CREATIVE DESIGN IN A TANGIBLE USER INTERFACE ENVIRONMENT

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Abstract. This paper shows that tangible user interfaces support cognitive actions that are associated with creative design. The evidence for this is a case study of designers using a tangible user interface environment for manipulating 3D models on a digital design workbench. Focussing on how the new interface technology changes designers' spatial cognition, we compare designers using tangible user interfaces with designers using graphical user interfaces in a collaborative design task. The results show that the combination of tangible interaction with Augmented Reality display techniques improve designers' perception of spatial relationships between 3D models and encourages designers to discover hidden spatial features. These characteristics of designing are associated with creative design.

1. Spatial Cognition and Creativity in Design

Creativity is generally characterised by aesthetic appeal, novelty, quality, unexpectedness, uncommonness, peer-recognition, influence, intelligence, learning, and popularity (Runco and Prizker 1998). Thus, creativity in the design process is associated with discoveries and ideas that are fundamentally novel, where designers discover hidden features in a representation and recognise a key concept as a sudden insight. We expect that a new tangible user interface environment for design can play a critical role in the creative design process by improving designers' spatial cognition. The changes of designers' perception of spatial knowledge when using tangible user interfaces might lead to such discoveries and to the production of creative ideas. We consider the existing digital workbenches as defining a class of design environments that use tangible user interfaces (TUIs) to be a departure from the traditional graphical user interfaces (GUIs) that designers are currently using to create and interact with digital design models.

We associate a designer’s perception of the form and spatial relationships of the design components with the designer’s spatial cognition. In our research, the meaning of ‘space’ to the designers is not an abstract of empty space, but rather of the identity and the relative locations of the objects in space. Space then is decomposed into particular objects and the spatial relationships among them. The spatial relationships may include functional issues since designing attempts to satisfy intended functions. Thus, we investigate designers’ spatial cognition or improved understanding of the form and spatial relationships between 3D objects with a focus on unexpected discoveries. This paper presents the results of a case study using protocol analysis.

1.1. CREATIVE PROBLEM SOLVING IN DESIGN

Gestalt theorists have emphasised productive thinking in contrast with reproductive thinking in the domain of creative problem solving (Wertheimer 1982). Productive thinking depends on past experience in only a general way and involves new structural understanding of the specific requirements of a problem. Gestalt analysis of creative thinking indicates the negative influences of past experiences on creative thinking. On the other hand, reproductive thinking theorists argue that the important issue for creative problem solving is not to abandon reproductive thinking itself but to reorganise the past experience for the current situation. Reproductive thinking applies some past knowledge to a present problem directly. Creative thinking is closely associated with the concepts of restructuring, which may form the basis for insight into the problem (Ohlsson 1984). Weisberg (Weisberg 1982) posed the results of case studies that creative thinking moves beyond established practises only slowly as a modification of the past rather than rejection of the past.

Cross and Dorst proposed that creative design can be modelled in terms of the co-evolution of problem and solution spaces, as described by Maher et al. (Dorst and Cross 2001; Maher 1996). That is, creative design involves a period of exploration in which both the formulation of the problem and ideas for its solution are developed and refined together, with constant iteration of analysis, synthesis and evaluation processes between the two ‘spaces’. Accordingly, a creative event occurs as the moment of insight at which a problem-solution pair is framed in a potentially resolvable form, where the designer’s ability of framing a design problem is emphasised as a key aspect of creativity. They introduce the notion of ‘default’ and ‘surprise’ problem/solution space to describe creative design, which keeps a designer from routine behaviour by leading to framing and reframing of the design problem. The common characteristic of creative thinking in these studies is the restructuring of information available to the designer while designing.

1.2. COGNITIVE ACTIONS FOR CREATIVE DESIGN: INSIGHT AND UNEXPECTED DISCOVERIES

Sometimes, people suddenly realise the answers during problem solving, even though they cannot figure out how to get to the solution (Davison 1995). The occurrence of "insight" associated with this 'Aha!' experience is one of characteristic features of creativity in design (Akin 1990). There are two conventional views of insight; the "special-process" views and the "nothing-special" views. Included in the special-process view is the idea that insight results from a restructuring of a problem that is accompanied by an unconscious leap in thinking, that it results from greatly accelerated mental processing, and that it is due to a short-circuiting of normal reasoning processes (Perkins 1981). In contrast, the nothing-special view proposes that insight is merely an extension of ordinary processes of perceiving, recognising, learning, and conceiving (Perkins 1981). Here we focus on the restructuring of a problem, a change in a person's perception of a problem situation, where the contribution of 'unexpected discoveries' is stressed.

