Studying Designers using a Tabletop System for 3D Design with a Focus on the Impact on Spatial Cognition

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ABSTRACT

Tabletop systems provide a platform for developing novel interaction systems, including tangible user interfaces (TUIs). This paper presents a study of the effects of a tabletop system with tangible user interfaces on designers' spatial cognition and design communication in collaborative design. In devising an experiment that can highlight the impact on spatial cognition while using TUIs, we compared designers using a tangible user interface (TUI) on a tabletop system to designers using a graphical user interface (GUI) on a typical desktop computer with mouse and keyboard. The designers were given a configuration design task in which they manipulated 3D objects to meet design specifications. Our preliminary findings are that designers using the tabletop system with TUIs reasoned about spatial relationships among 3D objects and discovered unexpected spatial relationships, while the designers using the traditional keyboard and mouse interfaces reasoned about individual 3D objects.

1. Introduction

Tangible user interfaces (TUIs) are new approaches to human-computer interaction that are often associated with "augmented reality" (AR). AR technology blends reality and virtuality to allow the seamless interaction between physical and digital worlds. We consider the existing tabletop systems as defining a class of design environments that enable TUIs to be a departure from the traditional GUIs that designers are currently using to create and interact with digital design models. Tabletop systems support designers in creating and interacting with digital models that go beyond the traditional human-computer interface of the keyboard, mouse, and vertical screen. They have been proposed as an alternative for design review meetings since they allow designers to intuitively modify 3D designs while still utilizing traditional communication mechanisms such as non-verbal behaviours.

A number of researchers have developed various configurations of tabletop systems, but, few of them evaluated them in a design situation and posed empirical evidence about the potential impact the tabletop system has on designers' cognitive actions. Thus, we investigated designers' spatial cognition or improved understanding of the spatial relationships of the components of the digital model. We associate the designers' perception of the form and spatial relationships of the design components with the designers' spatial cognition. The spatial relationships may include functional issues.

We expect that tabletop systems with TUIs to digital models as environments for design can play a critical role in improving designers' spatial cognition. This paper presents preliminary results of a pilot study using protocol analysis, which deals with designers' problem solving behaviours in 3D design.

2. Background

2.1. Tabletop Systems for Design

This research focuses on the tabletop systems with TUIs that support architecture, urban planning and interior design. Numerous tabletop systems have been customised for design applications. Ulmer and Ishii [**1**] constructed the metaDESK system with a focus on physical interaction to manipulate the digital environment. Standard 2D GUI elements like windows, icons, and menus, are given a physical instantiation as wooden frames, 'phicons, and trays, respectively. iNavigator is a CAD platform for designers to navigate and construct 3D models, which consists of a vertical tablet device for displaying a dynamic building section view and a horizontal table surface for displaying the corresponding building plan geometry [**2**]. BUILD-IT developed by Fjeld et al. [**3**] is a cooperative planning tool consisting of a table, bricks and a screen, which allows a group of designers, co-located around the table, to interact, by means of physical bricks, with models in a virtual 3D setting. A plan view is projected onto the table and a perspective view is projected on the wall.

Brave et al. [**4**] designed PSyBench and inTouch, employing telemanipulation technology to create the illusion of shared physical objects that distant users are interacting with. Although still in the early stage, it shows the potential of distributed tangible interfaces. URP developed by MIT media lab is a luminous tangible workbench for urban planning that integrates functions addressing a broad range of the field's concerns such as cast shadows, reflections and windflow into a single workbench setting. The URP system uses pre-existing building models as input to an urban planning system [**5**]. MIXDesign allows architects to interact with a real scale model of the design by using a paddle in a normal working setting, and also presents an enhanced version of the scale model with 3D virtual objects registered to the real ones [**6**]. ARTHUR system is an Augmented Round Table for architecture and urban planning, where virtual 3D objects are projected into the common working environment by semi-transparent stereoscopic head mounted display (HMDs). Placeholder objects (PHOs) and wand are used to control virtual objects [**7**].

These various configurations of tabletop systems, with and without AR, show a trend in developing technology. The different configurations described above draw on specific intended uses to define the components and their configuration. Few of the publications about tabletop systems for design evaluate the new interface technology with respect to spatial cognition or improved understanding of the spatial relationships of the components of the digital model. For example, Billinghurst et al. [**8**] presented an analysis of communication behaviour by carrying out a comparative study of GUI vs. TUI, taken into consideration gestures and verbal utterances. The focus of our research is on designers' spatial cognition in order to clarify the benefit of tabletop systems for 3D design.

