Exploring affordances of tangible user interfaces for interactive lighting

NICOLAAS PETER BIJMAN
Abstract

This paper explores interaction with lighting through a tangible user interface (TUI). In a TUI the physical object and space around it are part of the interface. A subset of tangible interaction called spatial interaction is the main focus of this paper. Spatial interaction refers to translation, rotation or location of objects or people within a space. The aim of this paper is to explore the relation between spatial inputs and lighting outputs based on different design properties.

A user test is set up to explore the effect that design properties of a TUI have on the lighting output that participants map to spatial inputs. The results of the conducted user test indicate that communicating affordances to the user is an important factor when designing couplings between spatial inputs and lighting outputs. The results further show that the shape of the interface plays a central role in communicating those affordances and that the overlap of input and output space of the interface improves the clarity of the coupling.
Sammanfattning


Ett användartest har utförts för att testa vad för effekt olika rumsliga indata och designegenskaper har på förväntad utdata för ljus och belysning. Resultatet från användartestet visar att starka affordances och begränsningar, tillsammans med överlappningen av rumslig indata och utdata för ljus och belysning, är de viktigaste egenskaperna för att designa tydliga övergångar.
Exploring affordances of tangible user interfaces for interactive lighting

Nicolaas Peter Bijman
Royal Institute of Technology
Stockholm, Sweden
bijman@kth.se

ABSTRACT
This paper explores interaction with lighting through a tangible user interface (TUI). In a TUI the physical object and space around it are part of the interface. A subset of tangible interaction called spatial interaction is the main focus of this paper. Spatial interaction refers to translation, rotation or location of objects or people within a space. The aim of this paper is to explore the relation between spatial inputs and lighting outputs based on different design properties.

A user test is set up to explore the effect that design properties of a TUI have on the lighting output that participants map to spatial inputs. The results of the conducted user test indicate that communicating affordances to the user is an important factor when designing couplings between spatial inputs and lighting outputs. The results further show that the shape of the interface plays a central role in communicating those affordances and that the overlap of input and output space of the interface improves the clarity of the coupling.

KEYWORDS
Spatial interaction, tangible user interface, lighting design, spatial couplings, affordances

INTRODUCTION
There are many types of interaction possible with the physical environment through location, sound, light, pressure and various other physical properties. This has led to diverse definitions within the field of tangible interaction. Graspable, physical and spatial interaction [6] are terms that describe scenarios that often apply to tangible interaction as well or are synonymous with each other.

In this paper spatial interaction with the physical environment is investigated. Spatial interaction is a term proposed by Hornecker (2006) as a subset of tangible interaction that focuses on the inherent ‘spatiality’ that TUIs possess. Spatiality refers to interactions through translation, rotation and location of objects or people in a space [6]. A system that maps spatial input to digital output is referred to as a spatial TUI [7]. This type of interface can involve sensors embedded in objects or a network of sensors within a physical space.

Spatial interaction with objects involves interaction through haptic touch, and movement as well as orientation of objects. An example of such an object is the mouse. According to Ullmer and Ishii’s [24] the mouse is a spatial TUI as it maps the physical two dimensional movement of the mouse to the digital movement of the cursor.

The spatial properties of a person’s body also falls within the area of spatial interaction. A user’s position, proximity to an object or presence within a space can be used as an input to control a lighting output. The following sections show different examples of object and user spatiality.

Figure 1: Research prototypes that explore sensor inputs (left) and design properties using low fidelity objects (right)
BACKGROUND

Spatial interaction with objects as inputs
Ishii, H. et al (1997) [11] propose a set of objects that serve as physical instantiations of their digital counterparts. These physical objects mirror the functionality that these elements have in a GUI. To exemplify, the lens represents the physical area that is included in the interaction, in the same way a window in a GUI defines the scope of what users can interact with (see figure 2). Users would be able to use their experience from interacting with GUIs and apply it to spatial interaction. However, as discussed by Ishii, designers should be aware that these elements can also insert layers of abstraction, which results in unclear relation between inputs and outputs. Therefore it is important to utilize tangible interface elements for one-to-one mappings between input and output, as discussed by Sharlin, E. (2004). These mappings mean that a single input results in a single output, which reflects many of the interactions with the physical world around us. These tangible elements raise further questions that interaction designers should ask themselves. Is it possible to directly instantiate GUI elements into the physical world and expect users to understand the relation between the input and output? Perhaps there are better relations between the physical and digital world.

