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# Comparing Graphical and Tangible User Interfaces for a Tower Defense Game

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## ABSTRACT

This paper presents the design and test results of a tabletop Tangible User Interface (TUI) for a real-time strategy game. An experiment was conducted comparing the TUI and Graphical User Interface (GUI) versions of the same tower defense game application. The results show that users performed better with the GUI and found it easier to use, but reported more interest and enjoyment with the TUI. Overall, however, preference was split evenly between the two interface types. Analysis of qualitative user feedback provided further insight into these results, and based on this, suggestions are made for future research in the area of Tangible User Interfaces.

### Keywords

User Interfaces, Tangible User Interface, Game Interface.

## INTRODUCTION

The past couple of decades have seen a rise in technologies that aim to further couple the digital and physical worlds; research is being done into interfaces that allow us to interact with computer systems in ways similar to how we naturally interact with our environment. These technologies have been classified as Natural User Interfaces (NUI) and are of a vast variety including multi-touch interaction, speech recognition, augmented reality and Tangible User Interfaces (TUI) – the focus of this study.

A TUI is a type of NUI that allows users to interact with computers via "tangibles" – physical objects that are both representations and controls for digital information (Ullmer and Ishii, 2000). The concept behind TUIs was first introduced as a paradigm called "Graspable User Interfaces" (Fitzmaurice, Ishii and Buxton, 1995). Since then, more Human-Computer Interaction (HCI) studies have been undertaken to contribute to the understanding of terms and design space. This study examines the advantages and/or disadvantages of Tangible over Graphical User Interfaces within the context of a gaming application. Specifically, a comparison is made between a Tangible User Interface and a Graphical User Interface for a single-player tower defense game, a type of spatial real-time strategy game.

A tower defense game was chosen for its characteristics – it is a spatial activity that requires cognitive effort and can be made collaborative. Given the general advantages of TUIs as noted in the literature, these characteristics make it a good match for TUIs. Moreover, tower defense games cannot easily be made to use a purely physical interface (i.e. in the style of traditional board games) because many aspects of its game play require digital computation. Examples of this include: enemy units' movement across the play area, defense towers' detection of nearby units, and all the dynamic modifiers involved such as differing speed of enemy movement, and tower strength. This reliance on digital computation, on top of its other TUI-compatible characteristics, make it an even better match for a TUI interface; particularly because it means utilization of TUIs' main characteristic – coupling of physical representations to underlying digital information (Ullmer and Ishii, 2000).

## A REVIEW OF USER INTERFACE TYPES

An early definition of NUI was of a system that would recognize physical objects and humans acting in a natural way (Rauterberg, 1999). However, his definition was focused largely on Augmented Reality as a general design strategy and limited NUIs to interfaces that supported a "mix of real and virtual objects". The scope for this term has since been broadened and a more recent definition defines NUI as a "user interface designed to reuse existing skills for interacting directly with content" (Blake, 2010). The NUI group - an online global community of academics, students, companies and hobbyists - has classified several products as NUIs; products that also bear classifications such as Gesture Interfaces, Augmented Reality, Multi-Touch Interaction and Tangible User Interfaces. Other umbrella terms for this class of user interface styles include Post-Wimp Interfaces and Reality-based Interaction (Jacob, Girouard, Hirshfield, Horn, Shaer, Solovey and Zigelbaum, 2007). Clearly these terms and their meanings are still evolving, and a formalized definition and list of the relevant subcategories of interface styles is required. In an effort to determine the path ahead for interface styles, research attention has focused on identifying patterns existing in major user interface styles (de los Reyes, 2009). These patterns describe trends in the changing characteristics of interface styles, according to dimensions represented in each of the rows shown in Table 1.

| **Interface type→ Attribute ↓** | **Command Line (CLI)** | **Graphical (GUI)** | **Natural (NUI)** |
|---|---|---|---|
| How the system is driven | Text | Graphics | Objects |
| General system behavior | Static | Responsive | Evocative |
| Coupling between cognitive and physical model | Disconnected | Indirect | Unmediated |
| Relationship between amount of possible paths and rate of interaction | Many-Low | Medium-Medium | Few-Fast |
| How user experience is driven | Directed | Exploratory | Contextual |
| User behavior when approaching the system | Recall | Recognition | Intuition |