2.2. Tangible Interactions using TUIs

TUIs augment the weaknesses of the other environment by using the strengths of each environment, which allow very different "reflective conversation" between physical and digital environments [**9**]. The physical objects of the TUIs are turned into input and output devices for computer interfaces producing a physical interaction. The strengths of physical interaction can be explained by two aspects; direct, naive manipulability and tactile feedback [**10**]. Kinaesthetic information through a haptic system provides us with the ability to construct a spatial map of objects that we touch [**11**]. It is the movement of a hand repeatedly colliding with objects that comes to define extra-personal space for each individual, as a consequence of repeatedly experienced associations [**12**].

The tangible interactions using TUIs in AR systems can be explained by the concept of "augmented affordance", posed by Seichter and Kvan [**13**]. From this point of view, TUIs can be seen as offering a conduit between the real or perceived affordances implied by the physical properties of the interface tool and the affordances created by the digital behaviours in the virtualised interface. The term "affordance" refers to the perceived and actual properties of the thing that determine just how the thing could possibly be used, which results from the mental interpretation of things, based on our past knowledge and experience applied to our perception of the things [14-16]. We predict that the tangible interaction of TUIs can be a crucial act for the improvement or changes of the designers' spatial cognition by modifying the content of the knowledge involved in the elaboration process as a cognitive tool.

2.3. Studying Designers using Protocol Analysis

Protocol analysis has been accepted as a prevailing experimental technique for exploring the understanding of how human designers design [**12, 17**]. A protocol is the recorded behaviour of the problem solver which is usually represented in the form of sketches, notes, video or audio recordings [**18**]. Recent design protocol studies employed analysis of actions such as drawing, moving hands and looking which provide a comprehensive picture of physical actions involved during design in addition to the verbal accounts given by subjects [**4, 19**]. A number of protocol studies have investigated single designers' cognitive activities [20-22].

Protocol approaches used in design research can be classified into two categories; concurrent protocols and retrospective protocols. Generally, concurrent protocols are utilized when focusing on the process-oriented aspect of designing, being based on the information processing view proposed by Simon [**23**], whereas retrospective protocols are utilized when focusing on the content-oriented or cognitive aspects of design, being concerned with the notion of reflection in action proposed by Schön [12, 24, 25]. In the concurrent protocols, the "think-aloud" technique is used, in which subjects are requested to verbalise their thoughts as they work on a given task [**26**]. It has been widely regarded as a reliable method, but the requirement of talking could interfere with the participant's perception [**27**].

On the other hand, retrospective protocols use the "retrospective report" technique. Participants are asked to remember and report their past thoughts after the task. This technique potentially has a disadvantage as well, that is selective retrieval due to decay of memory. In order to alleviate this problem, it allows participants to watch the videotape of their sketching activities while reporting [**28**]. By doing so, participants are provided with visual cues about the sequence of sketching, including the timing, hesitations, returns and redrawings to remember their past thoughts.

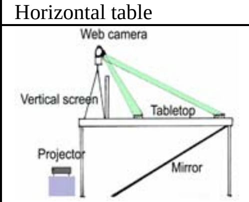
3. Experimental Setting: desktop design environment vs. tabletop design environment

Considering various scenarios, we chose a concurrent protocol analysis to compare design collaboration in the following settings: A tabletop design environment with TUIs and a desktop design environment with GUIs. We expect that this comparison will enable us to verify if and in what way the tabletop system affect designers' spatial understanding of 3D models in computer-mediated collaborative design [**29**].

3.1. Tabletop Design Environment

The tabletop design environment includes a horizontal projection surface with TUIs and a vertical display surface to facilitate multiple views of the 3D model. Designers using the TUI on a tabletop system manipulate 3D virtual objects directly, being spatially aware of each other as well as the design. The design of the tabletop is shown in table 1 [**30**]. We employ a display screen to display the 3D augmented reality scene rather than HMDs or shuttleglasses. According to the research done by Billinghurst et al. [**8**], the AR conditions with HMDs cause perceptual problems such as limited field of view, low resolution, and blurry imagery. As multiple, specialized input devices for TUIs, 3D blocks with tracking markers in ARToolKit [**31**] was used. 3D blocks are "space-multiplexed" input devices that can be attached to different functions, each independently accessible [**32**]. They produce a direct hands-on style of interaction, which offers a form of tactile influence on the design as handles to the virtual objects.

