Affordance-Based Design of Physical Interfaces for Ubiquitous Environments

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Abstract. Physical interfaces have been proposed as a way to realize natural interactions with ubiquitous computing environments. The successful design of such interfaces requires design approaches that integrate aspects of our world which are usually treated separately in traditional system development approaches. This paper describes a design approach based on Gibson concept of affordance. We demonstrate an experimental method for studying object affordance and show how it can be applied to the design of a concrete physical interface artefact.

1 Introduction

Ubiquitous computing promises a computing infrastructure that seamlessly aids users in accomplishing their tasks and that renders the actual computing devices and technology virtually invisible and distraction-free. Mark Weiser formulated this vision by describing a computer "so imbedded, so fitting, so natural, that we use it without even thinking about it" [1]. One way of realizing this vision is by building task-specific information appliances [2] and physical computer interfaces [3,4,5]. In fact, in recent years a number of toolkits kits for physical computer interfaces have appeared, including Phidgets [6], iSuff [7], SWEETPEA [8], Papier-Mâché [9] and MetaCricket [10]. While these toolkits provide adequate guidance during the construction phase of a physical interface, they do not provide any help in how to design a usable and intuitive physical interface.

The key idea of physical interfaces is to capitalize on our familiarity with the physical world. The design of such interfaces requires design approaches that incorporate different aspects of our world that are usually treated separately in traditional system development approaches. In particular, the actual physical form of an interface has rarely been considered in the context of physical interfaces and ubiquitous computing. This is in stark contrast to the fields of ergonomics and industrial design which have long recognized the importance of physical form for creating usable and appealing artefacts and products. One of the first researchers to systematically investigate the relationship between physical objects and people was the perceptual psychologist J. J. Gibson who introduced the theory of *affordance* [11]. This theory states that physical objects suggest by their shape and other attributes what actors can do with them. Yet, theories of affordance are predominantly used as analytical tool and

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applied after the design stage. We believe that a thorough investigation of object affordance should be a key component of the physical interface design process.

In this paper, we present our experiences with an affordance-based design method. Our approach focuses on three key dimensions: *affordance*, *capability* and *control.*

- *Affordance*: We propose that the design of physical interfaces should begin with an investigation of the object itself in relation to human perception and motor skills, because physical form fundamentally shapes the kinds of interactions users can perform. The goal is to identify the types of actions humans can perform on an object. We formulate the results of this study as *non-verbal dynamics*, a vocabulary of significant object-specific manipulations such as gripping, squeezing, rubbing and rotating.
- *Capability*: The second component in the design process is the investigation and specification the technical capabilities of the interface artefact in terms of sensing and actuation. Technological capabilities affect which object manipulations can be recognized and how feedback is realized. As well, technology affects the form or physical properties of the device, such as shape and size.
- *Control*: The ultimate purpose of a physical interface is determined by the control it gives users over an application or service. For example, a mobile phone interface needs to provide controls for initiating and terminating a call. The set of controls needs to be mapped to non-verbal dynamics and realized by object capabilities.

We believe that these design dimensions are not separable, but must be investigated together. Understanding and applying the relationships between these three dimensions is the key to modelling and creating computer interfaces that are useful and appropriate for the ubiquitous world.

In the remainder of this paper we present our experiences in applying affordance-based design to the design of a concrete physical interface artefact for a mobile phone. We focus on one particular object type, namely the cube. We demonstrate an experimental method for studying the affordances of objects and use the results to inform the design of the technology and interaction aspects of the interface artefact. Finally, we discuss results of a usability study and relate our approach to existing design frameworks from tangible and physical computing.

2 Case Study

To illustrate our affordance-based design approach we chose to design a physical interface for a mobile phone. As physical form we chose a six-sided cube. The goal was to design an interface that makes use of basic object manipulation skills rather than buttons. The cube interface is only used for input; output is presented on a separate (wrist-mounted or heads-up) display. We refer to our interface artefact as *Cubicle*.

