Metaphors, Analogies, Symbols: In Search of Naturalness in Tangible User Interfaces

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Abstract

In this paper we discuss how metaphors, and in general the translation of meaning between different knowledge domains, relate to the understanding of the interface between a human and a computing system, hence to its naturalness. Focusing on tangible user interfaces we analyze metaphors, analogies and symbolic representations developed in the computing interaction area to represent concepts in human computer interfaces along three main dimensions: the coherence of their use in linking concepts of some domain to the implementation of the interface, the coverage of the concepts implemented with respect to the amplitude of the knowledge domain, and their compliance with respect to the expectations of the human experience. We justify the choice of these properties by analyzing five simple tangible systems proposed in the literature according to these three dimensions, trying to understand how they support the development of interaction styles that users can exploit naturally.

1. Introduction

Natural interaction has received much attention since long, but only in recent times the availability of devices based on touch, tangible objects and gestures has created the conditions for the development of new products and interaction systems aimed at naturalness. A way to define a natural interaction is to consider that it occurs when the use of a new system does not require any form of learning. Pragmatically, the property of being natural is associated to interfaces that suggest their use through gestures related to the common human experience and to tangibles or vir-

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tual panels operated according to metaphors and analogies with the real world. Even if grounded on the affordances of the interaction devices, naturalness is a subjective property, difficult to evaluate since it depends on the user context, background, skill and goals. Nevertheless, empirical evaluation through task analysis and questionnaires helps designers to analyze, compare and evaluate different interface design solutions giving an indirect answer to the question of what a natural interface should be.

In this paper, after reviewing the relevant literature, we propose three properties to analyze and evaluate the naturalness and intuitiveness of a tangible interface based on a metaphoric correspondence between the interface objects and their operations at one side, and the functions and data of the digital application on the other side. We claim that interaction naturalness and intuitiveness derive mainy from three properties: (1) *coherence*, i.e., the degree of correspondence between the metaphor source and its tangible implementation in the interface; (2) *coverage*, i.e., the degree at which the interface is covered by features of the metaphor source; (3) *compliance*, i.e., the correspondence between the affordances of the interface objects and their use to activate the system's operations. We then analyze five tangible systems, whose interfaces are based on metaphors, according to such properties to assess the quality of the metaphors' implementation and evaluate the naturalness of the resulting interaction.

2. Related work

Metaphors are powerful conceptual devices to assist a designer in the conception and implementation of an interface. A metaphor consists in the translation of a concept from a *target domain* into a concept in a different domain, called *source domain*, more familiar in some context of discourse [14]. In a metaphoric interface the mapping relates concepts and operations between the two domains so that an interaction suggested by the metaphor source domain corresponds to the execution of the application implementing the metaphor target domain. The correspondence is subject to a suitable *interpretation* of the metaphor by the user that must match the interpretation that originated the interface design [5, 6, 18]. While in cognitive linguistics the word *metaphor* specifically refers to a correspondence between concepts of two different domains, the name is commonly used also for denoting other rethoric figures: *analogy* (explanations of a concept in terms of another), *synecdoche* (use of a part for the whole or viceversa), *metonymy* (use of the name of an object or concept to denote another object or concept) and, in visual form, *symbology* (graphic representation of an idea or of a concept). They are not mappings between different conceptual domains, but rather denote concepts of a domain with different representations; for this reason they remain associated to the idea of metaphor and are common in human-computer interfaces.

Tangible interfaces [11, 12, 20] are a form of reality based interfaces that use physical objects to operate with a computing system through a symbolic or metaphorical correspondence between the interface components and the system functions. The interface components and their use are designed to recall in their physical appearance the properties and behaviors of real world objects familiar to the user, so that an intuitive use of them should be sufficient to exploit the functionalities of the computing system. In a more general sense, an integration of physical and digital world through the use of physical objects, virtual representations and gestures is at the base of tangible interfaces qualified as natural to support the user's interaction with a system.

