THE IMPACT OF TANGIBLE USER INTERFACES ON COLLABORATIVE DESIGN

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ABSTRACT

Developments in tabletop systems that combine Augmented Reality and tangible user interfaces on a horizontal display surface provide a new kind of physical and digital environment for collaborative design. The combination of tangible interaction with Augmented Reality display technique changes the dynamics of communication and has an impact on designers' perception of 3D models. We are studying the effects of tangible user interfaces on designers' spatial cognition and design communication in order to identify how such tabletop systems can be used to provide better support for collaborative design. Specifically, we compare tangible user interfaces with graphical user interfaces in a collaborative design task with a focus on characterising the impact these user interfaces have on spatial cognition.

KEY WORDS

augmented reality, tabletop system, collaborative design, spatial cognition.

INTRODUCTION

In recent years, numerous tabletop systems have been customised for design applications demonstrating many potential uses for tangible user interfaces (TUIs). They restore some of the tangibility by providing various interfaces props with which the digital objects can be manipulated (Regenbrecht 2002). The tabletop systems, with and without Augmented Reality (AR), support designers in creating and interacting with digital models by coupling digital information with physical objects. Compared to graphical user interfaces (GUIs), the naturalness of the direct hands-on style of interaction afforded by TUIs has the potential to offer significant benefit to designers of 3D physical systems.

Most of the studies on TUIs on the tabletop systems are being undertaken from a Human-Computer Interaction viewpoint. They show a trend in developing technology, where the interactive environments employing position, speech and gesture recognition and state-of-the art graphical output are being explored. Few of them evaluate the new interface technology with respect to spatial cognition. The aim of this research is to obtain empirical evidence about the impact of TUIs that can be a basis for guidelines on tabletop design system configuration. We use the protocol analysis method to collect communication data while

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designers collaborate on a design task and analyse the verbal and gestural protocol to characterise the impact of the TUIs on collaborative design.

TABLETOP SYSTEMS WITH TANGIBLE USER INTERFACES

Various tabletop systems draw on specific intended uses to define the components and their configuration. They allow designers to explore design alternatives with modifiable models by integrating physical objects into input and output devices for computer interfaces. The design need not perform logical operations on an internal representation since it is sufficient to perform and observe appropriate physical operations on an external physical representation.

Some tabletop systems for design applications use generic items such as bricks, blocks and cubes for generalized tangible input (Anderson 2000; Fitzmaurice 1999; Pattern 2001; Rauterberg 1997). BUILD-IT developed by Fjeld et al. (Fjeld 1998) is a cooperative planning tool which allows a group of designers to interact, by means of physical bricks, with models in a virtual 3D setting made by a plan view of the table and a perspective view of the wall. When designers manipulate bricks, each brick allows direct control of virtual objects through physical handles by visually communicating digital information stored within the brick to the user. As physical pieces, it is easy to place and move bricks on the digitized tabletop and to avoid inadvertent co-location.

Other tabletop systems such as MixDesign, PSyBench and a prototype of an interior design application use paddles or square pieces of cards with tracking markers in ARToolKit. Paddles or square pieces of cards are also physical means of interaction between the user and the system that will trigger the functionalities of the platform, by way of gesturing. Using a paddle with a specific marker, designers can choose menu options, select and move objects, and geometrically transform an object by rotation or scaling. MIXDesign allows architects to interact with a physical scale model of the design by using a paddle in a normal working setting (Dias et al. 2002).