According to Suwa et al., "unexpected discoveries" refer to designers' perceptual actions of attending to implicit visuo-spatial features in sketches that are discovered in an unexpected way by later inspection (Suwa 2000). Designers sometimes notice consequences that were not intended when they drew (Schön and Wiggins 1992). They also 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 (S-invention)'. In terms of co-evolution, unexpected discoveries can be regarded as the act of finding new aspects of the developing solution-space and S-invention can be regarded as the act of expanding the problem-space. They found that unexpected discoveries of visuo-spatial features in sketches and S-inventions become the strong impetus for the occurrences of each other by using protocol analysis. The findings provide empirical evidence for the co-evolution view.

Research in design cognition has primarily dealt with 2D sketches, so we interpreted concepts and findings from studies of designing with 2D sketches in terms of 3D design and then applied them to our research. Since characteristics of creative design can be modelled in terms of the co-evolution of problem and solution spaces, we look for designers' restructuring a problem and their exploration of the problem space and the solution space. More specifically, we look for unexpected discoveries and S-invention in designing using TUI and GUI environments.

2. Spatial Cognition While Using Tangible Interfaces to Digital Design Models

TUIs are new approaches to human-computer interaction that are often associated with “augmented reality” (AR). Since AR technology blends reality and virtuality, TUIs combine physical and digital worlds, which allow very different “reflective conversation” between the two environments (Arias et al. 1997). Above all, TUIs provide a tangible interaction by turning the physical objects into input and output devices for computer interfaces. The strengths of physical interaction can be explained by two aspects; direct, naïve manipulability and tactile interaction as an additional dimension of interaction. Thus, they enable designers to create and interact with digital models that go beyond the traditional human-computer interface of the keyboard and mouse.

The tangible interactions using TUIs in AR systems can be explained by the concept of “augmented affordance”, posed by Seichter and Kvan (Seichter and Kvan 2004). 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 (Gibson 1979; Norman 1988). We predict that tangible interaction in TUIs account for changes in the designers’ spatial cognition of 3D digital models.

2.1. DESIGNERS’ SPATIAL COGNITION

As a consequence of the diversity of approaches and related disciplines, there is little consistency in what is meant by the term “spatial” (Foreman and Gillett 1997). In this research we define a designer’s spatial cognition as the designer’s perception of the form and spatial relationships of the objects or spaces in 3D design. Associated with the physical interaction, touch is emphasised as a spatial modality linking motor and spatial processes closely while using TUIs to digital models. Kinaesthetic information through a haptic system provides us with the ability to construct a spatial map of objects that we touch (Loomis and Lederman 1986). 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 (Foreman and Gillett 1997). Thus, the movement simulated by the mouse in desk-top systems lacks tactile and kinaesthetic feedback that normally accompanies movement.

Language draws on spatial cognition so that designers can talk about what they perceive and it thereby provides a window on the nature of spatial cognition (Anibaldi and Nualláin 1998). It is based on the assumption that people often use general purpose verbs and prepositions when the context is sufficiently clear to disambiguate them. Thus, we analyse the designers' conversation in order to investigate their spatial cognition. Gesture is also recognized as a good vehicle for capturing visual and spatial information as it is associated with visuo-spatial content. Furthermore, the movement of hands can facilitate recall of visuo-spatial items as well as verbal items (Wagner 2004). People produce some gestures along with their speech, and such speech-accompanying gestures are not just hand moving. Speech and gesture are both characterising the spatial relationships among entities, which are closely related to and may even be beneficial for cognitive processing (Goldin-Meadow 2003; Lavergne and Kimura 1987).

2.2. DIGITAL DESIGN WORKBENCHES

We reviewed various digital design workbenches: metaDESK, iNavigator, BUILD-IT, PSyBench, URP, MIXdesign and ARTHUR system. The metaDESK system was constructed by Ulmer and Ishii (Ullmer and Ishii 1997) with a focus on physical interaction to manipulate the digital environment. Standard 2D GUI elements like 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. The display tablet is served as "a cutting plane" (Lee et al. 2003). BUILD-IT developed by Fjeld et al. (Fjeld 1998) 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 of the scene is projected onto the table and a perspective view of the scene is projected on the wall.

