An Analysis of Input-Output Relations in Interaction with Smart Tangible Objects

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This article focuses on the conceptual relation between the user's input and a system's output in interaction with smart tangible objects. Understanding this input-output relation (IO relation) is a prerequisite for the design of meaningful interaction. A meaningful IO relation allows the user to know what to do with a system to achieve a certain goal and to evaluate the outcome. The work discussed in this article followed a design research process in which four concepts were developed and prototyped. An evaluation was performed using these prototypes to investigate the effect of highly different IO relations on the user's understanding of the interaction. The evaluation revealed two types of IO relations differing in functionality and the number of mappings between the user and system actions. These two types of relations are described by two IO models that provide an overview of these mappings. Furthermore, they illustrate the role of the user and the influence of the system in the process of understanding the interaction. The analysis of the two types of IO models illustrates the value of understanding IO relations for the design of smart tangible objects.

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1. INTRODUCTION

In their editorial introduction to the *Transactions on Interactive Intelligent Systems*, Jameson and Riedl [2011] point to common issues regarding interactive intelligent systems and their design. They state: "A . . . general issue concerns ways of dealing with the possible negative side effects that intelligent system processing can have if it is not designed with careful attention to the cognitive processes of users. For example, when and why is it important for users to be able reliably to predict, understand, and

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control a system that exhibits intelligence but sometimes errs, and how can we enable them to do so?" [Jameson and Riedl 2011, page 3].

In terms of the key concepts of the present article, we can frame this issue as follows: In interactive systems that are intelligent, there is a more complex "translation" between input and output in comparison to nonintelligent interactive systems; and to complicate things further, there might also be some degree of autonomous behavior. These typical properties can make intelligent systems harder for users to predict, understand, and control, thereby leading to reduced usability and a less satisfactory user experience.

Smart objects that are used for tangible interaction constitute a special class of intelligent systems for which this general issue arises in a somewhat different way. On the one hand, such smart tangible objects tend to be "intelligent" in more limited—and hence more easily understandable — ways than larger systems which may embody sophisticated, computationally intensive forms of perception, reasoning, learning, decision making, and communication. And their tangible nature can make their use especially intuitive and easy to learn. On the other hand, smart tangible objects often confront the user with methods of input and forms of output which are innovative and specific to the type of smart tangible object in question. The behavior of a smart tangible object can therefore give rise to problems of prediction, understanding, and control that are quite similar to those raised by many intelligent systems, even though they are due only in part (if at all) to the intelligent technology embodied in the object.

In this article, we will illustrate how both the favorable and problematic aspects of smart tangible objects can be analyzed in terms of *IO relations*: relationships between the user's input and the system's output.

Interaction designers strive to realize what may be called *meaningful interaction*, in which the possible actions and their purposes are suggested to the user and the feedback from each action is easily interpretable (see, e.g., Djajadiningrat et al. [2002]). Meaningful interaction helps the user to form a good *mental model* of the system [Norman 1986; Preece et al. 2002]. The mental model provides the user with an understanding of the relationships between the user's input and the system's output (which we will refer to as *IO relations*). This relationship encompasses various steps that are required to accomplish some goal while using a system. In this article, we are particularly interested in the steps between the user and the system on the input and/or output side (we will denote these steps with the term *mapping*).

The relation between input and output in physical (nonelectronic) artifacts is often more obvious than in electronic products, as the IO relations in these physical artifacts are often more visible and naturally coupled [Wensveen et al. 2004]. The field of Tangible Interaction (TI), which includes smart tangible objects, relies on physical interaction and thus offers good opportunities to provide meaning in interaction. Nevertheless, even within TI, creating meaning remains a challenge for designers. As will be seen in the examples discussed later in this article, the smart objects manipulated in TI respond to inputs and produce outputs in ways that often do not correspond with the behavior of normal physical objects. This fact would not be much of a problem if there existed consistently applied conventions for the behavior of smart tangible objects, which users could learn once and apply repeatedly. But in fact, the physical forms and the functions of smart tangible objects are highly diverse; and understandably designers of such objects choose a wide variety of forms of input, forms of output, and relationships between input and output. Consequently, a new user of a smart tangible object may have to learn unfamiliar input-output relations quickly. But there is little concrete guidance available for designers who want to support this type of learning (refer to Mazalek and Hoven [2009]). We aim to help fill this gap by contributing to the understanding of IO relations that arise in interaction with smart tangible objects.

The work addresses the following questions.

(1) What constitutes meaningful interaction?
(2) What is the effect of the relation between input and output on meaningful interaction?

The following section presents different perspectives on meaningful interaction and IO relations on the basis of literature (Question 1). These literature insights also provide a background for the subsequent sections of concept design and evaluation. This is part of the design research approach that was used to gain more understanding of the relation between input and output in connection with meaningful interaction (Question 2). In addition, this understanding enabled the modeling of the relation between input and output and provided knowledge on the strategic value that TI can bring to the design of meaningful interaction (see Section 5 on "Modeling IO relations").

2. VARIOUS PERSPECTIVES ON MEANINGFUL INTERACTION

Researchers from various disciplines have been working on meaningful interaction and the relation between input and output. Since these efforts all contribute to a better understanding of the interaction, meaningful interaction will be reviewed from different perspectives in the following sections.

2.1. An (Inter)action Perspective

People use a variety of tools to expand their bodily capabilities. When someone performs an action with a tool, this tool creates a certain effect. In this article we refer to this action-effect relation as the input-output relation (IO relation). The user's understanding of the interaction is influenced by this relation. In the physical (nonelectronic) world, interaction is relatively straightforward. The effect of the input is often clear to the person performing the action as the input and output are naturally coupled [Wensveen et al. 2004]. This coupling is usually perceivable which makes interaction in the physical world easy to understand. With the introduction of electronics, systems became more powerful, complex, and multifunctional. However, there was no longer a natural coupling between input and output since it is not perceivable what happens in the digital world. Therewith interaction often became more difficult to understand. Hence, efforts to make interaction more simple and understandable became increasingly important [Cheyer and Julia 1998], which requires the design of understandable IO relations. In literature, understandable IO relations are referred to as *natural mapping* [Norman 2002], or *meaningful coupling* [Djajadiningrat et al. 2004]. However, we would like to distinguish the IO relation (the entire process between user and system) from its underlying mappings (the translation steps between user and system on the input or output side of this process). We will use the term *meaningful IO relation* to denote a relation between system function, controls, input, and output that is understandable to the user. A meaningful IO relation makes use of existing experience and knowledge of the user [Norman 2002; Preece et al. 2002]. Therefore, it allows the user to concentrate on accomplishing the intended task, instead of controlling the interface [Cheyer and Julia 1998]. However, how to create these meaningful IO relations is not self-evident [Djajadiningrat et al. 2004].