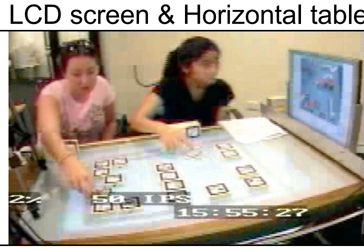
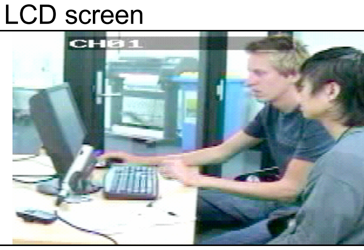
Bricks and paddles produce a form of tactile influence on the design process as handles to the virtual objects, which allow multiple users to make the selection, placement, and relocation of pieces on the table. 3D physical blocks can provide a significantly rich vocabulary of expression in terms of input devices that can be applied to any form of 2D or 3D design (Fitzmaurice 1995). On the other hand, for each marker, the pattern inside the square is captured and matched against some pre-trained pattern templates. We expect that the TUI design environments affect designers' spatial cognition and design communication, which may lead to the production of creative outcomes in the end.

EXPERIMENT SET-UP: A TABLETOP SYSTEM WITH TUIS VS. A DESKTOP SYSTEM WITH GUIS

In devising an experiment that can highlight the expected improvement in spatial cognition while using TUIs, we chose to compare designers in the following settings: A tabletop design environment with TUIs and a desktop design environment with GUIs (Maher and Kim 2005).

The tabletop design environment includes a horizontal table and a vertical screen to facilitate multiple views of the 3D model. 3D blocks with tracking markers in ARToolKit (Billinghurst et al. 2003) were placed on the tabletop and used as multiple, specialized input devices, where designers manipulate the 3D virtual objects directly. 3D blocks are “space-multiplexed” input devices that can be attached to different functions, each independently accessible. On the other hand, the desktop design environment is a typical computer comprising a screen, a mouse and keyboard. Despite the physical form, the mouse has no physical contextual awareness and the movement simulated by the mouse lacks tactile feedback. It produces indirect interaction as a generalised time-multiplexed input device controlling different functions at different times (Fitzmaurice 1996). Table 1 shows the experiment settings.

Table 1: Experiment settings

	A tabletop environment: TUI	**A desktop environment: GUI**
Hardware	Tabletop system	Desktop computer
Input device	3D blocks	Mouse & Keyboard
Interaction mode	Tangible interaction	Intangible interaction
Application	ARToolkit	ArchiCAD
Display	LCD screen & Horizontal table	LCD screen
Settings		

We conducted four experiments, each experiment consisting of the two sessions. Each pair of 2nd or 3rd year architecture students participated in a complete experiment since it was anticipated that the comparison of the same designers in two different environments would provide a better indication of the impact of the environment than using different designers and the same design task. We changed the order of interaction method and design tasks of similar complexity. The use of two environments is the major variable in the study, while the remaining variables are set in order to facilitate the experiment but not influence the results.

PROTOCOL CODING

DATA COLLECTION

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 communication and physical actions given by the designers. 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.

SEGMENTATION

Segmentation is dividing the protocol into small units as the first step of the protocol study. 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.

CODING SCHEME

Our coding scheme is divided into three main categories:

- **Cognitive actions** comprising 3D modelling, perceptual and set-up goal actions which reflects the content of designers' cognitive actions,
- **Co-evolution** which reflects the reformulation of and extending the design problem, and
- **Collaborative actions** which reflects designers' cognitive synchronisation and exhibited gestures. Multi-codes can be assigned to each segment in "perceptual actions" and "set-up goal actions" categories.

3D modelling actions refer to physical actions including the selection and placement of 3D objects, and this category has 9 codes as shown in Table 2. Perceptual actions refer to the actions of attending to visuo-spatial features of the artefacts or spaces, which measure the designers' perceptive ability for spatial knowledge. A designer's perception of the form and spatial relationships of the design components is associated with the designer's spatial cognition in this research. Set-up goal actions refer to the actions of introducing new design issues or functions, which are carried through the entire design process as one of the design requirements. This category highlights the designer's ability to extend the problem space by capturing important aspects of the given problem.

