the devices employ various 'recovery' strategies to make the non-physical aspects more obvious.

One of the techniques we have used is to represent separately the states of the device and of the underlying logical state (the left and right hand sides of figure 1). For each we have produced a simple state transition network and then examined the relationship between the two. However, we shall see that for certain types of physical interaction we find we need to extend normal state transition notation to deal with 'bounce-back' controls.

Exposed State

Some controls, such as simple on-off switches for lights, expose the underlying logical state of the system by their physical state. The interaction potential and feedback for the user is thus immediate as there is a direct mapping between the physical appearance and logical state. Thus, the interaction appears to be natural, and the user can immediately apprehend how to control the device.

The directness of this mapping is obvious if we draw the state diagrams corresponding to the controlling device and the underlying system. Figure 2 shows the state of a kettle switch and also of the kettle itself. There is a one-to-one mapping between the states of the switch and kettle.

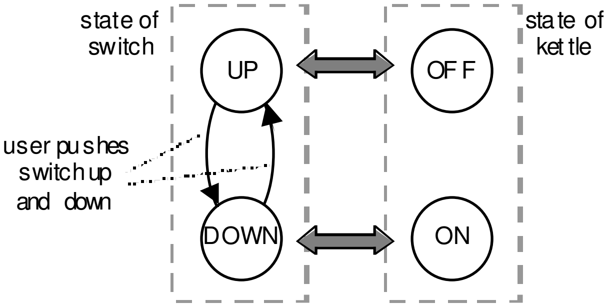

Figure 2. States for simple switch (UK conventions)

Of course, the ability to apprehend the state of the system from that of the device only holds so long as the user knows what aspect of the state is connected with the physical device and also the mapping.

Sometimes the corresponding state is obvious because of locality – the switch is on the kettle and there is only one thing to control. Where this is not the case naturalness breaks down, for example British people visiting the US often become confused when electrical outlets are not working – this is because the switches that control them may be wall mounted a long way off.

The mapping is often more difficult. Conventions can help … but of course often differ between cultures (e.g. US vs. UK light switches – is up on or off?). However, for devices such as kettles both up=on and down=on may be found at which point additional decoration is often applied – for example a red colour that is only visible when the switch is on.

The washing machine dial is a more complex example of visible state (see Figure 9). The dial shows the chosen program (indicated by written legends) and when a wash is in progress it also shows the current state of the wash cycle. This device displays the internal washer state as well allowing the user to set it (we will discuss this dual role later under Compliant Interaction).

Obviously, the visible state of a control can only be used when there are a corresponding number of internal states. This is a simple but very powerful design heuristic. This sounds almost too simple to be worth stating, but some years ago a friend of one of the authors was tasked with producing the software for a car audio system where the number of volume levels in the tuner and the number of LCD cells in the display were both fixed … and different!

Control of State

In most of the devices we studied, the control devices were under the complete control of the user: an on-off switch can be moved to both positions, the washing machine dial can be turned to any location. However, there are occasionally limitations. For example, whilst the washing machine dial can be turned clockwise to any position it cannot be turned anti-clockwise. If the dial is on 4 and you want programme 3 then you need to turn the machine off (to prevent it starting to do all sorts of things as you go past other programmes) and then turn it clockwise all the way around. The reason for this is probably mostly to do with the mechanical mechanism used, but may also be because clockwise is seen as 'advancing time'. Sometimes the control is even more limited. For example, water taps in public places often have a push-on action. You push the top down and the water flows for a while and then stops. The intention is to prevent the tap being left on. Usually these types of tap cannot be explicitly turned off after use, no matter how hard you pull, the top only rises at its own rate. Electric toasters are often similar. You put the toast in and then push down the handle. After a fixed period or when a sensor thinks the toast is ready it 'pops up'. However, if you notice the toast is burning some toasters do not allow you to simply pull the handle up and instead may have a button, or even force you to wait until the timer is ready. Older tape recorders also behave in this way. You can press down the 'play' button, but not lift it up; instead you need to press down the 'stop' button and then the 'play' button pops back up!

Clearly simple physical objects tend to either be immobile in some way or allow full control. It is largely mechanical or electronic artefacts that have the strange semi-controlled behaviour like the toaster or water taps. Not surprisingly it is common to see users of these devices attempting to force the controls expecting that full manipulation should be possible.

Hidden State

In contrast to exposed state, there are controls where the physical appearance does not expose the logical state. An example is the twist control of the speaker in figure 3, which has no intrinsic on/off position given by its physical shape. The naturalness hardly exists for the user to know how exactly to manipulate the device. Therefore, this type of device requires additional features to provide further information. Sometimes this can be supplied by physical markings, for example a dot on the dial. In this case there are marks on the casing that indicate which direction to increase or reduce the volume. However there is no mark on the dial itself to see where the current volume setting is. To some extent this is unnecessary – you can hear the volume, but without an indicator of the current setting it is hard to see where in the range it is – can you make it twice as loud, ten times as loud?

Whilst in this case the lack of any decoration to clarify the state is probably an aesthetic rather than usability decision, there are times when it is essential. For example, if the dial could turn completely round several times to increase or reduce volume there would be no one-to-one relationship between location and volume. Also if the same control is used to manipulate different aspects of the logical state in different modes or there are large numbers of internal states, then it may be impossible to have a simple mapping.

Figure 3. Speaker control.

Hidden state can be exposed in two ways, pre-use and while-using. Pre-use exposure is when additional features like text, signs, pictures, and lights that can be found around or close to physical controls give suggestions or instructions to the user of how to manipulate the device control. The marks are pre-use in the sense that before actually manipulating the device the user can begin to build a mental model of the hidden physical–logical mapping (c.f. Norman, 1988). While-use exposure occurs when the act of manipulating the device makes the state or changes in the state perceived through haptic, aural or other feedback. We will return to this later when we discuss tangible transitions.

In older devices the physical control was often connected directly to the internal mechanism. As controls have become electronic this connection is often lost and this becomes apparent in hidden state. Particularly problematic are ‘touch’ buttons. For example, old tape recorders have buttons that stay depressed while the corresponding activity is occurring (play, record etc.) – strong exposed state. In contrast, touch controls initiate the change of state but have no apparent state themselves. In the case of mechanical push buttons there is at least some intrinsic haptic feedback that the press has occurred whereas capacitative or low-travel buttons may have no physical feedback whatsoever. In such cases one sees the sure sign of poor exposed state – an additional on/off light or other soft visual display!