The presence of physical objects favors the design of metaphoric interfaces, that map objects belonging to the domain of everyday experience to specific functions of a digital system. Such design, however, is not properly driven by methodologies and guidelines, as noted by Alty et al [2] and Bakker et al [4]. Nevertheless, some notable efforts to improve metaphoric interfaces design have been made. Hints are given by Carroll and Mack [9] with reference to learning; they introduce concepts like base specificity, clarity, richness, abstractness, and point out the systematic aspect of metaphors. More recently, Blackwell [8] discusses interface design and actions making concrete, i.e., visible, the metaphor behind the relations between the interface and the digital application. Attempts for describing and classifying metaphorical tangible interfaces have also been explored [15, 16], aiming at supporting the design of metaphorical tangible interfaces. What is missing in these works, however, is the analysis of how the interface implementation really corresponds to the metaphor from which it has been drawn, i.e., how the reification of the metaphor into the interface and the way the interface drives the application are consistent with the metaphor components and with the mapping between the source and target domains. This concern is even more prevalent when it comes to tangible interface, because the use of an additional intermediate physical layer increase dramatically the way the metaphor reflects in the interface.

3. Analysis and evaluation of interface properties

Figure 1 shows four mappings that define the relations between an interaction metaphor and its implementation in a digital application: (1) the mapping between the metaphor source and target domains; (2) the reification of the metaphor source into the application interface; (3) the implementation of the metaphor target domain in the application; (4) the mapping of the interface to the application. Mappings (2) and (4) are relevant for our analysis: mapping (2) defines how the source metaphor is represented in the interface, while mapping (4) defines how the interface drives the application. Both contribute to the description and evaluation of a metaphorical interface because its quality is perceived through the behavior of the application. Mappings (1) and (3) are the result of design activities out of the scope of our analysis, even if they are important in the design and implementation of a correct application. Mapping (1) defines the metaphor itself, while mapping (3) defines how the application implements the requirements and specifications of the target domain. In the following of this paper we shall use the term *projection* to denote the implementation of the metaphor source on the application interface, labeled as (2) in Figure 1.

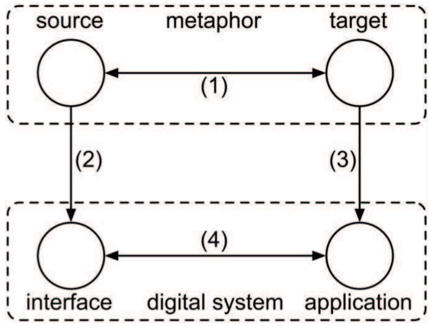

Figure 1. Mappings in interaction metaphors

To evaluate a tangible interface against natural behavior we propose three dimensions of analysis, identified by three properties: *coherence*, *coverage* and *compliance*. These three dimensions are related to key aspects of the projection of a metaphor onto a tangible interface: how the metaphor is projected onto the interface of the application (coherence), how complete is the projection (coverage), and at what extent the projection is recognizable in the objects used during interaction, in their affordances and in their relations (compliance). We note that mapping (2) is relevant to evaluate coherence and coverage, while mapping (4) is relevant to evaluate the compliance of the interface. We do not claim that these properties are exhaustive and must always be obeyed, but such analysis is helpful to orient good design and to evaluate the appropriateness of an interaction metaphor.

3.1. Coherence

In tangible systems the interface is related to the physical human experience, hence evaluating if the tangible interface is an appropriate and coherent (in the sense used by Lakoff and Johnson in [14]) implementation of the metaphor is an important issue. In the context of metaphorical tangible interfaces, we ground *coherence* on the correspondence between the physical elements of the interface and the concepts of the metaphor source at one side (mapping 1 in Figure 1), compared to the correspondence between the concepts of the metaphor target and the digital items implemented in the application on the other side (mapping 2 in Figure 1) . More specifically, with reference to the diagram of Figure 1, a metaphorical interface is coherent if: (1) for any element *E* of the interface which is a reification of a metaphor source concept *S*, there is a corresponding digital item *D* of the application which is the implementation of the metaphor target concept *T* corresponding to *S*; (2) any action *A* applied to an interface element *E* corresponds to a function *F* of the digital application that applies to the digital item *D* corresponding to *E*; (3) actions and sequences of actions on interface objects consistent with the meaning of the metaphor source map to the activation of functions and their sequences changing the application state consistently with the metaphor target meaning. Coherence is thus defined at two levels: the level of the interface components and the level of their structuring into meaningful interaction sequences properly changing the state of the application.

