Routledge
Taylor & Francis Group

Interactive Learning Environments

ISSN: 1049-4820 (Print) 1744-5191 (Online) Journal homepage: https://www.tandfonline.com/loi/nile20

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To cite this article: Jun Hu , Bram van der Vlist , Gerrit Niezen , Willem Willemsen , Don Willems & Loe Feijs (2013) Designing the Internet of Things for learning environmentally responsible behaviour, Interactive Learning Environments, 21:2, 211-226, DOI: 10.1080/10494820.2012.705858

To link to this article: https://doi.org/10.1080/10494820.2012.705858

Published online: 30 Jul 2012.

Interactive Learning Environments, 2013
Vol. 21, No. 2, 211–226, http://dx.doi.org/10.1080/10494820.2012.705858

Designing the Internet of Things for learning environmentally responsible behaviour

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(*Received 3 April 2012; final version received 3 April 2012*)

We present two designs in the area of the Internet of Things, utilizing the ontology-driven Smart Objects For Intelligent Applications (SOFIA) Interoperability Platform (IOP). The IOP connects domestic objects in the physical world to the information world, allowing for coaching the behaviour of, or raising awareness in, domestic energy consumption. The concept and architecture of the SOFIA IOP is introduced, in which the domestic objects are knowledge processors connected to a semantic information broker. This broker, using a blackboard design pattern, ontologies, and semantic web technologies, enables interoperability among both digital and physical entities. The two designs based on the SOFIA IOP are presented as examples for coaching with and learning from the Internet of Things. Although both designs are in the area of domestic energy consumption, they can be seen as good starting points towards broader areas of ubiquitous learning enabled by the Internet of Things.

Keywords: Internet of Things; ontology; semantic web; ubiquitous learning

Introduction

The environments that people inhabit are occupied with a growing number of digital and networked devices. With these technological developments, smart networked objects that were once envisioned in visions of the future, such as Ambient Intelligence (Aarts & Marzano, 2003), Pervasive Computing, Ubiquitous Computing (Weiser, 1991) and the more recent notion of an Internet of Things (Kranenburg, 2008), have arrived in our daily lives. In the home environment, this network of devices is usually referred to as the Smart Home; the home ubiquitous computing environment, where many objects can produce, exchange and even process information.

One of the key goals of these paradigms is "serendipitous interoperability," where devices which were not necessarily designed to work together (e.g. built for different purposes by different manufacturers at different times) should be able to discover each other's functionality and data, and be able to make use of it (W3C, 2004).

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One solution to solving the interoperability problem at the infrastructure level is a software platform developed within the Smart Objects For Intelligent Applications (SOFIA) project (http://www.sofia-project.eu). SOFIA is a European research project within the ARTEMIS framework that attempts to make information in the physical world available for smart services – connecting the physical world with the information world. Rather than promoting the compatibility within one specific service-level solution in terms of protocols or software stacks, it addresses information-level compatibility and the collaboration between different producers and consumers of information on a more abstract level. It does not add, nor require an additional single service-level infrastructure or middleware that all manufacturers must adopt, but builds on what is already available in the industry. The goal of the SOFIA Interoperability Platform (IOP) is that devices will be able to interact on a semantic level, utilizing (potentially different) existing underlying services or service architectures.

The Internet of Things is often referred to as a network of everyday objects tagged with Radio-Frequency Identification (RFID). In the context of SOFIA, the Internet of Things is much more. It is a network of smart objects where each object has (from very limited to extensive) computational power and connectivity. These smart objects form the "Internet," in an environment or across environments, which makes this close to the concept of ubiquitous computing, and creates new possibilities for innovative applications.

Together, people and things (devices, sensors, etc.) connected to the Internet create huge amounts of data that are available digitally. By making smart combinations with this data, a world of opportunities opens up. One of the test cases in which the SOFIA platform is expected to have potential value is the domain of energy saving. The SOFIA platform offers the possibility to exchange information about energy consumption between many of the smart objects in the smart space. Besides using this information to automatically save energy, e.g. by automatically dim or turn off lighting when nobody is present, or using usage information to intelligently switch off parts of the network when it is not used, energy consumption information can also be used to make users more aware of their behaviour. A good example of combining various sources of information to give meaning to data, that in itself might not be meaningful at all, is the Social Energy Meter by WideTag (http://www.widetag.com/projects/widetag-social-energy-meter/). By combining social media and energy consumption data, meaning is added to energy usage data by putting it in a social context.