Tangible Transitions

Some physical controls provide the naturalness of interaction by embedding a sense of feltness when manipulating the controls. This may augment exposed state or in the case of hidden state provide while-use exposure. In the example of the speaker control, the physical control has a palpable bump so that the user can feel it go past the on/off position. This does not give the user a knowledge of the current state before grasping the control, but whilst manipulating the device, the user is made aware of critical transitions.

The latter effect has been emulated in the iDrive haptic controller for the BMW series 7 (Immersion, 2003). The controller itself is a small knob with no specific markings and is used to control a variety of functions though a menu interface. Electronic haptic feedback means that as the user twists the knob to move through menu options a small bump is felt for each menu transition. This can allow the user to perform frequent selections without needing to look continuously at the screen – very important whilst driving!

Under certain circumstances, tangible transitions can become critical transitions. For instance, a critical effect will be the result of the transition the user made, especially in situations where a user is dealing with crucial operating machines or systems in laboratories, factories and others that are similar to these. Emphasising the transition of the different states makes the user aware of the changes they are about to make. It would be even more critical if the user cannot reverse the action (transition) that they just made.

Bounce Back

Some control devices return to their initial position soon after we release our fingers or hands from the knobs/buttons. For example, the on/off power button on many PCs, and on some models of washing machines – see figure 4. When we push the button in, the effect of this action starts up the system and the button returns to its initial position. This particular effect is what we call ‘bounce back’. Other examples that exploit bounce back include joysticks, mouse buttons, a mobile phone’s volume controller and MiniDisc controls.

Figure 4. On/Off control with bounce back – is it on or off now?

The bounce back control in figure 4 has aspects of both exposed and hidden states. It is exposed in that the user can immediately figure out how to manipulate the physical control, i.e. it exhibits strong affordances. Also the bounce-back on–off button has two clear states, one while the button is ‘out’ and one while the button is ‘in’. However, the ‘in’ state is a *transient state*, it only stays in the state while a finger is actually pressing it. As soon as the pressure is released it bounces back to the ‘out’ state and so there is only a single stable exposed state. This lack of a meaningful stable exposed state means that bounce-back buttons typically rely on a screen display or some other sort of indication to show the present state the system is currently in after the physical manipulation has taken place.

Because of the transient state(s) bounce-back devices have effect either at their transitions or due to the length of time they are held in the transient state. Where these natural properties are exploited bounce-back devices can be powerful, where they are used inappropriately they are confusing, even though we are very used to them.

We will explore the features of bounce back by using state diagrams of three examples that illustrate the unsymmetrical mapping between the physical and logical states of bounce-back interaction.

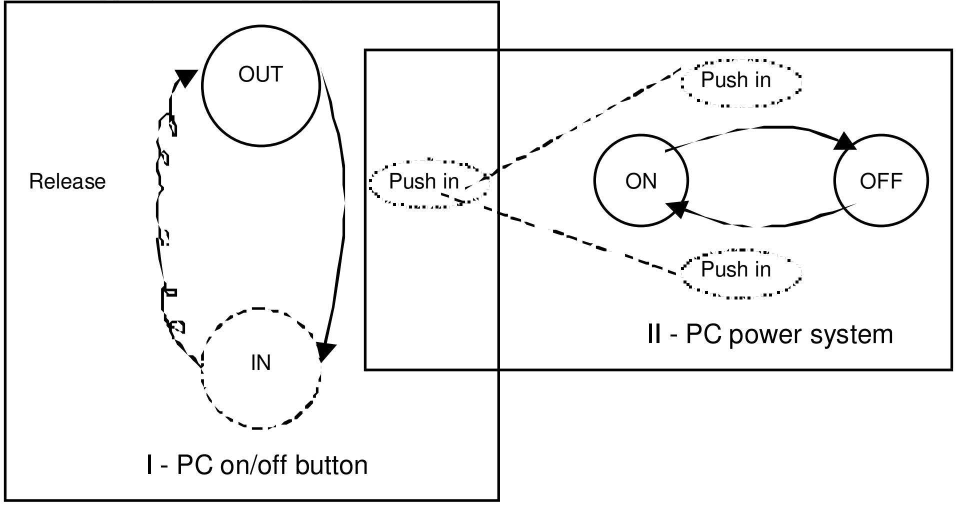

Figure 5. states of the bounce-back on/off button

Figure 5 shows the state diagram of the PC on/off power button. The left-hand box shows how the button bounces back (the spiral arrow) once the pushed-in button is released by the user. The 'in' state is drawn as a dashed circle to emphasise that it is a transient state. Instead of directly mapping to one particular logical function during the transient state of 'push in', the physical transition maps to two logical functions. It could be either turning the system on when the button is being pushed in, or shutting down the system. The releasing action does not have any impact on the logical function of the system.

Why is this design used instead of a more clear on–off switch with exposed state? There could be good reasons. For example, some PCs allow you to turn on the machine using the power button, but only have a 'soft' off invoked by software to ensure that data is properly saved. In this case the user would control the off-to-on transition, but the system would control the on-to-off transition.

In fact, the photographed system does not behave like this, as demonstrated in the state diagram. It appears to be an unnecessary case of hidden state with a characteristic power light near the button to expose the hidden state. The real reason for the bounce back seems to be aesthetic, a two state on–off switch would not look pretty on the front of the PC case!

Figure 6. MiniDisc controller

The second example is a MiniDisc controller. This has a number of bounce-back controls. There is a row of five tiny switches, each of which cycles through a different set of options. The small knob at the end is used to control the track and also volume. If the small buttons had been exposed state buttons there would not have been room for them all. Devices exploiting bounce back are often more compact and hence suitable for small devices.

The track controller at the end is even more interesting as the number of tracks depends on what is recorded on the MiniDisc. Bounce back is often used where the physical control allows the user to access a variable number of logical functions.