Brave et al. (Brave et al. 1999) designed PSyBench and inTouch, employing tele-manipulation 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 wind-flow into a single, physically based workbench setting. The URP system uses pre-existing building models as input to an urban planning system (Underkoffler and Ishii 1999). 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 (Dias et al. 2002). 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 (Granum et al. 2003).

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 digital workbenches evaluate the new interface technology with respect to spatial cognition or improved understanding of the spatial relationships of the components of the digital model. While TUIs and GUIs will continue to be alternative design environments for digital models, we focus on the differences between them in order to clarify the benefit of TUIs for designers.

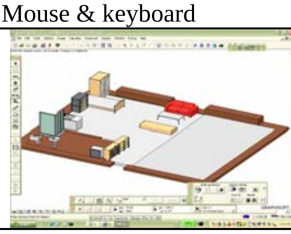
3. Experiment Setting: GUI-based and TUI-based Collaboration

In devising an experiment that can highlight the expected improvement in spatial cognition while using TUIs, we chose to compare design collaboration in the following settings: TUIs on a tabletop design environment and GUIs on a desktop design environment. We expect that this comparison will enable us to verify if and in what way TUIs affect designers' spatial understanding of 3D models in computer-mediated collaborative design.

3.1. DESIGN COLLABORATION IN A GUI ENVIRONMENT

The setting of the GUI design environment is a desktop computer with a GUI such as a mouse, a keyboard and a LCD screen shown in table 1.

TABLE 1. GUI design environment

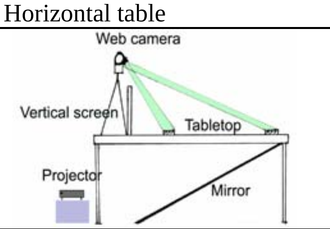
Hardware	Desktop computer/ Mouse & Keyboard
Application	ArchiCAD
Display space	Vertical LCD screen
Task space	Mouse & keyboard
Settings	 

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 time-multiplexed input device controlling different functions at different times (Fitzmaurice 1996). Despite the physical form, the mouse has no physical contextual awareness and lacks the efficiency of specialized tools. 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 (Magerkurth and Peter 2002).

3.2. DESIGN COLLABORATION IN A TUI ENVIRONMENT

We used a digital design workbench with TUIs as a setting for the TUI-based collaboration. The digital design workbench is specifically configured for 3D design and visualization, where designers can manipulate 3D virtual objects directly in a semi-immersive environment and can be spatially aware of each other as well as the design. 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. (Billinghurst et al. 2003), the AR conditions with HMDs cause perceptual problems such as limited field of view, low resolution, and blurry imagery. The design of the digital workbench is shown in table 2 (Daruwala 2004).

TABLE 2. TUI design environment

Hardware	Digital design workbench/3D blocks
Application	ARToolkit
Display	Vertical LCD screen & Horizontal table
Task space	Horizontal table
Settings	 

As multiple, specialized input devices for TUIs, 3D blocks with tracking markers in ARToolKit (Billinghurst et al. 2000) was used. 3D blocks are “space-multiplexed” input devices that can be attached to different functions, each independently accessible (Fitzmaurice 1996). 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.

3.3. EXPERIMENT DESIGN

We conducted four experiments, each experiment consisting of two sessions: a collaborative design task in a GUI environment and a collaborative design task in a TUI environment. 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. Each pair of designers participated in a complete experiment, so we could compare the same designers' across both environments. We will be reporting on one pair of designers in this paper since a change in designers may have a large impact on the results. The two design tasks were similar in complexity and type, and therefore shouldn't have an impact on the results. We needed to have different design tasks so the task would be new when a pair of designers moved to a different design environment. This ensures the designers were engaged in a design task at the same introductory stage. The relative complexity of ArchiCAD did not affect the results of the experiments because only several simple functions such as 'move' and 'rotate' were used for the design tasks.