2.2. A Tangible Interaction Perspective

A field that embraces meaningful IO relations is Tangible Interaction (TI) [Ishii 2008]. TI is characterized by the physical nature of electronics-based systems and has the opportunity to use qualities of the physical world [van den Hoven et al. 2012]. This enables TI to create meaningful IO relations by coupling physical objects to digital data [Ullmer and Ishii 2000]. TI is believed to provide cognitive benefits [Blackwell and Edge 2009], because common features of the physical world are processed extremely efficiently by people. In order to establish meaningful IO relations in the interaction with physical objects TI advocates a *seamless integration* of input and output into one coherent system [Ishii 2008; Sharlin et al. 2004]. We distinguish two forms of integration: *physical integration* and *conceptual integration*. Physical integration can be defined as the unification of action and perception space [Sharlin et al. 2004]. This relates to *embodiment* (the degree to which the input mechanism is closely tied to the output event [Fishkin 2004]). Conceptual integration is the cognitive relation between input and output, and helps people to understand the relation between their actions and the system's response to these actions. Therefore, understanding the user's perspective on this conceptual relation allows designers of TI systems to design conceptually meaningful relations between user input and system output. While this field has large potential for achieving meaningful relations, we observe that many existing TI systems (especially the more complex ones) often have interfaces that are relatively hard to understand.

The traditional human-computer interaction field has been studying conceptual integration for a long time. A well-adopted approach in this field is the conceptual model approach proposed by Norman [1986], which describes the relationship between the designer's conceptual model (design model) and user's mental model. The user finds out about the design model through the system image (the interface, its behavior, and documentation). If the system image is not able to convey the design model to the user in a clear and consistent manner, the user is likely to develop an incorrect mental model.

2.3. A Psychology Perspective

When experience produces a relatively enduring change in human behavior or capabilities, we call this learning [Passer and Smith 2005; Thompson 2005]. Learning plays a role in understanding system interaction. For example, *operant conditioning* [Skinner 1937] can be seen as a type of learning through trial and error. By providing input and reviewing the output, the IO relations of the interaction are learned. Learned relations and concepts (knowledge) are stored in *associative networks* [Millon 2003] and *schemas* [Bartlett 1995; Millon 2003]. An associative network is a network of ideas and concepts connected through resemblance, whereas a schema is an organized pattern of thought [Passer and Smith 2005]. Expectations are formed on the basis of schemas and associative networks through *insight* or *retrieval cues*. Insight is the sudden perception of a useful combination of previously learned relations that helps to solve a problem. A retrieval cue is a stimulus that motivates the activation of information stored in the associative networks or schemas [Passer and Smith 2005]. Whereas the cognitive phenomenon of insight cannot be designed, retrieval cues can be designed. Herewith we can conclude that interaction designers should be aware of their target group's associative networks and schemas, and consciously implement retrieval cues to trigger this knowledge. This is in accordance with the conceptual model approach [Norman 1986], as the system (with its retrieval cues) should evoke the user's right mental model (knowledge stored in the associative networks or schemas). The question of how to design systems in order to transfer meaning from the designer's conceptual model via the system to the user's mental model will be addressed next.

2.4. A Design Perspective

While all of the previous perspectives to some extent provide insight into meaningful interaction, concrete design guidance on creating meaningful IO relations is limited. In this section we present three propositions to create meaning in interaction design [Djajadiningrat et al. 2004; Fishkin 2004; Hurtienne and Israel 2007]. First, creating meaningful IO relations through the use of *metaphors* is suggested by Fishkin [2004]. A metaphor used in interaction is defined as a system effect of a user action that is analogous to the real-world effect of similar actions. Or as Lakoff and Johnson describe: "understanding and experiencing one kind of thing in terms of another" [Lakoff and Johnson 1980, page 12]. Thus, metaphors use the associative networks of our brains, to understand a new product in terms of similar familiar existing products. Fishkin proposes two types of metaphors in the design, namely noun and verb metaphors. Noun metaphors are those that show similarities in shape and appearance of the product, while verb metaphors show resemblance in the interaction with the product. Both metaphors can either exist individually or in combination. Another proposed way to create meaning is through *image schemas*. Image schemas are abstract representations that structure the way people understand the world on the basis of bodily experiences [Hurtienne and Israel 2007]. Thus, image schemas are based on the schemas that human beings create in their brains, rather than on the basis of associative networks. Hurtienne and Israel do not make a distinction between noun and verb. Instead, they refer to the sensory-motor nature of image schemas which can be seen as an inevitable coupling of form and action. The last proposed approach by Djajadiningrat et al. [2004] creates meaning through the *use of perceptual motor skills*, which is defined as "what the user can perceive with his senses and what he can do with his body" [Djajadiningrat et al. 2004, page 4]. The authors propose that the meaningful combination of appearance, action, and function should craft an understandable relation between input and output [Djajadiningrat et al. 2004]. While this approach relies mainly on perceptual motor skills, we believe that it is of great importance to rely on all human skills in interaction. As such, also image schemas and more cognitively oriented metaphors are valuable in conveying meaning to users. Interaction may be considered more meaningful and thus easier to understand when both perceptual motor skills and cognitive skills are addressed. We believe that the three proposed ways to create meaning in interaction presented in this section are not mutually exclusive. Depending on the type of system, one of these approaches or a combination of them may be more suitable to convey meaning via the system to the user's model.

In summary, the background section pointed out that physical and conceptual integration play an important role in the design of meaningful IO relations. Furthermore, by properly designing a system and its retrieval cues the right user's mental model should be evoked leading to thorough understanding of the interaction. The application of these insights in concept design will be illustrated next.

3. CONCEPT DESIGN

As part of our design research approach several concepts were designed to better understand the role of IO relations in meaningful interaction. Our approach to design research will be explained first, followed by a short description of the four concepts that were designed.

3.1. Design Research

Research can be defined as the "methodological search for knowledge" [Bunge 1999]. Aim of a design research approach, therefore, is to generate knowledge regarding design. In our design research approach (refer to van den Hoven et al. [2007]) concepts are specifically designed for further research. However, design research encompasses more than just practicing design or performing a usability evaluation alone. According to Friedman [2003] the practice of design is just one foundation of design knowledge. It is not practice but systematic and methodological inquiry into practice and other issues that constitutes design research [Friedman 2003]. Design research is similar to Archer's action research, which is described as "a systematic investigation through practical action calculated to devise or test new information, ideas, forms or procedures and to produce communicable knowledge" [Archer 1995, page 6].