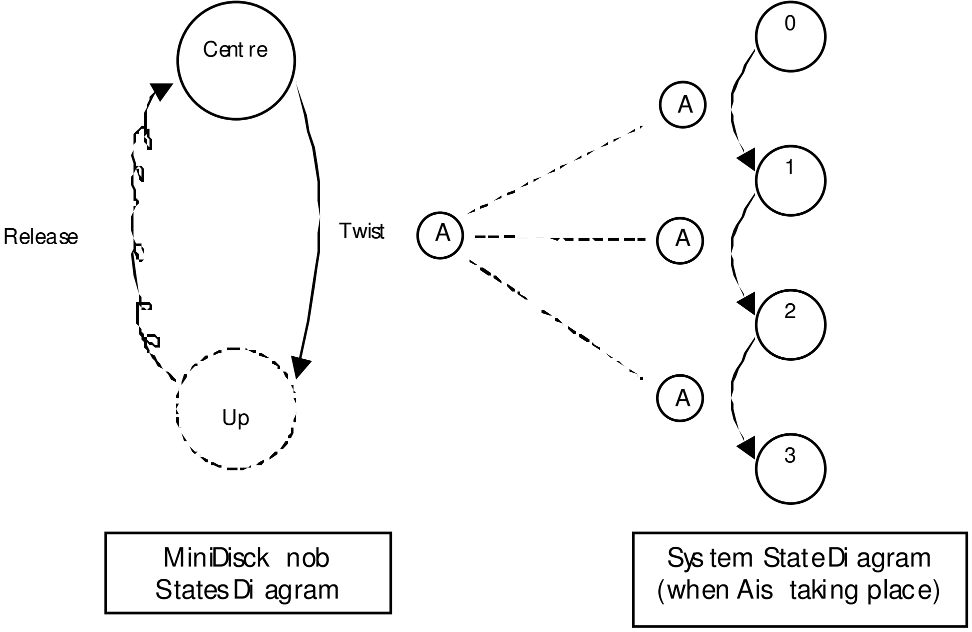

Figure 7. States of the MiniDisc track control

Figure 7 shows how the physical action of twisting the knob – A, can map to a variable number of functions, i.e. to various tracks for the different songs. By twisting the knob once, the system skips to the next song, i.e. from state 0 to state 1. When releasing the knob, the physical state is returned to its initial position, and the current state of the system remains there. The bounce-back effect, which does not affect the logical function, is understood by the user, and hence the user learns how to get to subsequent states – in this example, how to skip songs.

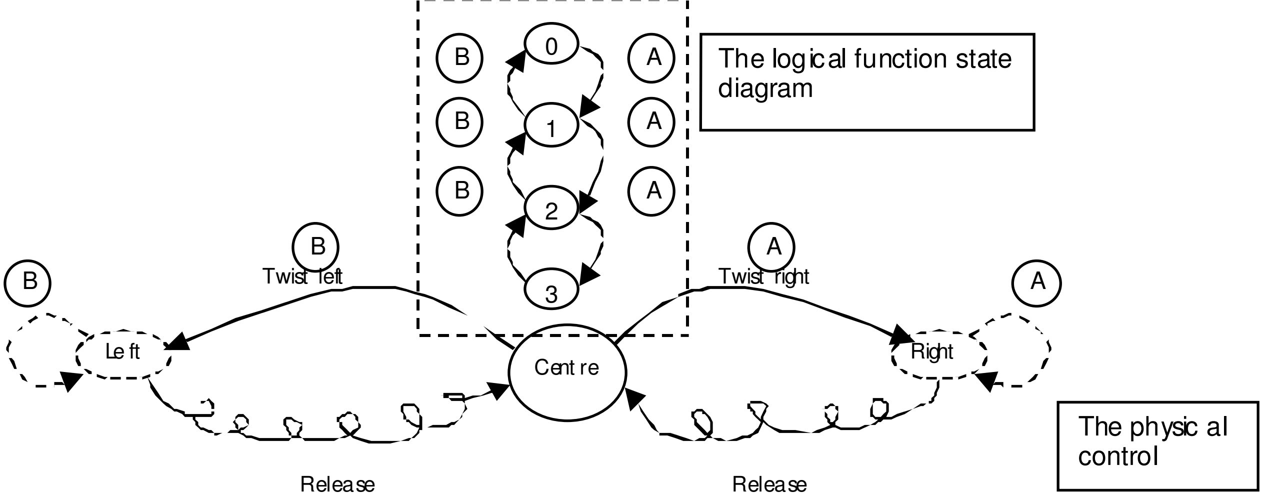

Figure 8. MiniDisc control left and right twist

In fact the full picture is a little more complex as the user can twist the knob anti-clockwise to step to previous tracks on the disk. Figure 8 shows the state diagram that corresponds to this behaviour: the knob can be turned right and left to skip to the next song(s) or to the previous song(s).

What makes this particular diagram significant is that the bounce back does not just map to a various number of states, but also is able to incorporate different functions by separating them according to the control's direction of movement. In addition to this, there is a strong coupling within the logical state of the system, i.e. the current state is ‘remembered’ despite the direction that the twisted knob may have taken. For example, when the knob is twisted to the right twice (0-1-2), and then is twisted to the left once, the current state at the end will be at 1 (2-1). Note that this is not a complete ‘undo’ if the playback is part way through a track; then turning the control right then left restarts the track rather then getting you back to where you are. We will return to this inverse action in the next section.

In addition, in figure 8 there are dashed arrows on the ‘left’ and ‘right’ states showing that the track keeps changing whilst the knob is held in the transient states. It is possible to rapidly skip through the tracks by twisting the knob and holding it to the right and left. As mentioned previously, when the knob is released, it instantaneously bounces back to the centre, due to the transient nature of the other states.

This example shows how a bounce back’s mapping of logical and physical can be varied in direction of movement and velocity. We can see the same in other controls such as a gaming joystick. In some cases (for example, video fast-forward), the longer the user holds the button/knob down, the slower or faster it changes the logical state. Where a device is being used to control the direction or velocity of the logical states, it is important to know where the ‘stationary’ position is. Note how the bounce back to the neutral centre position does this. If you simply release the control, movement stops. The bounce back also means that movement only occurs when the user is applying a positive pressure on the device – the transient state is also a tension state of the user. This makes it difficult to cause movement or change by accident.

From these three examples, we can summarise that bounce back is good when:

(i) there is a variable number of logical states
(ii) there is a large number of logical states
(iii) the physical control is applied in small devices (size)
(iv) a velocity device requires a neutral position

Finally we will look at the interaction of a piece of interactive household furniture called the Drift Table (Benford et al., 2003). This is a coffee table that comes with an aerial view of Great Britain. The movement of the map of Great Britain depends on the amount of weight put on the table, and its duration. Load sensors at each corner of the table measure the distribution of weight. If the things on the table are slightly heavier on the right-hand side the map drifts slowly, like a balloon in a breeze to the right over the aerial view and vice versa. This is therefore a very natural mapping of direction of movement.