In this paper, we present two designs that utilize these new possibilities for coaching the behaviour towards, or raising the awareness of, domestic energy consumption. A study by Burgess and Nye (2008) indicates that of all the energy that people consume, 30% is consumed in a domestic setting. Furthermore, it states that roughly 30% of domestic energy consumption can be attributed to behavioural choices. By stimulating more Environmentally Responsible Behaviour (ERB), consumption can be reduced by up to 10%. Instead of actively and explicitly teaching and coaching, the stimuli and advice are woven into everyday objects that are connected to energy consumption information, enabling people to learn from the Internet of Things to stimulate their ERB.

We now explain the basic structure and concept of the SOFIA platform, followed by two design cases. For each case, we show the design concept and prototype, as well as the feedback collected from preliminary user evaluations.

Energy consumption

Of the resources consumed in the home, electricity featured most prominently in our research, and is the focus of the two designs that are introduced in this paper. Electricity is not only the most widely used resource, it is also closely connected to the smart home, as almost all appliances run on it. It is quite easy to measure and can be measured at multiple points in the house, or even at every appliance. We observe the trend that many people are having trouble coping with the increasing amount of appliances, many of which need to be powered continuously (remaining in stand-by mode) or having power transformers that drain power even when the device is not in use.

Existing products and concepts

To help people to manage their energy consumption, various products and concepts have been proposed; some of them are currently commercially available. Faruqui, Sergici, and Sharif (2010) evaluated 12 In-Home Display pilot programs and found that the average saving that was achieved by using these products was 7%. Although many products are available, they are not yet wide spread among consumers. Meyers, Williams, and Matthews (2010) conclude that "a lack of consumer awareness of the technologies, high costs due to lack of economics of scale, and difficult user interfaces are currently the major hurdles toward adoption" (p. 563).

We explored the domain of home electricity metres by evaluating both existing products, as well as conceptual designs found in an Internet search. By laying out the existing products and conceptual designs in two-dimensional graphs, in which we consider the amount of effort required against complexity of information, and the type of information against complexity of information, gaps became apparent. These gaps served as an initial direction for our research. As is shown in Figure 1, the amount of effort needed to use the device appeared to be related to the complexity of the available information. Users would benefit from clearly presented information that is specifically meaningful for them.

By assisting users in finding the right information, less effort is required from them. It is also clear from Figure 2 that more in-depth information, presented in a meaningful way, has potential as an innovative solution. This is preferred to aiming for abstract awareness on the one hand, and having detailed numbers and graphs (that are hard to interpret for many users) on the other hand. With the added data available through the emerging Internet of Things, such a solution is feasible.

M3 architecture and the SOFIA IOP

The M3 (multi-device, multi-vendor, multi-domain) architecture is an IOP, based on a blackboard architectural model, which implements the idea of space-based computing (Honkola, Laine, Brown, & Tyrkko, 2010). It consists of two main components: a semantic information broker (SIB) that acts as a common, semantic-oriented store of information and device capabilities, and knowledge processors (KPs), virtual and physical smart objects that interact with one another through the SIB. Various SIB implementations exist that conform to the M3 specification, of which *Smart-M3* was the first open source reference implementation released in 2009 (Available from http://sourceforge.net/projects/smart-m3/).

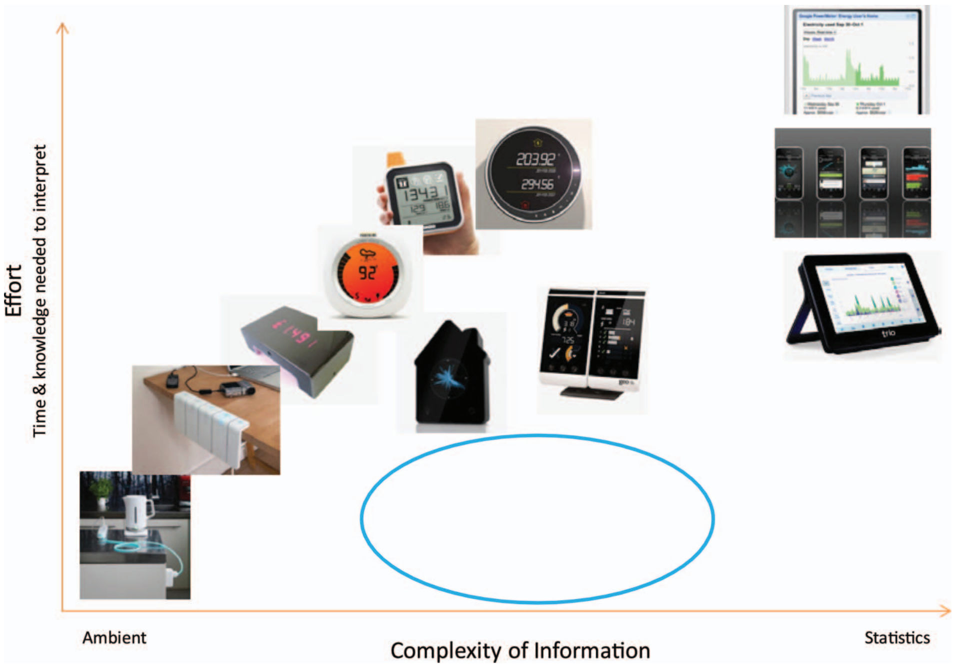

Figure 1. Effort vs. complexity of information.