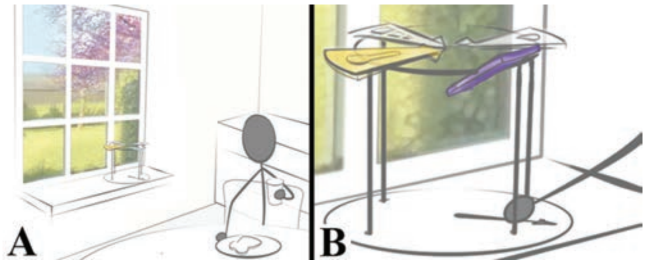

Fig. 1. Scenario illustrating ArtySistant concept.

Our design research process was set up to include multiple phases to support systematic and methodological inquiry of meaningful IO relations (literature review, concept development, concept design, concept evaluation, and modeling). Furthermore, four different concepts were designed to strive for diversity allowing systematic inquiry to generate in-depth knowledge regarding meaningful I/O relations.

An initial series of brainstorm sessions that aimed to develop novel concepts for TI resulted in 21 potentially valuable ideas that could be further developed. From these ideas four were selected to be used for the remainder of the study, namely ArtySistant, SmArtWindow, Connecting Cards, and Color Messaging. The selection from 21 ideas to four was based on the variety of relations between the user's input and the system's output, and resulted in various differences between the concepts (e.g., size of actions, level of complexity, abstract versus precise information, type of application, level of physical integration). This variety is important as the design research focused on the differences in IO relations and their effect on the user's understanding of this relation. The four concepts were specifically designed to enable such an investigation in the subsequent concept evaluation phase. While the aim of the concept design phase was to achieve a large variation between the four concepts, some of our design considerations and use of specific elements apply to more than one concept. In order to avoid too much repetition in the description of our concept design phase we will provide a detailed design description for two concepts in Sections 3.1 and 3.2 (ArtySistant and SmArtWindow), and a higher-level discussion for the other two concepts in Sections 3.3 and 3.4 of this article.

3.2. Concept 1: ArtySistant

The ArtySistant concept is an aesthetic object for living room or workspace that provides the user with various types of real-time information (e.g., stocks, traffic, email, weather). The ArtySistant is a form of informative art [Redström 2008] or information decoration [van Mensvoort 2007] with interaction options to specify the desired type of information. The information can be retrieved quickly and easily, and is provided in a calm and subtle way. The following scenario illustrates the ArtySistant concept for weather information (see Figure 1). While having breakfast and enjoying a beautiful spring scenery, you unconsciously see the ArtySistant indicating that the weather will become cloudier soon. Without actually thinking about any weather condition, you have some awareness of the current weather and what's to come (A). After breakfast, you have to decide whether to go out for groceries or do indoor tasks. You decide to check the weather forecast on the ArtySistant. Reviewing the forecast, you decide it's best to shop first, as there will be showers in a few hours (B).

In our implementation of the ArtySistant concept the weather forecast (output) was provided based on the time selection by the user (input, see Figure 2). Time can be selected by moving a "clock-hand" on the base of the ArtySistant along a nonlinear

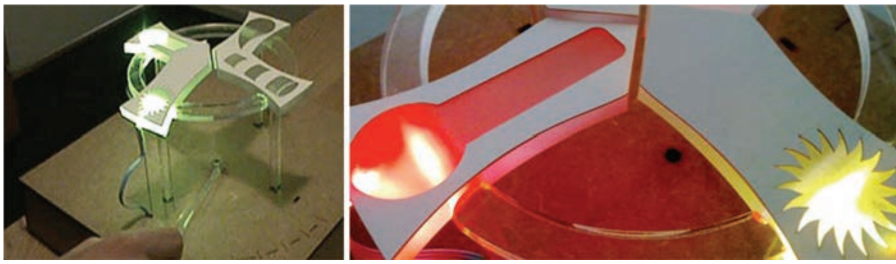

Fig. 2. ArtySistant implementation.

scale from current moment until two days ahead. Information is immediately provided to the user by means of the four arrows that each represent a weather parameter (precipitation, wind, temperature, and sun). Each parameter is visualized by a change in light (color and intensity) in the arrow (e.g., lots of sun results in a bright yellow arrow). Additionally, the angle of each arrow (up or down) indicates the trend of that parameter (e.g., if it will get sunnier the "sun arrow" will point upwards). The system consists of a wooden base housing the electronics. On top, a plexiglas assembly is placed that balances the four arrows. The arrows are actuated by servos in the base and have RGB LEDs integrated to change color. A clock-hand is connected to a potentiometer to provide user input for the system. In the actual design of this concept, literature insights on physical and conceptual integration played a role. The input and output were positioned at one and the same object, but were not entirely colocated (e.g., relying on distance characteristic of the framework by Wensveen et al. [2004], and nearby embodiment [Fishkin 2004]. Furthermore, the system responded in real time to input of participants (time characteristic [Wensveen et al. 2004]. Retrieval cues were provided to guide input, such as the shape of the clock-hand and the time scale provided. There were also retrieval cues designed which related to the output such as the icons used on the four arrows (well-known symbols used in Western culture in weather forecasts), the more/less image schema [Hurtienne and Israel 2007] was implemented in two ways: more or less brightness indicated more or less of that parameter at the selected time, and the angle of the arrows pointing up or down indicating an increasing or decreasing trend compared to the current weather.

3.3. Concept 2: SmArt Window

The SmArt Window allows people to change the appearance of their windows. A SmArt Window is divided into segments that can independently be given any color and transparency ranging from opaque to fully transparent. It can be used for different purposes (e.g., to create a certain atmosphere in the room, play with the view to the outside, or block the sun). The following scenario illustrates the SmArt Window concept (see Figure 3). On a grey morning, you start working in your home office. To brighten up the view outside, you decide to create a playful configuration on your window, which also results in a more pleasant light shining into your room (A). In the afternoon, the sun starts to shine and it produces some glare on your screen. You change the configuration on your window to block the sun on your screen while maintaining the view outside (B).