Co-evolution refers to the design process that explores the spaces of problem requirements and design solution iteratively, evolving separately and affecting each other. Exhibited gestures refer to the designers' movements other than the 3D modelling actions. Speech and gestures together characterise the designers' understanding of spatial relationships among entities, which are closely related to and may even be beneficial for cognitive processing. The code "Modelling action" is used when designers do not produce any gesture but perform a modelling action such as place, rotate and delete. Cognitive synchronization refers to design activities that are concerned with the construction of a shared representation of the current state of the solution or problem. We classified all uttered sentences into five different codes as shown in Table 2.

Table 2: Coding Scheme

3D modelling actions	
PlaceNew	Place a new object or relocate an existing object for the first time
PlaceExisting	Change the location of a initially given object for the first time
ReplaceExisting	Change the location of an existing object
Rotate	Change only the orientation of an existing object
InspectScreen	Inspect layout on the screen
InspectTable	Inspect layout on the table
InspectBrief	Inspect the design brief
Delete/remove	Delete/remove an existing object
Library	Check library for objects through screen or virtual library
Perceptual actions	
Pvf	Attend to a visual feature of an element
Pr	Attend to a relation among elements
Ps	Attend to a location of a space
Pl	Attend to a location of an object
Pnr	Creation of a new relation among elements
Pns	Creation of a new space among elements
Puf	discovery of a visual feature of an element
Pur	discovery of a relation among elements
Pus	discovery of an implicit space between elements
Set-up goal actions	
Gnk	goals to introduce new functions directed by the use of knowledge
Gnp	goals to introduce new functions extended from a previous goal
Gni	goals to introduce new functions in a way that is implicit
Gnb	goals to introduce new functions based on the given list of initial requirements
Gr	repeated goals from a previous segment
Co-evolution	
Problem	The features that specify required aspects of a design solution, or problem space
Solution	The features and behaviours of a range of design solutions
Exhibited gestures	
Design gesture	Hand movement above the 3D plan
General gesture	General speech-accompanying gestures
Pointing gesture	Point at the 3D object
Touch action	Touch a 3D object with hands (TUI) or a mouse (GUI)
Modelling action	Modelling action such as place, rotate and delete
Cognitive synchronisation	
Propose	Propose a new idea in solution space
Question	Question about the proposal made
Argument	Arguments supporting or not supporting the proposal
Resolution	Accept or reject the proposal
Consensus	Check for consensus from the partner on the proposal

COMBINED CODES

We combined some of the 3D modelling codes, the perceptual action codes and set-up goal action codes into generic activity components in order to highlight the behaviour patterns in the two design environments. A summary of the combined codes is shown in Table 3.

Table 3: Combined Codes

Combined Codes	Individual Codes	Coding Categories
New	PlaceNew, PlaceExisting	3D modelling actions
Revisited	ReplaceExisting, Rotate	
Existing	Pvf, Pr, Ps, Pl	Perceptual actions
Creating	Pnr, Pns	
Unexpected discovery	Puf, Pur, Pus	
Object	Pvf, Pl, Puf	
Space	Ps, Pns,Pus	
Spatial relation	Pr, Pnr, Pur	
S-invention	Gnk, Gnp, Gni	Set-up goal actions
Others	Gnb, Gr	

New _Revisited

'New' activities refer to the 3D modelling actions of importing an object from the furniture library or changing the location of a given object for the first time. When an object is re-arranged later, it is coded as a "Revisited" activity. These activities can be related to finding information that is hidden or hard to compute mentally.

Existing _Creating _Unexpected discovery

The perceptual action codes are combined into three generic activities: attention to an existing design feature, creating a new design feature, and unexpected discovery. These combined codes may be connected the notion of the co-evolution since the attention to an existing design feature takes place in the problem space, and creating a new feature and unexpected discovery take place in the solution space.

Object _Space _Spatial relation

The perceptual action codes are again combined in another way according to the focus of designers' attention; reasoning about individual objects, reasoning about space, and reasoning about spatial relationships among 3D objects.