The SOFIA software platform utilizes the blackboard architectural pattern to share information between smart devices, rather than have the devices explicitly send messages to one another. When this information is also stored according to some ontological representation, it becomes possible to share information between devices that do not share the same representational model, using the semantics of that information (Oliver & Honkola, 2008).

Ontologies lend themselves well to describing the characteristics of devices, the means to access such devices, and other technical constraints and requirements that affect incorporating a device into a smart environment (W3C, 2004). Using an ontology also simplifies the process of integrating different device capability descriptions, as the different entities and relationships in the SIB can be referred to unambiguously. Because communication via the SIB is standardized, integrating cross-vendor implementations is also simplified, and technical incompatibilities can be captured by the ontology.

Ontologies are used to enable the exchange of information without requiring up-front standardization. A notable feature of the SOFIA platform is the capability to subscribe to the changes of data (stored as triples) in the data store, and be notified every time these triples are updated, added or removed.

Smart-M3 takes the blackboard and publish/subscribe concepts, and implements them in a lightweight manner suitable for small, mobile devices. These devices (KPs) can operate autonomously and anonymously by sharing information through an information store. The SIB is the information store of the smart space, and contains the blackboard, ontologies and required service interfaces for the KPs. Figure 3 shows a simplified overview of the Smart-M3 infrastructure.

Figure 2. Type of information vs. complexity of information.

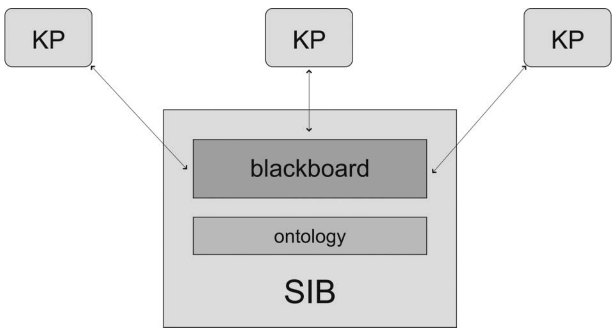

Figure 3. SOFIA infrastructure model.

For applications, a Description Logic (DL)-based ontology can be created in OWL, the Web Ontology Language (W3C, 2004). In the current ontology, all user interaction within the system is described in terms of interaction events (Niezen, van der Vlist, Hu, & Feijs, 2010). To enable our *semantic connections* interaction model, the connections between the devices need to be modelled. A `connectedTo` relationship can be added or removed between two existing devices in the ontology. It should be noted that this relationship is both *symmetric* and *irreflexive*. A symmetric property is its own inverse, which means that if we indicate a `connectedTo` relationship from device A to device B, device B will also have a `connectedTo` relationship to device A. Another way to think of symmetric properties is that they are bidirectional relationships. An irreflexive property is a property that never relates an individual to itself. This allows us to restrict our model by not allowing a `connectedTo` relationship from a device to itself. In our application to energy streams, other properties, such as transitivity and additivity can be added: if device A has access to energy from B and B can take energy from C then indirectly A has access to energy from C (transitivity). For a node, which is neither a source nor a sink, the sum of the incoming energy flows equals the sum of the outgoing energy flow (additivity).

In this structure, to determine which other smart objects a specific device with a `deviceID` is connected to, a simple SPARQL query suffices:

```
select distinct ?object where {
deviceID semcon:connectedTo ?object }
```

To get the last event belonging to a specific device, for example, the event triggered by Near Field Communication (NFC) when the device comes close to the other, the SPARQL query is a little bit more complex, but still surprisingly manageable (see Niezen et al., 2010 for more details):

```
select ?position ?eventType where{
deviceID semcon:hasRFIDTag ?tag .
?event  semcon:hasRFIDTag ?tag .
?event  semcon:hasPosition ?position .
?event  a ?eventType .
?event  semcon:inXSDDateTime ?time .
FILTER  (
?eventType = semcon:NFCEnterEvent ||
?eventType = semcon:NFCExitEvent)}
ORDER BY DESC (?time)
```

At a more conceptual level, the term “semantic connections” is used in the SOFIA project, referring to meaningful connections and relationships between entities of the Internet of Things (van der Vlist, Niezen, Hu & Feijs, 2010a, 2010b). The semantic connections exist in both the physical and the digital world. They have informative properties, i.e. they are perceivable in the physical world and have sensory qualities that inform users about their uses. However, these physical qualities might be hidden at some times, or only accessed on-demand, by a special purpose interaction device. The digital counterparts of semantic connections are modelled in the ontology. There may be very direct mappings, e.g. a connection between two real-world entities may be modelled by a `connectedTo` relationship between the representations of these entities in the ontology.

