Available online at www.sciencedirect.com
SciVerse ScienceDirect
Int. J. Human-Computer Studies 71 (2013) 803–820
International Journal of Human-Computer Studies
www.elsevier.com/locate/ijhcs

To TUI or not to TUI: Evaluating performance and preference in tangible vs. graphical user interfaces

Oren Zuckerman*, Ayelet Gal-Oz

Sammy Ofer School of Communications, The Interdisciplinary Center (IDC) Herzliya, P.O. Box 167, Herzliya 46150, Israel

Received 2 March 2012; received in revised form 21 March 2013; accepted 9 April 2013
Communicated by Anatole Lecuyer
Available online 25 April 2013

Abstract

Tangible user interfaces (TUIs) are often compared to graphical user interfaces (GUIs). However, the existing literature is unable to demonstrate clear advantages for either interface, as empirical studies yielded different findings, sometimes even contradicting ones. The current study set out to conduct an in-depth analysis of the strengths and weaknesses of both interfaces, based on a comparison between similar TUI and GUI versions of a modeling and simulation system called "FlowBlocks". Results showed most users preferred the TUI version over the GUI version. This is a surprising finding, considering both versions were equivalent in regard to most performance parameters, and the TUI version was even perceived as inferior to the GUI version in regard to usability. Interviews with users revealed this preference stemmed from high levels of stimulation and enjoyment, derived from three TUI properties: physical interaction, rich feedback, and high levels of realism. Potential underlying mechanisms for these findings and practical implications are discussed.

Keywords: TUI; GUI; Tangible; Physical; Graphical; Interaction design

1. Introduction

Since the early days of personal computers, the Windows, Icons, Menus, Pointing device (WIMP) interface, invented at Xerox PARC, has been dominant in many of the digital devices we use. WIMP interfaces, also referred to as Graphical User Interfaces (GUI), have remained the dominant interaction model in personal computers and in mobile devices, despite the fact that many other interfaces have been explored during the past two decades. To name a few: touch-based interface, gesture-based interface, voice-based interface, and tangible user interface (TUI), which is the focus of the current paper.

1.1. TUI

TUI is a type of user interface that leverages physical representation to connect between the physical and the digital worlds. TUI is a field of research within Human Computer Interaction (HCI), and has seen increasing interest among HCI researchers in the past two decades (Shaer and Hornecker, 2010). TUI was first explored by Fitzmaurice et al. (1995), who presented their seminal work on "Graspable User Interfaces", using their "Bricks" prototype to present three key ideas: (1) physical artifacts which act as handles for control, (2) the advantage of leveraging people's lifelong experience with the physical world, and (3) space-multiplexed vs. time-multiplexed devices. The term "Tangible User Interfaces" was coined by Ishii and Ullmer (1997), who defined TUI as a "new kind of HCI… coupling digital information to everyday physical objects and environments" (p. 235). They presented a series of prototypes and suggested a classification of TUI to three classes: Interactive Surfaces, Coupling of Bits and Atoms, and Ambient Media.

Following this early work, a range of prototypes have been developed in the TUI domain, including TUIs for learning, programming, problem solving and entertainment, for example: AlgoBlocks (Suzuki and Kato, 1995), Digital Manipulatives (Resnick et al., 1998), Electronic Duplo Blocks

*Corresponding author. Tel.: +972 9 9527609; fax: +972 9 9527650.
E-mail addresses: orenz@idc.ac.il (O. Zuckerman), goayelet@idc.ac.il (A. Gal-Oz).

1071-5819/$ - see front matter
http://dx.doi.org/10.1016/j.ijhcs.2013.04.003

(Wyeth and Purchase, 2002), SystemBlocks (Zuckerman and Resnick, 2003), Topobo (Raffle et al., 2004), BodaBlocks (Buechley and Eisenberg, 2007), Tangible Programming (Horn, 2008), Media Blocks (Ullmer and Ishii, 1999), Block-Jam (Newton-Dunn et al., 2003) and many more. TUI systems have been classified and studied by HCI researchers (e.g. Dourish, 2001; Hornecker and Buur, 2006; Rogers et al., 2002; Shaer and Jacob, 2009; Ullmer and Ishii, 2000), and some TUI prototypes have even been commercialized (e.g. Sifteo, see http://www.sifteo.com; Topobo, see http://www.topobo.com).