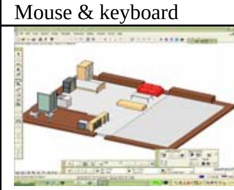
Table 1. Tabletop design environment

Hardware	Tabletop system / 3D blocks
Application	ARToolkit
Display	Vertical LCD screen & Horizontal table
Task space	Horizontal table
Settings	 

3.2. Desktop Design Environment

The desktop design environment is a typical desktop computer comprising a vertical display screen and a mouse and keyboard. Despite the physical form, the mouse has no physical contextual awareness, and the movement simulated by the mouse lacks tactile and kinaesthetic feedback that normally accompanies movement. We chose ArchiCAD as an application because it has typical GUIs feature such as a window, icons, menus and a pointing device. The mouse or keyboard produces indirect interaction with 3D models as a generalised time-multiplexed input device controlling different functions at different times [**32**]. The ability to use a single device for several tasks is a major benefit of the GUI, but given the nature of interaction where only one person can edit the model at a time, the GUI environment may change interactivity in collaborative design [**33**].

Table 2. Desktop design environment

Hardware	Desktop computer / Mouse & Keyboard
Application	ArchiCAD
Display	Vertical LCD screen
Task space	Mouse & keyboard
Settings	 

3.3. Experiment Design

We conducted four experiments consisting of GUI and TUI sessions, and had each pair of designers participate in a different experiment for design collaboration. The two design tasks were similar in complexity and type, and we changed the orders of interaction method and design tasks to eliminate learning effects that may influence the results achieved.

Table 3. Experiment design

Experiment	1		2		3		4	
Sessions	TUI	GUI	GUI	TUI	TUI	GUI	GUI	TUI
Task	A	B	A	B	B	A	B	A
Participant	Pair 1		Pair 2		Pair 3		Pair 4	

Task A: Home office apartment, Task B: Interior design office

The design tasks were designed to simulate design review meetings for a studio renovation, a home office apartment or an interior design office, so the designers inspected the current state of the 3D plan and produced new ideas working collaboratively. While the designers are developing a 2D layout by placing the furniture, they are reasoning about 3D objects and their spatial relationships to satisfy a pre-defined set of specifications in the design briefs. We recruited 2nd year architecture students and did not allow them access to a pen device or to the 2D view in ArchiCAD. A set of 3D objects were made available in the application's library for the furniture selection, and 20 minutes was allotted to them for working on the design task.

4. Segmentation and Coding Scheme

Our study is an adaptation of protocol analysis method: data collection, data segmentation, coding, analysis. During data collection, rather than ask the designers to think aloud, we recorded their conversation and gestures while they were collaborating on a predefined design task. The data collected for analysis includes verbal description of spatial knowledge and non-verbal data such as gestures. No questionnaire was used because we focus on capturing the contents of what designers do, attend to, and say while designing, looking for their perception of discovering new spatial information and actions that create new functions in the design.

4.1. Segmentation

We divided the protocol data into small segments, where each segment was then assigned codes that characterise the designers' cognitive actions. Instead of segmenting the protocols along lines of designer's intentions [**21**], we chose individual designers' utterances as segments and retained the utterances as a whole rather than breaking down them into "meaningful" segments. The intention-based segmentation that applies for single designers using think aloud protocols may be unsuitable for our communication protocols including pairs of designers. Thus, each utterance flagged the start of a new segment, where we looked at the content of the protocols and coded them using our coding scheme.

4.2. Coding Scheme

For each segment, we classified designers' cognitive actions into four categories including visual and non-visual information based on Suwa's definition [**21**]: 3D modelling actions, perceptual actions, functional actions and set-up goal actions.

The first category, 3D modelling actions, refers to physical actions including the selection, placement and relocation of 3D elements made by designers. We paid attention to the information of whether or not actions are new for each design action because we speculate that the revisited 3D modelling actions uncover information that is hidden or hard to compute mentally, and then this will play an important role in supporting designers' spatial cognition and idea production.