Design cases

Triggered by the opportunities that the concepts from the SOFIA IOP offer, two products were developed in the application area of stimulating people to improve their ERB in their home environments. These environments are conceptually smart spaces enabled by the SOFIA IOP and host various interoperating smart objects. Energy consuming appliances in these environments are KP-enabled smart objects that are connected to the SIB, hence they are interconnected, providing energy consumption status and history to the SIB. They accept and react on queries, events and commands from the SIB.

Smart objects can connect to the SIB using a variety of communication interfaces, including TCP/IP over WiFi/Ethernet and Bluetooth. Knowledge processor interfaces were developed in Java (Desktop and Android), Python and C (for embedded devices).

The events are not limited to basic on/off events, but can represent a range of data values of different data types. For example, an `AdjustLevelEvent` with a `dataValue` of 255 could be generated to adjust the brightness of a lamp. For a more detailed description of the M3 platform and the performance evaluation of an experimental setup with five KPs, please refer to Niezen, van der Vlist, Bhardwaj, and Ozcelebi (2012).

Doormate

Concept

The Doormate is first of all a doormat for wiping your feet, but also a coaching mate to support the lowering of electricity consumption. It does the latter by communicating information through an integrated low resolution LED display (Figure 4). The Doormate gathers data from the smart appliances in the home, such as time of use, frequency of use, intensity of the appliance during use and duration of use. By combining this data and evaluating changes, information on improving usage behaviour can follow. It allows people to easily turn off devices when leaving the house, as well as improve their energy consumption behaviour by learning from tailored coaching when entering their home again.

Figure 5 illustrates the interface. To switch off the depicted device, the user steps with one foot on the lit-up power icon (top left) and with the other foot applies pressure on the display, like putting out a cigarette. If more devices are available to be switched off, the arrows will light up and can be used to scroll through the icons. When entering the house the user can spend a moment to learn (or get a cue to remember) how certain behaviour can be changed to be more energy efficient. As the contact time between product and user is longer, animations are used to explain the coaching tips. If the user does not understand the animation, or wants to learn more

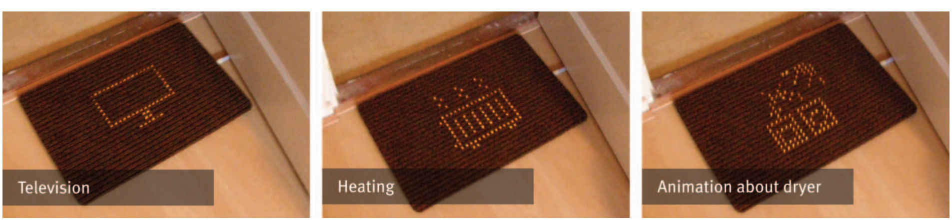

Figure 4. Doormate integrated with a low resolution LED display.