Input was given by placing and moving a wiper-shaped object onto one of the window segments (see Figure 4). Rotating the wiper is used to change color while applying more or less pressure would change transparency (A). Squeezing the wiper on a colored segment would store the color and transparency setting in the wiper. This was visualized by a RGB LED that would adopt the selected color (B). Squeezing the wiper on an

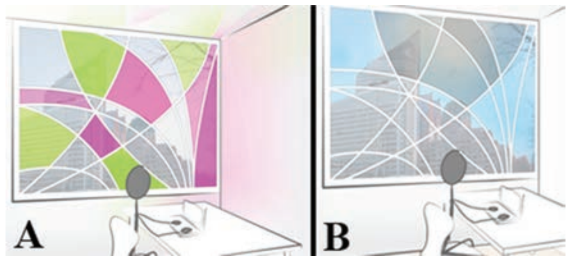

Fig. 3. Scenario illustrating SmArt Window concept.

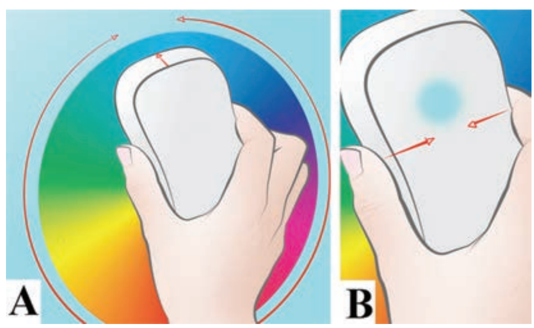

Fig. 4. (a) Adapt color/transparency by rotation/pressure of tool on the window. (b) squeeze sides to take up settings.

empty segment would paste the stored setting onto that segment. Segments could be cleared using the back of the wiper.

For our implementation of the SmArt Window concept an outside view was projected onto a translucent wall (see Figure 5). A second layer was used in the projection to create 12 rectangular (3×4) adjustable segments. The wiper was equipped with a reacTIVision fiducial marker [Kaltenbrunner and Bencina 2007] tracking its position and rotation using a camera located behind the window. The sensors used to detect squeezing and pressure on the window, as well as the RGB LED in the device, were wirelessly connected to the computer program that controlled the projection. Also in the design of the SmArt Window system, literature insights played a role. Physical integration was taken care of by requiring users to place the input tool onto the window. Furthermore by this physical connection there also becomes a conceptual connection between the window and the tool. There was no specific retrieval cue for rotating the tool to adapt the color, other than the fact that positioning the tool on the window immediately changed a segment's color. However, the use of an imaginary color circle is known from various drawing software packages. For absorbing a segment's settings the sponge metaphor was used (i.e., if you place a sponge on a just painted surface the sponge will absorb the color and viscoscity/transparency). The LED displayed the color that was absorbed by the tool to aid this conceptual relation. The more/less image schema [Hurtienne and Israel 2007] was also implemented in the SmArt Window: more pressure for more color, as with a sponge soaked in paint. There were no retrieval cues for placing the tool on the window, except for the shape and fabric of the tool hinting at a wiper metaphor.

3.4. Concept 3: Connecting Cards

The Connecting Cards concept intends to support the cognitive development of children. It is a platform consisting of a set of tiles, which can be used to play educational games. Depending on the content of the tiles different educational games can be played,

Fig. 5. Implementation of SmArt Window including tool.

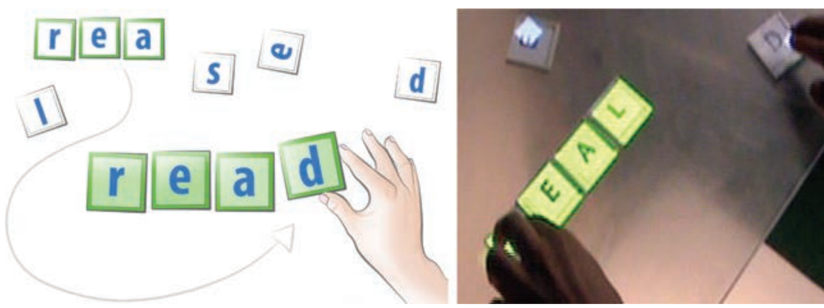

Fig. 6. Connecting Cards (left side: scenario; right side: implementation) can be used to create words with letter cards and get feedback about whether the word is correctly spelled or not.

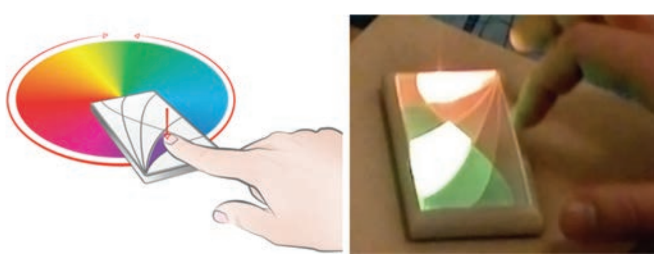

Fig. 7. Color Messaging (left side: scenario; right side: implementation) can be used to send a color composition by rotating a phone while touching segments.

such as clustering types of animals, connecting images to words, or memory. Clustering and sequencing the tiles is the most prominent form of interaction with the system. The system gives visual feedback on the sequences and clusters created. In our implementation of the concept, the tiles contained letters that could be used to create words (see Figure 6). Every time a tile is connected to other tiles, each tile in the sequence displays a green frame. Once a correct sequence (i.e., word) is created, all tiles in the sequence turn completely green. The position of the tiles was tracked using fiducial markers on the bottom of the tiles and the reacTIVision toolkit [Kaltenbrunner and Bencina 2007]. The visual feedback was projected on top of the tiles using a projector.

3.5. Concept 4: Color Messaging

Color Messaging is a novel communication channel for a new-generation mobile phone. The back of the phone is equipped with segments that can change color (see Figure 7). One can create a colorful composition on these segments and send this composition to a contact.

Color Messaging is meant for those moments when one cannot, or does not want to, communicate through a phone call or text message (e.g., business meeting or emotional situation). The sender may choose a color intuitively, or in agreement with the receiver. A color communication code may develop over time. It is intended to be fun, quick, and practical to use. A segment's color can be adjusted by placing a finger on a segment while rotating the phone. The resulting color is coupled to the rotation in the fashion of a color wheel (see Figure 7). By using several fingers while rotating, multiple segments can be manipulated at once. Segments can be turned off by double-tapping a colored segment. The color message can be sent by swiftly wiggling the phone. Our implementation of the concept consisted of a wooden frame in which a composition of translucent segments was placed, that represented the back of the phone. Below these segments buttons and RGB LEDs were integrated to detect touch and color the segments. The rotation of this assembly was measured using a potentiometer and the touched segments were colored accordingly.