One of the enabling technologies for spatial interaction is capacitive sensing. Most use cases for capacitive touch with regards to objects have traditionally been binary, which limits the amount of touch interactions that are available. However, Sato et al. (2012) [9] have developed a more sensitive form of capacitive interaction called Swept Frequency Capacitive Sensing. This form of interaction turns conductive everyday objects into inputs that allow for recognition of specific hand gestures (figure 3). These gestures can be recognized because of two main spatial properties. The area of contact of the hand as well as the location of touch. These properties are processed by machine learning algorithms that identify gestures based on their capacitance frequency spectrum. This allows designers to explore a new interaction space that makes use of spatial interactions based on touch.

Shape in design has traditionally been used as a static property to show the affordances [20] of a device and define the aesthetics. Changing the shape of a device can require complex mechanical constructions which is why it is rarely used as a way to control or display information within a design. Van Oosterhout, A., et al (2018) [12] challenge this notion by changing the shape of a device to communicate its state. (figure 4) Their user test shows that a shape that changes in size is related to the user’s perception of the affective state of the device.

Radio frequency identification (RFID) and Near-field communication (NFC) technology have enabled new means of the communication between physical objects. The components of these systems are based on communication between readers and tags. Passive RFID and NFC tags receive power from the reader which means they can be permanently embedded in objects as they receive energy externally [3]. The system is inherently spatial as they function based on the proximity of the card and reader. The information on the tags can also be rewritten. For object-to-object communication proximity can be utilized to enable objects to pass along information to one another,
establish connections and trigger actions [4]. Arnall et al. (2009) [8] utilize RFID for media interaction with physical cubes (figure 5), whose interaction bears resemblance to the marble machine by Bishop, D. (1992) [10]. The different coloured cubes are associated with a media output, as the coloured marbles of the answering machine were associated to the person who left a message on the machine.

**Spatial interaction with users as inputs**

The location of a person in a space can be used to adapt a device without explicit control. An example of this behaviour is shown in the “Farsight” feature from Nest, which adapts the size of the elements in the user interface based on the distance between the user and the device. When the distance increases the amount of UI elements decrease and become larger (figure 6). This allows users to retrieve the most important information from the device from any place in the room.

**Figure 6: Farsight feature of Nest**

Another example of using people as spatial inputs for a digital system is proximity based content. Different companies now produce beacons that provide users with digital information when they are close to the beacon (figure 7). In Scott Jensen's keynote at CHI 2014 [29] he argued that this form of interaction can extend digital information of physical products without the need of installing separate apps for every micro interaction with a physical device to allow users to focus on the physical device that is interacted with.

**Coincidence of input & output space**

According to Ullmer B. et al (2000) [24] to create a seamless interface a tangible user interface needs ‘coincidence of input and output space’. In everyday interactions the output almost always occurs directly at the location of the input, which strongly enforces the perceived relation between them. Ullmer shows an excellent example of coincidence of input and output in the Urban Planning Workbench (figure 8).

The location and orientation of objects are used as an input to project light on the workbench that shows insightful data regarding the configuration of those objects. The fact that the physical objects are in the same location as the projected light makes this tangible interface more valuable.

**Spatial couplings**

The relation between input and output in tangible interaction design can be defined as one-to-one or many-to-many couplings. Sharlin, E. et al. (2004) claim that one-to-one couplings reduce complexity by clearly linking one input to one output. They argue that these couplings work well because they resemble the daily interactions we have with objects and spaces. These causal and direct interactions serve as good options for a spatial TUI as users will understand actions that they
have experienced before. This is one area where tangible interaction differentiates from graphical user interaction. People are often able to understand complex visual information through GUIs, which makes those interfaces well suited for one-to-many or many-to-many interactions. Therefore Sharlin et al. argue that TUIs are better suited for specific purposes rather than generic tools [7]. Tholander et al. disagree with the notion that creating one-to-one couplings is the best approach for tangible interaction. In their prototype they utilize many-to-many relations between tangible items and code snippets displayed on a screen [27]. Their argument is that utilizing tangible objects as inputs for reusable actions allows for many-to-many interactions because in that scenario the items and configuration of the physical space no longer restrict what is displayed on the screen.

**Affordances**

The concept of affordances by Norman D.A (1999) in interaction design has been applied in many different fields of design. The affordances of an object are all the actions that you can take with that object. Designers can communicate what their design affords through properties such as the shape and material. One such example applied to TUIs is by Ullmer B., et al (2005) who argue that many functions in a digital system have no spatial couplings. For those scenarios they argue for the use of Token+ constraint systems [26] (figure 9). These systems rely on conventions that users are familiar with to communicate the relation between the physical and digital world. The constraints of the shape show the user which interactions are possible. They argue that the constraints are important to limit the interaction possibilities to one-to-one couplings, which creates clear relations between the input and output. The more degrees of freedom a shape has, the vaguer the connection between inputs and outputs becomes.