The decision to use a cube-shaped object was based on the fact there is extensive prior work on using cubes as tangible or physical interface objects (for example BUILD-IT [12], Flip Bricks [13], ActiveCube [14], Cognitive Cubes [15], Navigational Blocks [16] and CUBIK [17]). While many experiments use six-sided objects, very few explain why they chose this particular physical form over others, and none reports on experimentation with other shapes. One of the reasons cubes are attractive is that most people have an intuitive and immediate understanding of how it can be manipulated [16]. While some studies report that cubes provide a higher flexibility in operations [18, 19] there is little discussion about why cubes are particularly well suited for this capability. Ullmer [20] states that cubes were chosen because of the intended application, yet there is no discussion as to why cubes offer an advantage as compared to other shapes. Cohen et al. [21] alludes to Scrabble™ as a possible influence for the design of the "dominos" in LogJam but does not explicitly state this. While Rekimoto [29] discusses evaluating various shapes for the ToolStone application, he leaves this open as a future research direction.

The reason to use a mobile phone as application was based on the fact that most users are familiar with it. A mobile phone provides a familiar context for both a large majority of the local population and our design team. Rather than designing a complete interface for a fully functional phone we decided to concentrate on core functions of everyday mobile phone use. Using informal discussion and self-examination, we determined that the most common uses of a mobile phone are to make and receive phone calls as well as checking left messages. Furthermore, we selected call making rather than call receiving as our core task, as it causes users to interact more physically with the phone. Additionally, we discovered that a good number of people had a need to adjust the volume of their phone according to context, so we included this functionality in the design. We finally settled in the following functional repertoire: 1) *select entry in address book and make phone call*, 2) *select message and listen to it*, 3) *switch device on*, 4) *switch device off*, 5) *turn volume up*, and 6) *turn volume down*.

3 Studying Affordance

Our design process begins with an experimental investigation of cube affordances. The study focuses on human perception and motors skills and is an attempt to understand how people "naturally" interact with physical artefacts. Using the cube as example, we set out to explore the following questions:

- How do physical properties (such as size, shape and form) affect affordance?
- What types of manipulations are possible with cubes of various designs?
- What types and range of actions do humans naturally perform?

The primary goal of the affordance design study was to identify the types and range of actions humans naturally perform on an object. Our underlying hypothesis is that each artefact has its own *non-verbal dynamics* [31], a set of natural and object-specific object manipulations such as squeezing, rubbing and rotating. Furthermore, we expected to be able to group cubes according to non-verbal dynamics. To limit the scope of our investigation, we chose to ignore gestures such as waving and concentrate on grasp.

3.1 Study Overview

To measure the variance of non-verbal dynamics we designed several cube-like artefacts (Figures 2a - f).

Each artefact had a unique set of characteristics:

- Size: finger-sized cubes (Figure 2a), various small, medium and large cubes (Figure 2b).
- Texture: cube covered in various smooth (paper, lacquered) and rough (burlap, textured card) materials as well as squishable (Figure 2c) and organic, clay cubes (Figure 2f).
- Colour/Pattern: cubes with 2 colours placed in different arrangements on each face of the cube to create various patterns (Figure 2e).
- Weight: from heavy clay cubes (Figure 2f) to light paper cubes (Figure 2e).
- Shape: rhomboid (Figure 2f), star (Figure 2d).
- Sound: clay beads were added inside various cubes. As well, the squishy cubes caused a wheezing sound when being squeezed (Figure 2c).

We realized that some of our cubes were not cubes at all but rather "deformed" cubes, such as the star and rhomboid. However, we felt that it was necessary to include shape as one of our variables.

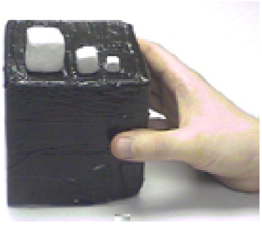

Fig. 2a. Finger-sized cubes resting on a large cube

Fig. 2b. Large, medium and small sized cubes

Fig. 2c. Large-sized squishy cube

Fig. 2d. Finger-sized star cube

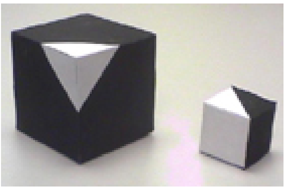

Fig. 2e. Patterned cubes

Fig. 2f. Rhomboid

3.2 Methodology

Participants were given the various cubes and asked to answer a set of questions. The questions were designed to provoke volunteers to manipulate the cubes – the specific answers given by the participants are of lesser importance compared to our ability to observe participants in action. The following five questions were used:

1. If you had to pick one cube, which cube would you pick and why? Where would you keep it?
2. If you had to carry one of the cubes with you at all times, which one would it be? Why that one? How would you carry it?
3. One of the cubes is to be used as a control mechanism. Which cube should it be and show me how it works.
4. Create your own cube. Describe its form, functionality and the experience you would gain from using it. Describe in words, on paper or by drawing a picture what your cube would look like.
5. If one of the cubes were an alien life form, which one would it be? Describe how it lives.

This is certainly not an exhaustive set of questions however, we attempted to design questions that would yield a high amount of physical manipulation and prolong action with the cubes.

The design study took place over one week at a new media art gallery in the UK [22]. We solicited volunteers through a local new media centre via email and posted a call for participation on their website. To record our data, we used qualitative procedures, including observations and questionnaires. We recorded observations with a video camera.

3.3 Results

Our results are grouped into four categories: observed manipulations helped us develop a classification of non-verbal dynamics; a classification of handling; user preferences; and, generalizations concerning grasp.

3.3.1 Non-verbal Dynamics

Non-verbal dynamics are the manipulations (gripping, not gesture) that take place when participants grip a cube (Table 1, see also [31]). We classify these dynamics according to action (manipulation), description of the action, whether an action is discrete or continuous, and events. The event is the type of action particular to that manipulation. For example, rotate is classified as a TURN event and is one that is dependent on the speed of turning, and possibly by the number of exposed sides.

The actions *Place* and *Pick up* appear in the table since they begin and end most events and they include the grasping actions *Hold* and *Press*. The column “Properties” describes the kinds of cubes that participants favoured for executing a particular dynamic. For example, participants would *roll* cubes with high malleability, soft textures, and a larger size. Not all dynamics were used to the same extent; particular cube properties suggested particular dynamics.

Programming the events describe in non-verbal dynamics will require that algorithms recognize the subtle differences between certain actions. This is an enormous task. For example, rotation consists of two-fold axis (vertex), three-fold axis (edges) or four-fold axis (faces) as well as speed. To detect rotation, physical interfaces would

Table 1. Non-verbal dynamics of cubes

Dynamic	Description	Discrete/ Continuous	Events	Property
Rotate	To turn cube about an axis or centre in a continuous, fluid motion exposing three sides of the cube at one time.	Continuous	TURN + (exposed sides) + (speed)	All
Roll	Impelling cube forward by causing it to turn over and over on a surface.	Continuous	TURN + (surface contact) SPIN + (surface contact)	High malleability, soft textures, large cubes
Twist	To rotate cube while taking a curving path or direction using the wrist.	Continuous	TURN + curve path	Rhomboid, patterned cubes, large cubes
Turn	To cause cube to move around an axis or a centre, exposing one side at a time.	Discrete	TURN (right, left, up, down)	All but particularly large cubes
Throw	To propel cube through the air by a forward motion of the hand and arm.	Continuous	TURN + (no contact with hands) TURN + (no contact with hands)	High malleability, soft textures
Flip	One fluid movement to cause cube to turn over to expose the opposite side of the cube.	Discrete	FLIP (top → bottom) FLIP (front → back) FLIP (side → side)	Large cubes, wooden, harder textures
Spin	To revolve the cube in a fast, fluid movement where all sides are exposed very quickly.	Continuous	SPIN (forward) SPIN (reverse)	Highly angular, particularly medium and large cubes
Hold	To have or maintain cube in the grasp.	Discrete	HOLD (no movement)	All
Shake	Sharp, fluid movements up and down.	Continuous	SHAKE (up→down→up) SHAKE (down→up→down)	Audio properties (cubes with beads)
Shake	Sharp, fluid movement side to side.	Continuous	SHAKE (left→right→left) SHAKE (right→left→right)	Audio properties (cubes with beads)
Place	To put cube in or as if in a particular place or position.	Discrete	PLACE→HOLD PLACE	All
Squeeze	Exert strong pressure on cube with hands or fingers.	Discrete	PRESS + (force)	High malleability, soft textures
Press	Steady pushing or thrusting force exerted in contact with cube.	Discrete	PRESS + (force) + (time)	High malleability, wooden cubes