**Table 1. Comparison between CLI, GUI and NUI.**

Ullmer and Ishii (2000) presented an interaction model for TUIs that extended upon the Model-View-Controller (MVC) model used for GUIs, an approach they named "MCRpd," for Model-Control-Representation (physical and digital). This was used as a tool to identify three key properties of TUIs:

- Physical representations are computationally coupled to digital information and models
- Physical representations embody mechanisms for interactive control
- Physical representations are perceptually coupled to actively mediated digital representations

TUIs, as are all NUIs, are largely seen as having advantageous features over traditional user interfaces including:

- Naturalness: TUIs exploit the natural ability of humans to act in physical space and interact with physical objects (Sharlin, Watson, Kitamura, Kishino and Itoh, 2004).
- Support for Collaboration: TUIs are well suited to social interaction through their multiple access points (Hornecker and Buur, 2006).
- Immediate Haptic Feedback: There is often a double interaction loop wherein users receive tactile feedback along with digital feedback. It is believed that this provides users a way to reduce their frustrations with delay of digital feedback for computers' actions (Ishii, 2008).

However, NUIs and by inference TUIs do have notable limitations. Disadvantages typically emerge when the following qualities are traded off for realism (Jacob, et al., 2007):

- Efficiency: Expert users of GUI applications usually make use of hot keys to speed up completion of tasks; an option not available with most NUIs.
- Versatility: A NUI system is typically special-purpose and supports specific tasks, while a GUI system is general-purpose and can be used for a wide variety of tasks.
- Accessibility: Natural interaction methods may not be suitable for the disabled.

## TUI DESIGN PRINCIPLES

Studies that seek to develop design principles for TUIs are scarce. Fishkin (2004) define a set of principles for Embodied Interaction; though only some of which are applicable to TUIs. Fishkin's work on developing a taxonomy for TUIs which led to an analysis that showed a trend in TUIs being developed – increasing levels of embodiment (coupling between input and output) and metaphor (analogy between physical and virtual objects and actions) over time. Sharlin et al. (2004) found that the fundamental quality of a TUI is determined by the strength of coupling between the TUI and the task it is designed to support, rather than the coupling between its physical and digital representations. Given the typically special-purpose nature of TUIs, further research is required of contextualized principles for TUI design in different application domains.

Existing research on TUI design has focused on the development of new kinds of systems. Examples of application domains include information visualization, entertainment, interactive music and education – though the exact advantages and disadvantages of TUIs in specific domains and contexts are still largely unknown. Also, very few direct comparisons have been made to traditional interfaces in specific application domains. Consequently there remains some uncertainty about which contexts TUIs are best suited. Hornecker and Buur (2006) have provided evidence that TUIs support collaboration and social interaction but, based on the other general advantages of TUIs, would TUIs also work well for single-user tasks? While some studies have concluded that enjoyment levels were similar for GUI and TUI jigsaw puzzles (Xie, Antle and Motamedi, 2008), what of other games genre? In particular, games that could take better advantage of the key properties of TUIs. What other application types could be positively transformed by this relatively new interface style?

## RESEARCH DESIGN

### Methodology

The study was done in two parts: HCI artifact construction (development of the TUI) and experimentation (comparison of the developed TUI application to its GUI counterpart). The following subsections describe how the study was carried out. The HCI "artifact" in this study pertains to the combination of: a tower defense game developed for a TUI, a tabletop TUI and descriptions of the interaction techniques designed.

A GUI tower defense game called *Immune Defense* had been previously developed by the first author (See Figure 1). For this study, a copy of the existing game was modified to support tangible user interaction on a tabletop interface. Immune Defense is a basic tower defense game. It is a simple strategy game wherein a player's opponents are computer-controlled creatures that try to travel from a given origin point to a given destination point. The player's goal is to keep the creatures from reaching their destination. To do this, players place objects called "towers" on the "map", a grid-based play area. There are different kinds of towers and these can work against creatures in various ways (e.g. towers can attack creatures or slow them down). Players gain "gold" to "buy" more towers by destroying opponents. A game level will run for a fixed time period with a fixed number of opponent assault waves that the player must survive. If a certain number of opponents reach their destination, the player runs out of health and the game is over.