S-invention _Others

The codes "Gnk", "Gnp" and "Gni" are instances of the S-invention, which refers to the emergence of new design issues or requirements. This code is an adaptation of the coding scheme developed by Suwa et al (Suwa 1998).

PROTOCOL ANALYSIS

We measured duration percentages of the coded data rather than the occurrence percentages since the same code was applied to many segments in a row. In order to compare two groups of cases on one variable, we used Mann-Whitney U test, which is equivalent to the independent group t-test.

3D MODELLING ACTIONS

Figure 2 shows the percentages of time on 3D modelling action codes in TUI versus GUI sessions. There is a significant difference in the duration of "New" and "Revisited" modelling actions across the two design environments (Z= -1.732, N=4, p=0.083).

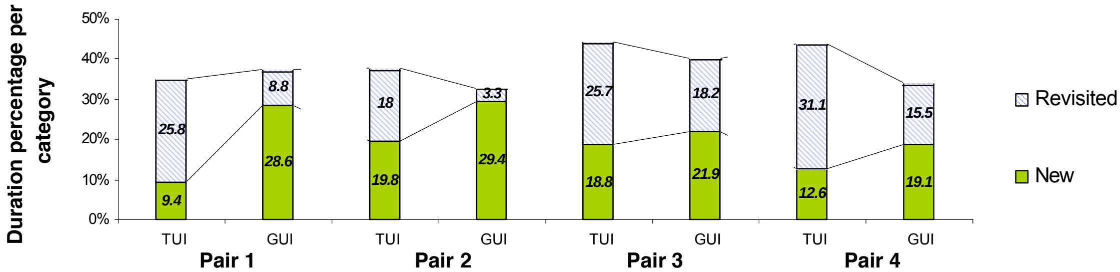


Figure 1: 3D modelling actions: *New _Revisited*

The result suggests that designers of the TUI session spent significantly more time in exploring design solutions through the revisited modelling actions, which can be explained as the reflection in action. On the other hand, designers in the GUI session focused on design making by placing new pieces of the furniture.

PERCEPTUAL ACTIONS

Figure 3 shows the percentages of time in each of the combined codes of the perceptual actions. We describe the result of one pair of designers to see the codes in a same figure.

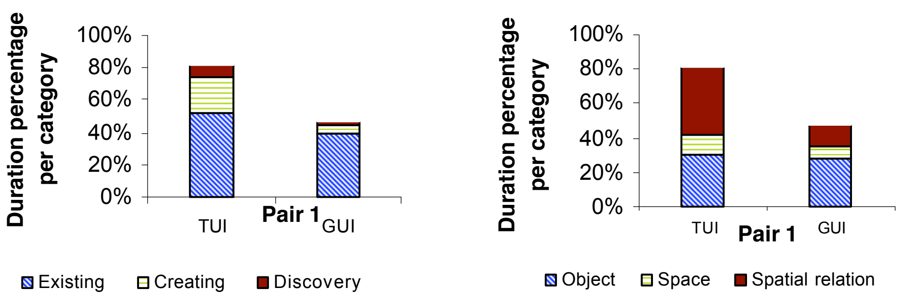


Figure 2: Perceptual actions: (a) *Existing _Creating _Discovery*
(b) *Object _Space _Spatial relation*

The designers spent more time in perceiving an existing design feature ($Z= -1.732$, $N=4$, $p=0.083$) and attended more unexpected discoveries ($Z= -2.309$, $N=4$, $p<0.05$) while using 3D blocks (Figure 3 (a)). In addition, they reasoned more about the spatial relationships of the design components ($Z= -2.021$, $N=4$, $p<0.05$) (Figure 3 (b)).