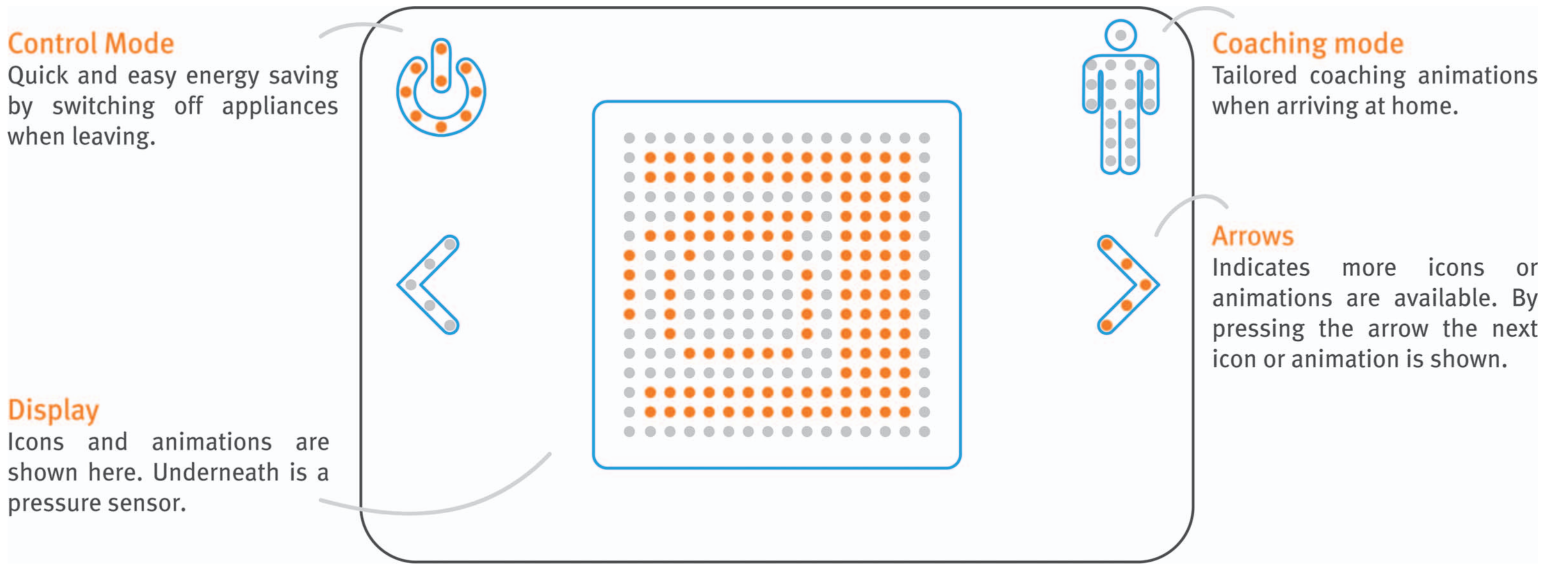

Figure 5. Doormate interface.

about a certain coaching suggestion, he or she can get more information later on his/her smart phone or laptop by both pressing the lit-up coaching icon (top right) as well as the display. In the case of the coaching state, the user is able to 'flip' through tips if more are advised.

Figure 6 shows two use case scenarios. The top scenario shows how a user forgets to switch off the lights and is then reminded by the Doormate. He then decides to switch them off using the Doormate. The bottom scenario shows how a person who is coming home is detected, and while he is taking off his coat, is shown an animation on how to be more electricity-efficient. As he does not understand it immediately, he asks the Doormate to send more information to his smart phone.

Evaluation

A preliminary evaluation was performed with seven participants. They were introduced to the prototype and asked to imagine how the Doormate would fit into their current living situation. The prototype was evaluated on three aspects: visibility and general understanding, animation and icon interpretation, and preference in initial coaching display. The effect of the light coming from a doormat, which is generally a very uninteresting and low-value object, surprised them and gave the mat more value. All participants were enthusiastic about the functionality to control devices in the home, as they all recognized the situation where they forgot to turn off appliances.

Six out of seven of the participants responded positively on the animations aimed at coaching users to improve their behaviour. They indicated that they appreciated the coaching and would probably comply with it. Among the responses of the six participants who valued the coaching benefits that were mentioned were: clear, directly usable tips presented to them without requiring extra effort; personalized coaching, always applicable to their personal behaviour; and they imagined the point of intervention and interaction to be very suited for this type of information. Some participants indicated that they would like information at other times than when they were entering the house. This could be achieved by pressing the coaching icon (top right corner). In this case, the point of interaction appeared less sensible to them.

The results in Table 1 show that the icons as well as the coffee-in-vacuum-flask animation were well understood. The other two animation examples were harder to understand immediately. Younger participants seemed to perform better in understanding the animations. These results and the general responses to the Doormate are promising. People recognized the benefits and envisioned themselves using the Doormate over a longer period of time. However, further testing is needed to improve several aspects of the Doormate:

Interaction: Although people acknowledged that the interaction was easy, it would be good to test how people will actually make use of the foot controls.

Icons and animations: Only a few depictions are presented in the prototype. More extensive experimentation and testing should be done to further refine the icons and animations.

Longer period of use test: To see the real benefit of the Doormate has to be tested over a longer period of time. Will the user still pay attention to the product after one week? Do users see the Doormate as an authority on electricity use and their