Pick up	To take hold of and lift up.	Discrete	PRESS→ (up)	All
Tap	Strike cube quickly and lightly so that strike produces a slight sound.	Discrete	PRESS + (force) + (time) + (sound)	Wooden cubes, harder textures
Rub	To move hand or fingers along the surface of the cube with pressure.	Continuous	PRESS + (force) + (temperature) + (area)	Rhomboid, high malleability, soft textures
Fiddle	To move the hands or fingers around the cube restlessly.	Continuous	Ambiguous movements	Star-shape, high malleability, soft textures, small cubes

need to determine both the axis type and the speed at which cube is being rotated. However, research has begun on possible implementation [23].

3.3.2 Handling

How a participant handles a cube determines the non-verbal dynamics that are available to them. We describe "handling" as *managing with the hands by touching, feeling and moving*. All handling is impactive, in that action occurs only when hands come in contact with a cube. We divide handling into four categories:

- One-handed manipulation: using one hand to perform dynamics (Figure 3a).
- One-handed finger manipulation: using one hand and fingers to perform dynamics (Figure 3b).
- Two-handed manipulation: using two hands to perform dynamics (Figure 3c).
- Two-handed finger manipulation: using two hands and fingers to perform dynamics (Figure 3d).

Fig. 3a. One-handed manipulation

Fig. 3b. One-handed finger manipulation

Fig. 3c. Two-handed manipulation

Fig. 3d. Two-handed finger manipulation

We can apply each of the four handling categories to the dynamics described in Table 1 to develop handling conventions.

3.3.3 Preferences

Every user is physically different and will have a unique set of preferences. However, our results suggest that there are certain attributes that are general to all physical interfaces and that may possibly make one physical interface more desirable than another. We discuss some of these here.

Break from usual form. Participants were drawn to cubes that broke from the usual form of a cube, such as a rhomboid and one with an extruded edge. As well, participants were able to explore more freely cubes that didn't already contain some conventional meaning or function. For example, participants rejected cubes that simply looked like gift boxes.

Feedback prolongs interaction. Some of the cubes "reacted" to user interaction. For example, cubes with beads in them produced rolling sounds and soft cubes retained a deformed shape after squeezing them. Participants interacted with these cubes more often than the other cubes and would hold them for long periods of time.

Wider multi-sensory experience prolongs interaction. Visual quality is not enough to sustain attention. Cubes that offered two or more types of sensory experience were favoured. Clay cubes felt organic and left a residue on hands would appeal to users' sense of touch and smell. Multi-sensory experiences blend visual and tactile texture, colour, smell, sound, size, form, and weight.

Some degree of weight is desirable. Having some degree of weight is desirable. Interfaces must be heavy enough that users are *aware* of the object but light enough that it can carry it for long periods. Weight allows people greater control over manipulation. Hinckley[36] suggests that weight contributes to an ease-of-use physical manipulation paradigm: weight can damp instabilities in hand motion; provide kinaesthetic feedback through inertia and the force of gravity; and, constrain manipulation.

Size is relative to the user and application. In terms of handling, the bigger something is the harder it is to carry but easier to find. Conversely, the smaller something is the easier it is to carry and the harder it is to find. Like weight, we need to design the interface so that it does not impinge too much on users' space. Participants suggested that smaller cubes could be attached to a key fob or worn as jewellery. Larger cubes could be useful for low-mobility users. If the application required that the user carry the cube in their pocket, then smaller cubes were favoured.

3.4 Summary

Conducting an affordance design study allowed us to develop a preliminary classification of non-verbal dynamics particular to grasp for cube-shaped objects as well as pointing to some general preferences. It seems as though varying the properties of objects constrains the actions users can perform on an object; object affordance changes the interaction between user and artefact.