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 intended to simulate design review meetings for a studio renovation, a home office apartment or an interior design office - the designers inspected the current state of the 3D plan and then produced new ideas by working collaboratively. While the designers developed a 2D layout by placing the furniture, they also had to reason 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 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 were 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 and 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

One way of segmentation is to divide protocols based on verbalization events such as pauses or syntactic markers for complete phrases and sentences (Ericsson and Simon 1993). Another way is looking at the content of the protocol, and divide the protocols into small units along lines of designer's intentions (Suwa 1998). We took the former approach because the intention-based segmentation that applies for single designers using think aloud protocols may be unsuitable for our communication protocols including pairs of designers. We chose individual designers' utterances as segments and retained the utterances as a whole rather than breaking down them into "meaningful" segments. 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. Our categories and definitions are an adaptation of Suwa's coding scheme (Suwa 1998): 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 the designers' actions of attending to visuo-spatial features of the artefacts or spaces. We investigated three types of attentions to an existing design feature, two types of creations of new design features, and three types of unexpected discoveries as a measure of designers' perceptive abilities for spatial knowledge. In particular, unexpected discoveries are regarded as one key to gaining creative outcomes in the end and classified into three distinct types; "visual-feature-type", "relation-type", and "implicit-space-type" (Suwa 2000).

TABLE 4. Types of perceptual actions

Type	Definition: Behaviour	Definition: Dependent on	Feature
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, considers whether the segment indicates if a new goal has been defined. This category is closely related to Suwa et al.'s research (Suwa 2000). In particular, type 1.2, type 1.3, type 1.4, and type 2 are instances of the S-invention of design issues since the issue emerged at that moment for the first time. This category is important in spatial cognition while using TUIs because it highlights the designers' ability to find new relationships in these kinds of new interactive environments. We coded the goals of inventing new functions to clarify designers' problem finding behaviours in the different design environments.

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 type 1.1, type 1.2 and type 1.3.
Type 2	goals to resolve problematic conflicts
Type 3	goals to apply previously introduced functions in the current context
Type 4	repeated goals from a previous segment

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.

5.1. OBSERVATION OF DESIGNERS' BEHAVIOURS

Through direct observation, we noticed that designers in the GUI sessions discussed ideas verbally and decided on a solution before performing 3D modelling actions whereas designers in the TUI sessions communicated design ideas by gesturing at and moving the objects visually and deciding on the location of each piece of furniture as they were manipulating 3D blocks.

Figure 1. GUI-based collaboration

In terms of collaborative interactions, the TUI environment enabled designers to collaborate on handling the 3D blocks more interactively by allowing concurrent access to the 3D blocks and to produce more revisited 3D modelling actions before producing the final outputs. Designers in the GUI environment shared a single mouse compared to multiple 3D blocks, thus one designer mainly manipulated the mouse. On the other hand, with the direct, naïve manipulability of physical objects and rapid visualization, designers in the TUI environment 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 of behaviour between the GUI and TUI sessions in terms of perceiving an existing object or space (type P1, P2, and P3). Designers in the GUI session focused on the individual location itself whereas designers in the TUI session 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 an unwanted 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 P3
GUI 3	Where's the sink? That's the utility area	Type P3
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 P2
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 P2

In terms of attending to a new relation or space (type P4 and P5), designers in the GUI session usually put an object in a position without considering any new relation or space based on the function of the object. On the other hand, designers in the TUI session created and attended to a new spatial relation by placing an object. Table 7 described 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 P4

In comparison to the GUI session, designers discovered a hidden space among objects or a feature of an object unexpectedly when they were revisited (type P6, P7 and P8) more times in the TUI session. 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. The following are examples of unexpected discoveries extracted from the verbal protocols of the two design sessions.

TABLE 8. Unexpected discoveries in the two sessions

Session	Transcript (GUI)	Category
GUI 1	I don't like… it locks very empty there	Type P8
Session	**Transcript (TUI)**	**Category**
TUI 1	You end up with empty space in the middle. how this sofa faces onto her	Type P8
	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 P6

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 TUIs kept attending to existing elements through the design session whereas designers using GUIs 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 TUIs because they suggest that designers' understanding of the spatial relationships of the elements is improved in the TUI environment. Further, the fact that unexpected discoveries are more frequent in the TUI session indicates that the TUI environment encourages designers to perceive hidden features or spaces, which can be interpreted as one of pathways to creative design.

5.3. CODING GOALS FOR S-INVNETION

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 TUI 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

5.3. 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 in the TUI environment are the key actions to discover a hidden feature or space compared to the 3D modelling actions of the GUI environment. 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 TUI and GUI 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 digital design workbench 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 and Future Plan

The results indicate that the digital design workbench with TUIs 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 digital design workbench as a very powerful platform for creative design that involves reasoning about 3D objects and their spatial relationships. Knowledge of the implications of the differences in spatial cognition provide a basis for developing and implementing new design environments as well as provide guidelines for their most effective use. 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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