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A framework for designing sensor-based interactions to promote exploration and reflection in play

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Abstract

Sensor-based interactions are increasingly being used in the design of user experiences, ranging from the activation of controls to the delivery of 'context-aware' information in the home. The benefits of doing so include the ability to deliver relevant information to people at appropriate times and to enable 'hands-free' control. A downside, however, is that sensor control often displaces user control, resulting in the user not knowing how to or being able to control aspects of a system. While this can be frustrating in many situations, it provides new opportunities for enhancing or augmenting various kinds of activities, where uncertainty can be exploited to good effect. We describe how we designed an adventure game for young children that incorporated a number of sensor-based interactions. We also present a preliminary conceptual framework intended to help designers and researchers develop novel user experiences using sensor-based interactions. A set of concepts are provided that characterize salient aspects of the user experience involved in sensing together with a discussion of the core properties of sensor technologies.

1. Introduction

Originally, sensor technology was developed to measure the environment, and allowed computers to react to changes in the environment. Earliest uses of sensors were monitoring activities, such as the thermostat of a central heating system. If the building was too cold the heating was switched on. Nowadays, sensors are being used in a range of appliances that interact with users, ranging from toilets to smart homes. Most notable are the use of sensor-based interactions for turning on and off taps, flushing toilets and switching on and off lights. Motivated by recent trends towards improving hygiene and energy saving, controlling devices that require explicit physical contact, such as taps, buttons and switches, are being replaced by the detection of body movements (e.g., presence of hands or body moving) requiring no physical contact.

Ideally, this form of sensor-based controlling should be effortless and intuitive. Walking into a room should be all that is needed for a light to come on. Likewise, placing one's hands in a basin should be all that is needed for the taps to turn on. However, it can often be the case that we get caught out and frustrated by the novel mode of interaction. For example, when we enter a new building that has sensor-based controls, we may not know what to do or where to look to activate a device or change an aspect of the environment. The physical cues (i.e., switches, taps) we have become accustomed to are no longer available in the environment to guide our actions. Instead we must learn to move our bodies, or parts of them, in specific ways to be detected by the sensors.

A main effect of replacing physical control with sensor-based control is to shift the agency of control. With physical-based interactions, the person is largely in control, deciding when to start, how much and when to stop an operation. With sensor-based interactions, the system is largely in control, deciding when to start, how much and when to stop an operation—based on the detection of changes in the environment. The problem with this shift in

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control is that, as Shneiderman (1998) has commented, in most situations humans like to be in control of their actions and interactions. We like to know what is going on, be involved in the action and have a sense of power over the system we are interacting with. Issuing instructions to systems—through typing in commands, selecting options from menus in a window environment or on a touch screen, or pressing buttons—provides us with this sense of control. We also like to be able to readily rectify mistakes, like turning the tap to slow the flow of water or change its temperature, or pressing the undo button after selecting the wrong menu item. Most of which is currently difficult or impossible to do with sensor-based interfaces.

The lack of control in sensor-based interactions can result in frustrating, annoying and distracting user experiences—especially when people are caught 'unaware'. What can be done to overcome these potentially negative aspects? One suggestion is to provide more information to the user so they know what the system is doing or about to do and why it is doing so (Bellotti and Edwards, 2001). This could involve designing additional kinds of system feedback. For example, LED lights and sounds could be used to alert people to where sensors are or when information will appear. Another solution might be to better inform users, by providing instructions and labels, showing them when, where and how to move 'correctly', during sensor-based interactions (e.g., see Fig. 1).

Fig. 1. Sign in the restrooms at Cincinnati airport.

Such 'informing' interfaces can address some of the limitations of using sensor-based interactions to replace physical-based interactions. Our approach, however, is quite different. Instead of seeing the uncertainty and lack of control associated with sensor-based interactions as *problems* to be overcome, we see them as *opportunities* to be exploited. We consider how to design interactions that impel people to reflect upon their ambiguous meanings (cf. Gaver et al., 2003). A benefit of creating puzzling and surprising experiences is that they can lead to insight, understanding and a sense of enjoyment (Hallnäs and Redström, 2001). Within this context, the goal of our research is to promote reflection in children's play, through designing new forms of provocative adventure games. In particular, we are interested in getting children to step back and think about what they are doing when taking part in a game; examining the rationale behind their choices when acting out and interacting with the sensor-based technologies and the environment and what the significance of their actions are with respect to the overall game. An example is a game where children have to discover a 'hidden' sensor-based interaction that requires them having to work out how to activate it and what it means.

Specifically, our research is concerned with how to exploit the uncertainty associated with sensor-based interactions in order to provoke children into thinking about what is happening and what they are doing while playing. By uncertainty, we are referring to both the inherent limitations of the sensor technology and the experience mediated through the technologies. Examples of the former include a sensor's lack of precision and its unreliable range of detection. Examples of the latter include giving the user unexpected or ambiguous feedback.

Playing is an area where a number of researchers have begun experimenting with sensor-based interactions. In particular, a variety of toys (e.g., Lego blocks, musical instruments) and 'tangibles' (e.g., necklaces, wands) have been embedded with RF tags and other sensor technology to encourage exploratory play, imaginative storytelling and collaboration (e.g., Resnick et al., 1998; Strommen, 1998; Cassell and Ryokai, 2001; Stanton et al., 2001; Montemayor et al., 2002). Recently, some projects have begun to create *sensor-based environments* to support playing and learning. Most notable are the Listen Reader system (Back et al., 2001) which was designed to enhance reading through enabling readers to discover ambient sounds associated with the story by moving their hands above a sensor-embedded book while sitting in a special 'reading chair' and KidsRoom which was a bedroom designed as an interactive narrative space, enabling children to move a narrative forward via interacting with the furniture in the room, each other and with virtual creatures projected onto the walls (Bobick et al., 1999). Likewise, in our research—as part of the Equator interdisciplinary research collaboration—we have begun designing a number of sensor-based environments, aimed at getting children to discover and reflect upon aspects of the world around them. The experiences are designed to enable the children to move through and interact with a number of physical/digital spaces, both indoors and outdoors, using familiar actions, such as walking and manipulating objects (Rogers et al., 2002a, b; Rogers et al., 2004).