4 Designing Interface Controls

Having investigated object affordances of a cube we went on to the design of the interface. This includes a) defining a appropriate manipulation vocabulary and b) investigating and realizing technical capabilities for sensing these manipulations. These two steps were done in parallel. In this section, we describe the interface design; the technology investigation is reported in the next section.

To design the interaction wit the phone interface we used scenarios, diagrams and storyboarding (Figure 4).

We decided to use three non-verbal dynamics as the manipulation vocabulary of our cube interface: *rotate*, *squeeze* and *shake*. The decision was based on our observations during the affordance study. The three selected dynamics seemed to offer the most natural and robust manipulation vocabulary and they could be recognized reliably with the available technology (see Section 5). Having decided on ROTATE, SHAKE and SQUEEZE as the non-verbal dynamics to be employed, we designed an interface based on a pared down version of a conventional mobile phone. The Cubicle phone featured an address book, a message centre, volume controls and power on/off. Each of these functions was mapped to a particular side of the cube as depicted in Figure 5. The top-level visual interface is matched to each cube face. Sub levels map closely to a standard mobile phone interface. However the phone book sub level varied slightly from a standard mobile phone interface in that names are listed alphabetically, one letter at a time.

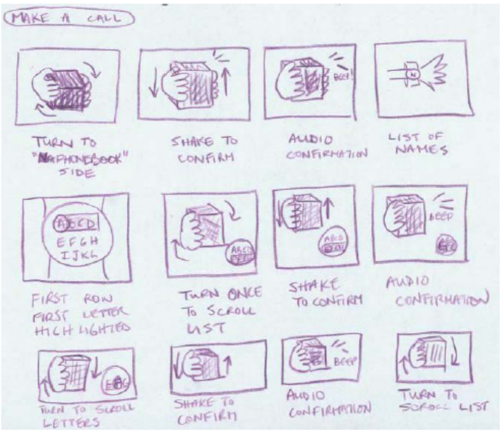

Fig. 4. Storyboard

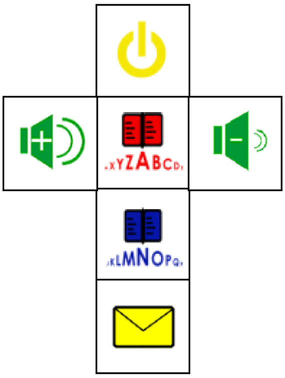

Fig. 5. Sides of the physical Cubicle interface

Table 2. Mapping of Non-verbal dynamics to control

Non-verbal dynamics	1st level Control	2nd level Control
Rotate	Switch between phone functions: 1. Message centre 2. Address book (letter a) 3. Address book (letter n) 4. Volume up 5. Volume down 6. Power on/off	In message centre: - Previous / next In address book: - Previous / next
Squeeze	SELECT / ENTER	In Volume up / down: - turn up / down by 1
Shake	CANCEL / BACK	

In our first iteration, we determined that unidirectional scrolling through the alphabet was time consuming. We redesigned our interface to allow entry at letter A and letter N.

The mapping of non-verbal dynamics to controls is listed in Table 2. The user selects a function by rotating the cube such that the chosen function is on top and then squeezes the cube. Once the message centre or phone book has been selected, rotating the cube scrolls up and down in the list. Shaking the cube cancels a function and goes back up to the main level.

5 Realizing Object Capabilities: The Cubicle Artefact

Having investigated object affordances of a cube we investigated technical capabilities for a digitally enhanced cube and implemented a prototype (Figure 6). The Cubicle is a foam covered wooden block with an embedded microchip and sensor hardware. Buttons placed underneath the foam enable the detection of SQUEEZE actions.

5.1 Sensing Hardware

During the prototyping phase, the choice of hardware is important, since it has direct consequences for the remainder of the system design. The cube as an object has to remain small and robust enough for the users to handle it, and its “digital self” needs to be accurate and autonomous so it can work properly for long periods without requiring cabling for power and communication.