Previously, we’ve seen how bounce back allows the user to manipulate the physical control and use it to ‘control’ the logical function(s). However, for the Drift Table, the bounce back does not occur in the physical appearance of the table, but on the load sensors. They do in fact give very slightly depending on the weight, but not noticeably. The only way to see whether the weight distribution of objects is neutral is to watch the view to see if it slowly changes. Furthermore, the table does not give the user any direct control or indication of overall location, just the speed of the movement and its duration. In fact where it was deployed in a home the user kept atlases nearby in order to work out where the table was!

This appears to suggest the Drift Table is a very bad example of a physical control. But in fact the intention of Drift Table is not functional but aesthetic and ludic – it is a form of play! The natural mapping of direction of pressure to direction of movement while you are explicitly ‘controlling’ allows skillful activity, but when unattended it ‘drifts’ and gives a sense of happenstance.

Inverse Actions

We return now to the speaker volume dial (figure 3). As with most dials, turning the rotary knob clockwise increases volume, turning it anti-clockwise decreases volume. Similarly with the MiniDisc control, twisting the knob right advances the track, twisting it left moves the track back (figure 8). These inverse effects, like the dial, exploit natural physical inverse actions – if you push a cup across the table you can also push it back in the opposite direction. Until it falls off the edge, opposite pressures have opposite effects.

Figure 9. Volume control – linked buttons.

Just as in graphical user interfaces, the existence of inverse actions acts as an ‘undo’ and so reduces the risk of exploration (Dix et al., 1995). However with physical devices it is not just that an inverse exists but that the inverse exploits a natural physical inverse such as push/pull, twist clockwise/anti-clockwise, or push up/down. In the best cases this is intrinsic to the device (as in the speaker’s rotary knob), but may also be made apparent using visual or tactile decoration. Figure 9 gives an example of the latter where two buttons are clearly linked by being ‘yoked’ together.

Inverse action is especially important if the user does not have a perfect knowledge of the physical–logical mapping. This allows the user to experiment with the physical control and find out the logical functions the control supports, by reducing the chances of getting the actions wrong.

A particular case of this is when a physical control may manipulate more than one logical function. The user can discover the different logical functions that lie under the physical appearance by inversing the actions. For example, some mobile phones have a small ‘scroll’ button that can be pressed up or downwards. This may control volume whilst in the middle of a call or scroll through lists when searching the address book. Although this sounds very confusing it does not prove to be in practice. There is an immediate visual or audible feedback of the effect of the control and if the effect is not as desired the natural inverse makes it easy to correct.

In some cases, inverse actions adopt the hidden state’s additional features in order to provide additional information of the logical function that the physical form supports. The speaker control, which has been described earlier, has around it painted dots of different sizes that increase from one end to another, indicating to the user that the volume increases as he/she turns the knob clockwise, and reduces in the opposite direction. This additional feature with the volume of sound coming from the speaker provides some sense of coherence between the physical state and the logical function.

Inverse actions, in some other cases, work together with exposed state to deliver natural interaction, the tuning frequency of an old radio for example. Besides the manipulation of tuning the frequency by rotating the knob clockwise and anti-clockwise, it also exposes the position of the frequency that is pointed by a vertical line from a display as the user rotates the knob.

The naturalness of inverse actions’ interaction may only be achieved when the user gets immediate feedback – for example, the sound of the speaker increasing and decreasing. Under certain circumstances, feedback may be delayed, for example in an electric cooker there is a lag due to the time it takes to heat the metal in the cooker’s rings. As we discussed, temporal locality is one of the features of physical interaction, and not surprisingly these delays are not dealt with naturally. For example, many people will adjust central heating beyond the desired temperature to ‘heat the room more quickly’. So strong is this effect it even applies to those who understand the system well and know it will not have the desired effect!

Compliant Interaction

The rotary knob on the washing machine (see Figure 10) is not just a good example of exposed state, but also exhibits symmetry of interaction. The user sets the program by turning the dial, but the system also turns the dial itself as the program advances.

Figure 10. Washing machine and its control.

Exposed state and compliant interaction differ in that compliant interaction has some kind of mechanical movement that advances when the program advances in the same way as the user would interact. A simpler example is the on/off switch on some electric kettles. This can be moved up and down by hand, but when the kettle boils flicks to the off position. Old tape recorders also did this and the ‘play’ button would bounce back up when the tape reached the end.

Note how the kettle’s on/off switch differs from a simple on/off switch such as a light switch. In the latter there is no control involved from the system, it solely depends on the user's interaction.

The state diagram in Figure 10 illustrates a simplified version of the washing machine control. Because it has an exposed state the internal and visible states coincide, so these are not distinguished as they are in Figure 2. The plain and dashed arrows show the user and system control of the device respectively. It is clear how these coincide except in that the system cannot turn the washing machine on from the stop state!

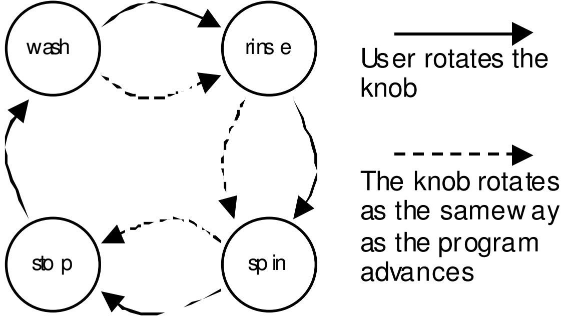

Figure 11. State diagram of washing machine.

Compliant interaction means that the user can easily learn the relationship between the state of the control and the state of the device. The naturalness of compliant interaction enables expert users to use the device to exert fine control over the system's action. This is evident in expert washing machine users who can intervene in the washing program, such as skipping parts of the program, and start in unconventional places, as they learn how to fine-tune the device.

In principle this control could give rise to confusion as turning the dial does not complete the wash cycle that the system has been programmed to do. In practice this does not seem to occur with washing machine use or the electric kettle (switching it off is not assumed to have magically boiled the kettle). However, this does appear to be a potential danger for less well-understood applications.

Note that compliant interaction is named from compliant motion as used in robotics. This refers to things like a tapered screw where the action of putting it into the hole is guided by the physical resistance of the screw. If the screw is placed slightly to one side there is a natural force pushing it into the right place. In contrast without the taper a slight miss means it just doesn't go in. The physical properties of the screw make automatic assembly easy.

fluidity of novel interactions

We will now consider how these concepts of physical– digital interaction can be applied to a particular novel input device, the Cubicle, before looking more generally at tangible interfaces in the next major section.