The early sensor-based systems that were built show much promise, suggesting there is much scope for designing a diversity of highly engaging and creative user experiences, that extend existing forms of playing, learning, etc., and which are quite different from those developed within the prevailing GUI-based paradigm. But much of the pioneering research-to-date has been exploratory making it difficult to generalize and begin drawing implications. Furthermore, existing frames of reference and design principles written for desktop applications do not scale up; sensor-based interactions have quite different parameters and properties than those associated with PC/keyboard/mouse interactions. What is needed, therefore, are new forms of conceptual and design guidance that can inform the selection, analysis and development of sensor-based interactions.

This paper outlines a nascent framework that conceptualizes a number of core dimensions of sensors together with aspects of the user experience that are considered important to take into account when designing sensor-based interactions. The framework is based on an analysis of the characteristics of sensors and the user experience together with our reflections of developing a novel interactive game for children using sensor-based interactions. We show how we used the framework when designing the game and the issues it raised. At the end of the paper we present a generalized version of our framework intended as an orienting device for those wanting to design novel user experiences that capitalize on the benefits of sensor-based interactions. Before describing the framework and the game, we briefly clarify the role of conceptual frameworks in the design process.

2. A note on frameworks

The term framework has a variety of meanings. For example, it has been used to refer to a model, an account and a form of prescription. Within HCI, it is commonly used to describe a form of guidance that is explicated in a particular way to inform design and analysis. Conventionally, it is derived from a theory or a set of assumptions about the structure and/or function of phenomena. For example, Bellotti et al.'s (2002) sensor-based interactions framework draws from ideas in the social sciences for its inspiration. Increasingly, however, frameworks are emerging in the field based on common sense, design practice and as a set of generalizations derived from user studies (Rogers, 2004).

Frameworks can serve a number of roles. These include providing predictive models, explanatory accounts, prescriptive guidance and generative constructs. The different frameworks offer their advice in a diversity of forms, including steps, questions, concepts, challenges, principles, heuristics, problems and dimensions. The more prescriptive a framework the more likely it will consist of a series of steps or principles to be followed. The more explanatory a framework, the more likely it will consist of a set of concepts or dimensions to be considered.

A primary motivation for applying a framework is to design a 'better' and more 'usable' system (i.e. one that is easier to use, more efficient and more satisfying). Another reason is to enhance the design process, through improving the quality of discussion among designers and researchers. For example, the cognitive dimensions framework was developed as a set of discussion tools to be used by designers and people evaluating designs (Blackwell and Green, 2003). Likewise, the locales framework was developed as a "principled design framework that allows for the constructions of shared abstractions among stakeholders (social scientists, computer scientists, users)" with the aim of bridging the gap between the different stakeholders concerns using a common language (Fitzpatrick, 2003, p. 7).

Frameworks that have been developed so far that offer advice on designing sensor-based technologies include Benford et al.'s (2005) expected sensed and desired framework, that shows how and why it is important to analyse the sense-able and sensible movements of devices; Bellotti and Edward's (2001) context-aware framework, outlining principles of intelligibility and accountability; Bellotti et al.'s (2002) making sense of sensing systems framework explicating challenges, design issues and problems; and Gaver et al.'s (2003) ambiguity framework, comprising a set of tactics for designing ambiguous representations, artefacts and situations aimed at getting people to interpret them differently. These frameworks have all been prescriptive in their design advice, suggesting what to do (or not to do)—for example Benford et al. (2005) recommend that designers "Analyze sensed movements by identifying all the known limitations of the sensing technologies… consider the range, speed, accuracy and stability of sensing" (p. 14). In contrast, our framework focuses on identifying both the properties of sensing technologies and the nature of the user experience underlying sensor-based interactions. Our objective is to outline the core dimensions of sensor-based interactions in relation to how people perceive what is going on and how this effects their understanding and subsequent behaviours. Thus, the framework is meant as an articulatory device helping to define and shape user experiences. Accordingly, we are not promoting *usable* design in the traditional HCI sense, but *creative* design, that seek to exploit the various properties of sensor-based interactions. To begin, we outline some of the core dimensions of sensor technologies that need to be considered.

3. Core dimensions of sensors

Sensors and activities have properties that determine their 'fit'. When considering combining a sensor and an activity, it is important to see how they match up. Three core dimensions to consider are:

- Discrete–continuous,
- level of precision,
- explicit–implicit.

3.1. Discrete– continuous

Some sensor-based objects are discrete (e.g., keyboard buttons) while others are continuous (e.g., location sensing glove). Likewise, some activities can be discrete (e.g., issuing commands to a word processor) while others are continuous (e.g., handling an object in a 3D cave). For most kinds of activities, an optimal match is between a discrete sensor type and a discrete activity type, such as issuing a 'save' command to a word processor with 'Control-S', or a continuous action with a continuous sensor, such as handling an object in a cave using a 3D location sensing glove. Certainly, it does not make sense to use a keyboard to handle an object in a cave or a gesture to control a nuclear power station. However, many interfaces have been designed that force inherently continuous activities into discrete button interfaces, where in fact it may be more desirable to use a continuous sensor input device (Maclean et al., 2000). For example, it can be far more pleasurable to browse T.V channels using a continuous movement associated with a handle or dial than having to press a series of buttons.

In contrast to the design of effective interfaces, we are interested in how to combine sensors with activities that vary along the discrete–continuous dimension with the purpose of creating unexpected events that will cause people to stop and think and reflect about them. A person can wander around (continuous) or place objects into something to discover more about it (discrete). Both continuous (ultrasonic location sensing) and discrete (RFID tags) sensors can be used to support these kinds of exploration.

3.2. Level of precision

Every activity has a required precision and every sensor has a degree of precision allowing fine- or coarse-grained input. As an example, heating a glass of milk in a microwave oven requires a precise amount of time. Too short and the milk will be cold, too long and the milk will have boiled over. Some microwave ovens have a numeric keypad that allows the time to be set precisely, while others have a dial with a linear scale where the time can only be set with a precision of plus or minus 30 s.