3.2. Coverage

We can also evaluate the *coverage* of the projection of a metaphor onto a tangible interface: it is defined as a measure of the amount of concepts mutuated by the metaphor source that are implemented in the tangible interface and used in the application. It is inspired from the concept of "conceptual baggage" [1–3] which represents "the proportion of features in a metaphor which do not map system functionality compared with those which do" [1, p.309]. Coverage is useful in interactive systems to anticipate the behavior of unknown actions, given the actions already known. Language metaphors are often incomplete, relying only on a few interesting concepts from the two

Figure 2. Five metaphoric tangible interfaces: Tangible Light [19], Slurp [21], Reactable [13], URP [20], MISE [17].

sides [14], and also in interfaces an extensive coverage is hardly obtained; while the knowledge domains on which the metaphors are based may be very large, the interface implementation covers a limited set of objects and actions relevant for the digital application.

3.3. Compliance

As a third relevant feature, we can evaluate if the projection of the metaphor onto the tangible interface is *compliant*, i.e., plausible and easy to understand because the affordances of interface objects suggest a correct use according to the metaphor source domain.

These three properties contribute to the evaluation of the implementation of an interaction model based on metaphors according to the dimensions proposed by Beaudouin-Lafon [7]: (1) *descriptive power*, the ability to describe a significant range of existing interfaces; (2) *evaluative power*, the ability to help assess multiple design alternatives; and (3) *generative power*, the ability to help designers create new designs. Besides the description dimension, which is supported by a unified view of the implementation of the metaphor projection, the main contribution concerns the evaluation and generation dimensions. They allow to compare different metaphors to judge at what extent they are well chosen and implemented, and assist the designer to design different metaphors based interactions to accomplish a set of tasks.

4. Five simple case studies

In this section we analyze five simple tangible systems presented in the literature (Figure 2). The interfaces are all based on some form of metaphor, analogy, or symbolic correspondence, from very simple mappings to more complex and articulated ones. For each system we evaluate the metaphor implementation in the interface in terms of the three properties discussed in previous section.

4.1. Tangible Light

Tangible Light [19] is a simple tangible interface for turning on and off an electric light shaped as a candle, based on the analogy with a true candle light: the user can blow, wave or clap hands to turn the light on and off. The goal of the authors is to study the link between emotions and interfaces, so the implementation is very limited; it is anyway interesting, in its simplicity, to apply our analysis.

About coherence, applying one of the three allowed actions to the only interface object (the light itself) causes the execution of the only function of the system: to change the light status. We note that the same user action executes two different and opposite functions. While this is not a fault, in principle, it is not coherent according to our definition because it violates the principle that the relations between objects and actions in the interface metaphorical interpretation must match the relations between data and functions in the application. In this case the actions in the interface (blowing, waving or clapping at the candle) map to two different operations in the application side of the metaphor (to turn the light on and off). This behavior is also counterintuitive, hence it affects the compliance, as we discuss below.

Coverage is assured, since the metaphor is very simple, composed of only one object and action. To evaluate compliance we need to distinguish the three actions supported by the system: blowing, waving with a hand in front of the light, and clapping hands to move air. At different degrees they are compliant for turning the light off, while they are counterintuitive for turning the light on. We could question about clapping hands to turn a candle off, but this behavior comes from the design goals of the system, i.e., studying human emotions. We can conclude that globally none of the three interfaces is either coherent or compliant to be considered natural in all its aspects.