The heart of the hardware is a Microchip PIC microprocessor (PIC18F252), which is small, fast (10 MIPS), consumes little energy (25 µA / 0.2 µA standby). The microcontroller we used has fourteen inputs for binary sensors and a built-in analogue-to-digital conversion unit that allows five analogue sensors to be attached. Our objective, however, to keep the hardware as simple and low-cost as possible without giving in too much on performance, means that we kept the number of sensors low:

- Two dual-axis accelerometers (ADXL311) measure both dynamic acceleration (e.g., vibration) and static acceleration (e.g., gravity) in a plane. The sensors’ ability to measure gravity gives us the opportunity to discriminate in contexts where acceleration may be zero (such as different positions of the cube). We used two accelerometers to get acceleration in three dimensions (X-Y and X-Z).
- One capacitive sensor (QT110) measures whether the user’s hand is nearby (i.e., whether the user is holding the cube or not), mainly to wake up the microcontroller from standby.

The system consists of two modules: the first estimates which is the top side of the cube, the second uses this information with prior states to estimate the direction to which all other sides are pointing.

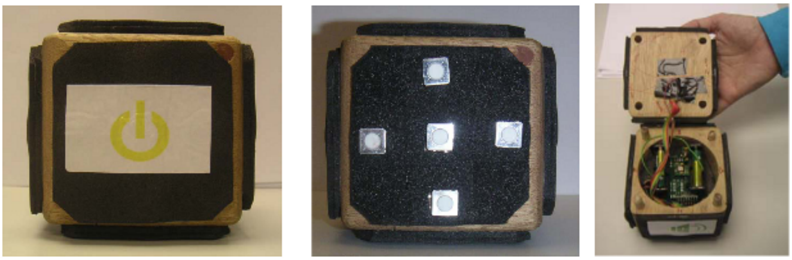

Fig. 6. Cubicle Interface Artefact

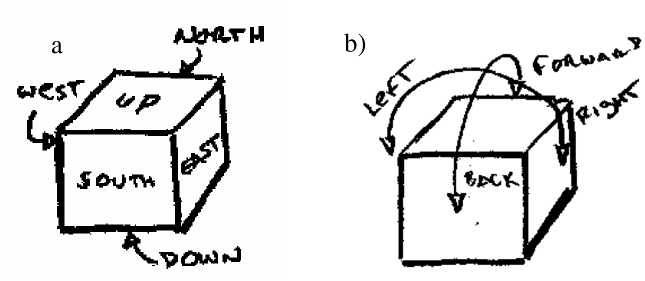

Fig. 7. a) A diagram of the six parameters for defining the cube's state from the user's view. b) The defined set of four possible transitions. The labels for the sides in both views are relative to the user's perspective.

5.2 Sensing Capabilities

The Cubicle implementation has the capability to recognize which side is facing up and in which direction it is rotated. The recognition capabilities are based on the definition of *states* where a state is defined as an arrangement of sides according to the following directions *from the view of the person holding it* (see Figure 7a for an illustration):

- *Top / Up*: the side that faces upward
- *Bottom / Down*: the side that faces downward
- *West*: the side that faces to the left
- *East*: the side that faces to the right
- *North*: the side that faces away from the user
- *South*: the side that faces toward the user

With these definitions in place, two important remarks can be made about the notation of a state: First, in general, for a person holding the cube without knowing or observing any labels of the sides, there are twenty-four possible states. Second, by exploiting the cube's structural properties and labelling each face of the cube as mentioned in the previous section, a given cube's state can be described by knowing only the direction of *two* adjacent faces. It is therefore sufficient to take two fixed directions (Top and South, for instance), rather than describing a state by all six directions.

Using the definition of states, we can define six possible 90-degree rotations between those states (two per axis, for positive or negative rotation).

- *Forward*: rotating the cube so that the Top side becomes the North side
- *Back*: rotating the cube so that the Top side becomes the South side
- *Left*: rotating the cube so that the Top side becomes the West side
- *Right*: rotating the cube so that the Top side becomes the East side

These states and transitions define a finite state machine that models the complete sensing capabilities of the Cubicle. The complete recognition algorithms and implementation of the state machine are described in [23].