Traditional sensor devices have a very high degree of precision. Buttons of a keyboard are exact, the only imprecision stems from the timing of the event. A mouse is slightly less precise, but this can be circumvented by having bigger targets on the screen, or by zooming part of the screen. More recent sensors are far less precise. For example, GPS has a precision of between 3 and 100 m, and accelerometers have precision limited by sampling rate and the type of gesture.

Ideally, the sensor must be precise enough to support the activity. This argument runs along the same lines of the continuous versus discrete dimension, except that it is not problematic using a precise sensor for an imprecise activity. In general, controlling activities, like typing, require a high degree of precision. In contrast, continuous activities like walking usually require less precision, as they involve moving in various directions.

A closely related concern is the randomness and reproducibility of the activity and sensor. Some activities require deterministic responses (e.g., word processors, spreadsheets), whereas others explicitly require a non-deterministic response, for example, games and cryptographic systems. Similarly, some sensors are reproducible, whereas others may arbitrarily fail. For example, an infrared detector in a toilet may fail to spot someone coming in from the cold. While this kind of unpredictability is infuriating for the person in the toilet, it may not be so problematic when considered in relation to play activities. For example, not knowing when something will appear can encourage children to reflect upon this and to consider a range of alternative strategies to make that something appear. If the something always appears in the same place and at a predictable time it can become boring and easily taken for granted or overlooked. On the other hand, too much unpredictability can be confusing. One way round this is to ensure that the something does appear at certain times or is of a certain kind but not when it might be expected or what it might be.

For most control-based activities, an optimal form of interaction is one that is discrete, precise and predictable. In contrast, when designing other types of user experiences—especially play activities, where the aim is to promote enjoyment, reflection and interpretation—random, imprecise and continuous sensors can be more creatively employed. User experiences can be designed to be deliberately ambiguous and vague with the objective of provoking people to think beyond their normal repertoire of expectations and understandings.

3.3. Explicit– implicit

When a sensor is coupled with an activity the designer has to make a decision on the nature of the interaction. In particular, is the interaction to be explicit or implicit? An implicit binding causes an inadvertent effect between a human and the sensor. A person can, for example, be walking past something (body temperature using an IR sensor), near to something (RF transmitters) or over something (pressure pads). The person will not know if it is he, she or something else that has triggered an event to happen. Also, they will not know when exactly the system received their input and when it will provide an output. There are ample examples of implicit sensor interactions used in everyday appliances: automatic light switches, automatically flushing toilets, and recently flat-pack furniture kits that warn the maker putting together the components when up should be down and back should be front.

An explicit link between a sensor and an activity is where the coupling is obvious and the system provides feedback that enables a person to understand this. An example of explicit interaction is that found in interfaces to arcade machines, where players are aware that a certain action on their part will cause the system to react. For example, dancing on pressure pads will cause a games console to speed-up the music. In contrast with implicit sensors, failure is explicit, and the player knows that failure is possible because it is an explicit interaction. Implicit interaction is usually imprecise and, as explained before, it can be problematic to use with control activities. In contrast, the design of implicit interaction can be an effective strategy where the goal is to create ambiguous states.

4. The sensor-based experience framework

Our sensor-based experience framework has evolved through a dialectic process of analysis, experimentation, reflection and critique. On the one hand, it draws from research on phenomenology, play and interaction design and, on the otherhand, it draws from our own reflections from designing playful experiences and experimenting with sensor-based technologies. To begin, we identify aspects of the user's experience, introducing the concept of *transforms*. By this term we mean the couplings between actions and effects in the world. We then outline the core cognitive processes of the user experience that are involved when sensing a transform and how these can be enhanced and accentuated through creating novel sensor-based interactions.

4.1. Transforms

The main objective of our conceptualization of sensor-based interactions is to provide ways of thinking about how to create novel user experiences that move across time, space and media (both physical and digital). Sensor-based interactions essentially involve a coupling between the detection of an object/person/process and the triggering of events/responses. This is quite different from the conceptual model that underlies most GUI systems where the user has a dialog with the system via a desktop machine. As a starting point, we propose the concept of transforms captures the essence of what happens between people and pervasive systems—where user actions and effects of actions take place causing changes in the state of the world (Rogers et al., 2002a, b). People encounter, and represent transforms between states of the world routinely in their everyday life, for example in perception (e.g., seeing an object disappear and then reappear on changing one's viewpoint), in action (e.g., when the purpose of a gesture changes) and in cognition (as when we re-represent and re-interpret the state of the world). Dealing with transforms involves some implicit or explicit theory of what causes changes of perceptual/cognitive states, i.e. some sort of causal link is usually involved. Transforms are a constant feature of ongoing perception and cognition and constitute the phenomenology of experience. Likewise, we see them as central to the design of sensor-based interactions.

The core phenomenological processes involved when encountering a transform, be it sensor-based or everyday, are:

- **perceiving**—noticing something is happening and distinguishing it from other events,
- **understanding**—understanding what is happening,
- **reflecting**—thinking about what and why it is happening.

These processes are viewed as integral to learning and engagement (e.g., Piaget and Inhelder, 1967; Bruner, 1979). Many of our everyday actions, however, have become highly routine; we take what we see and do for granted, not questioning the what, why or how behind them. It is only when something untoward, unexpected or unusual happens that the threshold of our perceiving, understanding and reflecting is lowered. Then, we might start to wonder and try to work things out. For example supposing a person is pouring cornflakes into a bowl for her breakfast when suddenly the packet starts singing "good morning". She would certainly notice something is happening and that it is different from before. She is highly likely to try to fathom out whether the singing is actually coming from the packet or some other source and would subsequently try to work out how it was possible, how to stop the singing and how to get it to happen again. That person is essentially reasoning about a novel transform, e.g., how does shaking a box and emptying its contents triggers such an unexpected digital event to occur?