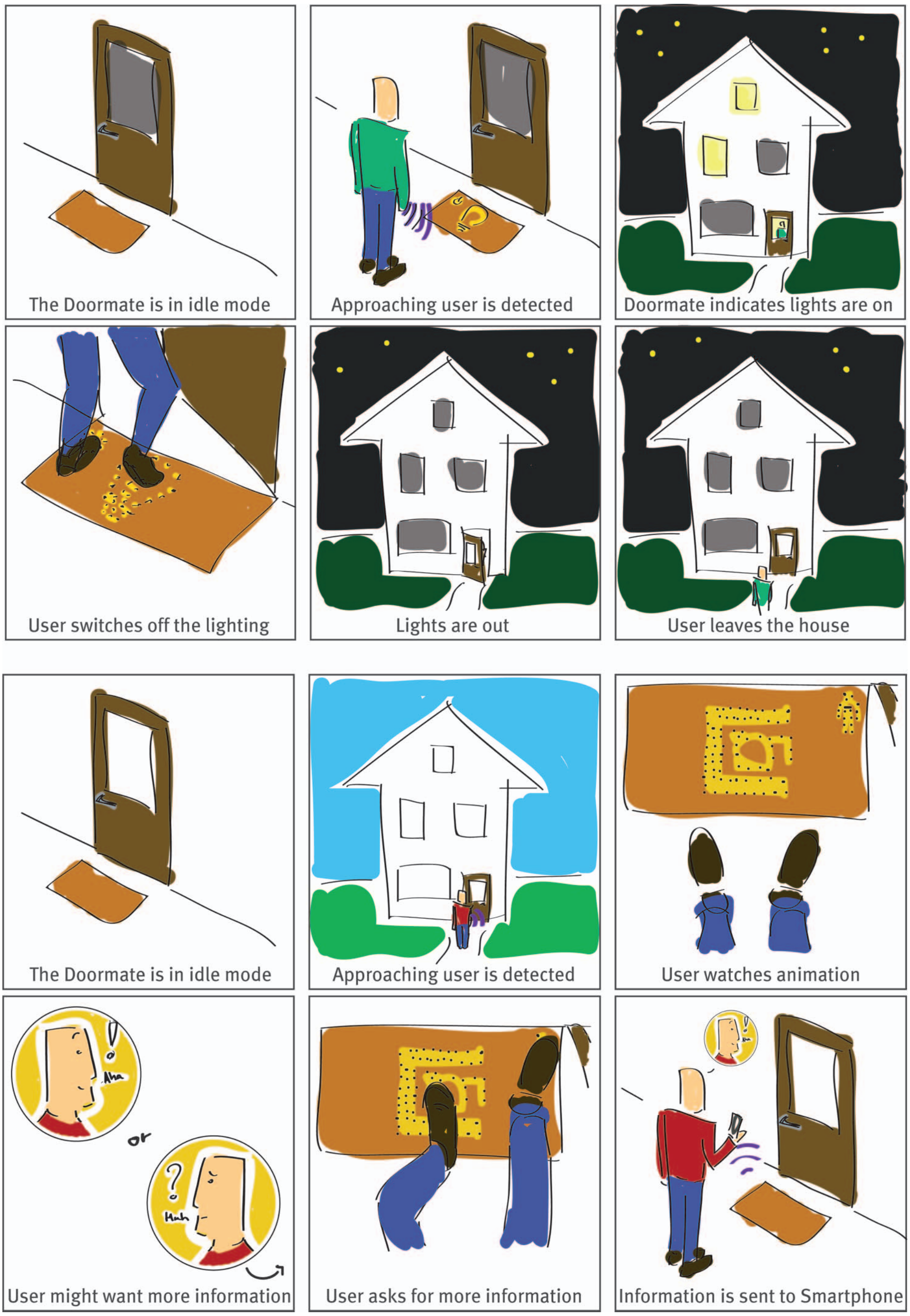

Figure 6. Doormate scenarios.

own behaviour? It could also become apparent that people are not pleased with the Doormate telling them to do certain things they intentionally choose to do in a certain way (Heijs, 2006).

Not only the field of changing ERB is an interesting application area for the Doormate, it may also be suitable in various other settings. As an example, consider accommodating social messaging or retrieving information from social media, or displaying personalized news or meeting times from the user's agenda. In bars or restaurants, it may be used to welcome people and make them aware of the specials, or point them to their friends when they come in.

Bonsai Garden

Concept

The SOFIA IOP hosts various interoperating smart objects that report their energy consumption on a regular basis. The SIB stores energy consumption status and history that can be used to calculate the changes in a person's ERB over time. These change measurements can then be used to provide feedback to the user. The product consists of local feedback devices and a central feedback device. The local feedback devices are consumer KPs (i.e. they connect to the SIB and subscribe to energy usage information) and give direct feedback to the user on their consumption. The central feedback device gives overall feedback on ERB of the different people in a household. A tree represents the overall feedback of a person's consumption and the trees are placed together in a "Bonsai Garden" (Figure 7). These trees consist of

Table 1. Icon and animation understanding mean scores (1 = Not understood, 2 = Help needed, 3 = Hesitation giving one answer, 4 = Needed a second look, 5 = immediately understood).