4. CONCEPT EVALUATION

Following the concept design phase, a concept evaluation was performed with all four concepts in order to explore the designed IO relations and investigate what makes them meaningful to a user. The main results of the evaluation will be presented and illustrated by two of these concepts (ArtySistant and SmArt Window). Similar results were obtained for the Connecting Cards and Color Messaging concepts.

4.1. Method

The four interactive prototypes of design concepts with varying interaction styles were developed to explore possible varieties in IO relations. These were evaluated with nine Ph.D. and graduate students from our Industrial Design Department. This participant group was selected to ensure their experience within the field of interaction design and capability of discussing and verbalizing their thoughts on various aspects of the interaction. None of the participants was related to the project or involved in the concept development phase. Four participants were female, and ages ranged from 22 to 32 years (mean 26.2). Participants had on average 5 years of experience in interaction design. Each evaluation session took 90 minutes. The order of the four concepts was counterbalanced between subjects to prevent any order effects. As carryover effects were assumed minimal due to the large variation between the four concepts, a within-subject design was chosen.

Norman's "Human Action Cycle" [Norman 2002] was the primary tool for evaluation. The Human Action Cycle describes the process of performing one interaction cycle with a system. This cycle consists of seven stages (see Figure 8). Using these stages as a guideline for analysis of the interaction allows a thorough understanding of the participant's thought process regarding the relation between her input and the system's output. During each session three types of measures were taken: (1) observation of "free exploration", (2) analysis of the Human Action Cycle, and (3) a semistructured interview about the experiences. The evaluation of each concept started with a short introduction on the purpose of the concept, without revealing anything about the interaction. Subsequently participants were asked to freely explore the concept for three minutes. Participants were requested to think out loud while exploring the concept, so the experimenter could get an idea of the participants' thoughts.

After the initial exploration, the participant had to discuss all stages of the Human Action Cycle regarding his interaction with the concept. Participants were asked to think thoroughly about each stage using their experiences in the initial exploration to verbalize their thoughts in writing as well as speech. This process was iterated for all seven stages of the cycle. Participants were not interrupted during the exploration of the concept and the completion of the Human Action Cycle. However, interesting situations were noted and discussed in the semistructured interview at the end of the evaluation.

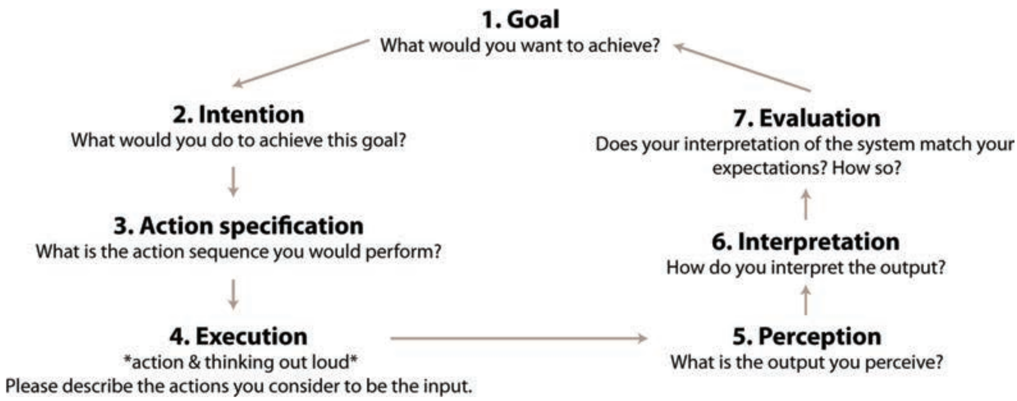

Fig. 8. Human Action Cycle adapted from Norman [2002].

After completion of the cycle for one concept, a semistructured interview was conducted. This interview consisted of general questions, participant-specific questions that were based on the Human Action Cycle, and the notes that were taken by the researcher. Special attention was paid to misconceptions in the interaction that were revealed by analysis of the Human Action Cycle. The general questions addressed the participant's understanding of the relation between input and output, overall impression of the concept, and weak and strong interaction aspects. This procedure was repeated for all four concepts. After the separate evaluation of all concepts, the participant was asked to make a judging comparison between the concepts regarding the interaction, and to motivate her choices.

4.2. Results and Discussion

The results of the concept evaluation provided information regarding participants' experiences and understanding of the relation between their actions (input) and system's response (output). The Human Action Cycles, experimenter notes, and interview answers were combined in the analysis. Additionally, interesting situations were further looked into by analyzing video recordings and verbatim transcription of relevant fragments. The results of the concept evaluation are first presented per concept, and afterwards abstracted to coherently model all aspects that form an IO relation.

4.2.1. ArtySistant. The input and the output of the ArtySistant concept (respectively "time" and "weather forecast") are two distinct parameters that were not conceptually coupled by the system design in any visible way (apart from the fact that they were located on the same object). However, even though the system does not strongly support the link between the input and output, participants had no problems understanding this relation. Participants indicated this to be logical considering the function of the system (weather forecasting) and the fact that weather changes over time. The input for the system appeared easy to understand, even though no actuated feedback was given related to the time input. The engraved time scale combined with an immediate response of the output arrows made the input easy to understand. Interpreting the output, however, proved harder. As indicated in the section Concept Design, the value of each weather parameter was represented by a change in color and light intensity of the arrows, as well as a change in the arrows' angles (pointing up/down) to show the future trend of that parameter. Interpreting the output led to a lot of misconceptions for two reasons. First, two output values were perceived (light and angle), whereas participants only expected one value for each parameter. Therefore, meaning was mostly applied to only one of them: “I understand the inclination [of the arrows] and the meaning of the elements, but I don’t understand colors in relation to the inclination”. Second, misconceptions were created by the abstract nature of the output. Not all participants interpreted the system output (i.e., color and angle) in the same way. For example, the arrow with the sun icon turning blue was interpreted by someone as blue sky, while another person interpreted it as rain. A disadvantage of these multi-interpretational mappings is that they can create assumptions of which the correctness cannot be immediately checked. Current literature insights do not give guidance on how to deal with this matter.