4.2. Slurp

Slurp [21] is a simple device whose purpose is to take, hold and deliver data across devices and computing equipments. It supports the so-called *abstract digital media* or *locative media* [10]. The *Slurp* tangible interface is based on the idea that any object can be a container of information related to it (e.g., history or specifications) that can be extracted to be read and processed. Extracting media and copying it to a computing device happens by physical proximity via RFID technology: an intermediate device is used to move data between objects with a metaphorical behavior inspired by an eyedropper. *Slurp* can extract ("slurp up") media by poiting at an object and "sucking up" the contained information, which can be injected into a computer by pointing at the screen and "squeezing" data out. The metaphor is simple and evident: data is a fluid. The state of the device (full or empty) is also visible, like in a real eyedropper.

Coherence evaluation starts by observing that the eyedropper is a container that can suck and squeeze its content, and corresponds metaphorically to an information container that can read and write files, one at a time. Three actions are relevant: to extract/pull data, to hold data and to insert/push data. The source and target information holders are selected by proximity. The metaphor is coherent since each action in the tangible interface corresponds to one function on data independent from the data itself, and the direction of transfer is compatible with the physics of the eyedropper bulb (squeezing to blow, releasing to suck). Hence the correspondence between the meaning of the interaction action (extract/insert data) and the metaphorical operations (suck/squeeze) is preserved by the interface implementation. Also coverage is assured, as expected in an interface with a limited operation set, since an eyedropper has no other purpose than taking, holding and pouring its content. As to compliance, the squeeze and suck actions are compatible with the affordances of the physical device, hence it is also assured. We can conclude that this interface does not require to learn artifical actions or concepts and can be defined natural.

4.3. Reactable

Reactable [13] is one of the first and most popular robust tangible interfaces. It is a music synthesizer where modules for music generation and processing are represented by small blocks placed on a round multitouch table. The blocks are labelled with abstract symbols (e.g., loop generators are represented as stylized documents) and symbols drawn from the electric circuitry conventions (e.g., filters, signal shapes). As they are deployed on the table, a sound processing circuitry is virtually built: lines are drawn representing connections between the modules and with the output, represented by a pulsating spot in the middle of the table. Moving the blocks changes, if appropriate, the connections between the modules; rotating the blocks like dials the sound parameters change and the effects on the audio signals is reflected in the appearence of the lines connecting them, which mimic the audio waveforms and the music rythm. The synthesis possibilities are quite ample, but we analyze only the basic functions of the interface.

The *Reactable* operations are not inspired by a metaphor in proper sense; rather, the design of the interface comes from the electric diagrams symbology. The knowledge domain of the interface, indeed, is the same than the domain of the application: the interface defines a tangible symbolic correspondence between the interaction domain (a virtual circuit connecting modules) and the execution domain (an audio signal processing application).

The coherence of this interface can be analyzed both at the level of the single interface components and of the structure of their connections. At the component level, the blocks placed on the table correspond to electronic modules able to generate audio signals and process music parameters. The manipulations permitted by each block (lay/remove, join to other modules, rotate right/left) correspond to the operations provided by the corresponding electronic circuits, i.e., changes in specific signal parameters (activate/deactivate, connect, increase/decrease) and in the signals' path. At the structural level their connections define the transport of audio signals through filters and other sound processors from generators to the output. The way the connecting lines are drawn recalls the properties of the sound (waveform, beat) and gives a visual feedback of the main music features such as pitch, timbre, volume and rythm. According to our definition of coherence the interface is coherent because: (1) each interface object corresponds to a different (instance of) music track or music processing module operating on a specific sound property;

(2) each action on an interface object corresponds to the modification of one of the processing module parameters; (3) multiple operations on a same interface object (deployment, contact and rotation) correspond to the activation and connection of the modules and modification of different parameters which do not conflict each other and are applied orthogonally; (4) the signals are carried across the processing modules as defined by the paths connecting the interface objects.

Coverage depends on the amount of sound processing modules and music loops available; for each module a range of parameter values is defined, and changes are applied within the range. We can assess that coverage is complete with respect to the functionality of the sound processing modules: each of them is operated by the virtual commands implemented in the interface and provides all possible inputs to the sound processing modules.