**Exploring spatial interaction**

The objective of this paper is to explore the relations between spatial inputs and lighting outputs. Sharlin et al (2004) argue that clear couplings are created when the object functionality is obvious from its physical and spatial characteristics. The design of the object that is interacted with defines those characteristics through its physical properties such as shape, material, colour and size.

The output that is explored in this paper is lighting. Using lighting as an output is motivated by two reasons. First and foremost, focusing on one output category makes it more feasible to create a prototype. Limiting the amount of output options allows me to focus on different spatial inputs and design properties. Furthermore I expect that lighting outputs will fit well with spatial inputs as it has a large influence on a space through emitted light and shadow. The following research question is defined based on spatial input, design properties and lighting output.

**RESEARCH QUESTION**

“How do the design properties of a tangible user interface influence the perceived couplings between spatial inputs and lighting outputs?”

A task-based user test and a follow-up experiment are set up to explore this research question. The aim of the tests is to observe how participants interact with tangible user interfaces that have different design properties, and how that influences the relation between spatial interactions and lighting output. The design properties that are included in the test are shape, material, size and colour. In their product design methodology Roozenburg, N.F. et al (1995) argue that these properties are among the first parameters for designers to consider when trying to communicate the relation between controls and their actions.

The methods chosen to explore the research question are based on research through design [28] as well as correlational research [17]. The preferred state of this body of work would be as a building block for interaction designers who want to create tangible prototypes that utilize spatial inputs.

**Figure 9: Token + constraints examples**
METHOD

The research question is explored by two different tasks that focus on testing different design properties and spatial inputs, as well as a follow-up experiment in which the insights from the user test are applied in a practical setup.

Figure 10: Design properties and spatial input tasks

Testing methodology

The qualitative data includes camera footage that aim to observe how participants engage in spatial interaction as well as notes that were made based on participant’s comments from the think aloud protocol. In the experiment qualitative data regarding the interactions was gathered through observations.

The quantitative data gathered in the user test includes the participant’s choice of lighting output for both the object property and spatial input options. This approach is similar to the ‘control cards’ used by Tholander et al. (2006) that participants could be used to indicate an action on a screen display based on a tangible input [27].

The participants that signed up for the user test are sampled based on availability around the KTH campus, resulting in 12 participants between 22-34 years old, 7 male and 5 female with interaction design backgrounds.

A within-subjects approach [18] is used in order to reduce the random noise that different ages, background or habits introduce as well as to gather more statistical significance from fewer participants. Learning effects are minimized by using a Latin square approach to randomization [19] (figure 11), which results in 3 groups of 4 participants testing the independent variables in different orders.

Figure 11: Latin square order groups

Object property test

In the first test participants are asked to map a spatial input to lighting outputs based on interaction with objects that have different design properties. Multiple low fidelity prototypes with different shapes, materials, colours and sizes were used to test these properties (figure 12). Design can be defined by many factors. I have chosen to focus on the physical properties such as shape, material, colour and size as the building blocks of design as is discussed by Roozenburg, N.F. et al (1995) within their product design methodology [5].

Figure 12: Exploring different object properties

The dependent variable in the test setup is the lighting response that the user chooses, represented by a card (figure 13).

Figure 13: Lighting output cards

The independent variables are the options within each tangible property. For example, I am interested to see if participants put down the same or different cards when I ask them to interact with a cone, ring or rectangular shape (figure 14).

Figure 14: Exploring various object properties
Two controlled variables are utilized to ensure that no other variables influence the data. These include the tangible property that is not being tested and the spatial input type. For example, if we are testing the effect of the shape of an object on the output then the different options should have the same size, material and colour. In the case of the shape options this results in Styrofoam material, which has the same colour and size (figure 12).

The input type represents how the user should interact with the different options. For instance, I’m asking the participant to rotate each shape 90 degree clockwise so that the input is the same for each option.

**Spatial input test**

The second part of the user test investigates which lighting output users choose based on different spatial inputs. A prototype is created to capture spatial inputs through sensors that have an effect on the lighting in the room.

The approach of the second test is the same as the first. The dependent variable is the lighting output chosen by the user. The independent variable is the spatial input type and the control variables the properties of the object that the participant interacts with.