### Interaction Techniques

Initially, a User Interface Description Language (UIDL) developed by Shaer and Jacob (2009) called Tangible User Interface Modeling Language (TUIML) was used; a set of techniques for specifying the structure and behavior of TUIs using both sketching and diagrammatic modeling. However, this later proved to be insufficient because it did not fully support documentation of an interface that had both tangible and touch interactions.

The GUI version Immune Defense game was modified to support tangible user interaction on a tabletop interface by taking the existing game and plugging in components from the reacTIVision framework, an "open-source cross-platform computer-vision framework designed for the construction of table-based tangible user interfaces" (Kaltenbrunner and Bencina, 2007). This framework was chosen because reacTIVision was originally designed to support real-time musical interaction, thus an emphasis has been placed on speed, robustness and compact symbol sizes – attributes that are also relevant to a gaming application.

However, the original GUI version of the Immune Defense game was implemented using XNA, Microsoft's framework for building games. Subsequently when converting to a TUI design, there was a mismatch in the frameworks used as the XNA framework (and most games in general) makes use of a polling technique to detect input, whereas the reacTIVision framework raises events whenever input is detected. Because of this, a software module was developed to wrap reacTIVision components in a facade that XNA could easily poll against.

March and Smith (1995) identified two design processes utilized in design science research – build and evaluate – which were used in the iterative development of the system and interaction techniques. Regular build and evaluation loops were embedded within the development of the TUI system prototype. These evaluations were largely informal, consisting of general feedback about the system from academic colleagues and gamers.

### Game Actions

The term "action" is used here to mean the main unit of analysis of a user's interaction with the game. This definition is based on Activity Theory wherein "an activity consists of actions or chains of actions, which in turn consist of operations" (Kuutti, 1996). In the case of Immune Defense, the activity is to play or win the game by preventing enemies from reaching their destination. The actions that a user can take during the game are presented in Figure 2. The final TUI implementation of the game consisted of a combination of tangible and touches screen interactions.