Note that whereas the previous discussion has been about analysing an existing device with a given physical–logical mapping, here we are considering a novel device and using the conceptual categories to suggest appropriate mappings.

Cubicles

Cubicles are cubes of various sizes that are instrumented with different kinds of sensors so that properties such as orientation, location etc. can be detected (Kortuem et al., 2003). These sensed attributes can then be used to control various devices.

Cubicles are being developed as part of the EQUATOR project investigating the integration of digital and physical life and use Smart-It technology to allow rapid prototyping of sensor-based systems (Smart-Its, 2003).

One example of a Cubicle is of a small cube with sides approximately 3 in (7.5 cm) that is used to control the feed into a large situated display in the seating area of the Lancaster Innovative Interactions Laboratory. Each of the sides is labelled with one of the possible feeds into the display: TV tuner, laptop cable, fixed computer, etc. The cube sits on the coffee table and is simply turned over to select a particular feed. Inside the cube is a standard Smart-Its main board with micro controller and wireless communications. A small Smart-Its plug-in module has accelerometers to detect orientation.

Other Cubicle designs have included much smaller or larger cubes and also cubes with different physical properties: soft ones that can be squeezed, furry ones that can be stroked. Separate work has investigated how these factors affect the way people choose to interact with Cubicles (Sheridan, 2003).

Visible State

In the screen-control Cubicle there is a very clear one-to-one mapping between the visible state of the Cubicle (the uppermost face) and the logical state of the situated display. However, like an on-off switch, this only allows the control of six-state applications. Also the unique labelling of the sides mean that it is largely a single purpose device. It is interesting to note however how subtle changes in the decoration of the Cubicle change the number of visible states and the way they can be used in interaction.

If a labelled Cubicle is placed on a flat surface and there is no preferred direction on the surface, then there are only 6 states corresponding to the uppermost face. In a situation like the communal coffee table this is exactly what we have.

If, however, there is a preferred direction, perhaps the direction of the display, then we can also distinguish the orientation of the cube. In principle, there are 360 degrees of orientation that could be detected, and if the Cubicle were a flat plate with an arrow inscribed on top, then these would all be potentially usable.

In fact, the strong rectilinear visual affordance of the cube suggests that states with a face or possibly corner facing towards the screen are preferred, so, for illustrative purposes we'll consider the cube as 'normally' in aligned face positions which means that strictly there are 24 states: 6 possibilities for the uppermost face and 4 further orientations.

In the case of the screen controller the fact that the faces were labelled with text (which suggests a single ‘correct’ orientation) and the lack of relation between the sides meant that this was effectively reduced to 6. An alternative decoration of the sides, for example, a squared-off globe would suggest treating the orientation as significant and hence allow all 24 states to be used.

Both the text labels and globe decoration are very much single purpose. One of the goals of Cubicles is also to use them as generic controllers, so we also consider more open decorations.

One extreme is a fully labelled cube, for example with each side a different colour, or as in the case of a normal die, a number. Here all 24 states are in principle available, although in the case of the die there are strong cultural suggestions that one should consider it a 6 state device.

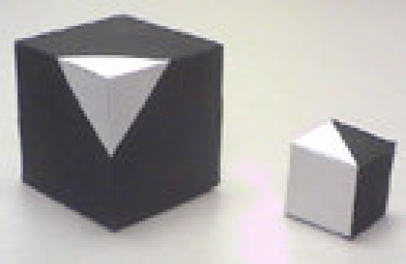

Figure 12. Coloured Cubicles

More minimal labellings include colouring one half of the cube so that one side becomes significant or painting one corner only (see Figure 11). In the former case there are 6 states (painted side down or up and 4 'sideways' states) although there are strong visual suggestions to regard these as 3 major states: face up, face down and sideways, with 4 orientation 'sub-states' when sideways. When the corner is painted there are 8 possible states although there is some suggestion that the corner could be used as a pointer, so possibly this may be used as a 360-degree controller.

Notice that some of the visible states of the Cubicle are given by its physical properties, but others depend on cultural or contextual factors.

Inverse Action

The simplest decoration of all is an entirely unlabelled cube, which has no distinguishable states whatsoever. Although this sounds not very useful it means that it can be used in the same way as a mouse or joystick can, where the absolute location is not important: it is the relative movements (rotating, twisting) that are significant.

For example, given a menu structure, tipping the cube from side-to-side can be used to cycle through options and tipping it forward can be used to select an option.

Depending on the sensors in the Cubicle, slowly tipping in a direction can be distinguished from a quick 'flick' in a direction or actually turning in the same direction. The desire to return to the 'natural' orientation of the cube with flat face up, suggests that the tipping action, rather like a sprung joystick, affords more continuous velocity effects, whereas a flick or turning of the face is a discrete action, more like cursor keys. Whilst movements like this can be used to make a Cubicle into a universal controller, there are problems of registration. Which way is 'forwards'? For the users this would probably be tipping the cube away from them, but if the Cubicle does not have any absolute location or orientation sensors (which are more difficult than tilt sensors) then this may not agree with the Cubicle's 'own' idea of 'forward'. Also a new user coming to the Cubicle, perhaps finding it on a coffee table, would need to learn the interactions.

Just as in the appliances we have studied, these are exactly the situations where natural inverse actions can help. The use of opposing directions for moving in different directions through a menu list means that tipping the cube in one direction can be undone by the opposite movement. Similarly if tipping forward is selection of an alternative, tipping backward should be the 'go back' action. So long as this is the case a user picking up the Cubicle in the 'wrong' direction can learn up the effects and if desired then re-orientate the Cubicle. Where the inverse action breaks down, for example when selecting an option has an irreversible effect, then some sort of orientation independent action, such as a sharp tap of the Cubicle, will be necessary.

Compliant Action and Haptic Feedback

As we have seen compliant action is comparatively rare, but very powerful when used appropriately as in the washing machine dial, or on-off buttons on electric kettles.

Cubicles are predominantly passive and untethered input devices, so do not naturally suggest control back from the application. However, some potential designs have a small display on each side. This would allow interactions where the user could rotate a particular face upwards, but this could then change over time under the applications control. For example, if the Cubicle is used to control a menu system, then the system could gradually 'fall back' into a standard state after a period of inaction.