The second category, perceptual actions shown in table 4, refers to actions of attending to visuo-spatial features of the artefacts or spaces they are designing with. Three types of attentions to an existing design feature, two types of creations of new design features, and three types of discoveries that occurred were investigated as a measure of designers' perceptive abilities for spatial knowledge. "Discoveries" refer to the perceptual actions of noticing consequences that were not intended by the designers when he or she moved a 3D object [**34**]. For example, even though a designer's initial intention was just to place a dining table near a sink, he or she happened to discover a couple of spaces in front of the sink as well as a spatial relation between these spaces. Discoveries are the act of finding new aspects of the developing solution-space and classified into three distinct types; "visual-feature-type", "relation-type", and "implicit-space-type" [**35**].

Table 4. Types of perceptual actions

Type	Definition		Feature
	Behaviour	**Dependent on**	
Type P1	attention to a visual feature of an element*	Look at previous layout	Attending to an existing one
Type P2	attention to a relation** among elements		
Type P3	attention to a location of an element		
Type P4	creation of a new relation	more than one "new" physical action	Creating new one
Type P5	creation of a new space		
Type P6	discovery of a visual feature	a single "old" physical action	Discovery
Type P7	discovery of a relation	more than one "old" physical action	
Type P8	discovery of an implicit space	implicit	

* The element can be an artefact or a space
** Each relation is divided into three classes; "furniture to furniture", "furniture to area" and "area to area"

The third category, functional actions, refers to actions of conceiving of non-visual information, but something with which the designers associate visual information. We include general functional actions, that is, thinking of a function of a space or an object, a circulation path, a view and a psychological reaction are involved. In particular, 'Re-interpretation' is coded when a designer defined a different function from a previous one when s/he revisits that part of the design.

The fourth category, set-up goal actions shown in table 5, is derived from Suwa et al.'s research [**35**]. Suwa et al argue that designers do not just synthesise solutions that satisfy initially given requirements but also invent design issues or requirements that capture important aspects of the given problem, and call this situated-invention.

Table 5. Types of goals to invent new functions

Type 1	goals to introduce new functions	
	Type 1.1	based on the given list of initial requirements
	Type 1.2	directed by the use of explicit knowledge or past case
	Type 1.3	extended from a previous goal (subtypes: concretizing & broadening)
	Type 1.4	in a way that is not supported by knowledge, given requirements, or a previous goal
Type 2	goals to resolve problematic conflicts	
Type 3	goals to apply previously introduced functions or arrangements in the current context	
Type 4	repeated goals from a previous segment	

This category is important in spatial cognition while using tabletop systems because it highlights the designers' ability to find new relationships in these kinds of HCI environments. We coded the goals of inventing new functions to clarify designers' problem finding behaviours in the different design environments. In particular, type 1.2, type 1.3, type 1.4, and type2 are instances of the S-invention of design issues since the issue emerged at that moment for the first time.

5. Analysis

The following analysis is a preliminary interpretation of the data collected. We focussed on finding patterns of designers' behaviours and cognitive actions, specifically looking for significant differences in the data collected from the GUI sessions and the data collected from the TUI sessions. We adopt an exploratory study for this research to understand the outputs "in depth" and included the results on perceptual actions, set-up goal actions and correlation among cognitive actions in this section.

5.1. Observation of Designers' Behaviours

Through observation, we noticed that designers using the desktop computer discussed ideas verbally and decided on a solution before performing 3D modelling actions whereas designers using the tabletop system communicated design ideas by gesturing at and moving the objects, and decided on the location of furniture when they were manipulating 3D blocks to test and visualize design ideas.

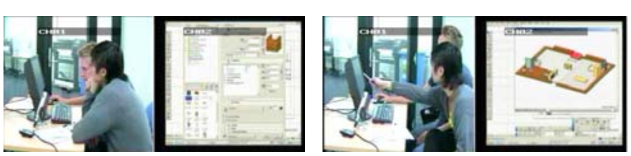


Figure 1. GUI-based collaboration

In terms of collaborative interactions, the tabletop design environment enabled designers to collaborate on handling the 3D blocks more interactively and to produce more revisited 3D modelling actions before the final configuration. These results may be caused by the different properties of the tools. Designers in the desktop design environment shared a single mouse compared to multiple 3D blocks, thus one designer mainly manipulated the mouse. On the other hand, with the direct, naive manipulability of physical objects and rapid visualization, designers using 3D blocks seemed to produce more multiple cognitive actions and completed the design tasks faster.