Concerning compliance, the interface blocks are manipulated in two ways: by rotation and by connecting them to other command blocks. Rotation is compliant with the behavior of physical knobs in music banks. The connections between the objects representing the sound processing modules is compliant with the transport of electrical signals along wires between electrical modules. It is important to note, however, that compliance is evaluated on a set of *symbolic* representations of the processing modules and their operation modalities; their meaning is known to experts of the application domain but can be obscure to causal users of the system. Hence, reasoning about the naturalness of this interfaces is not immediate: it is natural for users skilled in sound processing that know the related simbology while it could be more obscure (even if engaging to play with) to casual users.

4.4. URP, Urban Planning

Urp [20] is a tangible interface based on a table on which models of buildings can be placed to reason about urban planning with an immediate and perceptually rich feedback. A projector casts shadows and other information on the table according to the buldings' position and to the time of day set on a *clock* tool. The properties of buildings are set by another tangible tool, a *material wand*, that sets the material used for their constructions, adapting their behavior for light and sun reflection (e.g., as in case of large glass surfaces). A third tool is an *arrow* defining the direction of wind, which is projected over the table as a flow of stream lines. Urp combines realistic models of buildings, which define a strict correspondence between the tangible and the digital information, with metaphors (the clock, the material wand and the wind arrow) that allow a user to dynamically adapt a simulation of the scene to the environmental parameters selected.

The analysis of coherence is more articulated than in previous case studies because the interface mixes metaphors with models of reality. Little needs to be told about the buildings, that are the main controllers of the application execution; as objects, their relations with the application behavior is coherent since only their position is relevant. Their mutual placement obeys the rules of physical space occupation (they cannot intersect) and the geometric rules about shadowing. More can be said about the metaphorical components of the interface. The clock is an analogy where time is coherently represented by the position of the hands; the time is defined in a non ambiguous way, and the operations allowed are coherent with the meaning of a clock, since by rotating the clock the solar illumination is changed according to the corresponding daytime. The material wand is a metaphor associating a touch of the wand to the change of the material of the building. As an object it is coherent with the idea of having a "magic" change of a property. Its operations being simple (a touch on a building) also the operations are coherent since the change is applied only to the touched object (but it can have effects on the shadows set by and on other buildings). The wind arrow is also based on an analogy between the direction set by the arrow on the table and the simulated wind direction. At the component level the interface is thus coherent. At the structure level the whole interface is coherent because the actions permitted by the different objects and tools are applied orthogonally, hence their composition produces the same result independently of the sequence of changes applied. This corresponds to the behavior of the real world.

Speaking about coverage, the models of buildings can be moved in any position as long as they do not conflict in space. They are indeed wireframe models defining a volume, hence the question about their correct placement in architectural terms (e.g., laid down on a side) is not relevant in this context. About the tools, we can say that each of them provides only one operation that changes a specific physical property of the environment, hence the coverage is complete for what concerns the possible variations in the simulation parameters; conversely, each change defined by operating a tool or moving a building reflects in a new scene projected on the table as the result of a new simulation step.

Compliance is also assured: the models of the building, like in building toys for children, are moved as blocks and support no other action; the three tools are operated according to their meaning as objects of the real world (the clock) or as symbols known in the human experience (the arrow) or in the tales tradition (the material wand).

4.5. Mixed Interactive Systems for Eutrophication

MISE, *Mixed Interactive Systems for Eutrophication* [17], is an educational prototype used in a museum to explain *pond eutrophication*, i.e., how a pond is progressively transformed into a forest because of environmental reasons and human activities that accelerate this process. It is based on a physical model representing a natural environment around a pond: a few houses with gardens, a field and a forest. This physical model is used as an input and gives no direct feedback to visitors, which is instead projected as a virtual 3D scene in front of the model. Manipulations of physical objects have a direct impact on a digital environment representing the pond and teh state of environmental parameters. It includes a 3D representation of the pond, a timeline representing its life expectancy and environmental information relevant to pond eutrophication such as water temperature, potassium rate, water level, and mud level.