	Icons			Animations		
Icon/animation name	Light bulb	Television	Heating	Dishwasher	Coffee	Dryer
Mean scores	5	5	4.3	3.1	4.4	3.6

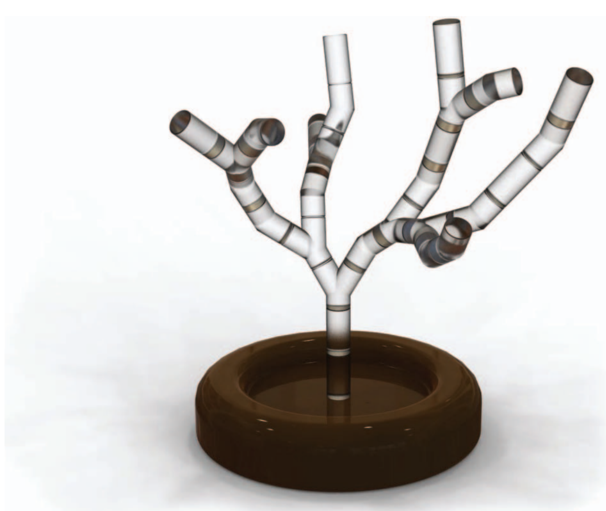

Figure 7. Bonsai Garden.

building blocks and each individual user can construct their personal tree in any way they want. There are three different kinds of building blocks (straight, angled and split pieces) and they provide endless building possibilities. The amount of building blocks and thus the size of the tree represent the user's personal effort on reducing resource consumption. The user can earn building blocks with good ERB and direct feedback on ERB is given by the local feedback devices (triggers). These triggers show when the user earns points for ERB by changing shape and standing upright. These points are represented by lights in the building blocks for that person's tree. When all building blocks are lit up, the user can add a piece to it.

The SOFIA IOP provides energy consumption information for devices in the house. The Bonsai trees are connected to the IOP and subscribe to this information. The person's ERB will affect the number of lit building blocks available to the user.

The target group of this design is families with young children (8–12 years old). The involvement of the entire family adds to the social aspect of motivation. The design contains game elements, derived from on the work of Chatfield (2010). These elements were implemented in this project to create motivation for ERB (Figure 8): (1) gaining levels: the size of the tree represents the level of good ERB from a person; (2) long- and short-term goals: the trigger is short-term and the tree represents a long-term goal; (3) always reward effort: users get rewarded for trying to behave well; (4) rapid, clear and frequent feedback: a trigger responds to each resource-consuming event; (5) an element of uncertainty: users do not know what kind of building block they will get next; (6) involving other people: users can compare their trees and compete for the best building results.

Evaluation

The prototype was used to evaluate two aspects: motivation through competition and motivation through personalization. The main goal of this first test was to gauge if building a tree is fun for children of this age group. The evaluation was done with five children from the target user group (Figure 9). These children were all Dutch and either in the final years of primary or the first years of secondary school. The evaluation was performed in a home situation and the results were recorded with a

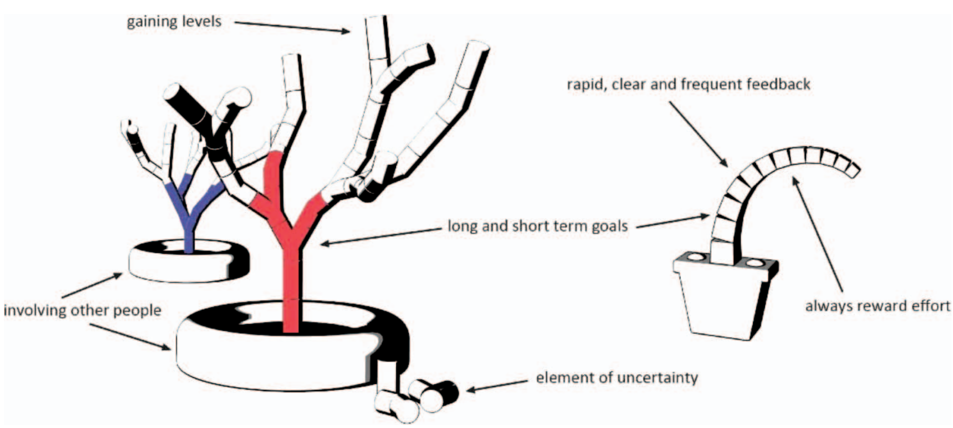

Figure 8. Gaming elements in Bonsai Garden.

camera and by taking notes of events and comments. The evaluation was performed with a prototype that allowed the participants to build a tree out of building blocks. This prototype consisted of a base unit and 30 building blocks, which allowed for complete freedom to build a unique tree.

The evaluation started with an introduction to the design and how the participants could build their own tree at the end of the test. The next step was a questionnaire about ways to improve ERB. Each right answer would result in earning two building blocks for the tree. We discussed the correctness of the answers with the group of children, since some of the answers were not to be taken seriously (e.g. "never flushing the toilet anymore"). The valid number of improvements each participant came up with is shown in Table 2. The number of ERB improvements has no definitive meaning – it is simply an indication of the effort the children put in coming up with ERB improvements. The competition element of the concept was evaluated by having each participant build their own tree and compare them in a discussion. During this discussion the nicest tree would be chosen through voting, to gauge the competitiveness of the children.