Explicit reasoning about the world is what we consider to be central to creating an engaging experience. While there are others aspects of engagement that are important to consider when designing games (e.g., in terms of emotion, attention and flow) the focus of our framework here is to show how provocative experiences can be designed through developing novel transforms. In particular, we propose that sensor-interactions that are designed to be unexpected and uncertain can lead to high levels of engagement, triggering phenomenological cycles of perceiving, understanding and reflecting. Two important parameters to consider are:

- **uncertainty**—experiencing a tension or incongruity, resulting in not knowing what to do,

- **unexpectedness**—experiencing something different to what normally one would expect in a similar situation.

5. Designing sensor-based interactions as part of a novel exploratory environment: the Hunting of the Snark game

Our framework is intended to help designers and researchers make choices when formulating the design of a user experience using sensor-based interactions. We initially developed the framework in order to inform the design of a playful and creative experience, where children mixed colours, using a variety of familiar and novel transforms (Rogers et al., 2002b). Here, we describe how it helped us design, experiment with and reflect upon a children's adventure game, called the Hunting of the Snark. The name of the game—The Hunting of the Snark—is borrowed from the title of the poem written by Carroll (1876) that is about a motley group of explorers who are searching for a legendary beast that appears and disappears in various guises and whom they can never quite catch. In our game, the Snark was designed as an elusive creature that, similarly, never appears in its entirety, but only in a variety of shapes and sounds, that the children have to 'catch' through their interactions with it in different environments. Our goal was to build an interactive environment that would enable young children to reflect upon an unfolding narrative that they are part of through integrating disparate pieces of information they glean over time, space and media.

The rationale behind the game: An imaginary virtual creature (the Snark) was created that the children have to find and interact with in various ways to discover as much as they can about it (e.g., its appearance, its likes and dislikes). To provoke their engagement in the cycle of perception/understanding and reflection, the children are only ever given tantalizing glimpses of it; it appears and disappears in all sorts of places, in different shapes and forms in response to their various movements and actions. To enable the Snark to appear in this uncertain manner, we decided to use a variety of sensor-based interactions, some implicit, and others explicit. A range of abstract representations of the Snark, in the form of animations, images and sounds, were also used to convey its different moods, personality traits and emotions. Again, a main motivation for using these forms of representation was to create an air of intrigue, encouraging the children to infer for themselves what was happening and why.

Designing the game: The game was designed to provide a series of interlinked transforms. We began by conceptualizing the types of activity that we wanted to augment, including:

- looking for and identifying something,
- using something to cause an effect,
- viewing or hearing something,
- collecting different things and transforming them,
- integrating different views of things.

We then considered which aspects of the user experience to promote that would enable children to interact with, and, in so doing, change the behaviour of the Snark, through different forms of physical actions. These were:

- walking with it,
- flying with it,
- feeding it,
- communicating with it,
- chasing it,
- capturing aspects of it.

Next we considered where and how these activities would take place. A series of interconnected activity spaces were designed, where the children could find the Snark and interact with it in different ways. These were:

(i) The Snooper room—where the children have to discover hidden virtual tokens which they need to find out about the Snark.
(ii) A well—where the children can find the Snark swimming and feed it with food tokens.
(iii) A cave—where the children can hear the Snark in response to their walking on the ground.
(iv) The sky—where the children can fly with the Snark.

To design each of the activity spaces required us to work out in more detail the nature of the transforms. This involves determining which type of interface (e.g., visible or hidden) to use for each activity space. It also required deciding which kind of physical action (e.g., walking, waving, dancing) to couple with which kind of response from the Snark (e.g., visual, audio, tactile feedback).

We explored these design issues with respect to the different aspect of the user experience we wished to promote:

> *Perceiving*—How do we design the interactions in each activity space such that the children know something has taken place? Moreover, does it matter if they do something and the Snark does not respond, and conversely, the Snark does something but they do not notice it has happened?

In considering these issues, we thought comprehension and reflection would be triggered if an activity space was set up such that the children do not necessarily notice a response from the Snark every time they carry out an action or try to interact with it. If they do something which they think will cause the Snark to respond and it does not, it can lead them to reflect upon why this is the case. However, it is important to note, that if the coupling between action and response becomes too unpredictable it can lead to confusion. Hence, we needed to get the right balance between uncertainty and certainty such that the children could discover the various Snark's responses through their actions and interactions in the different activity spaces, which could lead them to think about and understand how they did so (as opposed to them simply taking for granted that *certain* things happen because they 'just do').

Understanding—what kinds of sensor-based interactions could we use to enable the children to understand the relationship between what they do and how the Snark responds?

Our objective was to design the activity spaces such that the children could understand the Snark's responses, after they had perceived them, with respect to what they were doing. Understanding the coupling between their actions and the Snark's behaviour could provide a basis from which to attribute intentions and inner states of the Snark.

Reflecting—How could we encourage the children to reflect upon their experiences with the Snark?

One way to promote reflection is to get the children to think about why their actions result in unexpected responses. In our previous research on colour-mixing, we found how coupling familiar actions with unfamiliar responses resulted in children developing and articulating a diversity of accounts (Rogers et al., 2002b). Here, we chose to provide only glimpses of the Snark, in the form of abstract representations, as a way of provoking the children to work out their meaning and relation to one another.

Uncertainty—What do the children do when they come across unpredictable events that are contrary to their expectations? Will this get them acting differently and trying out alternative strategies?

We considered it important that the children could perceive the responses that are triggered by their actions as Snark behaviour or digital events that the Snark will respond to. If the mapping between what the children do and how the Snark responds is too arbitrary the children could end up becoming confused and not being able to make sense of the Snark's personality, behaviour, etc.

Unexpectedness—What does the Snark do if the children do not interact in the activity spaces to trigger the sensors and how do the children cope if it provides unexpected responses?

We assumed that it would not matter if children do not immediately know how to interact in the activity spaces. Part of the challenge of the game is that they have to work out the range of physical actions that can be detected for a given Snark response and to adapt their way of interacting, accordingly.