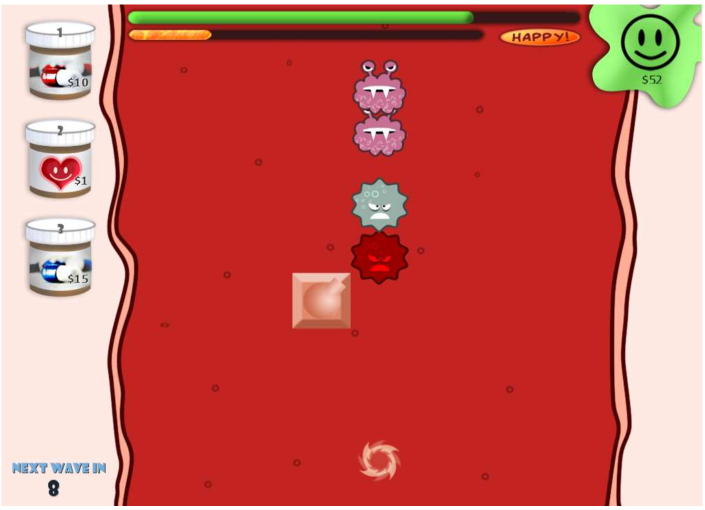


**Figure 1. Screenshot of Immune Defense game play.**

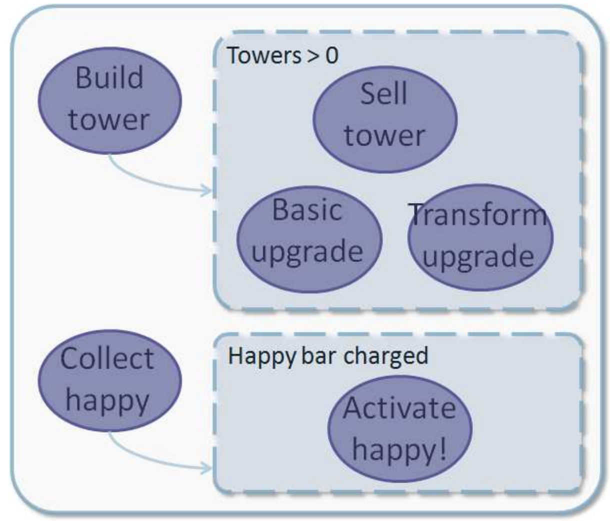


**Figure 2. Immune Defense game actions.**

### Experimentation

Aside from methodical engineering evaluations of the TUI system during development, a final evaluation was undertaken by users who compared the TUI with its original GUI counterpart. A convenience sample of sixteen participants evaluated the TUI and GUI interfaces developed for the tower defense game. Participants were chosen based on extensive experience using computers, an interest in tower defense games, and a medium to high level of skill in playing tower defense games. These characteristics are relevant to the aims of this project because a user-centered design process was used during artifact construction, and thus it is important for the evaluation to come from actual users of this type of system. Recruitment of participants began with a small pool of personal acquaintances. The sample of participants was expanded using the snowball technique where subjects identified similarly qualified acquaintances (Patton, 2002).

Potential users or novices were excluded from the research design to avoid the results being confounded by user experience factors. However, there is a trade-off between reality and efficiency and how this relates to natural UIs including TUIs: these systems currently don't have a counterpart for GUIs' keyboard shortcuts – something used by expert users to improve their efficiency (Jacob et al., 2007). For this study, this consideration has been scoped out and put aside as a possible extension for future research.

#### *Experiment Design*

A within-subjects design was used, where each participant played the tower defense game under both conditions – GUI and TUI. One half of participants used the TUI first, while the remaining participants used the GUI first. This design was chosen to avoid learning effects between trials because of the subjective nature of interface style comparison. According to Birnbaum (1999), context is needed for subjective judgment to be made. A within-subjects design gives participants that context; the different interface styles are compared. This also "lowers the possibility of individual differences skewing the results" (Shuttleworth, 2009).

Participants were asked to play the tower defense game using each interface style –GUI and TUI. There was only one level of game play but game difficulty increased as a function of time; participants played for as long as they could survive. Data collected at this stage was both quantitative and qualitative including: total play time, final game score and observational notes of general behavior and strategy.

A Post-Game Questionnaire was administered at the conclusion of each play to evaluate participants' enjoyment and other subjective elements of user experience with each interface. This questionnaire includes: a modified version of the Intrinsic Motivation Inventory (IMI), a multidimensional Likert scale questionnaire based on Self-Determination Theory that is used to assess participants' subjective experience related to a target activity in laboratory experiments (McAuley, Duncan and Tammen, 1989) and scale items to measure perceived ease-of-use (Davis, 1989). Construct items used in this study are provided in the Appendix.

Finally, participants were asked to fill out an Interface Preference Survey indicating which interface they preferred and open-ended questions regarding their preferred choice and overall experience with the systems.

### *Experimental Conditions*

Key differences between the two conditions – traditional GUI and tabletop TUI – are listed in Table 2. These differences are reflective of the distinguishing features of typical implementations of each interaction style in everyday settings.

## TABLETOP TUI SYSTEM

The tabletop TUI system was developed following guidelines set by Kaltenbrunner et al. (2007) as well as other guides for constructing a multi-touch tabletop capable of operating with a computer-vision framework. Tangibles placed on a glass surface are tagged with 'fiducials', symbols that can be identified and tracked by the framework through the camera. Information about the tracked tangibles is sent from to the TUI Application and used as input to control the game. The game is projected back onto the glass surface.

A table was custom built to support a 100 cm x 80 cm sanded glass surface, enclosed to allow for diffusion of infrared light. Based on the distance short-throw projectors must be from a surface to project an image of about 100 cm x 80 cm, the table is 90 cm high. Grooves were cut into the table to allow adjustment of the position of the inner shelf, so that the distance between the camera, lights and projector to the screen surface could be varied based on the size of the projected image.