4.2.2. SmArt Window. The “wiper”-designed affordances of the input device (shape and fabric) in the SmArt Window concept were recognized most of the time, leading users to place the object on the window. From that point on users acted differently: some thought they should wipe to create colors as they referred to the object as a blackboard wiper. Others noticed the change in color when rotating the wiper and could successfully change colors. Many participants pointed out it was strange to select a color by rotating a wiper-shaped object: “the block reminds me of a board wiper, I would want to wipe color on and off”, “It reminds me of a wiper, so I want to wipe”. If the participants’ first expected mapping was not correct (wiper mapping), they found it hard to let go of this. However, if the mapping was understood correctly (color wheel), the interaction was perceived to be easy. This shows the importance of coherence in the mapping of both appearance and action. Actually, displaying a color wheel could have solved this problem. Similarly, the pressure-transparency mapping was not visible in the appearance of the wiper. This mapping (based on a paint-soaked sponge releasing more paint when pressed harder) appeared to be unclear as participants always applied some pressure and assumed the resulting transparency to be default. Participants had great difficulty understanding how to manipulate transparency because they were more focused on setting color than adjusting transparency. Once the system was explained, participants stated that the individual mappings were quite logical; however, their combination (board wiper, sponge, and color wheel) was experienced as unusual by most. This is elaborated in the discussion.

4.2.3. Comparison of the Two Concepts. In the ArtySistant the user intention, and thus the IO relation, is focused on information access. This is very different from a user wanting to apply color with the SmArt Window system. In the SmArt Window the user’s mental model does not match the system image when the system does not respond as expected (e.g., when setting a blue color results in a red window, something is wrong and the user will have to change his mental model). On the contrary, when retrieving weather information using the ArtySistant, it is possible users are not able to check the correctness of their mental model as both the input and output mappings are unknown variables. For example, when checking the weather at 3PM results in a blue color in the icon representing the sky, the user does not know whether this means “blue sky” or “rain”. There is also no way to check this as the user does not know what the weather will be at 3PM.

5. MODELING IO RELATIONS

As stated earlier, a design research approach was taken aiming to understand the principles of IO relations in order to provide handles for the design of these relations. The previous sections presented the insights gained through the stages of our design research approach (literature review, concept design, and concept evaluation). In this section, an abstraction of the gained insights is used as the basis for two coherent models of IO relations. A qualitative analysis in the form of affinity diagramming was performed on the basis of literature review, concept design, and concept evaluation. The

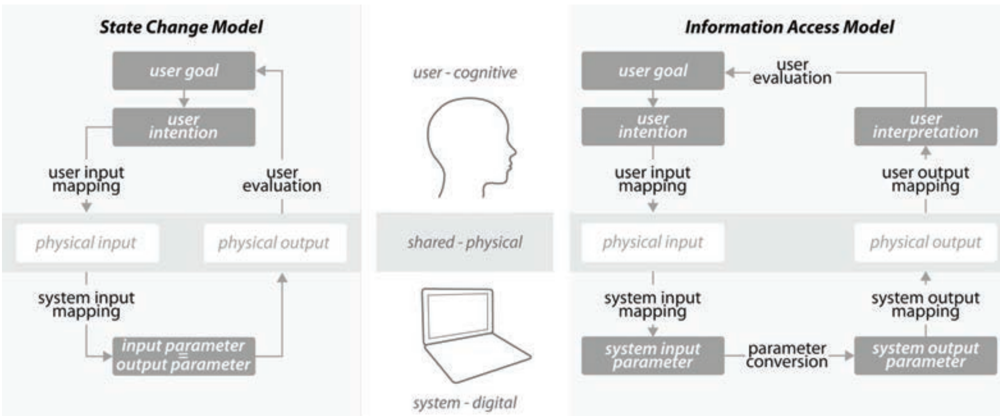

Fig. 9. Illustration of the two IO models: The State Change Model (left side) and Information Access Model (right side) and the three layers of interaction (center).

analysis results in a formalized understanding of IO relations and the identification of two different types of these relations. These two types of IO relations were captured in two IO models (see Figure 9). First, we will provide insight into the basic structure of the IO models. Then, we will give a more detailed explanation of the interaction steps involved in both IO models. Finally, we will describe the main difference between the two models.

The basic structure of the IO models consists of three different interaction layers (see Figure 9). The first cognitive layer takes place inside the user's head (see top section in Figure 9). The second layer is a physical layer that is shared by the user and the system; it represents the physical interaction between the user and system (see middle section in Figure 9). The third layer is the system's digital processing (see bottom section in Figure 9). The IO models also show the user and system mappings involved in an interaction. These mappings are used to make translations between the shared physical interaction layer and one of the other layers involved in the interaction. The first cognitive layer shows the user mappings and third digital layer shows the system mappings.

The interaction cycle that is described by both IO models consists of several steps via which a user is interacting with a system. It is important to emphasize that multiple IO relations can coexist in one system and therefore it is an IO relation rather than a system that is represented by the State Change or Information Access model. Since the IO models represent one interaction cycle, the first and last step in the interaction take place in the same layer, namely the user's cognitive layer. Every interaction starts with the formulation of a goal by the user (user goal). The user then determines what is required to achieve that goal (user intention) and uses an input mapping to translate that into a physical action (user input mapping). In the second (shared physical) layer the user performs this physical interaction with the system. Hence, the user's physical input action is obtained by the system (physical input). In the third (system digital) layer this physical input is translated through a mapping into an input parameter by the system (system input mapping). This input parameter is interpreted and digitally processed by the system. The outcome of the system is subsequently brought back to the physical layer to provide its physical output to the user (physical output). Finally, the output is evaluated by the user in the cognitive layer (user evaluation).

Despite this similarity in the steps of the interaction, the differences between the two IO models are caused by different IO relations. Table I explicates the differences between the State Change and Information Access model and their underlying

Table I. Comparison of State Change and Information Access IO Models

	State Change Model	Information Access Model
Mappings	1 Mapping (input only)	2 Mappings (input and output)
Main Purpose of IO Relation	Support state change of system's setting	Support information access
Example of IO relation in design concepts	Setting transparency of a segment of the SmArt Window	Requesting the weather at a certain point in time using ArtySistant
Other examples of IO relations in TI	Playing a message on *the Marble Answering Machine* (Bishop, 1995)	Checking wind flow information from the *Urp* (Underkoffler and Ishii, 1999)
Other examples of IO relations in daily practice	Switching on a light	Using a voltage-tester screwdriver
System's input and output parameters are	Identical (e.g., color as input and output in the SmArt Window)	Different (e.g., time as input and weather as output in the ArtySistant)
System response to user input for parameter 'X'	Same parameter X	Parameter Y based on relation to parameter X
Meaning of output	Output has no meaning other than the system state (e.g., window color in the SmArt Window)	The output 'means' something for both system and user (e.g., colors communicate weather conditions in the ArtySistant)

IO relations. In each IO relation the user has different interaction goals and the system has different ways of processing the input to the output, resulting in varying levels of complexity in the interaction. In the case of the State Change model the user's goal is to modify the state of a system setting. In the case of the Information Access model the user's goal is to access information.