Figure 2. TUI-based collaboration

5.2. Coding Perceptual Actions

Looking into the content of cognitive actions, we found different patterns between the GUI and TUI sessions in terms of perceiving an existing object or space (type 1, 2, and 3). Designers in the desktop environment focused on the individual location whereas designers in the tabletop design environment attended more to a spatial relation among objects or spaces. The following table shows an example of locating a sink in a design task A; the home office apartment. Designers in the GUI session just clarified the location of the sink without noticing the problem in relation to the bedroom whereas designers in the TUI session perceived the wrong spatial relation.

Table 6. Perceptual actions on the location of a sink

Session	Transcript (GUI)	Category
GUI 2	Which she does not yet have… well she has a sink in her ba-bedroom, and then living/meeting area	Type 3
GUI 3	Where's the sink? That's the utility area	Type 3
Session	**Transcript (TUI)**	**Category**
TUI 1	It shouldn't be near the bathroom or I mean, I think it shouldn't be near the bedroom, sorry. It shouldn't have a kitchen sink.	Type 2
TUI 4	The sink sink, sink dosen't need to be in the bedroom. yeah sink in the kitchen. sink over here for now	Type 2

In terms of attending to a new relation or space (type 4 and 5), designers in the desktop environment usually considered the function of the object and put it in a relevant position directly. On the other hand, designers in the tabletop design environment created and attended to a new spatial relation by placing an object. Table 7 describes an example of the placement of a new desk in design task B; the interior design office.

Table 7. Perceptual actions on placement of a desk

Session	Transcript (GUI)	Category
GUI 1	That one's got a little computer thing on it, and that can go in the corner….	none
GUI 4	How about we put in a new desk in this corner here	none
Session	**Transcript (TUI)**	**Category**
TUI 2	I am thinking of like a corner things. so we got…	none
TUI 3	We need a desk, first of all, for his um office area.. maybe one of this.. maybe in the corner there…..now we want the desk to go near the windows, so he can look out the window	Type 4

In comparison to the desktop computer, designers discovered a hidden space among objects or a feature of an object unexpectedly when they were revisited (type 6, 7 and 8) more times on the tabletop system. The following are examples of discoveries extracted from the verbal protocols of the two design sessions.

Table 8. Discoveries in the two sessions

Session	Transcript (GUI)	Category
GUI 1	Ok . I get you. But don't you think with that corner there its ugly? Aesthetically?	Type 8
	I don't like… it locks very empty there	Type 8
Session	**Transcript (TUI)**	**Category**
TUI 1	You end up with empty space in the middle. how this sofa faces onto her	Type 8
	You know how they have those kitchens that are just two long rows. And then that would be like, become like the bar. The breakfast bar.	Type 6

Table 9 shows the number of occurrences of perceptual actions derived from the 1st experiment. The overall distribution of number is different between the two design sessions. We noticed that designers using the tabletop system kept attending to existing elements through the design session whereas designers using the desktop system produced design actions, not referring to their perception as much.

Table 9. The occurrences of perceptual actions

Types	TUI session		GUI session	
Type P1	14	75	5	23
Type P2	34		3	
Type P3	27		15	
Type P4	21	28	9	13
Type P5	7		4	
Type P6	4	13	0	2
Type P7	2		0	
Type P8	7		2	

We interpret the above findings as empirical evidence for the changes of designers' spatial cognition when using a tabletop system because they suggest that designers' understanding of the spatial relationships of the elements is improved in the tabletop design environment. Further, the fact that discoveries are more frequent in the tabletop system indicates that the tabletop environment encourages designers to perceive hidden features or spaces, which can be interpreted as one of pathways to creative design.

5.3. Coding Set-up Goal Actions

During the design sessions, the designers spoke about goals, and these segments were coded as set-up goals. Examples of set-up goal actions are shown in table 10 and the number of goal actions for each type occurring in the 1st experiment is shown in table 11. The largest number of goals is type 1 goals: the goals to introduce new functions for the four required spatial areas and relevant furniture layouts. This result could be from the kind of design tasks given to the designers. The design tasks are renovation tasks to be completed in a short time, so the designers rushed to provide new ideas based on their perception of the current states of the 3D design.