5.3 Sensing Limitations and Design Implications

The Cubicle prototype is limited in that it is not able to identify how it is rotated which respect to where the user is in relation to the Cubicle. For example, the Cubicle is not able to determine if the user rotates the top side away from the body or towards it. We determined that the Cubicle's inability to have reliable directional scrolling is a major design problem. If we provide users with the ability to scroll in more than one direction (varying according to the Cubicle's orientation), we expect this inconsistency to cause navigation problems. Therefore, we decided to implement unidirectional scrolling. While it is possible for the Cubicle's accelerometer to sense many of the events described in the Table 1, we questioned whether we could distinguish between similar events such as TURN, ROTATE and TWIST. Because of time constraints, we determined that to implement reliable recognition of similar actions was unrealistic and so avoided actions with similar manipulation. Given the common occurrence of the TURN/ROTATE events in the design study, we decided to couple navigation with rotation. We mapped ROTATE to scrolling and SHAKE and SQUEEZE were chosen as additional inputs, as they were commonly observed in the design study, particularly with cubes that gave audio feedback when shaken or with cubes that were pliant. Consequently, we ensured that our interface provided audio feedback and that the cube was pliant.

6 Usability Study

To understand the usability issues of the Cubicle phone interface we conducted a qualitative usability study. The aim was not to arrive at a final verdict about the Cubicle interface because we expected that there would be errors in the use of the phone and that some of these would be caused both by hardware and software issues, as the Cubicle phone is at an early stage of development. However, we expected to see a device that fulfils basic usability criteria.

The study involved 10 people and used two different set-ups: In the first condition, the Cubicle was connected to a regular desktop computer; in the second condition participants were asked to repeat the tasks whilst wearing a head mounted display (HMD) and walking around a lab. We collected data by observation, questionnaires and video camera.

6.1 Results

Most participants described the Cubicle as easy to learn and none reported that they had found it difficult. Most criticism on learnability was directed at the unreliability of input recognition. Many participants like the novel nature of the Cubicle, describing it as "fun" or "cool". Almost 20 percent of participants described the Cubicle as "intuitive" while several others referred to it as "simple" or "easy to use." The biggest criticism with the Cubicle phone was not related to its form at all. Of the participants, 75% complained about the unreliability of input recognition in one way or another. Other criticisms were its large size and difficultly in squeezing it. Participants suggested that a decrease in size, improved pliability, and an increase in reliability of input recognition would enhance its appeal. Another suggestion was the use of haptics (touch perception) to assist participants in knowing which side should face upwards. Some participants recommended embedding the display in a cube face or replacing the visual display with audio. In terms of scrolling, participants suggested that scrolling should relate to the direction of the cube, and to map the rate of scrolling to the speed of rotation. Types of applications included control device for household appliances, as an alternative input device for children, or for gaming applications. The majority of responses suggest that the Cubicle is best suited to applications involving simple selection tasks. Task completion for all participants followed the expected pattern very closely. Although there was some two-handed finger rotation, over 80% of participants used two-handed rotation to navigate. Interestingly, during certain tasks over 10% of participants used one-handed rotation; participants would use a desk as a supporting surface and roll the Cubicle across the desk to achieve rotation. These participants tended to press the top surface of the Cubicle to initiate SQUEEZE. Since the bottom Cubicle face was pressed against the desk, this strategy did work but required a fair amount of force. Pressing the top of the cube was quite common and a lot of the participants seemed to think that they needed to press the face related to a given function rather than just squeezing the cube. Some participants failed to return to standby mode and ignored this part of the instruction and several participants had trouble working out how to delete a message, and several participants accidentally deleted a message. A number of participants tried to use the action ROTATE to change the direction of scrolling. As well, many participants tried to rotate quickly or slowly when trying to scroll a long distance or short distance. If input was not recognized, participants shook or squeezed the Cubicle harder.

6.2 Usability Summary

The Cubicle is an easily learned interface that provides some degree of user satisfaction. However our results indicate that future iterations require:

- Improved reliability of input recognition
- Better mapping to understanding of the physical world, particularly directional scrolling
- A decrease in size
- An increase in pliability
- Improved consistency in the visual interface

In its current form, the Cubicle seems best suited to relatively simple applications, particularly those that involve selection. Whether a more reliable Cubicle with more varied input will be useful for more complex applications is a question for future study. However such study seems worthwhile from the tentative findings of this evaluation.