The State Change model covers the type of relation that uses only one input mapping (consisting of a user mapping and a system mapping; see Figure 9). The parameter on the input side of the interaction is the same as on the output side; only its state is changed through interaction. A user input mapping is used by the user to translate the user intention into a physical action that is needed to adjust the system setting. The system directly outputs this input to the physical layer (physical output) without any translation by a mapping. The user is able to evaluate this output directly, in the cognitive layer, as the parameter itself is still the same; a second mapping on the output side is therefore not needed. An example is changing (or setting) the color in the SmArt Window concept. Other examples are switching on or off a light, or adjusting the temperature of a heating system. This type of IO relation represents an interaction cycle where a user aims to change the state of a particular system setting. Therefore, the physical output carries no particular meaning in the State Change model, other than the state it corresponds to, which requires no to limited interpretation by the user.

The Information Access model describes a relation that uses one mapping for translation of the input and a completely different mapping for translation of the output (see Figure 9), which requires much more interpretation by the user. Also in this model there is a user input mapping to convey what physical user action is needed to set the input parameter. This input parameter is processed by the system and converted into another parameter on the output side. This parameter conversion is based on a relation described by a database or computational model. The output parameter is translated by a second system mapping into a physical output (system output mapping). This output requires a second user mapping before the user is able to evaluate the output with the goal (user output mapping). This allows the user to interpret the output in the cognitive layer to evaluate if the user's goal was reached (user evaluation). An example of such an IO relation is retrieving a weather forecast (output) for a particular time in the future (input) selected by the user of the ArtySistant. The ArtySistant uses a forecast database to convert the input parameter "time" into the output parameter "weather". Other examples are figuring out the exchange rate (output) for dollars to euros (input), or checking a particular route (input) for traffic jams (output). This type of IO relation is information oriented; if the user wants to obtain this information, then the output which carries specific meaning needs to be understood.

If the user and system mappings on the one side of the interaction (either input or output) do not match, the interaction will not be understood initially. In ArtySistant, the mappings on the output side (system and user mapping 2) did not match for some participants in the evaluation. For example, the blue light representing the weather condition "rain" was often interpreted as "blue skies". The evaluation of the other two design concepts (Connecting Cards and Color Messaging) revealed similar issues with regard to the user's understanding of the IO relations to the ones described in this section. Therefore, the results for these two design concepts will not be described separately.

5.1. Applying the IO Models for Meaningful TI

The two IO models describe the functional or technical IO relations that are determined by the design of the system. The distinction between the two IO models and the value of this distinction for Tangible Interaction becomes most evident when looking at the essence of the interaction between user and system.

In the State Change model, where the user's intention is to change the state of the system, there is only one mapping, since the input and output parameters are similar. Take for example the interaction of switching a light on or off. In this interaction the mapping of changing the state of the lamp is the only mapping, since the input parameter is similar to the output parameter (switch light on or off). As such, there is only one mapping that has to be taken into consideration, both by the designer and the user. This mapping between the light output and the input action required for that can be more or less suitable, depending on the product semantics [Krippendorff and Butter 1984] of the switch. Misinterpretations on behalf of the user are fairly easily discovered. If the desired system state is not obtained after interaction, then either the input action was incorrect or the system has broken down.

The functional value of interaction according to the State Change model for the user is in the physical state change, thus the fact that there will be light after successfully completing the interaction (i.e., the light switches on). The input action of the user has a clear relation to the output, which both take place in the physical layer. In this respect adding a digital layer does not substantially add to the function of the interaction, it only replaces part of the system processing from the physical to the digital domain. The fact that an interaction is mainly physical or digital does not change the IO relation itself (the function that can be performed is the same), however, it can change the experience and use of the IO relation. Since the input action of the user and the output action of the system both take place in the physical layer, the physical properties of TI may make this relation even more clear in comparison to digital interaction. Furthermore, because of the qualities of TI [van den Hoven et al. 2012], tangible interaction has more potential for users to express a sense of ownership or attach personal meaning, or emotional value to a product compared to digital interaction (e.g., gold-colored "buttons" on a touch screen will not provide the same status as a solid-gold physical light switch).

In an Information Access relation, however, the digital layer is an essential part of the function. The functional value of the interaction is in the information or intelligence provided through the parameter conversion in the digital layer of this model. Nevertheless, since the user's intention in this IO model is to obtain information, the eventual effect will be a change in the user's cognitive layer. The intelligence provides added value, but also makes the interaction more complex for the user [Rijsdijk et al. 2007]. The fact that the digital layer is essential for information accessing means that a form of TI for these types of IO relations supports the core of the interaction. The digital layer could be replaced by a human being that is knowledgeable and capable of providing the information (e.g., weatherman, teacher).

In the IO model for Information Access an additional mapping has to be taken into consideration. For example, when looking at traffic jam information the mapping between user and system on the input side is road number, and on the output side the mapping is traffic jam or not. Not only does this second mapping require attention in itself, the awareness of the relation between these two mappings is of importance as well. The user interpretation of either one of them may be influenced by the other. When both on the input and output side numbers are used one may be confused about the meaning of these numbers (e.g., does this number refer to road number, length of traffic jam, or location of traffic jam?). The input action of the user is indirectly related to the output, which makes the interpretation of the output more difficult for the user. Thus, if something goes wrong in interaction concerning Information Access, the problem or underlying cause is not as easily discovered as in the case of State Change interaction. Hence, the role of feedback and feedforward becomes more important in the case of Information Access.

5.2. Applying the IO Models in Design

We believe that a thorough understanding of the mappings that make up an IO relation and the distinction between the two types of relations shows the potential value of Tangible Interaction in the design of meaningful electronic systems. Since both IO models start with the user's intention, there is no possibility for the designer to choose between the State Change or Information Access model. The distinction between the two IO models makes clear that for State Change interactions the emphasis should be put on the physical layer. In the case of Information Access more attention should be paid to the connection between the different cognitive, physical, and digital layers in the interaction. While in the State Change model only the input side is crucial in understanding the IO relation, for the Information Access model both the input and the output side play a role in this respect.