SET-UP GOAL ACTIONS

Figure 4 shows the occurrence of the combined code in the set-up goal actions. The amount of time on the generation of the goals is relatively little percentage of the total time, so we investigated the occurrence of the set-up goal actions to identify if there is any significant difference. The following result indicates that the designers produced more new functional relationships (S-invention) in the TUI design environment ($Z= -1.888$, $N=4$, $p=0.59$). According to Suwa et al. S-inventions become driving force for the occurrences of unexpected discoveries as the act of expanding the problem space.

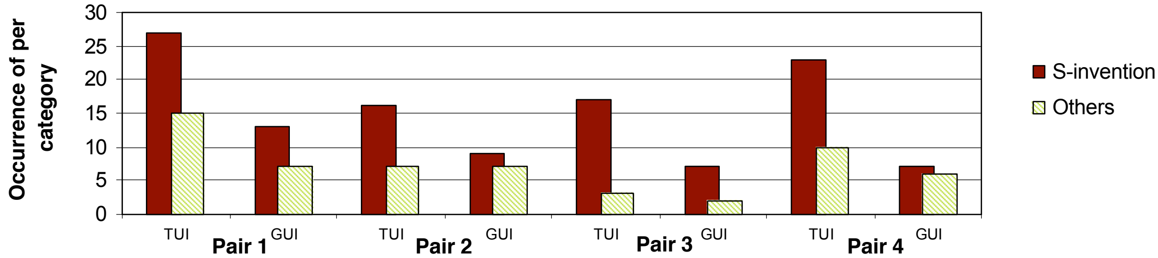


Figure 3: Set-up goal actions: *S-invention _Others*

CO-EVOLUTION

The amount of time spent in the two design spaces is measured and shown in Figure 5. The designers in the TUI session spent significantly more time in the reformulation of design problems ($Z= -2.309$, $N=4$, $p<0.05$), and this is characteristic of creative design. Creative design seems more to be a matter of developing and refining together both the formulation of a problem and ideas for a solution (Dorst and Cross 2001).

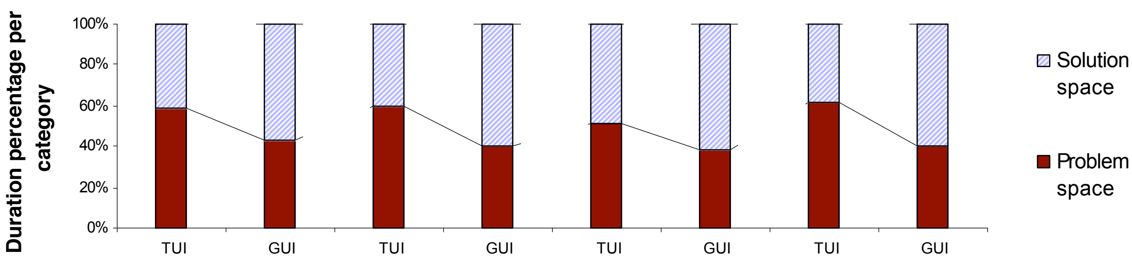


Figure 4: Co-evolution

EXHIBITED GESTURE

The measurement of gestures is shown in Figure 6. It was found that the time spent on design gesture ($Z= -2.021$, $N=4$, $p<0.05$) and on pointing action ($Z= -2.309$, $N=4$, $p<0.05$) was significantly different across the two design environments.