Having conceptualized and articulated the scope and nature of the user experience for the activity spaces, the next stage of the design required working out how to design and implement the game. While the framework was able to orient us to design concerns and raised many issues about using sensor-based interactions to support a particular kind of user experience, it could not do the design for us. In addition, it is necessary to carry out iterative design, such as scenario-based design, prototyping and user studies (Preece et al., 2002). Where the framework can be useful again is in interpreting findings from this stage of the design process, enabling us to have a better informed rationale for making choices from the possible designs.

Given the diversity of sensor-based technologies available, we did not know which to use for each activity. Should we use accelerometers, pressure pads, RFID tags, ultrasonics, etc.? Which would be most appropriate for supporting the different kinds of exploratory-based activities outlined above? To help us decide we carried out a series of user studies. We report here on how the framework helped us interpret the findings from the user studies in relation to the design of the Snark game.

6. Sensor-based user studies: informing the design of the hunting of the Snark game

We looked at a range of sensor-based devices and technologies to determine which to use and how to design them for the proposed Snark activity spaces (see Table 1). This led us to ask what each kind of sensor is capable of sensing and how to design the various Snark activity spaces to enable the user experiences to take place.

We report here on the four kinds of sensing-based interactions we experimented with, by using different sensing technologies, highlighting the important issues they raised with respect to the design of the Snark activities. They were each conducted as informal studies. The number of participants for each one, ranged from 2–5, depending

Table 1
The relationship between the sensing-based interactions, sensor technologies and Snark activity space that was being designed for

Sensing-based interaction	Sensor technology	Snark activity
Sensing location to detect virtual objects	Ultrasonics Pingers Handheld computers	Finding hidden virtual tokens using a Snooper tool
Sensing placement of objects	RFID Tags Barcodes	Feeding the Snark with food tokens
Sensing real-time gestures	Accelerometers	Flying with the Snark by moving arms
Sensing body movements	Pressure pads	Exploring a cave to make sounds for the Snark to listen to

on the variability of responses we were interested in. Sometimes we used ourselves, if it was a simple proof of concept we were interested in examining. We wish to stress here that these are user studies and not scientific experiments (see Preece et al., 2002). As such, predictability and generalizability of the behaviours observed are not driving concerns; in fact, if anything, the opposite. Instead, we wanted to observe the diversity of behaviours; what was possible and how the children obliged or contravened our expectations in relation to the sensor-based interactions. As such, the findings reported here are meant to be illustrative, showing how they were used to inform the design of sensor-based interactions to be part of the Snark game.

6.1. Location sensing to detect hidden objects in a room: designing the snooping activity

What we constructed: In our first activity space, we wanted to enable children to discover how their movements in a physical space could trigger digital events to happen. To this end, we experimented with a mobile sensing device with an attached display (called the 'snooper') and explored different techniques for the discovery of both virtual and real objects hidden at specific locations within a room (see Fig. 2). Our concern was to determine how best to reveal virtual objects and what display format to use to guide the children to discover them.

The activity of finding objects in a (virtual) space is both continuous and discrete in nature. The space is continuous while finding an object is a discrete operation.

In it simplest form, the display was designed to show an object (e.g., a virtual fried egg) so that when the child holding it, walks across the spot where the object is it appears on the PDA display (see Fig. 3). This was implemented using RF pingers. This mode of operating ignores the continuous part of the activity altogether. In order to take the continuous part of the searching activity into account, we employed an enhanced ultrasound position sensing device (Randell and Muller, 2001) which tells the PDA where it is at any one time, and a compass that measures the orientation of the device. Having the additional information of location and orientation, enables various display formats to be designed to show where the person holding it is and where the hidden objects are. More cues can be provided on the screen as to whether the person is getting closer to the hidden object. We designed a number of abstract representations for this purpose based on different spatial metaphors, e.g., a radar, a map, and a lens (see Fig. 4). The additional information was updated as the children moved around, providing them with a simple dynamic representation of where they were in relation to the hidden objects.

Fig. 2. Child using Snooper tool to find hidden virtual objects in a room.

Fig. 3. Example of virtual food token appearing on Snooper display.

What we found: The ultrasonic location system has very good precision, and, in general, the location is not more than a couple of inches off. However, a problem that can occur is when the children bend over the PDA to look closely at the screen the ultrasonic system is obscured. Rather than this being a cause of frustration, our study showed that on discovering this, the children adapted their posture, and began walking around holding the Snooper device in a horizontal position in front of them, in the same way they might with a metal detector. They also slowed their walking movements down and became quite methodical in their sweeping of the physical space ensuring they did not miss an area. As a result, they learnt how to navigate and explore the physical space to provide the Snooper tool with optimal location results.

When a hidden object is sensed by the Snooper tool it appears as a digital representation on the PDA screen. The

Fig. 4. Radar map used on Snooper display to guide children.

sudden appearance of an egg or a tomato on the screen provided an element of surprise. The children were never sure what, where or when something would pop up in response to their explorations. Rather than detract from the experience it made it more exciting. The activity space provided an unexpected transform that provides an opportunity for the children to work out what was going on, what they had to do and how their agency affected the system responses. In particular, the children rapidly understood that their movements in conjunction with the device were what enabled the hidden objects to be revealed on the screen. Moreover, they learnt that by changing the way they moved and held the device, they could master the imprecision of the sensing system.

6.2. Sensing the placement of objects: designing the feeding activity

What we constructed: For the second activity space, we wanted the children to explicitly create an unexpected digital effect by interacting with a novel physical artefact. To this end, we chose the activity of feeding the Snark. Our objective was to encourage the children to work out what kind of creature the Snark was, and, in particular, its likes and dislikes (e.g., being a vegetarian, a carnivore, greedy, having a sweet tooth, not hungry). The children were given an opportunity to feed the Snark a variety of food types (e.g., meat, vegetables, sweets) to which the Snark would respond accordingly.

In terms of our framework, we thought about how the children would detect that the sensor system had done something and how to respond. We considered how to design the activity of feeding food to a creature to make it react, where the food items were physical and the creature's response digital. Hence, we needed to design a sensor-based interaction that linked the physical and digital, and which would provoke the children into understanding the transform underlying what they did and what they observed. How could we achieve this?