### Illumination

Four 850nm infrared 48-LED lights were used for illumination. These lamps were first positioned such that they pointed toward the top corners of the table to help diffuse the light. However, because the table was constructed in such a way that the glass surface was positioned more to the left side of the cabinet, the light on the right side seemed to be better diffused than on the left, where there was less space for the light to reflect. This meant that the light was so bright on the left side of the table that fiducials placed there could not be seen by the camera. To work around this, the lamps on the left side were made to point to slightly downwards, and a matte black material was placed underneath to allow for better diffusion.

| **Attributes** | **Traditional GUI** | **Tabletop TUI** |
|---|---|---|
| Display Size | Medium | Large |
| Orientation | Vertical | Horizontal |
| AV Feedback | ✓ | ✓ |
| Tactile Feedback | × | ✓ |
| Direct Object Manipulation | × | ✓ |
| Integration of I/O Space | × | ✓ |
| Bimanual | × | ✓ |

**Table 2. Differences between experimental conditions.**

### Camera and Projector

A single camera was used: The Imaging Source DMK 31BU03 USB CCD Monochrome Camera. This camera was chosen because it could detect infrared light and could capture 1024x768 pixel images, up to 30 frames per second. This resolution was found to be better suited to the surface size - when an 800x600 pixel camera was used, the images were too blurry and reacTIVision wasn't able to detect the fiducials. To be able to capture the entire surface from a close distance, a wide angle lens was used - 1.67mm 113˚ FOV CS Lens (No Distortion). A short-throw BenQ MX810ST projector was used to allow projections of the required size from a shorter distance.

### Tangibles

Round transparent pucks were used as tangibles. They were designed to allow for easier gripping. Specifications for the tangibles are shown in Figure 3. Fiducials were cut to fit the shape of the tangibles and glued to the bottom. Transparent tangibles were used to allow them to take the color of the object they represent, as can be seen in Figure 4.

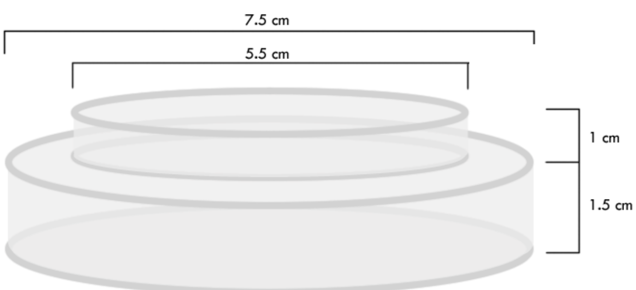


**Figure 3. Tangible specifications.**

**Figure 4. Tangibles with fiducials.**

## RESULTS

### Analysis of Quantitative Data

Total Play Time was measured in milliseconds. Since the goal of the game is to survive for as long as possible, the greater the Total Play Time the better. The results from MANOVA indicated that there were significant differences for both Total Play Time ($p < 0.001$) and Final Game Score ($p < 0.002$), and both higher for both variables under the GUI condition than for the TUI condition. Descriptive statistics are shown in Table 3.

| Interface Style | | TPT (ms) | FGS |
|---|---|---|---|
| **GUI n=16** | Min | 203000.00 | 273000.00 |
| | Max | 325000.00 | 646000.00 |
| | Mean | 263437.50 | 422125.00 |
| | Std Dev | 39053.76 | 106916.09 |
| **TUI n=16** | Min | 142000.00 | 167000.00 |
| | Max | 291000.00 | 423000.00 |
| | Mean | 208250.00 | 308531.25 |
| | Std Dev | 43830.74 | 75111.80 |

**Table 3. Descriptive statistics for Total Play Time (TPT) and Final Game Score (FGS).**

For the IMI subscales and Ease of Use questions, MANCOVA was conducted to test Interest/Enjoyment, Pressure/Tension and Ease of Use. Perceived Competence was treated as a covariate because of it likely influence on other variables, The MANCOVA was significant ($p < 0.001$). After adjustment for Perceived Competence, the scores for Interest/Enjoyment were significantly higher for the TUI condition than the GUI condition ($p<0.05$), while scores for Ease of Use were significantly higher for the GUI condition than for the TUI condition ($p<0.003$). No significant difference was found between the scores for Pressure/Tension. Descriptive statistics by interface style are shown in Table 4.

| Interface Style | | IE | PC | PT | EOU |
|---|---|---|---|---|---|
| **GUI n=16** | Min | 3.67 | 3.33 | 1.50 | 3.50 |
| | Max | 7.00 | 7.00 | 5.00 | 7.00 |
| | Mean | 5.38 | 5.06 | 2.94 | 5.53 |
| | Std Dev | 0.85 | 1.12 | 1.09 | 0.91 |
| **TUI n=16** | Min | 4.00 | 1.67 | 1.50 | 1.67 |
| | Max | 7.00 | 6.67 | 6.00 | 6.00 |
| | Mean | 5.69 | 4.31 | 3.41 | 4.27 |
| | Std Dev | 0.85 | 1.47 | 1.49 | 1.24 |