Haptic feedback is even more problematic although a heavy gyroscope could be used to give controllable resistance to rotation or even used to autonomously flip the cube!

More practically a ball-bearing moving within a face-centred octahedral void within the Cubicle would enhance the 'joystick' effect – as one tipped the cube, even in mid air, it would be trying to get back to a face down state. Alternatively having a ball bearing roll within the cube itself would tend to suggest holding it with a corner pointing down and hence radically change its interaction affordances.

Tangible Design

Existing tangible devices

It is clear that good design of day-to-day appliances should offer benefits for the design of tangible devices. Having understood the principles of physical design, we now look at examples of tangible devices that embody the principles, and look at where in the design space of tangible interaction the principles can contribute to improving design.

Collaborage (Moran et al., 1999), Marble Telephone Answering Machine (Crampton, 1995) and Illuminating Light (Underkoffler, 1998) are good examples that exploit the *exposed state* principle. Collaborage uses badges, which are the tagged tokens that can be moved between the In/Out columns and on the In/Out/Away board located in the hallway to trace the users' positions. The changes are tracked by the system and are updated in the database. In the Marble Telephone Answering Machine, a marble is used as the device control to play the message by dropping the marble into an indentation in the machine. The marble is also used to dial the caller automatically by placing it onto the augmented telephone. Of the three examples, the Illuminating Light exploits the exposed state principle the most. Physical models of optical elements (prism etc.) are used to create a simulated optical layout. The system then simulates the corresponding light patterns. The simulated optical layout is not just about control and feedback, but is a direct representation of the actual thing.

As we already know, to ensure the natural interaction exists in *hidden state*, we have to provide additional information in order to assist the user to understand how to manipulate the device. In tangible devices, the situation is a bit different; the examples that follow seem to be using hidden state not because of the constraints of the interface but for specific purposes. The Storytent by Fraser (Fraser, 2003) uses UV light to reveal the hidden writing on an electronically tagged paper to make the experience of unearthing the logical functions (digital) more interesting. Rather like the Drift Table uses a 'bad' neutral state for ludic effect the Storytent uses hiddenness in an exploratory experience. Super Cilia Skin (Raffle, 2003) is also focused on the aesthetic. It is a computationally enhanced membrane, which is actuated by electromagnets, coupling together tactile/kinaesthetic input with tactile/visual output. It attempts to make the tangible-logical mapping more exciting. Both examples have aspects of natural interaction as the UV light directly points onto the surface of the turntable, and the tactile aspects of the membrane draw the users to touch it. Hartson calls these sensory affordances (Hartson, 2003).

Most tangible devices exploit *inverse actions*, which allow the users to undo and reverse the actions, for example, Phicons in metaDesk (Ullmer and Ishii, 1998) and Senseboard (Jacob et al., 2002). At one level the invertibility is there by virtue of the physicality of the tokens being used to control the manipulation. However, it is not a necessary property of the augmented system but depends on there being a functional relationship between the state of the physical tokens and the state of the logical system. For example, Senseboard has been used to organise conference paper sessions. It is designed to show conflicts, but an alternative design might have had the users manipulating just some of the papers physically and others being reorganised by the system to maintain constraints. When a paper is moved by the user the system would reorganise the rest, but then it could easily be the case that moving a paper and then moving it back did not lead to the same overall situation. The same thing occurs with a word processor if you move the cursor down and then up when at the bottom of the screen. It is relatively 'easy' to make tangible interfaces obey the inverse action principle, but still needs to be considered explicitly in design.

Although these systems support inverse action, they do not have a real 'undo' in that they do not provide or represent the actual "path" of movements that have been made. Thus the user performs the reverse action(s) depending solely on what they can remember. One example that actually records and displays the history of the movement to allow inverse action is Outpost (Everitt et al., 2003), which is about organising information of Post-it notes that are used as the physical media. Note that this exposes several purposes of 'undo' or invertible actions in GUI systems that are usually elided: (i) to correct slips immediately, (ii) to allow 'homing' actions such as mouse movement or rapid cursor movement, (iii) to allow low risk exploration of alternatives, (iv) to 'turn back the clock' when after several actions some problem is found. In a GUI (iv) requires some form of multi-step undo menu, (ii) and (iii) are typically achieved using invertible actions, although using an explicit 'undo' button for (iii) is possible, and (i) may be achieved using either invertible actions or undo depending on the erroneous action. However, (iv) is most needed when there are large amounts of hidden state, or complicated computations so less relevant for TUIs. The focus in tangible interfaces is less about backward error recovery, restoring a past state, and instead more about forward error recovery, moving on from where you are towards a goal (Abowd and Dix, 1992).

It was quite difficult to find examples of tangible devices that have all of the properties that make one have *compliant interaction*. Most of the existing tangible devices let the user easily learn the relationship between the physical and logical states that enable the user to have control over the system actions. Often these system actions are virtual (e.g. projections as in Illuminating Light), but there are examples of physical effects being produced. For instance, Actuated Workbench (Pangaro et al., 2002) is a device that uses magnetic forces to move objects on a table in two dimensions. The user controls the graphical output by manipulating the physical input, which is composed by positions and movements. The input is tracked and responded to by the workbench. Pinwheels (Dahley et al., 1998) use an ambient display that shows the presence and state of digital activity within a space through changes in airflow. The speed of Pinwheels is based upon their input information source – users' activities. However it is rare to have the same physical effect controlled by both user and system. The only example that we have found conforming to compliant interaction principle is Rototack (Wrensch et al., 2000). Besides allowing the user to have control over the system's action, it also exhibits symmetry of interaction. Rototack is a small computationally-enhanced tack that provides a source of programmable rotational motion provided by a small stepper motor. The user has control over the tack, i.e. by writing a program for the tack. The tack then in response runs its program. The user can stop the program at any point; even this means that the tack has not yet completed its cycle.

The above examples show that the physical design principles can be used to analyse existing tangible devices and expose where they exhibit natural interaction. We now will see how these findings fit more broadly within a tangible user-interface framework.

A TUI framework

The TUI framework by Koleva et. al. (2003) is based around the degree of coherence between the physical and digital objects. The framework places TUI objects into six proposed categories of TUI types that depict the relationship of physical and digital objects. These categories are positioned along a 'coherence' scale based on five properties that are used to describe the physical-digital links.