Table 10. Set-up goal actions in the two sessions

Session	Transcript (GUI)	Category
GUI 1	you can't have direct light on the drawing board, because of glare and stuff	Type 1.2
	our designer and utility in one half of the room…	Type 1.4
Session	**Transcript (TUI)**	**Category**
TUI 1	We need sleeping area, kitchen and working area	Type 1.1
	you've gotta leave a gap for walking	Type 1.2

Table 11 shows the differences in the number of goals generated in the two design sessions. Compared to the GUI session, designers in the TUI session set up goals to introduce new functions extended from a previous goal. This can be interpreted that the tabletop environment stimulates designers to generate new ideas by broadening their previous ideas as the design process is going on.

Table 11. The occurrences of set-up goal actions

Types		TUI session	GUI session
Type 1			
	Type 1.1	4	1
	Type 1.2	23	17
	Type 1.3	10	2
	Type 1.4	23	16
Subtotal of Type 1		60	36
Type 2		0	0
Type 3		0	2
Type 4		15	5
Goals for S-invention (type 1.2, 1.3, 1.4 and type 2)		56	35
Total		75	43

5.4. Correlation Among Cognitive Actions

We found several set up goal actions occurred with 3D modelling actions in the TUI session. Thus, we carried out a statistical analysis using the data of 1st experiment to roughly see whether or not there are correlations among designers' perceptual actions, 3D modelling actions and set-up goals actions. For this examination, we chunked every five segments, and re-categorised perceptual actions into four groups, type 1& 3, type 2, type 4 & 5, and type 6-8, which is related with the different patterns of perceptual actions discovered in the protocol analysis.

In the TUI sessions, correlations were produced between two types of perceptual actions of creating new one and goals for S-invention of functions, and between 3D modelling actions and three types of discoveries. The two tailed Pearson coefficient of the correlations is more than 0.8. On the other hand, there was no significant result regarding the correlation in the GUI sessions. The correlation of 3D modelling actions and discoveries implies that 3D modelling actions on the tabletop system are the key actions to discover a hidden feature or space compared to the 3D modelling actions of the desktop computer. Further, the correlation of goals for s-invention and new attention to a relation or an empty space indicates that the designers' enhanced spatial cognition has a significant relationship with idea fluency. However, more protocols have to be analysed to reinforce these findings.

6. Results

The pilot study has shown that the tabletop and desktop design environments produced different outcomes in terms of designers' behaviours and cognitive actions. The former was derived from the observation and the latter derived from the protocol analysis. Compared to designers using a GUI on a desktop computer, designers using a TUI on a tabletop system exhibited the following behaviours:

- communicated design ideas by gesturing at and moving the objects visually;
- re-visited a design frequently while coordinating design ideas; and
- collaborated on handling 3D blocks interactively.

The differences in designers' cognitive actions are (TUI/GUI):

- attended to spatial relations among elements (34/3);
- created and attended a new relations or space by placing an object (21/9);
- discovered a space (7/2) or feature of an existing element unexpectedly (4/0);
- produced more goals to introduce new functions (56/35);
- indicated a correlation between two types of perceptual actions of creating a new design feature and goals for S-invention of functions; and
- indicated a correlation between 3D modelling actions and three types of discoveries.

7. Conclusion

The results indicate that the tabletop system effectively supports co-located, multi-user interaction and allows designers to attend to or to create spatial relations between artefacts or spaces. Further, the changes of designers' spatial cognition lead to idea production and to encourage designers to discover hidden features or spaces. Thus, we consider the tabletop system as a very powerful platform for reasoning about 3D objects and their spatial relationships. We do not think that tabletop systems will replace desktop systems. Rather, new developments in tabletop systems will provide alternative design environments that complement existing desktop systems.

We expect that this research will contribute to the decision on both tabletop system configuration and functionality for design application. In our next set of experiments, we will analyse design sessions in which a single designer designs using the think aloud method. We expect that the think aloud method will result in more verbal articulation of the perceived spatial relationships and spatial cognition.

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