**Table 4. Descriptive statistics for the Intrinsic Motivation Inventory subscales and Ease of Use (IE = Interesting / Enjoyable; PC = Perceived Competence; PT = Pressure Tension; and EOU=Ease of Use).**

### Analysis of Qualitative Data

After each participant completed the game on both conditions, they were asked to indicate their preference and share any comments they have regarding their overall experience. The qualitative data collected was processed using thematic analysis and used to contextualize the quantitative findings. Results are discussed below for each theme found in the participants' comments.

#### *Responsiveness*

Most of the feedback from participants revolved around the issue of responsiveness of the TUI. However, these issues appeared to relate more to the apparent expectations of users that the TUI respond as an extension of human movement and action (i.e., a heightened level of responsiveness). We concluded that this outcome related to the immersive qualities of the TUI version of the game.

#### *Enjoyment*

Many participants said that they enjoyed the game on both interfaces but especially the TUI. The reasons they gave for finding the TUI more entertaining fall under two major categories – naturalness and novelty.

#### *Naturalness*

One participant said that because the TUI was more "hands-on", it got their full attention and because it was more engaging, the game was more enjoyable. Some participants said they found the TUI fun because it had more physical interaction, and one participant remarked that they liked how the TUI had a good combination of physical and intellectual aspects.

#### *Novelty*

Quite a few participants mentioned novelty as a reason why they considered the TUI more entertaining – the TUI was associated with terms such as "futuristic" and "unusual experience" and as one participant put it: "It's different. I like new things." However, another participant pointed out that while they found the TUI "new and interesting", they were uncertain whether that novelty would last for long.

*Game Strategy Formation*

There were conflicting views concerning which interface better supported strategizing for the game. One participant preferred the GUI for this because "everything's right there" and "it's easier to see what's happening on the screen"; while another participant believed strategizing was easier on the TUI because of the physicality and larger workspace that made them feel "more part of the game" and more "in control" of what was happening. These comments can be related more to the difference in display size and orientation of the two interface styles, and possibly differing cognitive styles. This may need to be investigated further.

## CONCLUSION

Users performed better with the GUI and found it easier to use, but reported more interest and enjoyment with the TUI. Overall, however, preference was split evenly between the two interface types. Analysis of qualitative findings provided further insight into these results, and the implications are as follows:

There is much potential for the use of a tabletop TUI for tower defense games. The designed tabletop TUI game leverages upon TUIs' fundamental characteristic and advantages noted in the literature - coupling of the physical and the digital worlds; and naturalness - creating an enjoyable experience for the users, even as a non-collaborative game. Contrary to the expectations based on existing theory, the GUI was found to be better in terms of ease of use. Feedback also suggested that, in line with existing theory, the TUI can be enhanced by tailoring it to not just the specific application type, but the specific game.

The analysis of findings has also raised questions that may be explored in further research. First, novelty was mentioned in users' comments pertaining to their preference for the TUI. This poses an interesting question: What happens when natural interfaces become commonplace and the novelty is lost? Second, combining different interface technologies may allow for the integration of alternative interaction techniques to further mould the TUI to the specific application, and to take greater advantage of the strengths of this new wave of natural user interfaces.

## APPENDIX

### Construct Items:

*Interest/Enjoyment (IE)*

- I would describe the game as very interesting
- The game did not hold my attention at all (reverse score)
- I thought the game was quite enjoyable and I would play it again

*Perceived Competence (PC)*

- After playing for a short while, I felt fairly competent
- I think I did pretty well at the game
- I am satisfied with my performance at the game

*Pressure/Tension (PT)*

- I felt very tense while playing
- I was very relaxed while playing the game (reverse score)

*Ease of Use (EOU)*

- I found the game interface easy to use
- Learning to operate the game interface was easy for me
- I found it easy to get the game interface to do what I wanted it to do
- My interaction with the game interface was clear and understandable

- I found the game interface to be flexible to interact with
- It was easy for me to become skillful at using the game interface

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