Furthermore, designers should be aware that the IO model of Information Access does not relate to information-oriented applications or systems alone, since the IO models do not reflect entire systems, but just one cycle of interaction. We will provide two examples to illustrate this. If a user wants to switch a light on that is turned off, this concerns the State Change model, but if the user wants to know whether the light is switched on or off, this concerns Information Access. When a user wants to know the weather forecast this concerns Information Access, but in user-initiated interaction the first part of the interaction will concern State Change (i.e., specifying the period or location for which the weather forecast is needed).

6. DISCUSSION

As the aim of our research was to generate knowledge for design, we deliberately chose to limit the focus of our research and design of the exploratory concepts to the notion of meaningful IO relations. Applying this single focus supported the development of in-depth knowledge in this area. While meaningful IO relations are not enough for successful interaction, we believe that awareness of the mappings in State Change and Information Access relations as we presented in this article is useful for designers to make conscious decisions for interaction design. Through a design research approach we have shown the influence the different mappings can have on users' interaction with and understanding of interactive systems, providing us with a different perspective on Tangible Interaction.

In existing work the relation between input and output is often described by a single mapping. Based on this notion we addressed the IO relation in its totality in the concept design phase of our work and consequently only distinguished mappings on the input side from mappings on the output side of the interaction cycle. This resulted, however, in interactions where part of this relation was not clear to the user (e.g., participants misinterpreted the color-coded output in ArtySistant; in the Smart Window some struggled to discover the mapping between their actions and setting the transparency). Through abstraction of the insights gained from the design research approach, a formalized understanding of IO relations resulted in the IO models. Contrary to existing work, the IO models in this article do not address the IO relation in its totality, but they make explicit all the relevant mappings between user and system.

In the concept evaluation phase we used Norman's Human Action Cycle [Norman 2002] as a tool to guide the participants' explanation of their understanding of the interaction. This proved to be a valuable way of retrieving information from the participants. Insights into the participants' thoughts about all steps of the interaction were gathered, rather than only about those aspects that participants would mention spontaneously. It also provided structure to the qualitative data, and thus supported data analysis. Furthermore, this approach helped in the identification of the two IO relations and IO models.

There are similarities between the IO models presented in this article and other work that describes the interaction between user and system. Our IO models provide a detailed view on meaningful interaction and distinguish three relevant layers: the user's cognitive, the system's digital, and a shared physical layer. These three elements appear, for example, in Norman's work. His conceptual models approach helps to understand problems in designing meaningful interaction by pointing at the possibility of inconsistent models between designer, user, and system [Norman 2002]. The conceptual models, however, do not provide detail on the possible inconsistencies that may arise. According to Crilly [2011] what is missing in the conceptual model approach is the user's mental model of the designer's intention, as this will influence the users' response to a system, regardless of the correctness of this model. This occurred in our concept evaluation as well. Furthermore, in the evaluation of our design concepts it became evident that the implementation of a mapping in a particular design has a large influence on how this mapping is interpreted by the user. Therefore, the meaningfulness of interaction is not only determined by the notion underlying the mapping (i.e., the image schema more-less relates more pressure to a more opaque color in Smart Window), but also by the actual implementation of the mapping (e.g., does the appearance make clear the need to provide pressure, and whether more pressure relates to more opacity or to more transparency). This implies that the designer's original intention as well as the success of obtaining this through design is crucial for the user's understanding of the interaction. Lloyd and Snelders suggest that besides the designer's intentions also the producer and press play a role in the user's perception of a system [Lloyd and Snelders 2003].

The MCRpd model [Ullmer and Ishii 2000] and TAC paradigm [Shaer et al. 2004] provide a detailed description of tangible interactive systems. The TAC paradigm can be used for classifying TI systems by specifying tokens and constraints (i.e., physical object with limited behavior possibilities). The MCRpd model distinguishes a physical and digital layer. However, neither the MCRpd model nor the TAC paradigm explicitly include the user and his understanding of the interaction. This understanding is addressed in the Frogger framework by Wensveen et al. that stresses the importance of a coupling between action (input) and information (output) for meaningful interaction

[Wensveen et al. 2004]. Wensveen et al. provide six practical characteristics that enable this coupling. In their framework, however, there is a strong focus on the relation (coupling) between input and output from a perceptual motor perspective, and less focus on the conceptual understanding of the interaction.

The work presented in this article focused on the conceptual understanding of Tangible Interaction, more specifically on the relation between the user's input and a system's output in interaction. It is crucial for a user to understand this IO relation, as it will enable the user to know what to do with a system in order to achieve a certain functional goal and to evaluate the resulting outcome. As indicated before, the functional value of interaction according to the State Change model for the user is in the physical state change (e.g., the light switches on). The IO relation described by this model is fairly straightforward, since the input parameter is equal to the output parameter. Nevertheless, because the input action of the user and the output of the system both take place in the physical layer, the physical properties of TI may be beneficial to make the relation between the user's input action and the system's output even more clear in comparison to digital interaction. In the Information Access model, it is the digital layer that forms an essential part of the function (obtaining information) through parameter conversion. Both the mappings on the input side and the mappings on the output side require the user's attention. Furthermore, the understanding of the interaction is further influenced by the user's awareness of the relation between these two mappings. Therefore, in the case of Information Access specific attention should be paid to the connection between the different cognitive, physical, and digital layers in design of the interaction. Since TI has both digital and physical qualities, we propose that it may form a unique strategy in the design of meaningful interactive systems.

7. CONCLUSION

On the basis of a literature review, concept design, and concept evaluation, this article has offered an analysis of input-output relations in interactive systems that is intended in particular to enhance understanding of subtle aspects of interaction with smart tangible objects. Two different IO relations were identified, captured in the IO models, and illustrated with reference to four design concepts: the State Change and the Information Access models. The State Change model represents the type of IO relation that supports setting parameters; it has one mapping that the user and the system share to create meaningful input. The Information Access model represents the type of IO relation that supports obtaining information and has a second mapping that connects the system and user with regard to the output. The IO models illustrate the role of the user and the influence of the system in the process of understanding the interaction.

We believe that the potential of smart tangible objects for creating meaningful interaction can be realized more effectively if designers take into account these IO models. In particular, for interactions that involve parameter setting, the physical qualities of TI can be exploited. In the case of Information Access, attention to the relevant IO model can lead to a better understanding of the relationships between the various mappings and the cognitive, physical, and digital layers in the interaction.

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