The Effects of a Tangible User Interface On designers' spatial cognition

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Abstract. A tangible user interface for designers changes the way in which the designers perceive and interact with a digital model. We studied the changes a specific tangible user interface has on designers' spatial cognition through the comparison of designers using tangible user interface and graphical user interface environments. The results reveal that TUIs change designers' spatial cognition, and then the changes in spatial cognition affect the design processes by increasing designers' problem-finding behaviours leading to a creative design.

Keywords. Tangible user interface, tabletop system, spatial cognition, augmented reality and 3D design

1. Introduction

Tabletop systems employing tangible user interfaces (TUIs) on a horizontal surface provide a new interactive design environment. TUIs offer physical objects with a direct correlation to digital objects as an alternative to typical computer input and output devices, and are often combined with augmented reality (AR). Thus, the physical interaction allows designers to interact with 3D digital models more directly and naturally, and the seamless interaction between physical and digital worlds augments designers' perception and interaction in the physical world (Seichter and Kvan 2004).

Most studies on tabletop systems with TUIs have focused on the functionality of the prototypes. A more in depth understanding of the effects of TUIs on designers' spatial cognition provides a perspective other than usability and is essential for the development of tabletop systems. Thus, we investigate what aspects of spatial cognition are changed by the TUIs, and then how the design process will be affected by the changes of the spatial cognition using protocol analysis. The significance of this research is to fill a gap in the existing research on TUIs with an empirical cognitive study.

2. Tangible User Interfaces and Spatial Cognition in Designing

Understanding spatial cognition is a precursor to studying tangible user interfaces and their affect on the way in which humans perceive and interact with digital models. Spatial cognition can be defined as visuospatial information reasoning through visual perception with sensory support or the construction of mental representations without sensory support (Vega et al. 1996). Based on the definition and Visser's view (Visser 2004) that designing is an opportunistically organized activity, we define a designer's spatial cognition as reflective interaction between the external representation and the designer's internal cognitive model of the problem solving processed by perception and reasoning about visuospatial information.

In terms of human-computer interaction (HCI), we are interested in the role of tactile modality of the interfaces in structuring a designer's spatial cognition based on the argument that epistemic actions improve a designer's cognition by reducing cognitive loads, and this is the potential affordance of interfaces having manipulable physical objects like TUIs (Fitzmaurice 1996). Epistemic actions refer to 'exploratory' motor activity (Kirsh and Maglio 1994). Further, we consider designers' gestures along with their design activity to be beneficial for cognitive processing (Goldin-Meadow 2003).

Regarding the design process, we focus on problem-finding behaviours that reformulate the design problem in response to visuo-spatial reasoning. Suwa et al. (Suwa 2000) proposed that unexpected discoveries of visuo-spatial features and the invention of design requirements (S-invention) are keys to gaining a creative outcome. These two notions are consistent with the co-evolution model where the design problem space and the design solution space co-evolve during the design process (Maher et al. 1996).

3. Comparing GUI to TUI

We compare designers using a TUI in a tabletop system to designers using a GUI in a desktop system with a focus the impact on designers' spatial cognition. A study of designers using a GUI is a baseline to which the designers using a TUI is compared. Seven 2nd year-architecture students were recruited, and each of them participated in a complete experiment, consisting of a design task in a TUI session and a second task in a GUI session. The design tasks are renovation tasks in which designers configure an arrangement of furniture to stimulate designers' perceptual actions on 3D objects, their relationships to each other, and their location within a 3D space.

3.1. Experiments

The tabletop system with a TUI includes a horizontal table and a vertical screen to facilitate multiple views of the 3D model (Fig. 1. (a)). 3D blocks with tracking markers in ARToolKit (Billinghurst et al. 2003) are "space-multiplexed" input devices. The desktop system with GUI is a typical computer comprising a screen, a mouse and a keyboard, where ArchiCAD was chosen as an application (Fig. 1. (b)). The mouse is a time-multiplexed input device, and the movement lacks tactile feedback (Fitzmaurice 1996). All design sessions were recorded on the DVR system.