We began by conceiving of the feeding activity in terms of moving tagged physical objects across a target, resulting in different digital responses, each triggered by a programmed state-machine. We looked at the different ways tagged objects are moved in front of continuous surfaces (e.g., a table surface, a wall). Tagging entails implicit sensing and so it is not obvious where or how to place objects in order for them to be reliably sensed. A key design issue for us was how to make the sensing and responding appear as a magical event, while ensuring that the children's actions of picking up the tagged objects and moving them across the target could be reliably read. We experimented with barcode and RF technology as ways of changing the state of an object that could trigger digital responses. We discovered that barcode technology, while being very robust was actually very inflexible, requiring that the reader or barcoded object be held in a particular way. Hence, a great deal of precision is required for it to be read. In contrast, RF tag technology is much more flexible, allowing the person or an object to trigger digital events in a number of ways.

In terms of instantiating the activity of feeding the Snark we wanted to build an interface that would allow physical tokens of food to be transformed into digital representations on the water's surface that could then appear to be eaten by the virtual Snark swimming around in a virtual well. Designing the interface in this way would mean that the children could feed the Snark (familiar action) while the Snark could choose momentarily to appear to swallow the food and subsequently display a digital response on the water's surface (unexpected response). Initially, we thought we could design this form of interaction through allowing the children to place tagged tokens of food (see Fig. 5a) directly onto the water's surface using an RF tag reader. Two problems that we were faced with the technology, however, were the detection of the shape and number of objects. Objects are best detected when they are at a right angle to the aerial part of the RF tag reader. Our experiments showed that using flattish objects provided the best presentation to the tag reader. Another concern was how to control the number of objects read at a given time. We discovered that when given a set of tagged objects, two children together will try to place more than one down on a reader (usually four, using both hands), whereas our reader could only read a single tag at a time. This required the system to cope with multiple objects, and give a meaning to every combination of objects. Instead of allowing the children to place multiple food tokens simultaneously onto the water's surface, therefore, we worked out an alternative way of constraining the feeding of the Snark to one token at a time, via a feeding chute (Fig. 5b). Only one food item at a time can be placed into the chute. The tag reader was mounted on the side of the chute. This enabled the system to respond to each piece of food in turn, and in so doing, allow for accurate readings to result each time, independent of how the children fed the Snark. For example, they could place food gently or forcefully throw it in; they could place it in the chute any way up (e.g., chicken leg first; jam tart upside down). This meant that the children did not have to focus their attention on the action of selecting a food item and positioning it in the correct way to be read. It meant, too, they could readily perceive their actions of placing a specific food item in relation to the Snark's response (see Fig. 6).

What we found: In our study, the children focused their attention on feeding the Snark with the food tokens and observing the outcome. They clearly knew the food was only plastic but they all readily suspended their disbelief and were genuinely intrigued as to what the Snark would do each time it was fed different items of food. As anticipated, all the children initially placed the items of food on the water's surface (which was a disguised computer monitor) because it is such a learned behaviour, rather than down the chute to entice the Snark to come up from the bottom of the well. When this action did not get a response from the Snark the children quickly discovered, by themselves, that the way to feed and get a reaction from the Snark was to place an item of food down the chute. In so doing, the familiar activity of feeding was transformed into an unexpected physical–digital coupling, which fascinated the children and provoked them to reflect upon what was happening and why the Snark responded in the different ways.

6.3. Wearables to sense real-time gestures: designing the flying activity

What we constructed: For our third activity space, we experimented with wearable technology, enabling children's arm movements to trigger digital events to happen. Our aim was to allow the children to interact with the Snark by appearing to fly, resulting in the Snark flying with them in particular ways. In so doing, the children could discover what kinds of flying the Snark responded to

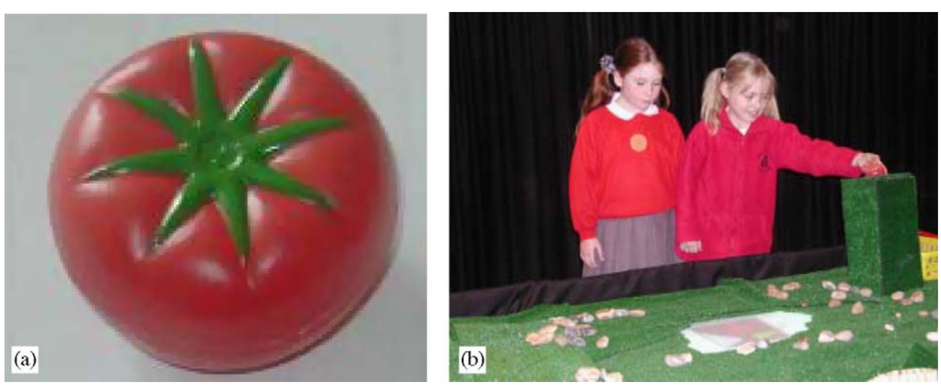

Fig. 5. (a) Plastic RF tagged food token and (b) feeding it to the Snark down the chute.

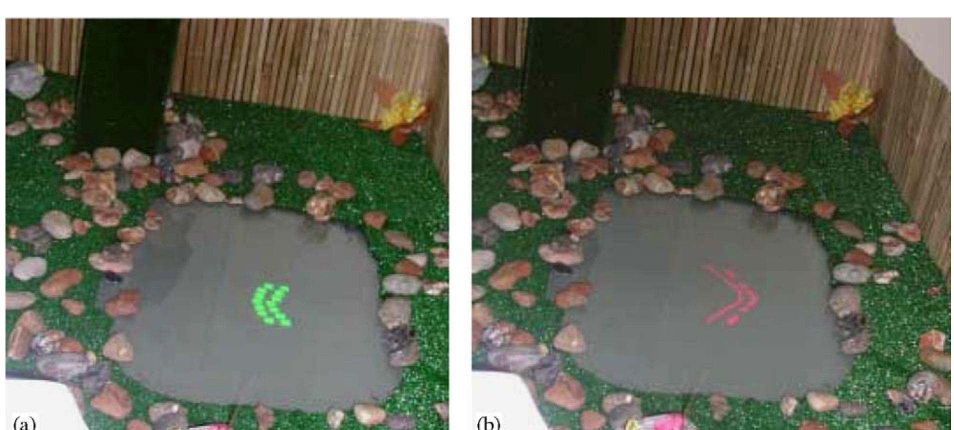

Fig. 6. (a) Pleasure and (b) disgust facial expressions of Snark appearing on surface of the water after being fed different food tokens.