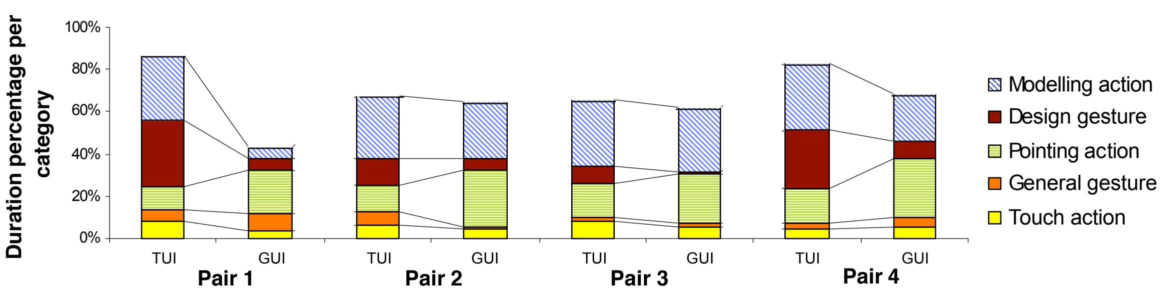


Figure 5: Exhibited Gesture

The designers did whole body interaction with the representation, using "design gestures" such as large hand movement in the TUI session. The time spent on pointing actions is the highest in the GUI session in all cases, which could be considered as a signal of misunderstanding in case there are only utterances. Furthermore, it was observed that the designer often touched the 3D blocks in the TUI session like the speech-accompanying gestures using the mouse in the GUI session.

COGNITIVE SYNCHRONISATION

Figure 8 shows the time spent on cognitive synchronisation. We did not find any significant difference in this category through the Mann-Whitney U test, but noticed that the patterns of interweave of three codes "Propose", "Argument" and "Resolution" were different between the two design sessions. The graphs show the first ten minutes of the design sessions.

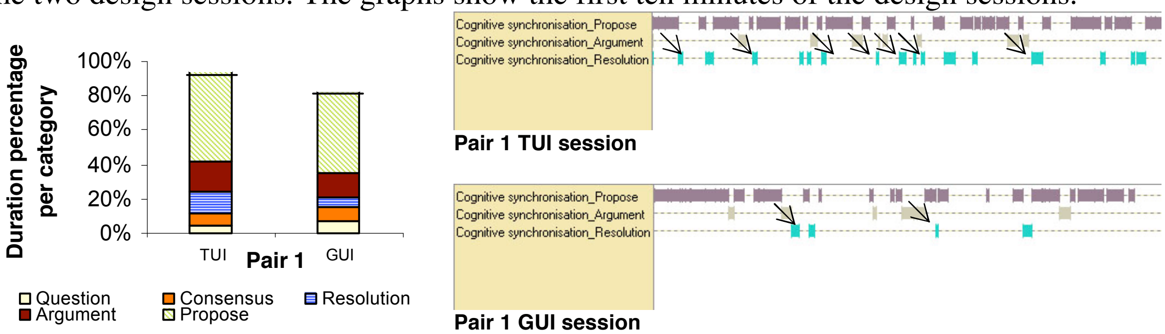


Figure 6: Cognitive synchronisation: (a*) Duration percentage per category*
(b) "Propose-Argument-Resolution" actions over time (10 minutes)

Looking at the chain of actions "Propose-argument-resolution", we observed that designers in the TUI environment reached a decision more often through argument compared to the GUI session, implying that design communication was effective.

CONCLUSIONS

The results of this case study indicate that when using a tabletop system with TUIs, the designer attends to or creates new spatial relations between artefacts or spaces more than when using a GUI. Further, a change in the designer's spatial cognition encourages the discovery of hidden features or spaces, leading to the invention of new idea issues. We interpret the above findings as empirical evidence for the changes of designers' spatial cognition when using TUIs because they suggest that designers' understanding of the spatial relationships of the elements is improved in the TUI environment.

Furthermore designers using 3D blocks more frequently displayed "problem-finding" behaviours during the task, which can be strongly associated with creative outcomes (Gerzels and Csikszentmihalyi, 1976). They also exhibited large hand movement over the plan to communicate their design ideas, which can influence designers' cognitive actions. We consider the tabletop system with TUIs as a very powerful platform for co-located collaborative design that involves reasoning about 3D objects and their spatial relationships. Knowledge of the implications of the differences in spatial cognition can be a basis for guidelines on the development and use of tabletop systems for design applications. More protocols on individual designing using the think aloud method are being analysed to reinforce these findings.

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