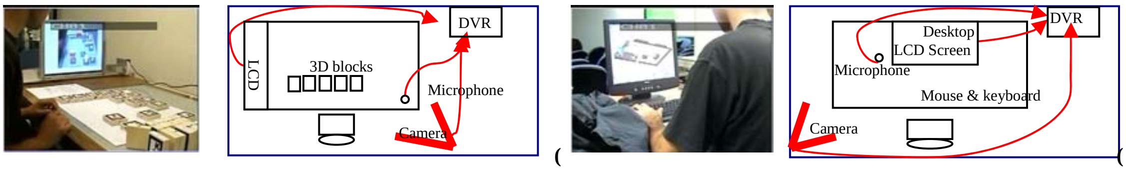

Fig. 1. Experiment Set-up: (a), (b) TUI session and (b) GUI session

3.2. Protocol Analysis

We collected concurrent protocols using the think-aloud method, which were transcribed, and then segmented along the lines of designer's intentions or changes in their actions. Each segment was encoded using a customised coding scheme comprising three different levels of spatial cognition: 3D modelling and gesture actions at HCI level, perceptual and reasoning actions at designer level, set-up goal actions and co-evolution at design process level.

4. Results

The structures of the designers' cognitive actions are explored visually in the graphs. The average segment duration of the TUI sessions (10.6 sec) is shorter than that of the GUI sessions (17.9 sec), which suggests that designers in the TUI sessions started new actions more and quicker in the same amount of time.

4.1. HCI Level: *3D Modelling and Gesture Actions*

There are significant differences in the average occurrence of 'new' ($Z=-2.888$, $N=7$, $p<0.05$) and 'revisited' ($Z=-1.857$, $N=7$, $p=0.063$) modelling actions. However, the average time spent is longer in the

GUI session, which indicates that cognitive load present in the GUI session might be reduced in the TUI session. Fig. 2. shows an example of the structure of 3D modelling actions, where each horizontal bar represents the duration of each action. The manipulation of 3D blocks had breakdowns made by short and frequent modelling actions, and these discontinuities suggest that 3D modelling actions of the TUI session have more potential to be recognised as an insight.

We investigated the relative proportions of gestures in each session. Designers did whole body interaction such as 'design gesture' and 'general gesture' with the blocks while changing the 3D representation in the TUI session, which suggests a kind of immersion in the design.

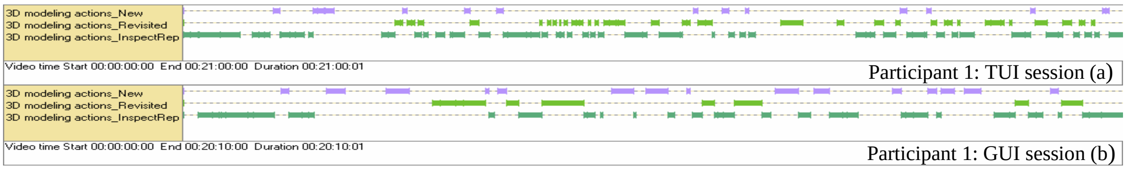

Fig. 2. 3D modelling actions

4.2. Designer Level: *Perceptual and Reasoning Actions*

Table 1. shows the average occurrence of the combined codes. The result of the group 1 indicates that designers created and discovered more new visuo-spatial features while using 3D blocks. In terms of the focus of perception, as shown in group 2, designers in the TUI session attended more to spatial relationships among the design components compared to the GUI sessions.

The occurrence of reasoning actions shows that designers in the TUI session thought more of functional issues on areas (Z=-2.888, N=7, p<0.05), exploring alternatives at an abstract level.

Table 1. Average occurrence of perceptual actions

Perceptual actions		TUI session	GUI session
Combined code group 1	Existing	Mean: 49, Std.D: 7.1	Mean: 29, Std.D: 5.6
	Creating*	Mean: 18, Std.D: 3.7	Mean: 9, Std.D: 1.9
	Discovery**	Mean: 6, Std.D: 0.9	Mean: 1, Std.D: 0.4
Combined code group 2	Object	Mean: 24, Std.D: 3.5	Mean: 15, Std.D: 3.7
	Space	Mean: 15, Std.D: 2.4	Mean: 11, Std.D: 2.8
	Spatial relation***	Mean: 34, Std.D: 5.3	Mean: 15, Std.D: 2.2

*Z=-1.863, N=7, p=0.062; **Z=-2.716, N=7, p<0.05; ***Z=-2.753, N=7, p<0.05.