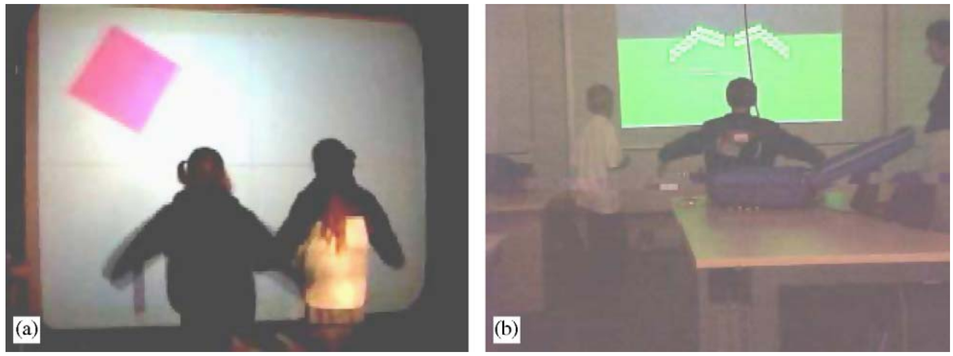

Fig. 7. Children flying with the Snark: (a) showing its emotional state in response to their flying and (b) mimicking their arm movements.

and its responses. Flying was enabled by the familiar action of arm flapping. Arm movements that were detected were the flapping of arms up and down and banking left to right.

Two magic 'flying' jackets were designed to enable the children to interact with a visual dynamic representation of the Snark. The equipment used was made from two separate systems, a Cyberjacket and a visualization server that communicated via a wireless network.

Accelerometer sensors were placed in the jacket sleeves to measure arm movements. These are continuous low-precision measurement sensors. The lack of precision was accommodated by mapping the movements onto a small set of discrete states. The visualization server showed dynamic representations of the Snark's personality that were selected in response to the gesture that was identified during sampling. As with the other sensor-based interactions, the Snark's responses were designed to be very simple abstract representations. For example, if both children were flapping their arms together then the Snark came close, soaring and swinging and gliding (see Fig. 7a).

What we found: Given that we were able to collect real-time recordings of the children's movements when interacting with the Snark, we also looked at how we might represent this data to the children. In an early version of the system, we designed the feedback to show the Snark mimicking the children's arm movements, albeit with a short time lag (Fig. 7b). This proved to be not very interesting to the children, nor did they learn much about the Snark. Also, the time lag interfered with the flow of their movements; they tended to slow down their actions as if waiting for the Snark to catch up with them. In a later version, we looked at whether having a representation of self plus Snark's movements were important for the children to understand the underlying coupling. We compared this with solely presenting the Snark's set of responses to the moving of the children's arms. The combination of self and Snark worked much better; the children were able to understand what was going on and make more inferences about the Snark's behaviour (e.g. "it liked it when I flapped my arms in this way").

Our study of sensing real-time arm gestures, using accelerometer sensors, showed that the lack of precision and continuity, characteristic of this form of sensing technology, could be put to good use. Arm gestures are also continuous; the children capitalized on this by adapting theirs in ways that increased the chances of getting a Snark response. In other words, it became part of the user experience to master the imprecision.

6.4. Using pressure sensitive pads to sense body movements: designing the cave explorations

What we constructed: For the fourth activity space we were interested in creating a playful experience where the children have to move their whole body to trigger digital responses from the Snark. To this end, we experimented with pressure-sensing pads, which were placed on the floor and disguised as different kinds of surfaces (e.g., grass, water, mud). Standing on the different pressure pads caused different sounds to be played. We were particularly interested in looking at what exploratory behaviour children would engage in. Would they walk together, apart, roll around or run about? As with the other activity spaces, we were interested in seeing how they would understand the nature of their movements in relation to the Snark's responses. Would this cause them to try out different body movements? Would the production of different sounds cause them to move around differently?

A pressure pad is a discrete device. It is either on or off; jumping up and down on it causes it to switch on and off in rapid succession. A key design concern is to determine how many to use and where to place them in relation to each other. We tried 2, 3 and 4 matrix combinations, placed adjacent to each other and apart. In the end, we decided upon a 3×3 matrix, providing nine spaces. The 2×2 matrix was considered too simple to master and the 4×4 too complex for the children to remember which combinations they had explored.

The discrete nature of the sensing device, combined with the nature of the activity (sound played) can cause problems. If every off-to-on transition triggers the audio, then actions are re-triggered on every step. That is not

Fig. 8. Children exploring inside the cave by walking over the pressure pads.

desirable for longer sounds. If a continuous sensing device had been available, we could measure the location of the children's feet as they moved around, and use this measure to continuously change volumes of various sounds, without actually triggering them.

As with the other activity spaces we deliberately chose to exploit the implicitness of the sensor technology, with the aim of creating an uncertain and magical transform between the children's actions and the system response. On entering the cave, the children have to find out what sounds the Snark likes and dislikes in relation to their body movements (see Fig. 8).

The children have to determine where to move in relation to one another (two new target pads are selected each time they enter the cave) to obtain maximum volume. This requires them walking together and apart, to stop and start and discover which is the loudest sound. When the children happen upon the 'correct' location, a flash of light appears on one side of the cave and the Snark cries out. The Snark vocalizations were designed to vary, from being excited, scared to nonchalant. Hence, the children have to discover and subsequently reflect upon why they think the Snark emits a particular sound, based on their movements in the cave.