The TUI categories are as follows moving from low coherence to high coherence:

- *General-purpose tool* – a tool that gives the user a choice to manipulate any one of many digital objects and perform different transformations. It establishes the weakest level of coherence
- *Specialised tool* – objects that have a more specialised function, yet still temporarily connect to potentially various digital objects
- *Identifier* – interface objects that act as bookmarks for retrieving computational artefacts
- *Proxy* – interface objects that are of proxy category are more permanently associated with, and allow a more extensive manipulation of their digital counterpart
- *Projection* – digital artefact that is seen as a direct representation of some properties of the physical object. Its existence is dependent on the physical object
- *Illusion of same objects* – this category has the strongest coherence. Objects that fall into this category give the illusion that the two coupled objects are one and the same

The physical-digital links can also be described in terms of their five properties:

- *Transformation* – this describes whether the effect mediated between linked objects is literal or transformed
- *Sensing of interaction* – this describes what interactions with the interface object and its surrounding environment are sensed and transmitted to the destination object
- *Configurability of transformation* – this describes whether the transformation mediated between two linked objects remains fixed for the lifetime of the link or whether it is configurable over time
- *Lifetime of link* – this describes for how long a physical and a digital object remain linked
- *Autonomy* – this describes to what extent the existence of the destination object is reliant upon the existence of the link and the source object

Although individual TUI objects and applications exhibit differing spectra of properties, there is a general correlation between the scales giving rise to an overall 'level of coherence' continuum. This is illustrated in figure 13 and in Koleva et. al. (2003) a range of TUI applications and devices, including most of those examined in the last section, are placed into the categories.

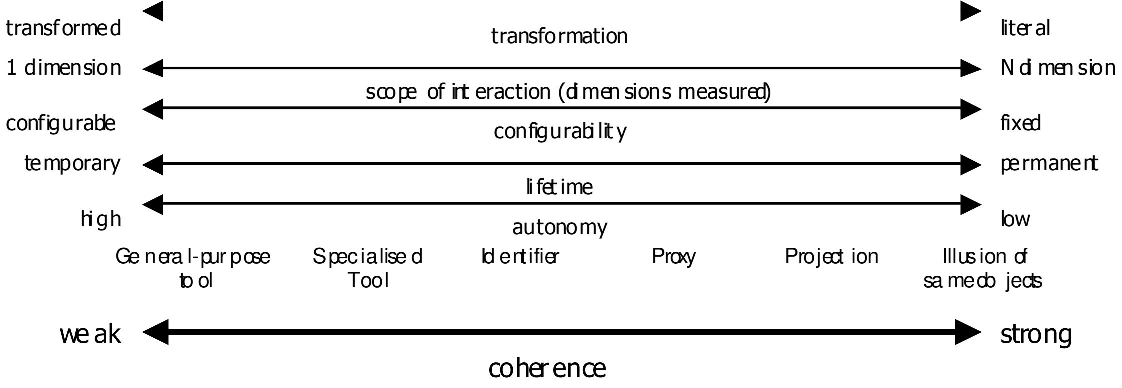

Figure 13. TUI categories along the coherence continuum (from Koleva et. al., 2003)

Impact on TUI framework

Just as individual TUI objects vary in their spectra of coherence properties, they clearly also differ in the extent to which they satisfy the various physical design principles. In general, high coherence and satisfaction of 'good' principles are related; however, some of the principles seem particularly related to particular categories. So, we will explore the findings from the previous sections against the properties and categories of figure 13.

Exposed State – Collaborage (identifier), Marble Telephone Answering Machine (specialised tool), Illuminating Light (specialised tool), Actuated Workbench (proxy), Pinwheels (projection) and Rototack (projection) all exhibit exposed state. However, when we categorise them according to the TUI categories (see brackets) the categories that exhibit exposed state the most have both strong physical-digital links and natural interaction and range from the 'proxy' category, to 'illusion of same objects' category. In addition, the examples that fall within these categories all have fixed configuration and permanent lifetime. The stronger the coherence, the more dependent autonomy the objects have (Rototack has dependent autonomy, whilst Actuated Workbench is autonomous) and of course exposed state is most effective with a fixed relationship between device state and logical state.

The Cubicle used to control the feed into the situated display in the seating area has each of the sides labelled with the possible feeds into the display. It thus exhibits the fixed configuration property suggesting the proxy category. However, this relationship between labels and functions is highly symbolic and is also malleable in the long term, rather like written labels on function keys on a keyboard. The Cubicle thus has a 'feel' more of a specialised tool. Although it has an exposed state the affordances are exposed linguistically rather than through its intrinsic properties.

Hidden State – Identifier, Specialised tool and Generalised-purpose tool categories tend to exploit the hidden state principle because they are likely to be mapping the same physical device to different logical states. The Storytent for example, belongs to 'specialised tool', whilst the Super Cilia Skin belongs to the 'identifier' category. The nature of these three categories is that the mapping of the representation of the physical and digital is not that direct, comparing to the proxy categories and beyond. The weak coherence that the objects exhibit, for example, the Storytent, is also indicated by fixed configuration, temporary lifetime and autonomous properties.

A different experimental use of the Cubicle as AV controller uses an unlabelled cubicle and gestures to navigate between feeds and to control options for each feed (e.g. navigate in web browser, adjust volume of video playback, etc. This is clearly an example of hidden state and more clearly belongs to the specialised tool category as it temporarily connects to many different digital objects, for example, TV tuner and fixed computer. Being able to consecutively link to different digital objects in the lifetime of the application shows that the Cubicle has the temporary lifetime property. The cubicle also embodies the fixed configuration property.

Note how the Cubicle's classification depends on its visual decoration and application context. Both the physical interaction principles and the TUI framework properties are not about a device in isolation, but about the device in an interaction context.

Inverse Actions – All tangible devices from 'identifier' category to 'illusions of same objects' category seem to exploit the inverse actions principle. Howver, previously we have seen that most of the tangible devices that fall in these categories do not provide the user with the actual 'path' to perform undo/redo actions, but rather a more local ability to simply 'move back'. This gives rise to a strong physical-digital mapping and exhibits natural interaction. For example, Outpost, in particular, has a literal transformation in that its physical movement gives an effect of moving the digital object, with permanent lifetime. As we discussed when looking at consumer appliances, the inverse action principle is very important when the user does not have a clear idea of the effect of the action, allowing exploratory interaction; that is where configurability is high and lifetime low. Paradoxically inverse effects are exhibited most in high coherence objects, but perhaps required most in low coherence.