4.3. Design Process Level: *Set-up goal Actions and Co-evolution*

The relative proportions of set-up goal actions shows that designers in the TUI session introduced more new functional issues (S-invention) as requirements, derived from their interactions with the tangible objects whereas they introduced more functions based on the requirements and repeated the same goals in the GUI session. Designers in the TUI session constructed goals while interacting with the design solution whereas designers in the GUI session retrieved goals from initially given information.

We found more discontinuities in the TUI sessions in the transition between the "problem" and "solution" spaces as shown in Fig. 3. This finding suggests that designers refined the formulation of a problem and ideas for a solution more pervasively in the TUI session.

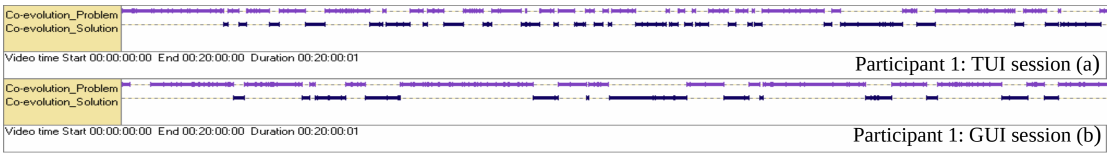

Fig. 3. Problem-Solution spaces

4.4. Correlation between 3D Modelling Actions and Perceptual Actions

'Revisited' modelling and perceptual actions overlapped each other in the TUI session (Fig. 4. (a)), which suggests that perceptual actions in the TUIs were often triggered by 'revisited' modelling actions. Further, 'revisited' modelling actions appear in parallel with 'creating new perceptual actions in the TUI session, which suggests that 'revisited' modelling actions using TUIs support designers' creating and perceiving new visuo-spatial features, and this may be caused by reducing the cognitive load as epistemic actions.

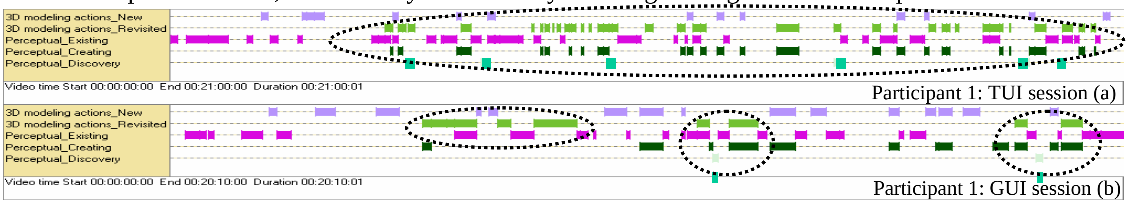

Fig. 4. 3D Modelling actions and Perceptual actions in (a) TUI session, (b) GUI session

5. Conclusion

This research presents empirical results on the effects of TUIs on designers' spatial cognition using a protocol analysis. The result of the analysis reveals different outcomes between the TUI and GUI design environments in terms of designers' spatial cognition.

We found that the short and frequent 3D modelling actions using 3D blocks lead to a design process comprised of epistemic actions, which have potential for reflective interaction with the external representation. Further, the designers using the TUI exhibited more gestures that are beneficial for designers' perceptual actions as a complementary strategy to the 3D modelling actions. At the designer level, designers' perception and reasoning for the visuo-spatial information, especially on 'spatial relationships', were improved while using the 3D blocks. Designers created and 'discovered' more new visuo-spatial features and reasoned on functional issues embodied in spatial relationships among 3D objects. In terms of the design processes, we noticed that designers' problem finding behaviours associated with design creativity were increased in parallel with the improvement of designers' spatial cognition. In conclusion, these findings from the three levels of spatial cognition have provided empirical evidence for our views on TUIs: first, TUIs change designers' spatial cognition, and secondly, the changes in spatial cognition affect the design processes by increasing designers' problem-solving behaviours leading to a creative design in the TUI session.

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