**Modular sensor prototype**

A prototype is created that facilitates the detection of different spatial inputs. For the object interaction capacitive, acceleration and gyroscopic sensors are used to detect translation, rotation and touch interaction with objects. Passive infrared, distance and gesture sensors are used to detect a user’s presence in the object’s surroundings.

The sensor’s input is processed by an ESP32 which creates a web server that communicates with a Philips Hue bridge through a Node.js library to control the lights. The sensors are connected to the light outputs through a wireless connection established through the microcomputer, which allows for reconfiguration between inputs and outputs.

The sensors use magnetic connectors based on the LittleBits modular electronics platform for quick prototyping of spatial interactions. These modular connections can quickly be swapped out to test the effect that different sensors have on the interaction between participants and the prototype (figure 15).

**Experiment**

A follow-up experiment of the prototype in a practical setting was set up, in which the insights from the think aloud protocol of the user test are applied. The sensor based prototype was tested by integrating sensors in the lamp and the space around it in the context of an event. The objective of the experiment is to observe and learn from how people initiate spatial interactions with the prototype without prior knowledge about the inputs or outputs.

**Figure 16: Couplings of spatial inputs and light outputs**

Three couplings between inputs and outputs were used for the experiment setup (figure 16). A short tap of the frame of the lamp would turn the light on/off, holding the frame for a longer time would change the colour temperature between the minimum and maximum value. A capacitive sensor was used to differentiate the different types of touch. Sato .M (2012)[9] swept frequency touch interaction approach is implemented in its design to be able to differentiate grab from touch interactions.
The activity in the space is reflected by the brightness of the lamp. The value would increase and decrease based on the movement within the room. The activity was represented by the aggregated triggers from a passive infrared sensor in a given timespan within that space.

RESULTS

The objective is to find out if users are more or less likely to choose certain light output options. This insight is gained by measuring the variation of the distribution of the choices from participants. An approach to calculating the variation of the distribution needs to be found. The data that is gathered from the object and sensor test is an aggregation of the participant’s choice of output. This makes the data type ordinal. Analysing distributions of ordinal data is referred to as calculating qualitative variation [17]. Finding the qualitative variation for ordinal data can be accomplished with Shannon’s approach to describing entropy. High entropy means that the aggregated choices of participants is spread out. Low entropy means that the choices are concentrated. The following scenario exemplifies the analysis. A participant is asked to rotate an object 90° clockwise and to choose which light output best fits that scenario for a given object:

A: Increase the brightness
B: Turn the lights on
C: Change light colour
D: Nothing happens

For options [A,B,C,D] 12 Participants chose the following outputs: [8,3,0,1]. We calculate the relative distribution

\[
H = -\sum_{i=1}^{M} P_i \log_2 P_i
\]

and use Shannon’s formula for calculating the entropy value.

A = 8/12 = 0.666
B = 3/12 = 0.25
D = 1/12 = 0.083

\[
H = -[(0.66\log 2 0.66 + 0.25\log 2 0.25 + 0.083\log 2 0.083)]
\]

H = 1.188

The value is then normalized from the maximum and minimum entropy value to a range of 0 and 1 as described by Wilcox et al (1973)[17]. 0 represent minimum entropy and 1 maximum entropy. Maximum entropy occurs when the distribution is evenly spread across the options. A [8,3,0,1] distribution of cards results in a variation of 0.38. The more spread out the choice of cards the closer the value is to 1. For example for 12 participants with card choices [A,B,C,D,E,F] a distribution of [2,1,3,2,3,1] has a variation of 0.69.

Object property test results

Graph 1 shows the variance values for the different object properties that have been tested. The closer the variance is to 0, the more consistent the participant’s responses are. While it is hard to draw conclusions from an isolated variance value, the data does show which options have stronger couplings between input and output through the comparison of the variances.
The variances differ most between the different shape and combined options. The cone and bubble wrap have a high variance and rectangle and the large button a relatively low variance. The other object properties variances are relatively close to each other with the size object properties having the highest variances.

Spatial input test results
The result of the spatial input test (graph 2) shows a low variance for rotate and high variance for the move and touch spatial inputs. The presence spatial input has a lower variance than proximity and location.

The main feedback from the think aloud protocol was that users prefer to directly interact with the lights through touch, rather than remotely control the lights with abstracted objects. This lead to the development of the experiment in which touch interaction with the lights is further explored.