Compliant Interaction – As we saw, compliant interaction is related to exposed state, which is common in TUI applications. However, in addition to this, those tangible devices that exploit this principle show a strong and symmetric coupling of the physical and digital link. The examples that most closely exhibit this, the Actuated Workbench, Pinwheels and Rototack, are of the 'proxy' and 'projection' categories. In general, the tangible devices that fall in 'proxy' category to 'illusion of same object' category are most likely to exhibit compliant interaction. However, as we have seen few of the tangible devices exhibit really symmetric interactions, due partly to the difficulty of engineering haptic feedback on untethered devices.

Figure 14 shows the property settings and level of coherence from figure 13 amended based on the impacts made by the physical design principles. From the diagram, we can conclude that the stronger the coupling of the physical and digital, the more natural the interaction.

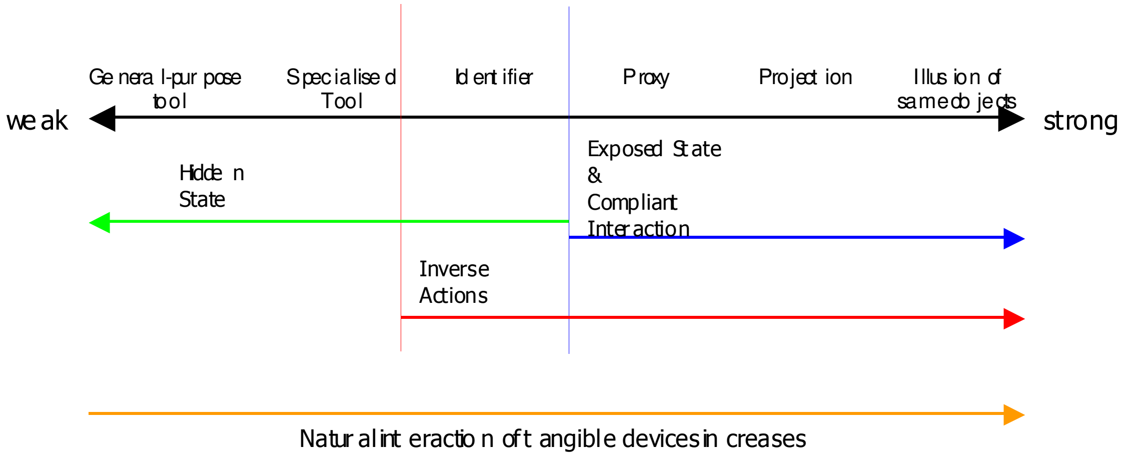

Figure 14. principles of naturalness and levels of coherence

Discussion

In this paper we have explored the thesis that the design features of current day-to-day appliances can be used to inform next generation interfaces. We have focused on the aspects of the physical controls that correspond to natural physical interactions in the world. Studying these day-to-day devices has led to a number of principles and issues of physical interaction. This has enabled us to examine a particular novel interaction device, the Cubicle, and also to see how these principles correspond to generic categories of tangible interface object.

Table 2 summarises some of the broad guidelines that emerge from this discussion although we would not regard these as definitive. These guidelines emerged from examining the day-to-day artefacts and were largely followed by many of the tangible interfaces. Amongst the issues that arose a few are worth noting especially.

Exposed state and inverse action seem to almost follow by course from the physicality of tangible interface objects. However, this only follows for their own physical state and not the logical functions and state influenced by them. These need to be explicitly considered during TUI design not left to chance.

Compliant interaction seems to be extremely powerful where it is employed in consumer devices leading to clear state, ease of discovery and natural control. It effectively emulates the symmetry when we as people collaboratively manipulate an object with each other. However, the difficulty of symmetric haptic feedback means that few current interfaces make use of this powerful technique.

Although some of the principles are generally 'good' ones: exposed state, inverse action, compliant interaction; there are circumstances where they are and should be broken. For example, if there are many states or a variable mapping then exposed state is not possible. Furthermore, we saw that 'bad' interaction is sometimes good interaction for ludic purposes!

Some broader methodological issues also emerge from this work.

We have seen that many of the physical design principles and the TUI coherence properties relate not just to a device in isolation, but instead to a device with an associated physical–logical mapping. Because of the experimental nature of tangible interfaces and more broadly ubiquitous computing, it is frequently the case that a device is used in one application only. It is therefore easy to elide the intrinsic properties of a device or mode of interaction with the application for which it is used.

Our investigative approach has combined what can be thought of as an epidemiological study of devices that are extant, more psychological analysis of device use, common knowledge about good and bad design and detailed formal analysis. Most of the devices we have studied exhibit several 'good' and 'bad' properties and the effectiveness is a combination of designed and accidental properties of the device combined with skilled human behaviours arising from cultural, learnt and innate causes. To attempt to disentangle completely all these issues would not be productive for design purposes and our multi-paradigm approach has allowed a broad analysis. However, attempting to obtain some purchase on the complex interactions and trade-offs of physical design does lead not only to insight but also potential directions for more detailed experimental studies of individual effects.

We intend to continue to explore these issues and hope that this paper will also inspire others to look more closely at the everyday world around them to inform and inspire the effective design of novel interaction.

Exposed State	- The ideal design - to provide simple interaction, i.e. one-to-one mapping of logical-physical - to provide more complex interaction (c.f. compliant interaction)
Hidden State	- when there is some kind of constraints – limited space / restricted interface - must supplement the device controls with additional information - making interaction interesting/exciting
Inverse Action	- to allow undo, or backward action to recover immediate mistakes - to allow exploration of the device, esp. when the physical–logical mapping is variable - to allow overshoots in 'homing' or rapid target selection tasks
Compliant Interaction	- to express the meaning of the states of a control (because it shows current state) - to expose the physical control's movement (because it shows changes) - to allow the expert users to have control over the system (e.g. intervene in the programme)
Bounce Back	- to map to a variable number of states - to map to large number of states - when there is limitation of space - with a neutral position for direction of movement or velocity control
Tangible Transition	- when designing haptic interaction - to make the users aware of the transition that they are making - when the user can only glance when manipulating the control

Table 2. guidelines for tangible control

ACKNOWLEDGMENTS

The study described in this paper was supported by the UK EPSRC funded Equator IRC (www.equator.ac.uk) and by a Malaysian Public Services Department and University Putra Malaysia PhD Studentship.

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