7 Discussion and Related Work

A thorough understanding of how we as humans interact with the physical world is of great importance when designing tangible artefacts and interfaces. We thus believe that understanding and applying the relationships between object affordance, object capability and control is key for modelling and creating computer interfaces that are useful and appropriate for the ubiquitous world.

The case study reported in this paper has provided us with insights into the usefulness and effectiveness of our approach. We believe that our approach has the following key advantages:

- It introduces a systematic empirical method for discovering and representing object affordances. The result of studying affordances as suggested by our approach is a sound foundation for the two subsequent design phases, the specification of object capabilities and controls. In particular, the affordance study helps designers to discover non-verbal dynamics and basic sensing requirements.
- Our approach integrates three key design aspects that are usually considered distinct. This is achieved by using a unified terminology for representing key design aspects that enables designers to link design decisions from more than one design dimension.
- The approach assists designers in evaluating and identifying design problems and suggests entry points for systematic redesign.

The results from the case study suggest that following our approach leads to usable and desirable physical interfaces. Our approach, however, does not guarantee superior interfaces, it is simply a way for interaction designers and technology experts to communicate and work together towards a satisfactory design. The point we are trying to make in this paper is not that the particular interface we designed is optimal in any sense, but that the process we followed is useful and effective. More design iterations will be necessary to improve the Cubicles mobile phone interface. Although we have applied our approach only to cubes and cube-like shapes, we believe that it applies to physical objects in general.

7.1 Related Work

There are many theories explaining our perception and interaction with the physical world, but it is less clear how we can apply these theories in a constructive way for the design of concrete physical interfaces.

In recent years, the theory of affordance has been applied to human-computer interaction and the design of user interfaces. While Norman popularized the idea of affordance in *The Design of Everyday Things* [24] his approach focused on designing for usability and for error, in particular for "everyday" things. More recently Benford *et al* [25] have developed the sensible/sensable/desirable framework which focuses on the affordances of ubiquitous devices and how affordance can suggest opportunities for manipulation and extending the physical-digital mapping. They identify three key areas of interest in the design of a physical interface; what is sensible, sensable and desirable. They suggest that in addition to considering these areas on their own, there is value in looking at the overlap between them in order to provide designers with problems and/or opportunities.

The area of tangible computing has produced a number of descriptive frameworks for linking the physical and digital realms. Ishii and Ullmer [3] introduced a model-control-representation (MCRpd) interaction framework. Similarly, Holmquist et al. [26] introduced a common vocabulary for describing physical objects that are linked to digital information. Holmquist bases the schema on three types of physical objects: containers, tokens and tools, and pays particular attention to token-based access systems. More recently, Koleva et al. [27] makes a first attempt at classifying existing tangible interface systems based on the "degree of coherence" between physical and digital objects, which is further broken into links and a set of underlying properties. Marshall et al. [28] are first to cite a lack of conceptual frameworks for applying design decisions when designing physical interfaces, particularly for play and learning.

These models and frameworks are mainly descriptive, rather than prescriptive: they are useful for understanding the nature of physical and tangible interfaces and for classifying them, but they do not define concrete techniques, activities, or processes that we can use to design physical interfaces in a systematic and repeatable manner. It seems likely that human beings who have evolved and lived within the physical world should be well equipped to use and understand physical objects. The concept of affordance, and the immediate understanding of objects that it proposes, suggest this. Our approach for the first time operationalises the concept of affordance and makes it accessible to designers of physical interfaces.

8 Conclusions

Physical interfaces have been proposed as a way to realize natural interactions with ubiquitous computing environments. The successful design of such interfaces requires design approaches that integrate aspects of our world which are usually treated separately in traditional system development approaches. In this paper, we presented an affordance-based design approach for physical user interfaces. In particular, we demonstrated an experimental method for exploring object affordance using cube-shaped objects as type example. Our approach integrates three key design dimensions (affordance, capability, and control) in a systematic way. Our results suggest that following our approach leads to usable and desirable physical interfaces. It also assists designers in evaluating and identifying design problems and suggests entry points for systematic redesign. Although we have applied our approach only to cubes and cube-like shapes, we believe that it applies to physical objects in general.

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