DISCUSSION
I would argue the cause of the different variances of the object properties (graph 1) are the result of the quality of the perceived affordances [20]. The perceived affordance is the user’s expectation of what they can do with an object. For example, a participant is asked to rotate a shape 90° clockwise, which fits well with the rectangular shape as it has 4 discrete sides. The cone affords for rotation, but has no particular meaning associated to a 90° clockwise turn, which results in an unclear interaction that spreads out the possible lighting outcomes that participants choose. In the case of the button & bubble wrap the participant is asked to push their hand down on the object. For a large button with a single flat surface participants chose binary turning the light on/off, while pushing down on bubble wrap led participants to many different outcomes. The material does not afford for pressing down with a full hand, but rather pressure with a single finger. The combination of the interaction (pressing hand down) and the design (large flat surface with force feedback) determine the strength of the perceived affordance. The stronger the affordance, the better the understanding between the input and output.

I would argue that the resulting variances for the different spatial inputs (graph 2 left column) can be explained by the circular shape of the object that was interacted with. (figure 17). I would argue that circular shapes have a strong perceived affordance for rotation, while moving or touching this shape is not inherently significant. Participants most often chose the ‘Increase Brightness’ output for rotating the circular shape, most likely because rotating a circle is a standard that is used in light dimmers. Norman, D.A., (1999) refers to these cultural standards as conventions.

The “user as an input” results (graph 2, right column) show a similar reliance on conventions. If you approach a light in a public space it is common that it will turn on when a motion sensor is triggered. Proximity and location have less established forms of interaction with regards to lighting outputs, which results in a higher variance of participant choices for those options.

The comments from the think aloud protocol showed that participant choices were often motivated material related sub-properties.

![Figure 17: Spatial input for circular shape](image)

Figure 18: Temperature determines the light output
One of the participants linked the temperature of the material to the colour temperature of the light (figure 18). This shows that a material is actually a combination of lower level physical properties that lead to a high level material.

![Figure 19: Semantics determine the light output](image)

Semantics that participants lend to objects played an important role in the decisions of lighting outputs. One of the options was a large button prototype from the
'Widgets of unusual size' project by Anderson, Z. et al [25] (figure 19 top image). The large size and force feedback of the button led some people to attribute conceptual importance to the interaction. An outcome that Anderson, Z. et al [25] also found in their research.

Another semantic link that is found is the absence of an output for the foam button because of the feeling that pushing the foam 'absorbed the interaction', which reduced the effect of the output.

Testing the prototype in the context of an event (figure 20) showed the importance of tangible interaction with the lamp itself. People were able to quickly identify different touch interactions, which is something that took much longer during the user test. I would argue that this is caused by removing the abstraction between the input and output. The user test used abstracted objects controls, while in this experiment the light is the control itself. In tangible interaction literature this concept is referred to as the *overlap of physical input and digital output space* [24].

People were not aware of the link between the amount of movement in the room and the brightness of the light. I think the main cause of this is that the clarity of the couplings between spatial inputs and digital outputs are affected by the amount of inputs. The more people present in the room, the more inputs affect a single output. This effectively results in a many-to-one couplings, which reduces the clarity of the spatial interaction [7,24].

Furthermore, using people within a space as inputs to control digital outputs creates many unintended interactions. At an event it might be interesting to adapt brightness based on user presence, but for many everyday scenarios this interaction is not wanted. In Scott Jensen’s keynote at CHI 2014 [29] he argues that these unintended interactions occur because designers underestimate the complexity of designing products with different contexts in mind.

Ishii H. et al (1997) [22] instead uses a person's location for ambient media in the background of a user's attention span (figure 21). This shows how spatial interaction can be effective at communicating information at a user's periphery, rather than using the input as a means of control.

**CONCLUSION**

The results from the user test indicate that the *perceived affordance* of a tangible user interface plays an important role when creating couplings between spatial inputs and lighting outputs. I would argue that participants are more consistent in their choice of lighting output when the perceived affordance becomes clearer. The *shape* of the design is a useful property to communicate those affordances to the user. The other types of relations that participants establish between inputs and outputs are based on *conventions* and *semantics*.

The experiment that followed the user test showed that people understood the couplings between input and output quicker when there is an *overlap of spatial input and lighting output space*. Using the location of people as an input is shown to be a challenge as it can result in unclear couplings and lead to unintended interactions.

This paper has explored the couplings between spatial inputs and lighting outputs, which aims to contribute to the discussion regarding spatial interaction.

**ACKNOWLEDGMENTS**

I would like to thank Charles Windlin for the insightful discussions as well as Karey, Glenn and Theofronia for all the feedback during the writing process.

**REFERENCES**


null