What we found: Our study sensing body movements using pressure sensitive pads showed how this sensing technology was the most difficult to capitalize on in terms of its imprecise dimensions. Mapping a continuous activity (moving) with a discrete sensing system proved to be confusing and difficult to maintain. Making the system response continuous (e.g., increasing volume as opposed to changing sounds) was more effective at getting the children to understand what was happening. Interestingly, because it was not obvious to the children how to change the sounds with their movements (they found it easier and more obvious to change the Snark's response with the flying activity) it encouraged them to be more adventurous and try out new combinations of movements. Again, an impetus behind their explorations was to master the imprecision and ambiguity.

7. The game

The final Hunting of the Snark game was made up of the four different activity spaces, which ten pairs of children, aged 6–10 years, visited in sequence. The children were told that the goal of the game was to find and discover as much as they could about the Snark. They could do this by exploring the environment around them and interacting with the Snark in different ways. At the outset of the game the children were given a special camera to capture aspects of the Snark. In the first activity space (the Snooper room) the children collected the various tokens, enabling them to interact with the Snark in the other activity spaces. At the end of the game the children downloaded the images and sounds they had captured onto a computer. They were then encouraged to reflect and talk about the Snark, what they had discovered and their experiences with it.

Our findings showed that the children were fully engrossed throughout their participation with the Snark game. They found it easy to switch in and out of the different levels of the game, suspending disbelief when interacting with the Snark and reflecting on what to do with the various tokens and where to find the Snark next when it disappeared. The children were highly captivated by having to discover how to interact with and find out about the Snark. This captivation increased the level of interest the children had in the game, provoking a desire to continue playing the Snark game and explore further. It also stimulated the children readily to share their experiences with each other after the game (see Price, 2003).

8. Framework revisited and conclusions

There is much scope for designing a new genre of sensor-based interfaces that go beyond the existing repertoire of interactions commonly associated with the graphical user interface (GUI) and the desktop computer, providing opportunities for creating more physical and embodied actions and interactions (cf Ishii and Ulmer, 1997; Dourish, 2002). A wide range of actions and interactions that take place in the physical environment can be enhanced and augmented through using sensor-based technologies that can detect the presence of something (a person, an object, a deviation) at a given time and location. With this information, a variety of system responses can be provided in different environmental settings, including automatically switching controls on in a building (e.g., lights, TV) and serendipitously delivering context relevant information to someone walking through a city. As commented by Abowd and Mynatt (2000, p. 521) this has the potential of enabling "the tighter integration of information and perception… allowing for more natural, seamless, hands-busy, and serendipitous interaction."

Sensing technologies, however, can be limited in what they can detect and how they detect it, especially when the sensing involves people's interactions that contravene the range of detection—through no fault of their own. For

Table 2
A generalized version of the sense-making experience framework

1. Transforms
The concept of transforms provides a way of describing how a person experiences and deals with the couplings between actions and effects in physical and digital worlds. It contrasts from the dialog conceptualization that has characterized most GUI design. The phenomenological processes involved are:
- *perceiving*—how does a person detect that the sensor system has done something?
- *understanding*—how does a person understand the causal links between their actions and the system's response?
- *reflecting*—to what extent does a person reflect upon which action caused which effect?

When designing for controlling activities it is preferable to design transforms that are expected (i.e., where the user is able to readily perceive and understand what they are doing in relation to the system's responses.
When designing for playful and other user experiences where control is not important, consider designing novel and unexpected transforms that will surprise people and trigger high levels of perception, understanding and reflection.
Take into account:
- *uncertainty*—where a person experiences a tension or incongruity, resulting in not knowing what to do
- *unexpectedness*—where a person experiences something different to what normally he/she would expect in a similar situation

2. Activities to consider
Activities that are well suited to sensor-based interactions are exploratory and discovery-based (e.g., looking, collecting, searching, chasing). Consider what aspect of the user experience is desirable to be enhanced or extended (e.g., eliciting awareness, promoting reflection), and consider how to couple continuous actions (e.g., walking, waving, dancing) with different kinds of effects (e.g. multi-modal, audio, visual, tactile).

3. Sensor properties to consider
Discrete–continuous: When designing for user experiences where control is desirable (e.g., driving, information seeking) couple discrete activities (e.g., switching on and off) with discrete objects (e.g., buttons and knobs)
When designing for user experiences that are intended to provoke surprise (e.g., treasure hunts, mystery tours) consider combining continuous activities (e.g., running) with continuous sensors (e.g., location sensing)
Precision: Use precise sensors for controlling activities (e.g. interacting with cell phones), and consider coupling imprecise sensors (e.g., GPS) with digital events to create provocative user experiences (e.g., learning)
Explicit–implicit: Provide explicit and obvious feedback between sensors and activities when it is important for users to know what the nature of the coupling is (e.g., tourist guides).
Consider using implicit couplings between sensors and activities to create ambiguous or random transforms to promote interest, reflection and creativity (e.g., social events, displaying images in public forums)

example, sometimes the sensing technology will not work because it cannot distinguish the person from the background (see Fig. 1) or it requires the person to do something that is unfamiliar (e.g., walk onto a stationary escalator to make it move) or the person is out of range (e.g., too cold for a temperature-based sensor to detect them). The outcome of which can result in mild amusement to outright frustration.

Many possibilities are available to designers when deciding which sensor technology to couple with which system response (and how). A few were demonstrated in the design of the Hunting of the Snark game. Table 2 presents a more generalized version of our sensor-based experience framework intended to provide designers and researchers with a set of concepts and concerns by which to frame, articulate, explore and evaluate the design of sensor-based user experiences. In addition to children's adventure games, the framework suggests a number of other activities and user experiences that would be amenable to sensor-based interactions.

In summary, while people may be forgiving of the imprecision and uncertainty of sensing systems, that have been designed to replace physical controlling systems—by learning to exaggerate, repeat or adapt their behaviour—we propose that another way of thinking about them is to design activities that can exploit them to good effect. We suggest one fruitful domain is play where uncertainty can be deliberately designed as an integral part of the user experience. In particular, games, interactive art and public-based, social activities can be designed to be engaging and provocative using a variety of sensor-based interactions, and where people have to discover how to move, or what to place where, in order to progress an activity. Having to master and understand uncertainty can make for a challenging user experience. One way of designing for this is to deliberately construct transforms that provoke reflection.

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