1.2. The "TUI advantage"—theoretical explanations

Several HCI researchers suggested that tangible user interfaces have added advantages over graphical user interfaces. The pioneers of the field (Fitzmaurice and Buxton, 1997; Fitzmaurice et al., 1995) emphasized the bimanualism and space-multiplexed advantage of TUI vs. the time-multiplexed nature of GUI, and the advantages of natural affordances in tangible objects. More recently, Marshall (2007) claimed that TUI has great potential to support learning due to its "hands-on" nature, which allows physical manipulation of objects. However, he highlighted the need for additional evidence to validate the utility of TUI.

Klemmer et al. (2006) drew from psychology, sociology, and philosophy in order to formulate five theoretical themes explaining the importance of physical elements in interaction design. The first theme, *thinking through doing*, describes how thought and action are inherently integrated and together can produce learning and reasoning. The second theme, *performance*, describes how actions are faster and more nuanced compared to symbolic cognition. The third theme, *visibility,* describes the role of artifacts in collaboration and cooperation. The fourth theme, *risk*, explores how the uncertainty and risk attributes of physical co-presence shape interpersonal and human–computer interactions. The fifth theme, *thickness of practice*, suggests that embodied interaction is a more prudent path. Based on these themes, Klemmer et al. encourage interaction designers to integrate the computational and physical worlds.

Further support for the assumed "TUI advantage" can be found beyond the HCI literature, in psychological and educational research, demonstrating how various forms of physical interaction can enhance memory, performance and learning. For example, Hecht et al. (2008) demonstrated superior performance once a haptic signal was added to visual and audio signals. Participants in their study were able to detect the tri-modal combination (visual–auditory–haptic) faster than any of the bi-modal combinations, which in turn were detected faster than any of the uni-modal signals.

The same research group (Hecht et al., 2005) also highlighted the advantage of the visual–auditory–haptic combination in establishing a greater sense of presence in virtual environments. The authors hypothesized that the underlying cognitive mechanism is related to faster mental processing of multimodal events. The tri-modal combination enables users to start their cognitive process sooner, thus, in a similar exposure time, they can pay attention to a wider range of details and subtle cues. The integration of informative cues from different sensory modalities results in a richer and more coherent experience, which in turn leads to a greater sense of presence.

Moreover, gesturing was found to improve memory (Stevanoni and Salmon, 2005) and learning (Broaders et al., 2007). Goldin-Meadow et al. (2009) suggested that gesturing facilitates learning by helping learners extract information from their own hand movements.

In sum, various theoretical explanations, both within and beyond HCI literature, imply that tangible interfaces should be superior to graphical interfaces in regard to performance and learning. Accordingly, several researchers attempted to empirically demonstrate this presumed "TUI advantage".

1.3. The "TUI advantage"—empirical findings

Numerous studies compared between TUI and GUI or more generally between physical and digital interactions. Table 1 summarizes the main studies, their design and key findings[1].

As can be seen in the table, previous studies comparing TUI to GUI differ from one another in several ways. In regard to target population, some focused on children (e.g. Cheng et al., 2011; Manches et al., 2009) while others on adults (e.g. Marshall et al., 2010; Patten and Ishii, 2000). Overall, the majority of participants in comparative studies were children. Previous studies also differ from one another in regard to the specific research method employed, ranging from naturalistic observations (e.g.: Horn et al., 2009; Marshall et al., 2009) to highly controlled experiments (e.g.: Tuddenham et al., 2010; Xie et al., 2008). A key challenge of any comparative research is balancing conditions. In trying to balance between GUI and TUI conditions, unique affordances of one type of interface might get constrained or even entirely eliminated. Consequently, the benefits of the interface might get eliminated as well. As a whole, the existent body of knowledge overcomes this challenge by employing different research methods in different studies: some researchers employed a highly controlled experimental design, attempting to balance between TUI and GUI conditions to allow an accurate comparison. Others preferred a less controlled design, so the unique affordances of TUI and GUI could be explored.

In regard to evidence for the existence of a "TUI advantage", prior work remains inconclusive. While some studies suggest that TUI has a performance advantage over GUI (Fitzmaurice and Buxton, 1997; Tuddenham et al., 2010; Xie et al., 2008), others suggest it does not (Horn et al., 2009). Similarly, while some studies suggest TUI enhances cognitive functioning (Patten and Ishii, 2000), others were unable to demonstrate any advantages in the context of learning (Fitzmaurice and Buxton, 1997; Marshall et al., 2010). In addition, while several studies show that TUI is more inviting and engaging than GUI (Horn et al., 2009), others did not find any significant differences in

[1]A similar summary table was presented by Cheng et al. (2011). The current table is updated and extended to include additional studies and details regarding method and participants.