Through these manipulations, visitors can simulate some human activities and observe their effect on the digital representation of the pond and associated parameters. Human activities that can be simulated include: pumping water by turning a tap in a private garden or using a hose over a field, adding weed killer with a crop duster over a field, or removing mud of the pond with a shovel. In this prototype buildings, gardens, fields and forest are direct representations of physical artifact. They serve to provide a tangible context to the interactive application and cannot be manipulated. The tap, the field hose, the weed killer bag and the shovel are also models of reality that can be manipulated to represent metaphorically the activities that change environmental parameters affecting the pond eutrophication: opening the tap is directly linked to the level of water in the pond, flying the crop duster refers to the augmentation of potassium and digging with the shovel increases the amount of mud in the pond. The metaphorical aspects of the interface can be found in the relations between the action performed by the user and the environmental parameters affected. For example, pouring water onto the garden is a *synecdoche* associating garden watering with a modification at a local scale, while a crop duster is a *metonymy* for the increase of potassium into the soil at a global scale.

With reference to the coherence property introduced in Section 3, the mapping between the input tangible artifacts and the simulation is coherently preserved in the components of the interface. For each tangible object there is a corresponding parameter of the digital simulation that is affected, and acting on it changes the parameter value of some amount defined by the simulation logic.

At the structure level, each part of the tangible interface is independent — there is no combined effect managed in the simulation — so sequences of actions are executed independently from their order. This is a simplification with respect of the real world behavior, introduced to keep the simulation oriented to an educational goal and not to a complete scientific analysis. Such simplification affects also coverage: as noted above, each human action in the tangible environment has been linked to the modification of only one parameter of the eutrophication process for sake of clarity. Clearly this is not true in the real world. Adding weed killer modifies the potassium ratio but also increase animals' death and therefore increases the mud level. Coverage is thus not complete with regards to the real eutrophication process but is sufficient for a pedagogical setting. Finally, the use of the different artifacts (opening the tap, moving the hose, flying the crop duster digging with the shovel) is compliant with the affordances of these object in the real world. The interface thus shows a sufficient degree of naturalness within the constraints of an edutainment application.

5. Conclusion

In this paper we have focused on the analysis of five different tangible interfaces based on metaphors, analogies and symbols with a specific point of view on the naturalness of the interaction during the use of the system. Being a subjective notion, we proposed to refine the definition of naturalness through the identification of three main properties related to the metaphors subsumed by the interfaces themselves: coherence, coverage and compliance. Each of the five use cases has been analyzed along these three properties. Doing this structured and refined analysis led to the identification of different and multiple potential causes that may affect the user's interaction naturalness.

Concretely it appears that, in analyzing how an interface has been implemented after some metaphor, the amount of coherence can be related to the learning time required: indeed, adopting a coherent metaphor establishes direct links between elements familiar to the user (the source domain of the metaphor) and elements of the interface. Learning how to use the interface becomes easier as it is suggested by the metaphor source. In addition, coverage can be associated to the user's satisfaction with the interface, through the level of frustration which is implied: if every element of the interface is linked to one aspect of a metaphor, the user will face less inconsistency or questions when using the interface. Finally, compliance refers to the arbitrary property of the interaction: choosing tangible objects unrelated to the referred metaphor will not easily bring the correct affordances and therefore results in the necessity of performing arbitrary gestures, actions or objects manipulations. Analyzing the naturalness of a tangible interface thus results in establishing a three scale analysis of the interaction based on the three properties we have introduced. Designing and implementing natural interfaces should result from the identification and selection of a trade-off between the three mentioned interaction characteristics. Providing an assessment of the naturalness according to these three facets also contributes to the usability evaluation of the interface. It is only one dimension that must be enriched with traditional approaches including satisfaction, effectiveness and efficiency of the interface.

Future work will be targeted at two main goals. We are first interested in establishing to what extent the naturalness of the interface plays a role in its usability with comparison to the other dimensions. We will also seek to confirm and better elaborate how much these properties influence the interaction experience, especially in the terms mentioned above, i.e. ease of learning, arbitrary design and user frustration.

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