Figure 9. Children build their Bonsai trees.
Note: The faces of the children are blurred to protect anonymity.

Table 2. Results of the questionnaire about ways to improve ERB.

Participants	Age; gender	ERB improvements
Mario	11 years old; male	Seven improvements
Siem	9 years old; male	Nine improvements
Evi	10 years old; female	Nine improvements
Huub	10 years old; male	Eight improvements
Dimme	11 years old; male	Nine improvements

Based on the discussion after and the observations made during the evaluation, we can conclude that building the trees was a fun experience for all the children. It was a social process, where they advised and commented on each other's trees. Every participant tried to make their tree unique and as different from the others as possible. The prospect of earning building blocks and building their own tree was a big motivation for the children and they were very concentrated on thinking of ways to improve ERB. However, further testing is needed to improve certain aspects of the Bonsai Garden:

Interaction: Interaction with the tree was evaluated with target users, and it was fun and challenging enough for them. Interaction with the underlying system (Internet of Things) should be developed further.

Design metaphors: It was clear to the children participating in the user test that the growth of the tree was a positive thing and that this quality of the tree represents their own positive ERB. Other parts of the design metaphor should still be mapped to the appropriate aspects of ERB.

Longer period of use test: Sustained interaction with the tree over time needs to be evaluated. After a while, the building of it might become less fun, and adding or removing one building block might not be a concern to the user anymore. The concept should be able to provide new and extended challenges over time to maintain the stimulating effect of the concept.

Concluding remarks

The SOFIA IOP platform enables the possibility to embed intelligence into everyday objects and allows these objects to connect to each other and to information entities and services, bridging different products and services from different manufacturers and providers. Two products were designed based on the concepts from this platform for improving people's ERB in energy consumption in domestic environments, implementing different learning strategies. The Doormate provides the convenience of controlling home appliances, while at the same time providing behaviour coaching. The Bonsai Garden tries to raise awareness by employing game elements in the design. Although the Internet of Things concept was limited to one specific domain, the idea of providing ubiquitous learning with smart daily objects is promising. In addition to smart home environments, we are also experimenting with different scenarios, such as personal spaces and the smart city in the SOFIA project. The technology can be applied for ubiquitous learning to a broader extent.

Acknowledgement

SOFIA is funded by the European Artemis programme under the subprogramme SP3 Smart environments and scalable digital service.

Notes on Contributors

Dr. Jun Hu has a PhD in Industrial Design and a Professional Doctorate in User-system Interaction, both from Eindhoven University of Technology (TU/e). He has also a B.Sc in Mathematics and a M. Eng in Computer Science. He is now an Assistant Professor in the Department of Industrial Design, TU/e, a Guest Professor at School of Digital Media, Jiangnan University. His current research activities are directed towards Design Research on Social Computing.

Bram van der Vlist studied Industrial Design at the Eindhoven University of Technology and received both his B.Sc. (2006) and M.Sc. (2009). In 2009 he joined the Designed Intelligence group at the Eindhoven University of Technology as a PhD candidate, where he is appointed to the SOFIA project. His focus within the project is on the design of, and interaction with interoperable smart products.

Gerrit Niezen received B. Eng. Computer Engineering and M. Eng. Computer Engineering (with distinction) degrees from the University of Pretoria in South Africa. He joined the Designed Intelligence research group at TU Eindhoven as a PhD candidate in July 2009 and submitted his thesis, entitled 'Ontologies for Interaction: enabling serendipitous interoperability' in July 2012. Gerrit's research interests include interaction design, semantic web technologies, wireless sensor networks, ubiquitous computing and gesture recognition.

Willem Willemsen is a Master student at the Department of Industrial Design, Eindhoven University of Technology. His design aims at using design and technology to enable or empower the user to enrich their lives.

Don Willems has an M.Sc. degree in Industrial Design and is specialised in the design of interactive products and systems. With his designs he aims to introduce new technologies in the social fabric of life. His current work involves the stimulation of user creativity in their interaction with open systems.

Prof. Dr. Ir. Loe Feijs has a Ph.D. in Computer Science. From 1998 to 2001 he was scientific director of the Eindhoven Embedded Systems Institute and in 2001 he was appointed full professor for the chair Industrial Design of Embedded Systems. From 2001 to 2006 he was the vice-dean of the Department of Industrial Design. His recent research interests are in new disciplinary areas such as Product Semantics and Creative Programming and new applications such as Biofeedback and Neonatology.

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